DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

AUTOMATION SYSTEMS AND DESIGN OF AN AUTOMATED PACKAGING MACHINE

by
Emin KAYSERİLİOĞLU

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İZMİR

AUTOMATION SYSTEMS
AND
DESIGN OF AN AUTOMATED
PACKAGING MACHINE

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"AUTOMATION SYSTEMS AND DESIGN OF AN AUTOMATED PACKAGING MACHINE"** completed by **EMİN KAYSERİLİOĞLU** under supervision of **ASSIST.PROF.DR. ZEKİ KIRAL** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Assist. Prof. Dr. Zeki KIRAL

Supervisor

Prof.Dr. Hira KARAGÜLLE

(Jury Member)

Assist.Prof.Dr. Ahmet ÖZKURT

(Jury Member)

Prof.Dr. Cahit HELVACI
Director
Graduate School of Natural and Applied Sciences

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AUTOMATION SYSTEMS AND DESIGN OF AN AUTOMATED PACKAGING MACHINE

ABSTRACT

Automation is designing, building and implementing automatic machines/systems by which a process or a procedure accomplished without human assistance. The major motivation for automated solutions is the the unit cost decreasing characteristics of automation systems due to the high processing speeds that can't be reached by human.

Automated solutions include several sub-systems which are related with mechanics,electric/electronics and computer technoloy,so modular and mechatronic designing strategies should be routed for integrating these components.

In this thesis, firstly these related sub-systems classsified and explained. After that, an automated packaging machine which is gripping the parts that are being fed with an indexing system, and locating it into a package designed, manufactured, implemented, and tested. Designed packaging machine have five actuators. Two step motors have choosen for indexing rotary and part's holding head linear motions. Other actuators are two pneumatic cylinders which are used for holding head up-and-down motions and package linear feeding and a pneumatic gripper which is designed in the scope of this thesis. Control system of the machine is including three PIC microcontrollers that are a 16F877 used as an master controller (PLC-like functions) and two 16F84s used as step motor controllers. The electronic circuits for PICs designed and assembled on electronic boards and PICs programmed with C. Finally, a control cabinet designed and assembled which is used as an enclousure for the electronic boards and pneumatic valves.

Keywords : Automation sytems, robots, mechatronics, packaging machines.

OTOMASYON SİSTEMLERİ VE OTOMATİK BİR PAKETLEME MAKİNESİNİN TASARIMI

ÖZ

Otomasyon, insan yardımı olmadan çalışan makine ya da sistemlerin tasarımı, inşa ve kurulumu/devreye alınması olarak tanımlanabilir. Otomatik çalışan makinelerin insanların ulaşamayacağı çalışma hızı kapasitelerine ulaşabilmesinin getirdiği birim zaman maliyetlerindeki azalma karakteri, bu tip sistemlerin geliştirilmesindeki temel motivasyon olmaktadır.

Otomatikleştirilmiş çözümler/sistemler mekanik, elektrik/elektronik ve bilgisayar teknolojilerini kapsayan pekçok alt bileşenden oluşmaktadır. Dolayısıyla bu tip sistemlerin inşasında modüler ve mekatronik tasarım stratejilerinin uygulanması gerekmektedir.

Bu tezde, öncelikle bahsi geçen bileşenler sınıflandırılarak açıklanmıştır. Daha sonra bir indeksleme sisteminden beslenen parçaları kavrayıp paketi içine yerleştiren bir otomatik paketleme makinesi tasarlanmış, imalatı gerçeklenmiş, kurulmuş ve test edilmiştir. Tasarlanan makine beş adet hareketlendiriciye sahiptir. İki adet step motor indeksleme sisteminin rotasyonel ve parça taşıyıcı kafanın doğrusal hareketi için seçilmiştir. Geri kalan aktüatörler, taşıyıcı kafanın aşağı-yukarı hareketini ve paketin doğrusal sürülmesini sağlayan iki adet pnömatik silindir ve tez kapsamında tasarlanan pnömatik bir kavrayıcı'dır. Makinenin kontrol sistemi üç adet PIC mikrodenetleyiciden oluşmaktadır. 16F877 ana kontrolcü (PLC-tipi fonksiyonlar) ve iki adet 16F84 step motor kontrolcüsü olarak kullanılmıştır. PIC'ler için gerekli elektronik devreler tasarlanmış, elektronik kartlara monte edilmiş ve PIC'ler C'de proğramlanmıştır. Son olarak, elektronik kart ve pnömatik valflerin muhafaza edildiği bir kontrol panosu tasarlanmış ve montajı gerçekleştirilmiştir.

Anahtar sözcükler : Otomasyon sistemleri, robotlar, mekatronik, paketleme makineleri

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CHAPTER ONE
INTRODUCTION

1.1 Introduction

Automation is designing, building and implementing automatic machines/systems by which a process or a procedure accomplished without human assistance(Sandler, 1999).

Automated solutions include several sub-systems which are related with mechanics, electric/electronics and computer technoloy, so modular and mechatronic designing strategies should be routed for integrating these components.

Roughly speaking, thesis structured with two modules: first module which includes Chapter 1 to 9 gives the related concepts about automation and automation systems components. In Chapter 9, the second module, an automated packaging machine designed, manufactured, implemented and tested in the context which is given in the second paragraph above.

Briefly speaking, the thesis is organized as follows:

Chapter 1 is an introductory chapter and gives the basic concepts about automation, industry and automation relationships and advantages/disadvantages of automated solutions.

Chapter 2 focuses to the manufacturing facilities and gives the related concepts which should be known by the automation systems/solutions designers/providers.

Chapter 3 gives the automation systems layout and explains the concepts which are important in designing automated machines like accuracy, resolution, etc. Finally, the modern trends in automation like modularity, mechatronics, turn-key, etc. have given.

Chapter 4 includes the detailed explanations of the automation systems components with using the "hard" and "soft" task analogies for classification.

Chapter 5 gives the basic concepts about the robotic systems which should be thought as an auxiliary elements of the automated solutions.

Chapter 6 explains and gives examples about applications of the robotic systems in industry.

Chapter 7 gives the related concepts about the control systems which are the "brains" of the automated solutions.

Chapter 8 gives the related concepts about packaging and packaging machines.

Chapter 9 explains the designing process of the automated packaging machine.

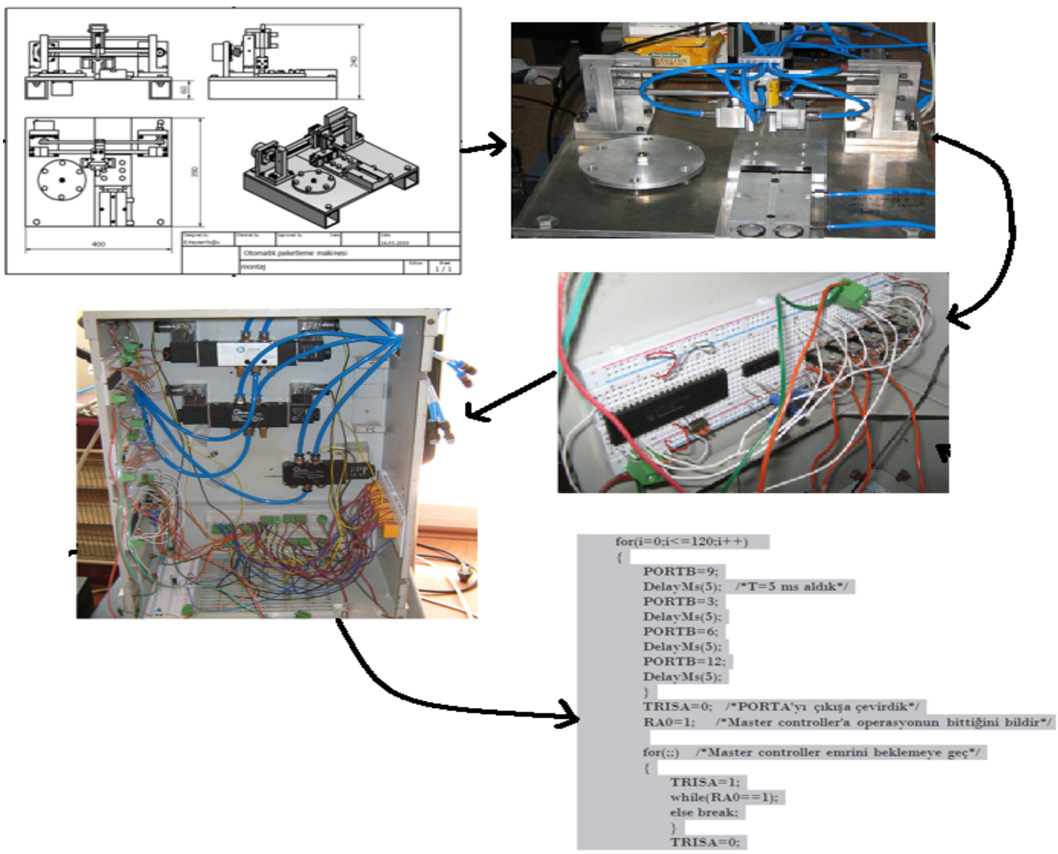


Figure 1.1 Design process of the automated packaging machine

It includes concept of the automated process, selection/designing of the system components, cost and performance analysis and performance improvements simulations as if we were used closed-loop control based servo actuators for the critical motions accept open-loop control based actuators that we had been actually used e.g. the stepper motor we used for gripper holding head's linear motion.

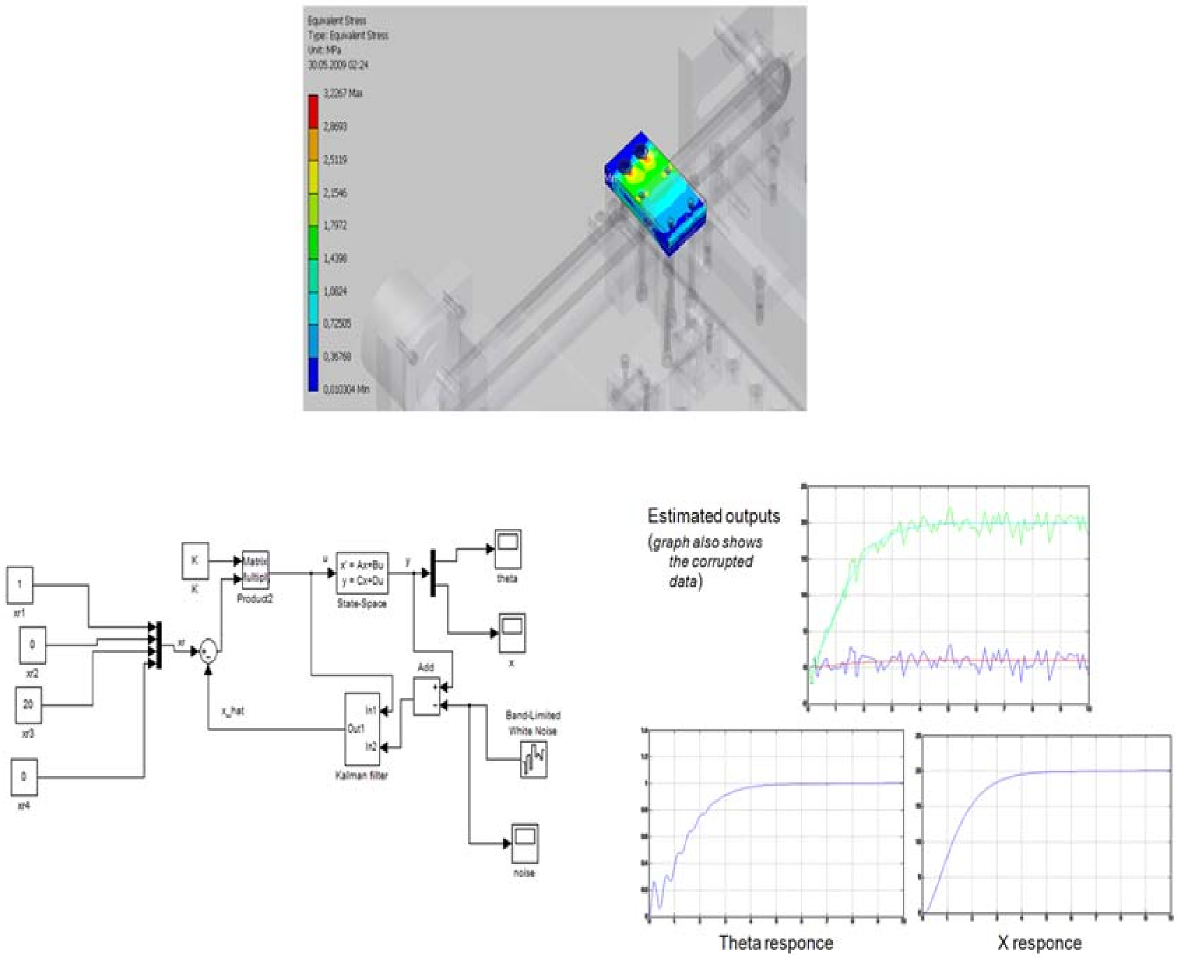


Figure 1.2 Simulation examples which will be explained in Chapter 9

As explained in the previous paragraphs, designing the automated solutions needs modular and mechatronic designing strategies which are generally based on using off-the-shelf components and focuses to the integration of these. In this study, these concepts have been used but for spesific needs, special parts and components also designed with the CAD tools e.g. the gripper used in the automated packaging machine. The CAD based designing process and the result after the manufacturing processes can be seen in the figure 1.3 which is given below.

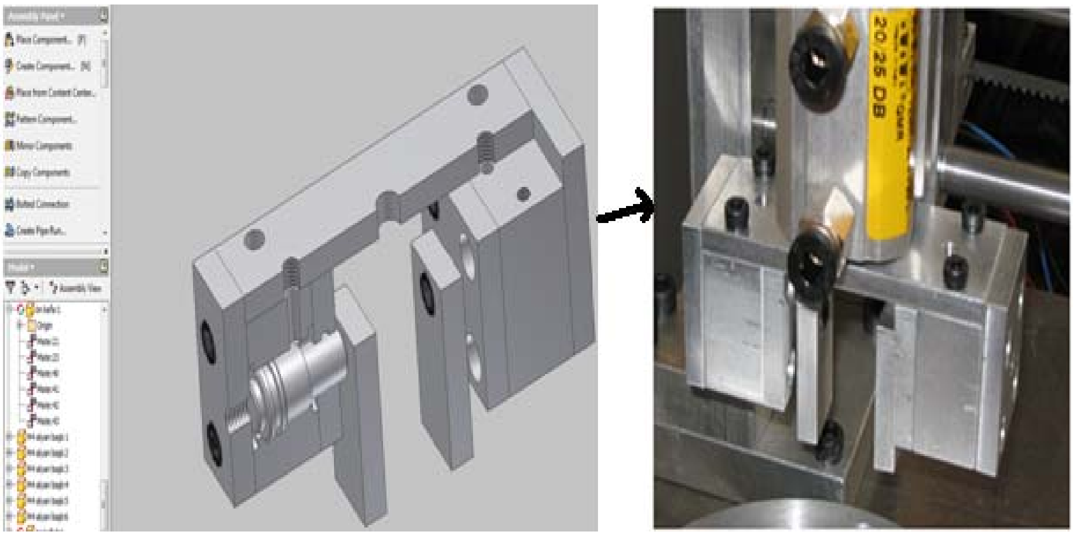


Figure 1.3 Gripper design process

Chapter 10 draws conclusions from the research work documented in this thesis. In addition, the recommendations for the future work are given.

This thesis includes six appendices. Appendix A.1 gives the detailed informations about the industries which the automated solutions have relationships. Appendix A.2 gives the manufacturing drawings for the designed packaging machine. Appendix A.3 gives the electrical circuit diagrams used for "PIC based" master and motor controllers. Appendix A.4 gives the Matlab "m" files used for the simulations of the servo actuators. Appendix A.5 and A.6 gives the "C" codes used for the implementation of the "PICs".

1.2 Industry and Automation

Industry consists of enterprises and organizations that produce and/or supply goods and/or services and can be classified primary, secondary, and service.

Primary industries are those that cultivate and exploit natural resources, such as agriculture and mining. Secondary industries convert outputs of the primary industries into products. Service industries constitutes the service sector of the economy(Groover, 2001).

Generally speaking any industrial activity consisting of a fixed process/procedure can be automated. Secondary industries are the major automation related category of all due to the sequential and fixed nature of manufacturing activities, but automation solutions are also increasing their roles in the other two industries.

A list of spesific industries in these categories is presented in Table 1.1(detailed informations about the industries can be found in Appendix A.1)

Table 1.1 A list of spesific industries

Primary	**Secondary**	**Service(*tertiary*)**
Agriculture	Aerospace	Entertainment
Forestry	Automotive	Financial services
Fishing	Basic&Fabricated metals	Health care
Livestock	Building materials	Hospitality
Quarries	Chemicals	Real estate
Mining	Computer	Telecommunication
Petroleum	Construction	Tourism
	Electronics	Transportation
	Food&Beverage processing	
	Furniture	
	Glass&Ceramics	
	Heavy machinery	
	Home appliances	
	Paper	
	Pharmaceuticals	
	Plastics	
	Publishing	
	Textile&Apparel	
	Utilities	

1.3 Advantages and Disadvantages of Automation

Advantages commonly attributed to automation include higher production rates and increased productivity, more efficient use of materials, better product quality, improved safety, shorter workweeks for labour, and reduced factory lead times. Higher output and increased productivity have been two of the biggest reasons in justifying the use of automation. Despite the claims of high quality from good workmanship by humans, automated systems typically perform the manufacturing process with less variability than human workers, resulting in greater control and consistency of product quality. Also, increased process control makes more efficient use of materials, resulting in less scrap.

Worker safety is an important reason for automating an industrial operation. Automated systems often remove workers from the workplace, thus safeguarding them against the hazards of the factory environment. In the United States the Occupational Safety and Health Act of 1970 (OSHA) was enacted with the national objective of making work safer and protecting the physical well-being of the worker. OSHA has had the effect of promoting the use of automation and robotics in the factory.

Another benefit of automation is the reduction in the number of hours worked on average per week by factory workers. About 1900 the average workweek was approximately 70 hours. This has gradually been reduced to a standard workweek in the United States of about 40 hours. Mechanization and automation have played a significant role in this reduction. Finally, the time required to process a typical production order through the factory is generally reduced with automation.

A main disadvantage often associated with automation, worker displacement, has been discussed above. Despite the social benefits that might result from retraining displaced workers for other jobs, in almost all cases the worker whose job has been taken over by a machine undergoes a period of emotional stress. In addition to displacement from work, the worker may be displaced geographically. In order to find other work, an individual may have to relocate, which is another source of stress.

Other disadvantages of automated equipment include the high capital expenditure required to invest in automation(an automated system can cost millions of dollars to design, fabricate, and install), a higher level of maintenance needed than with a manually operated machine, and a generally lower degree of flexibility in terms of the possible products as compared with a manual system(even flexible automation is less flexible than humans, the most versatile machines of all).

Also there are potential risks that automation technology will ultimately subjugate rather than serve humankind. The risks include the possibility that workers will become slaves to automated machines, that the privacy of humans will be invaded by vast computer data networks, that human error in the management of technology will somehow endanger civilization, and that society will become dependent on automation for its economic well-being.

These dangers aside, automation technology, if used wisely and effectively, can yield substantial opportunities for the future. There is an opportunity to relieve humans from repetitive, hazardous, and unpleasant labour in all forms. And there is an opportunity for future automation technologies to provide a growing social and economic environment in which humans can enjoy a higher standard of living and a better way of life(Britannica, 2009).

CHAPTER TWO
MANUFACTURING MATTERS

2.1 Manufacturing Matters

In the earlier part of the 20th century, manufacturing became a capital intensive activity. A rigid mode of mass production replaced mostly small batch and make-to-order fabrication of products. A turning point was the 1920s. With increased household incomes in North America and Europe came large-scale production of household appliances and motor vehicles. These products steadily increased in complexity, thus requiring design standardization on the one hand and labor specialization on the other. Product complexity combined with manufacturing inflexibility led to long product life cycles (up to 5 to 7 years, as opposed to as low as 6 months to 1 year in today's communication and computation industries), thus slowing down the introduction of innovative products. In the post–World War II (WWII) era we saw a second boom in the manufacturing industries in Western Europe, the U.S.A., and Japan, with many domestic companies competing for their respective market shares. In the early 1950s, most of these countries imposed heavy tariffs on imports in order to protect local companies. Some national governments went a step further by either acquiring large equities in numerous strategic companies or providing them with substantial subsidies. Today, however, we witness the fall of many of these domestic barriers and the emergence of multinational companies attempting to gain international competitive advantage via distributed design and manufacturing across a number of countries(sometimes several continents), though it is important to note that most such successful companies are normally those that encountered and survived intense domestic competition, such as Toyota, General Motors, Northern Telecom(Nortel), Sony, and Siemens. Rapid expansion of foreign investment opportunities continue to require these companies to be innovative and maintain a competitive edge via a highly productive manufacturing base. In the absence of continuous improvement, any company can experience a rapid drop in investor confidence that may lead to severe market share loss.

One can thus conclude that the manufacturing company of the future will be multinational, capital as well as knowledge intensive, with a high level of production automation, whose competitiveness will heavily depend on the effective utilization of information technology(IT)(Benhabib,2003).

2.2 Post-Industrial Revolution History of Manufacturing Technologies

The industrial revolution(1770–1830) was marked by the introduction of steam power to replace waterpower(for industrial purposes) as well as animal-muscle power. The first successful uses for such power in the U.K. and U.S.A. were for river and rail transport. Subsequently, steam power began to be widely used in mechanization for manufacturing(textile, metal forming, woodworking, etc.). The use of steam power in factories peaked around the 1900s with the start of the wide adoption of electric power. Factory electrification was a primary contributor to significant productivity improvements in 1920s and 1930s.

Due to factory mechanization and social changes over the past century, yearly hours worked per person has declined from almost 3000 hours to 1500 hours across Europe and to 1600 hours in North America. However, these decreases have been accompanied by significant increases in labor productivity. Notable advances occurred in the standard of living of the population in these continents. Gross Domestic Product(GDP) per worker increased seven fold in the U.S., 10-fold in Germany, and more than 20-fold in Japan between 1870s and the 1980s (Benhabib,2003).

2.2.1 Machine Tools

Material-removal machines are commonly referred to as ‘‘machine tools”. Such machines are utilized extensively in the manufacturing industry for a variety of material-removal tasks, ranging from simple hole making(e.g.,via drilling and boring) to producing complex contoured surfaces on rotational or prismatic parts (e.g., via turning and milling).

Metal cutting and forming has been a major manufacturing challenge since the late 1700s. Although modern machine tools and presses tend to be similar to their early versions, current machines are more powerful and effective. A primary reason for up to 100-fold improvements is the advancement in materials used in cutting tools and dies. Tougher titanium carbide tools followed by the ceramic and boronnitride(artificial diamond) tools of today provide many orders of magnitude improvement in cutting speeds. Naturally, with the introduction of automatic-control technologies in 1950s, these machines became easier to utilize in the production of complex-geometry workpieces, while providing excellent repeatability. Due to the worldwide extensive utilization of machine tools by small, medium, and large manufacturing enterprises and the longevity of these machines, it is impossible to tell with certainty their current numbers(which may be as high as 3 to 4 million worldwide). Some recent statistics, however, quote sales of machine tools in the U.S.A. to be in the range of 3 to 5 billion dollars annually during the period of 1995 to 2000(in contrast to $300–500 million annually for metal-forming machines). It has also been stated that up to 30% of existing machine tools in Europe, Japan, and the U.S. are of the numerical control(NC) type. This percentage of NC machines has been steadily growing since the mid-1980s, when the percentage was below 10% due to rapid advancements in computing technologies. In Sec. 2.3 we will further address the history of automation in machine-tool control during the 1950s and 1960s(Benhabib,2003).

2.2.2 Industrial Robots

Their initial utilization on factory floors were for simple repetitive tasks in either handling bulky and heavy workpieces or heavy welding guns in point-to-point motion. With significant improvements in computing technologies, their application spectrum was later widened to include arc welding and spray painting in continuous-path motion. Although the commercial use of robots in the manufacturing industry can be traced back to the early 1960s, their widespread use only started in the 1970s and peaked in the 1980s. The 1990s saw a marked decline in the use of industrial robots due to the lack of technological support these robots needed in terms of coping with uncertainties in their environments. The high expectations of industries to replace the human labor force with a robotic one did not materialize. The robots lacked artificial perception ability and could not operate in autonomous environments without external decision-making support to deal with diagnosis and error recovery issues. In many instances, robots replaced human operators for manipulative tasks only to be monitored by the same operators in order to cope with uncertainties. In late 1980s, Japan clearly led in the number of industrial robots. However, most of these were manipulators with reduced degrees of freedom(2 to 4); they were pneumatic and utilized in a playback mode. Actually,only about 10% of the(over 200,000) robot population could be classified as ‘‘intelligent’’ robots complying with the ISO/TR 8373 definition. The percentage would be as high as 80%, though, if one were to count the playback manipulators mostly used in the automotive industry. Today, industrial robots can be found in many high-precision and high-speed applications. They come in various geometries: serial anthropomorphic, cylindrical, and gantry) as well as parallel(Stewart platform and hexapod). However, still, due to the lack of effective sensors, industrial robots cannot be utilized to their full capacity in an integrated sense with other production machines. They are mostly restricted to repetitive tasks, whose pick and place locations or trajectories are a priori known; they are not robust to positional deviations of workpiece locations(Benhabib,2003).

2.2.3 Automotive Manufacturing Industry

The automotive industry still plays a major economic role in many countries where it directly and indirectly employs 5 to 15% of the workforce. Based on its history of successful mass production that spans a century, many valuable lessons learned in this industry can be extrapolated to other manufacturing industries.

Since the beginnings of the industry, productivity has been primarily achieved via product standardization and mass production at the expense of competitiveness via innovation. Competitors have mostly provided customers with a price advantage over an innovative advantage. Almost 70 automotive companies early on provided customers with substantial innovative differences in their products, but today there remain only three major U.S. car companies that provide technologically very similar products. From 1909 to 1926, Ford's policy of making a single, but best-priced,car allowed its competitors slowly to gain market share, as mentioned above, via technologically similar but broader product lines. By 1925,General Motors(GM) held approximately 40% of the market versus 25% of Ford and 22% of Chrysler. In 1927, although Ford discontinued its production of the Model T, its strategy remained unchanged. It introduced a second generation of its Model A with an even a lower price(Ford discontinued production for 9 months in order to switch from Model T to Model A). However, once again, the competitiveness-via-price strategy of Ford did not survive long. It was completely abandoned in the early 1930s(primarily owing to the introduction of the V-8 engine), finally leading to some variability in Ford's product line. In 1923–1924, industrial design became a mainstream issue in the automobile industry. The focus was on internal design as well as external styling and color choices. In contrast to Ford's strategy, GM, under the general management of A. P. Sloan(an MIT graduate), decided to develop a line of cars in multiple pricing categories, from the lowest to the highest. Sloan insisted on making GM cars different from the competition's, different from each other, and different from year to year, naturally at the expense of technological innovation. The objective was not a radical innovation but an offer of variety in frequent intervals, namely incremental changes in design as well as in production processes. Sloan rationalized product variety by introducing several platforms as well as frequent model changes within each platform. His approach to increased productivity was however very similar to Ford's in that each platform was manufactured in a different plant and yearly model changes were only minor owing to prohibitive costs in radically changing tooling and fixturing more than once every 4 to 6 years. The approach of manufacturing multiple platforms in the same plant in a mixed manufacturing environment was only introduced in the late 1970s by Toyota. The question at hand is, naturally, how many platforms does a company need today to be competitive in the decades to come ? Chrysler followed GM's lead and offered four basic car lines in 1929; Chrysler, DeSoto, Dodge, and Plymouth. Unlike GM and Ford, however, Chrysler was less vertically integrated and thus more open to innovation introduced by its past suppliers(This policy allowed Chrysler to gain market share through design flexibility in the pre-WWII era). The automobile's widespread introduction in the 1920s as a non-luxury consumer good benefited other industries, first through the spin-off of manufacturing technologies (e.g., sheet-metal rolling used in home appliances) and second through stimulation of purchases by credit. Annual production of washing machines doubled between 1919 and 1929, while annual refrigerator production rose from 5000 to 890,000 during the same period. Concurrently, the spillover effect of utilization of styling and color as a marketing tool became very apparent. The market was flooded with purple bathroom fixtures, red cookware, and enamelled furniture. One can draw parallels to the period of 1997–2000, when numerous companies, including Apple and Epson, adopted marketing strategies that led to the production of colorful personal computers, printers, disk drives, and so forth(Benhabib,2003).

2.3 Recent History of Computing Technologies

The first electronic computer was built by a team led by P. Eckert and J.Mauchley, University of Pennsylvania, from 1944 to 1947 under the auspices of the U.S. Defense Department. The result was the Electronic Numerical Integrator and Computer(ENIAC); the subsequent commercial version, UNIVAC I, became available in 1950. The first breakthrough toward the development of modern computers came, however, with the fabrication of semiconductor switching elements (transistors) in 1948. What followed was the rapid miniaturization of the transistors and their combination with capacitors, resistors, etc. in multilayered silicon-based integrated circuits(ICs). Today, millions of such elements are configured within extremely small areas to produce processor,memory, and other types of ICs commonly found in our personal computers and other devices(such as calculators, portable phones, and personal organizers). Until the late 1970s, a typical computer network included a centralized processing unit(''main-frame''), most probably an IBM make(such as IBM-360), which was accessed by users first by punched cards (1950–1965) and then by ''dumb'' terminals(1965–1980). The 1970s can be considered as the decade when the computing industry went through a revolution, first with the introduction of ‘‘smart’’ graphic terminals and then with the development of smaller main-frame computers, such as the DEC-PDP minicomputer. Finally came the personal(micro) computers that allowed distributed computing and sophisticated graphical user interfaces(GUIs). In the late 1980s, the impact of revolutionary advances in computer development on manufacturing was twofold. First, with the introduction of computer-aided design(CAD) software(and ‘‘smart’’ graphic terminals), engineers could now easily develop the geometric models of products, which they wanted to analyze via existing engineering analysis software (such as ANSYS). One must, however, not forget that computers(hardware and software) were long being utilized for computer-aided engineering(CAE) before the introduction of CAD software. The second major impact of computing technology was naturally in automatic and intelligent control of production machines. But we must yet again remember that numerical control(NC) was conceived of long before the first computer, at the beginning of the 20th century, though the widespread implementation of automatic-control technology did not start before the 1950s. An MIT team is recognized with the development of the NC machine-tool concept in 1951 and its first commercial application in 1955. The evolution of computer hardware and software has been mirrored by corresponding advances in manufacturing control strategies on factory floors. In late 1960s, the strategy of direct numerical control(DNC) resulted in large numbers of NC machines being brought under the control of a central main-frame computer. A major drawback with such a centralized control architecture was the total stoppage of manufacturing activities when the main-frame computer failed. As one would expect, even short periods of downtime on factory floors are not acceptable. Thus the DNC strategy was quickly abandoned until the introduction of computer numerical control(CNC) machines. In the early 1970s, with the development of microprocessors and their widespread use in the automatic control of machine tools, the era of CNC started. These were stand-alone machines with(software-based) local processing computing units that could be networked to other computers. However, owing to negative experience that manufacturers had with earlier DNC strategies and the lack of enterprise-wide CIM-implementation strategies, companies refrained from networking the CNC machines until the 1990s. That decade witnessed the introduction of a new strategy, distributed computer numerical control(DCNC), in which CNC machines were networked and connected to a central computer. Unlike in a DNC environment, the role of a main-frame computer here is one of distributing tasks and collecting vital operational information, as opposed to direct control (Benhabib,2003).

2.3.1 CAD Software and Hardware

Research and development activities during the 1960s to 1980s resulted in proprietary CAD software running on proprietary computer platforms. In 1963, a 2-D CAD software SKETCHPAD was developed at M.I.T.CADAM by Lockheed in 1969, CADD by Unigraphics, and FASTDRAW by McDonell-Douglas followed this initial development. The 1970s were dominated by two major players, Computer Vision and Intergraph. IBM significantly penetrated the CAD market during the late 1970s and early 1980s with its CATIA software, which was originally developed by Dessault Industries in France, which naturally ran on IBM's main-frame (4300) computer, providing a time-sharing environment to multiple concurrent users. With the introduction of minicomputers(SUN, DEC, HP) in the late 1970s and early 1980s, the linkage of CAD software and proprietary hardware was finally broken, allowing software developers to market their products on multiple platforms. Today, the market leaders in CAD software(ProEngineer and I-DEAS) even sell scaled-down versions of their packages for engineering students(for $300 to 400) that run on personal computers(Benhabib,2003).

2.4 Manufacturing Management Strategies

It has been said many times, especially during the early 1980s, that a nation can prosper without a manufacturing base and survive solely on its service industry. Fortunately, this opinion was soundly rejected during the 1990s, and manufacturing once again enjoys the close attention of engineers, managers, and academics. It is now agreed that an enterprise must have a competitive manufacturing strategy, setting a clear vision for the company and a set of achievable objectives. A manufacturing strategy must deal with a variety of issues from operational to tactical to strategic levels. These include decisions on the level of vertical integration, facilities and capacity, technology and workforce, and of course organizational structure. The successful(multinational) manufacturing enterprise of today is normally divided into a number of business units for effective and streamlined decision making for the successful launch of products and their production management as they reach maturity and eventually the end of life. A business unit is expected continually and semi-independently to make decisions on marketing and sales, research and development, procurement, manufacturing and support, and financial matters. Naturally, a manufacturing strategy must be robust and evolve concurrently with the product. As the history of manufacturing shows us, companies will have to make difficult decisions during their lives(which can be as short as a few years if managed unsuccessfully) in regard to remaining competitive via marketing efforts or innovative designs. As one would expect, innovation requires investment (time and capital): it is risky, and return on investment can span several years. Thus the majority of products introduced into the market are only marginally different from their competitors and rarely survive beyond an initial period. No manufacturing enterprise can afford the ultraflexibility continually to introduce new and innovative products into the market place. Most,instead, only devote limited resources to risky endeavors. A successful manufacturing company must strike a balance between design innovation and process innovation. The enterprise must maintain a niche and a dominant product line, in which incremental improvements must be compatible with existing manufacturing capability, i.e., fit within the operational flexibility of the plant. It is expected that a portion of profits and cost reductions achieved via process innovations on mature product lines today will be invested in the R&D of the innovative product of tomorrow. One must remember that these innovative products of the future can achieve up to 50 to 70% market-share penetration within a short period from their introduction(Benhabib,2003).

2.4.1 Manufacturing Flexibility

Manufacturing flexibility has been described as the ability of an enterprise to cope with environmental uncertainties: ‘‘upstream’’ uncertainties, such as production problems(e.g., machine failures and process-quality problems) and supplier-delivery problems, as well as ‘‘downstream’’ uncertainties due to customer-demand volatility and competitors’ behavior. Rapid technological shifts, declining product life cycles, greater customization, and increased globalization have all put increased pressure on manufacturing companies significantly to increase their flexibility. Thus a competitive company must today have the ability to respond to customer and market demands in a timely and profitable manner. Sony is such a company, that has introduced hundreds of variations of its original Walkman in the past decade. Manufacturing flexibility is a continuous medium spanning from operational to strategic flexibilities on each end of the spectrum: operational flexibility(equipment versatility in terms of reconfigurability and reprogrammability), tactical flexibility (mix, volume, and product-modification robustness), and strategic flexibility(new product introduction ability)(Benhabib,2003).

2.4.2 Vertical Integration Versus Outsourcing

Every company at some time faces the simple question of ‘‘make or buy’’. As discussed above, there exists a school of thought in which one maintains tactical or even strategic flexibility through outsourcing. But it is also common manufacturing wisdom that production adds value to a product,whereas assembly and distribution simply add cost. Thus outsourcing must be viewed in the light of establishing strategic alliances while companies join together with a common objective and admit that two hands sometimes can do better than one. Naturally, one can argue that such alliances are in fact a form of vertical integration. The American auto industry, in its early stages, comprised companies that were totally vertically integrated. They started their production with the raw material(for most of the vehicle components) and concluded their organizational structure with controlling distribution and retail sales. Chrysler was one of the first American companies to break this organizational structure and adopt the utilization of(closely allied) supply chains. IBM was one of the latecomers in reducing its vertical integration and forming alliances with chip makers and software developers for its PC product line. Managers argue in favor of vertical integration by pointing to potential lower costs through savings on overall product design and process optimization,better coordination and concurrency among the activities of different manufacturing functions(financial, marketing, logistics), and finally by maintaining directly their hand on the pulse of their customers. Another strong argument is the reduction of uncertainties via better control over the environment(product quality, lead times, pricing strategies, and of course intellectual property). A common argument against vertical integration has been that once a company crosses an optimal size, it becomes difficult to manage, and it loses its innovative edge over its competitors. Many such companies quickly(and sometimes not so quickly) realize that expected cost reductions do not materialize and they may even increase. Vertical integration may also lead a company to have less control over its own departments. While it is easier to let an under-performing supplier go, the same simple strategy cannot be easily pursued in-house(Benhabib,2003).

2.4.3 Taylor/Ford Versus Multitalented Labor

Prior to discussing the role of labor in manufacturing, it would be appropriate briefly to review production scales. Goods produced for the population at large are manufactured on a larger scale than the machines used to produce them. Cars, bicycles, personal computers, phones, and household appliances are manufactured on the largest scale possible. Normally, these are manufactured in dedicated plants where production flexibility refers to a family of minor variations. Machine tools, presses, aircraft engines, buses, and military vehicles on the other hand are manufactured in small batches and over long periods of time. Naturally, one cannot expect a uniform labor force suitable for both scales of manufacturing. While operators in a job-shop environment are expected to be multitalented(‘‘flexible’’), the labor force in the mass production environment is a collection of specialists. The latter is a direct product of the labor profile advocated by F. Taylor(an engineer by training) at the turn of the 20th century and perfected on the assembly lines of Ford

Motor Company. In the pre-mass-production era of the late 1880s, manufacturing companies emphasized ‘‘piece rates’’ in order to increase productivity, while floor management was left to the foremen. However, labor was not cooperative in driving up productivity, fearing possible reductions in piece rates. In response to this gridlock, Taylor introduced the ‘‘scientific management’’ concept and claimed that both productivity and salaries(based on piece rates) could be significantly improved. The basis of the claim was optimization of work methods through a detailed study of the process as well as of the ergonomic capability of the workers(Some trace the beginning of the discipline of industrial engineering to these studies). Taylor advocated the breaking down of processes into their smallest possible units to determine the optimal way(i.e., the minimum of time) of accomplishing the individual tasks. Naturally at first implementation depended on the workers’ willingness to specialize on doing a repetitive task daily, which did not require much skill, in order to receive increased financial compensation(Some claim that these well-paying blue-collar jobs significantly reduced motivation to gain knowledge and skills in the subsequent generations of labor). In order to reduce wasted time, Taylor required companies to shorten material-handling routes and accurately to time the deliveries of the subassemblies to their next destination, which led to in-depth studies of routing and scheduling, and furthermore of plant layouts. Despite significant productivity increases, however, Taylor’s ideas could not be implemented in job shops, where the work involved the utilization of complex processes that required skilled machinists to make decisions about process planning. Lack of mathematical modeling of such processes, even today, is a major factor in this failure, restricting Taylor’s scientific management ideas to simple assembly tasks that could be timed with a stopwatch. Taylor’s work, though developed during 1880 to 1900, was only implemented on a larger scale by H. Ford on his assembly lines during 1900 to 1920 (and much later in Europe). The result was synchronous production lines, where operators(treated like machines) performed specialized tasks during their shifts for months. They were often subjected to time analyses in order to save, sometimes, just a few seconds. On a larger scale,companies extrapolated this specialization to the level of factories, where plants were designed to produce a single car model, whose discontinued production often resulted in the economic collapse of small towns. The standarization of products combined with specialized labor increased efficiency and labor productivity at the expense of flexibility. Ford Motor Company's response to growing demands for product variety was ''They can have any color Model T car, so long as it is black.'' This attitude almost caused its collapse in the face of competition from GM under the management of A. Sloan, which started to market four different models by 1926. GM managed to remain competitive by maintaining standarization at the fundamental component and subassembly level, while permitting customers to have some choice in other areas. Following the era of the Taylor/Ford paradigm of inflexibility, flexible manufacturing was developed as a strategy, among others, in response to increased demand for customization of products, significantly reduced leadtimes, and a need for cost savings through in-process and post-process inventory reductions. The strategy has become a viable alternative for largebatch manufacturing because of (1) increases in in-process quality control(product and process), (2) technological advancements spearheaded via innovations in computing hardware and software, and (3) changes in production strategies(cellular manufacturing, just-in-time production, quick setup changes, etc.). One can note a marked increased in customer inflexibility over the past two decades and their lack of willingness to compromise on quality and lead-time. Furthermore, today companies find it increasingly hard to maintain a steady base of loyal customers as global competitiveness provides customers with a large selection of goods. In response, manufacturing enterprises must now have the ability to cope with the production of a variety of designs within a family of products, to change or to increase existing product families and be innovative. Due to almost revolutionary changes in computing and industrial automation technologies, shop-floor workers must be continually educated and trained on the state of the art. The above described ''factory of the future'' requires labor skilled not only in specific manufacturing processes but as well in general computing and control technologies. Naturally, operators will be helped with monitoring and decision-making hardware and software integrated across the factory. A paramount task for labor in manufacturing will be maintenance of highly complex mechatronic systems. Thus these people will be continuously facing intellectual challenges, in contrast to the boredom that faced the specialists of the Taylor Ford factories(Benhabib,2003).

2.4.4 MRP Versus JIT

A follow-up to Taylor's paradigm of minimizing waste due to poor scheduling was the development of the material requirements planning(MRP) technique in the 1960s. MRP is time-phased scheduling of a product's components based on the required delivery deadline of the product itself. An accurate bill of materials(BOM) is a necessity for the successful implementation of MRP. The objective is to minimize in-process inventory via precise scheduling carried out on computers. Just-in-time(JIT) manufacturing, as pioneered in Japan by the Toyota Motor Company in early 1970s and known as the kanban or card system, requires operators to place orders to an earlier operation, normally by passing cards. As with MRP, the objective is inventory minimization by delaying production of components until the very last moment. Although often contrasted, MRP and JIT strategies can be seen as complementary inventory management strategies. JIT emphasizes that production of any component should not be initiated until a firm order has been placed—a pull system. MRP complements this strategy by backscheduling the start of the production of this part in order to avoid potential delays for lengthy production activities. MRP anticipates a pull command in advance of its occurrence and triggers the start of production for timely completion and meeting a future demand for the product in a timely manner. U.S. manufacturers, prior to their encounter with JIT manufacturing, expected MRP magically to solve their complex scheduling problems in the early 1970s, they quickly abandoned it while failing to understand its potential. Although the modest gains of MRP were to be strengthened by the development of manufacturing resource planning(also known as MRP II) in the 1980s, with the introduction of JIT at the same time period, many manufacturing managers opted out from implementing MRP II in favor of JIT, only to recognize later that the two were not competitive but actually complementary techniques for inventory management. A key factor in this was the common but false belief that MRP requires large-batch production owing to the long periods of time needed to retool the machines. Naturally, JIT was quickly noted to be not as a simple technique as it appeared to be but very challenging to implement. JIT had arrived to the U.S.A. from Japan, where the concept of single-minute die exchange(SMDE) allowed manufacturers to have small batches and product mix on the same line. SMDE, when combined with in-process quality control, was a winning strategy. It took almost a decade for the U.S. manufacturers to meet the triple-headed challenge of JIT, SMDE, and quality control. Today one can easily see the natural place of JIT in manufacturing enterprises, where orders are received via the internet and passed on to the factory floor as they arrive. JIT eliminates large in-process(or even post production) inventories and allows companies to pass on the significant cost savings to the customers. However, with reduced in-process inventories,a plant is required to have eliminated all potential problems in production in regard to machine failures and product quality. For example,it is not unusual for an automotive parts manufacturing company to work with half-a-day inventory. Industrial customers expect multiple daily deliveries from their suppliers, with potentially severe penalties imposed on delivery delays(Benhabib,2003).

2.5 International Manufacturing Management Strategies

The 20th century witnessed the development of manufacturing strategies typical to certain continents, countries, and even some specific regions within federalist countries. Current multinational companies, however, must develop manufacturing strategies tailored to local markets as well as have an overall business strategy to compete globally. Prior to a brief review of several key economic engines in the world, it would be appropriate to define manufacturing strategy as a plan to design, produce, and market a wellengineered product with a long-range vision. Competitive priorities in this context can be identified as quality(highest ranked), service, cost, delivery,and product variety. Thus a comprehensive strategy would require design and manufacture of a superior product(backed by an excellent service team) produced at lower costs than the competitor’s and delivered in a timely manner (Benhabib,2003).

2.6 Information technology-based Manufacturing

The transition from the agrarian society of the 1700s to the industrial society of the 1900s resulted in the industrialization of agriculture, and not its disappearance. Today, only 3% of Americans are engaged in agricultural activities in contrast to the 90% of the workforce in the 1700s. Similarly, in the past century, we did not witness the disappearance of manufacturing, but only its automation. By 1999, the manufacturing sectors in the U.S.A. constituted only 18% of overall employment, while the number for Japan was down to 21%. At the same time, the services industry grew to 72% in the U.S.A. and to 63.7% in Japan. As we progress through the first decades of the information age, it is expected that globalization will cause the total entanglement of the world's economies as never before(Benhabib,2003).

2.6.1 The Internet and the World Wide Web

The start of the World Wide Web(WWW), or simply the web, can be traced to the work of T. Berners-Lee at the European Particle Physics Laboratory(CERN) in Switzerland around 1989. Although the internet was already around since the 1970s, the difficulty of transferring information between locations restricted its use primarily to academic institutions. It took more than two decades and tens of dedicated computer scientists in Europe and the U.S.A. to bring the web into the forefront. The first version of the hypertext application software only ran on one platform(NEXT, developed by S. Jobs, cofounder of Apple Computer) and was released to a limited number of users in 1991. P. Wiu, a Berkeley university student, released a graphical browser in the U.S.A. in 1992 that was capable of displaying HTML graphics, doing animation, and downloading embedded applications off the internet. The two following browsers were Mosaic, developed in 1993, and Gopher, developed at the University of Minnesota at about the same time. However,when the University of Minnesota announced that they would consider a licensing fee for Gopher, it was disowned by the academic community and died quickly. The principle at stake was the threat to academic sharing of knowledge in the most open way. In 1994, the general public was for the first time given access to the web through several internet service providers via modem connections. The year was also marked by the release of Netscape's first version of Navigator, originally named Mozilla, free of charge. Finally, late in the year, the WWW Consortium(W3C) was established to oversee all future developments and set standards. Microsoft's version of their browser, Internet Explorer, was released bundled with their Windows 95 version after a failed attempt to reach a deal with Netscape. By 1996, millions of people around the world were accessing the web, an activity that finally caught the attention of many manufacturing companies and started the transformation of the whole industry into information technology(IT)-based supply chains(spanning from customers at one end to component suppliers at the other)(Benhabib,2003).

2.6.2 IT-Based Manufacturing

As mentioned above, the transformation to an IT-based economy began in the 1970s with rapid advances in computing and the continued spirit of academics who believe in the free spread of knowledge. The 1990s were marked by the emergence of the web as a commercial vehicle. Today, highly competitive markets force manufacturing enterprises to network; they must place the customer at the center of their business while continuing to improve on their relationships with suppliers. This transformation will, however, only come easy to companies that spent the past two decades trying to achieve manufacturing flexibility via advanced technologies(for design, production, and overall integration of knowledge sharing) and implementation of quality-control measures. IT-based manufacturing requires rapid response to meet personalized customer demands. A common trend for manufacturing enterprises is to establish reliable interconnected supply chains by pursuing connectivity and coordination. A critical factor to the success of these companies will be the managing of(almost instantaneous) shared information within the company through intranets and with the outside world through extranets. The task becomes increasingly more difficult with large product-variation offerings. Information sharing is an important tool in reducing uncertainties in forecasting and in thus providing manufacturers with accurate production orders. In the next decade, we should move toward total collaboration between the companies within a supply chain, as opposed to current underutilization of the web through simple information exchange on demand via extranets. True collaboration requires the real-time sharing of operational information between two supply-chain partners, in which each has a window to the other's latest operational status. In a retail market supply environment this could involve individual suppliers having real-time knowledge of inventories as well as sales patterns and make autonomous decisions on when and what quantity to resupply. Similarly, in supplying assemblers, component manufacturers can access the formers' production plans and shop status to decide on their orders and timing. Whether the web has been the missing link in the advancement of manufacturing beyond the utilization of the latest autonomous technologies will be answered in the upcoming decade by manufacturing strategy analysts. In the meantime, enterprises should strive to achieve high productivity and offer their employees intellectually challenging working environments via the utilization of what we know now as opposed to reluctantly waiting for the future to arrive(Benhabib,2003).

CHAPTER THREE
AUTOMATION SYSTEMS

3.1 Automation Systems Layout

It is possible to describe a generalized layout of automated machines/systems almost regardless of the level of control to which are belongs. The building-block approach is an effective means of design/describe of automated machines/systems and the following building blocks may be used in the layout of automation systems.

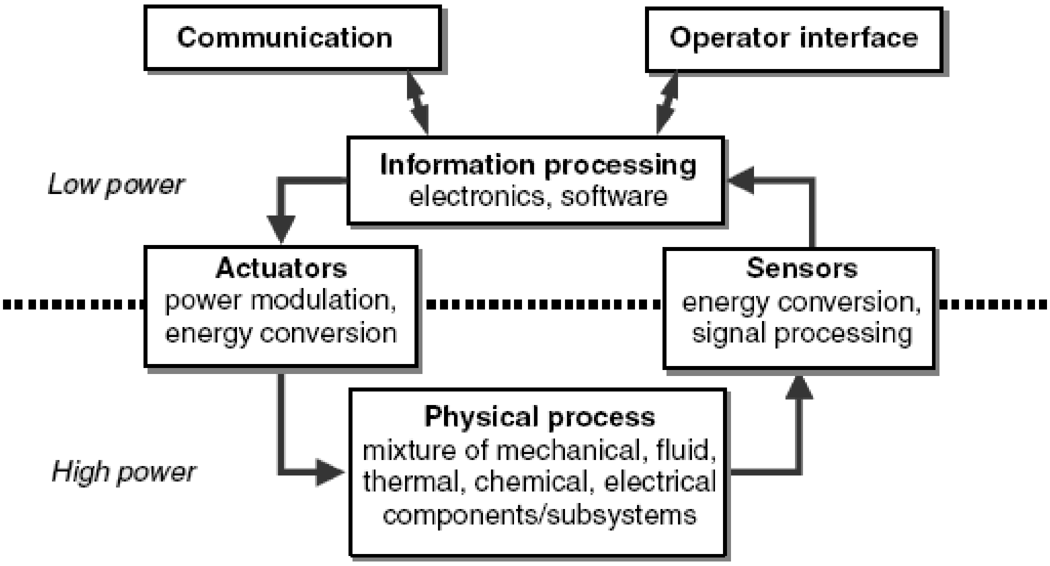


Figure 3.1 Layout of automation systems with the building blocks approach(Skvarenina, 2002)

3.2 Finding the Concept of a Process/Procedure to Automate

There are several approaches to this problem. *The first approach* is to try to *copy the manual process,* that is, to imitate the manipulations of the human hands and arms by mechanical means.

The *second approach* to the question framed in the title of this section: *copy existing concepts in the same industry or in adjacent industrial fields*.

Finally, the *third approach* to the search for manufacturing concepts involves *scientific or engineering research.* This situation arises when:

- A completely new product is under consideration and no prototypes can be found in any technical field or industry.
- The existing prototypes of the processing techniques are too slow, too expensive,yield unsatisfactory quality, or require inaccessible materials or techniques(Sandler,1999).

3.3 Performance Criterians for the Automated Machines

Any machine, from a machine tool to a photocopier to a camera, is an assembly of components that are designed to work together to achieve a desired level of performance, and the automated machines are not the exception. Each machine has a budget for cost and performance, and achieving the best balance between the two, regardless of the function of the machine.

In order to be able to effectively develop a design for an automated machine, the design engineer must simultaneously envision in his/her head the functions the machine must perform alongside a pictorial library of component technologies(e.g., bearings, actuators, and sensors), generic machine configurations(e.g., cast or welded articulated and/or prismatic structures), analysis techniques(e.g., back-of-the-envelope and finite element methods), and manufacturing methods(e.g., machine, hand, or replication finished). In addition, the machine design engineer must be aware of the basic issues faced by the sensor and electronics engineer, the manufacturing engineer, the analyst, and the controls engineer. Only by a simultaneous consideration of all design factors can a viable and effective design be rapidly converged upon. Awareness of current technological limitations *in all fields* can also help a design engineer to develop new processes, machines, and/or components.

The goal of the automated machine design engineer is to make all the components of the machine in proper proportion of each other, both in relation to their physical size and the capabilities of the servocontroller and power systems. If a component is oversized, it may increase the cost of the machine while performance may not be increased. If a component is too small, the rest of the machine's components may never reach their potential and machine performance will suffer. Note that size is a function of static and dynamic qualifiers. Components that behave well statically do not necessarily have good dynamic performance.

In today's world where rapid time to market is essential, the design of quality automated machines depends on the ability of the design and the manufacturing engineers to predict how the machine will perform before it is built. Kinematics of a machine are easily tested for gross functionality using mechanism synthesis and analysis software. Wear rates, fatigue, and corrosion are often difficult to predict and control, but for the most part are understood problems in the context of machine tool design.Hence perhaps the most important factors affecting the quality of a machine are the accuracy, repeatability,and resolution of its components and the manner in which they are combined. Accordingly, minimizing machine cost and maximizing machine quality mandate predictability of accuracy, repeatability, and resolution.

In the light of understanding the science of design, one must always consider practical applied philosophy. A few broad design guidelines for the automated machine designer include:

- Subject all decisions to an "is there a better way" value analysis based on system considerations.
- Always picture in your mind how the system will be manufactured, assembled, used, and maintained.
- Minimize the number of parts in an assembly and minimize their complexity.
- Maximize the number of instances where reference surfaces and self-locating "snap together" parts can be used.
- Whenever possible, take advantage of kinematic design principles.

- Utilize new materials and technologies to their fullest potential.
- Read continuously and familiarize yourself with technologies in many areas.
- Observe continuously and familiarize yourself with products in many areas (Kreith,1999).

3.3.1 Accuracy,Repeatability,and Resolution

There are three basic definitions to remember with respect to how well a machine moving parts can position its axes: *accuracy, repeatability(precision)*, and *resolution*.

Accuracy is the maximum translational or rotational error between the desired and the real position.

Repeatability(precision) is the error between a number of successive attempts to move the machine to the same position, or the ability of the machine to make the same motion over and over. Bidirectional repeatability is the repeatability achieved when the point is approached from two different directions. This includes the effect of backlash in a leadscrew. Accuracy is often defined in terms of the mean, and repeatability in terms of the standard deviation. The standard deviation is used in the determination of the probability of occurrence of an event in a system that has a normal distribution. Often the key to repeatability is not within the machine itself, but in isolating the machine from variations in the environment.

Resolution is the larger of the smallest programmable step or the smallest mechanical step the machine can make during point-to-point motion. Resolution is important because it gives a lower bound on the repeatability. When a machine's repeatable error is mapped, the resolution becomes important if the mapped errors are to be compensated for by other axes.

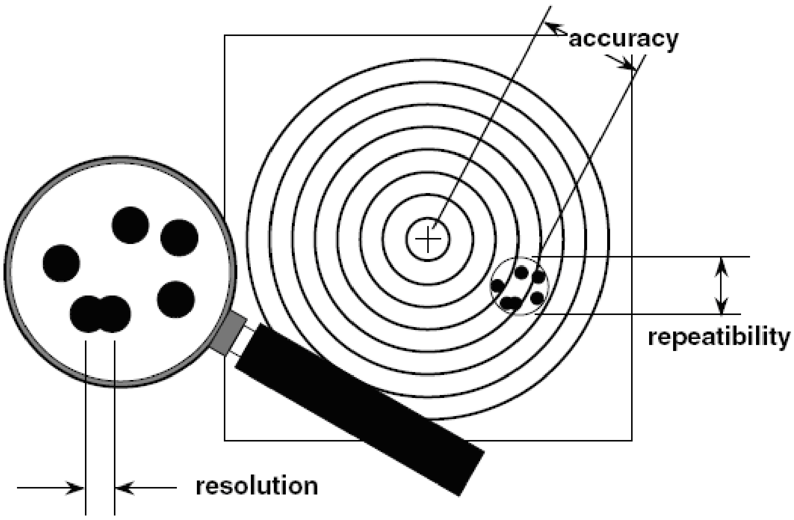


Figure 3.2 Visualization of accuracy,repetability,and resolution(Kreith, 1999)

3.3.2 Sources of Errors

Generally, the sources of errors may be broken into six categories: geometric errors, dynamic errors, workpiece effects, thermal errors, external load errors and assembly affects.

Geometric errors manifest themselves in both translational and rotational errors on a machine tool. Typical causes of such errors are lack of straightness in slideways, nonsquareness of axes, angular errors, and static deflection of the machine tool. Angular errors are, perhaps, the least understood and most costly of the various geometric errors. They are enhanced and complicated by the fact that they are typically amplified by the linear distance between the measurement device and the point of measurement(Abbe error). They are also the errors that can result in the largest improvement with simple design modifications like reducing the Abbe offset. With proper procedures, instrumentation and careful metrology, many errors can be identified, predicted and held within the desired level of the error budget.

Dynamic errors are typically caused by machine tool vibration(or chatter). They are generated by exciting resonances within the machine tool's structure. Current research is investigating the prediction of vibrations in machine tools; however, from a practical perspective, this is quite difficult. Usually, a machine tool is built and its resonant frequencies are determined experimentally. The machine's controller can then be programmed to avoid combinations of feeds and speeds that may excite its various resonances. Typically, the best one can do during the design phases of machine tools is to design a structure that is stiff, light weight, and well damped.

The workpiece can affect a machine tool's accuracy and precision in two manners: deflection during the functional process and inertial effects due to motion. Deflection may be addressed by reducing the overall compliance of the machine tool. This is a relatively simple and well understood solution. Inertial effects of the workpiece, however, are not as simple to address. They become more pronounced with the increased speed that is associated with higher production rates. They are one of the critical limiting factors in high speed machining and typically their severity increases nonlinearly with respect to speed. Inertial effects may manifest themselves in several manners including asymmetry about a rotating axis and overshoot on a linear slide. A typical solution to these rotary problems is to balance the spindle with the workpiece mounted on it. Proper design of servo systems as well as reasonable trajectories(smooth acceleration and velocity profiles) can substantially reduce inertial errors. Also, position probes used in conjunction with the machine tool can inform the controller if the workpiece is, indeed, tracking the proper trajectory.

Thermal errors are probably the most significant set of factors that cause apparent non-repeatable errors in a machine tool. These errors result from fluctuating temperatures within and around the machine tool. They also result from nonfluctuating conditions at constant temperatures other than 20°C. Although deviations in machine tool geometry from thermal causes may be theoretically calculated, in practice such an analysis is difficult at best to successfully achieve even in the simplest of machine tools. Thus, proper thermal control is required. For typical machine tools, thermal errors may be caused by a wide variety of fluctuating heat sources including motors, people, coolant, bearings, and the cutting process. Furthermore, variations in the temperature of the environment may cause substantial thermal errors.

External Load-Induced Errors that cause errors in a machine include gravity loads, cutting loads, and axis acceleration loads. The difficulty in modeling load-induced errors lies in their often distributed and/or varying effects. The types of errors discussed thus far have been geometrically induced and were a function of position. Load-induced errors, on the other hand, are often distributed throughout the structure.

Assembly effected errors can be induced even if all machine components are within required tolerance prior to assembly, additional load-induced errors can be introduced during assembly. The first type of error is forced geometric congruence between moving parts. An example is the bolting of a leadscrew to a carriage, where the nonstraightness of the leadscrew shaft creates a straightness error in the carriage with a period equal to the lead of the screw. A common example is mounting a mirror at its four corners, which often creates a visible distortion. The second type of error is the effect of the assembly process on the stiffness of the structure itself. A third type of error, one that can be predicted, is the deformation of the machine when forces are applied to preload bearings and bolts. In addition, errors may also be caused by clamping or locking mechanisms(Hurmuzlu,2002 and Kreith,1999).

3.4 Trends in Automation Systems

3.4.1 Mechatronics

The definition of mechatronics has evolved since the original definition by the Yasakawa Electric Company.In trademark application documents, Yasakawa defined mechatronics in this way:

The word, Mechatronics, is composed of ‘mecha’ from mechanism and the ‘tronics’ from electronics.In other words, technologies and developed products will be incorporating electronics more and more into mechanisms, intimately and organically, and making it impossible to tell where one ends and the other begins.

The definition of mechatronics continued to evolve after Yasakawa suggested the original definition, e.g. from the Internet's free encyclopedia, Wikipedia, we find the description that

Mechatronics is centered on mechanics, electronics and computing which, combined, make possible the generation of simpler, more economical, reliable and versatile systems(Bishop,2008).

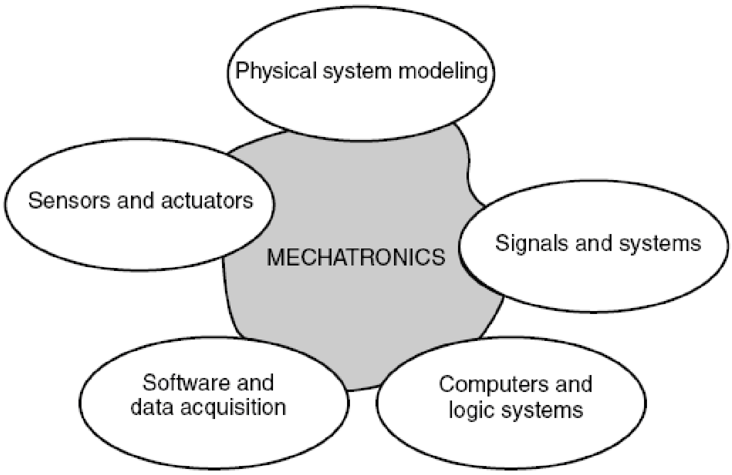


Figure 3.3 Key elements of mechatronics(Bishop, 2008)

3.4.2 Modularity

Modularity is a general systems concept, typically defined as a continuum describing the degree to which a system's components may be separated and recombined. It refers to both the tightness of coupling between components, and the degree to which the "rules" of the system architecture enable(or prohibit) the mixing and matching of components. Its use, however, can vary somewhat by context. In engineering and automation modularity means: building larger systems by combining smaller subsystems(Wikipedia,2009).

Newly developed machines and plants must bring the machine manufacturer a quick return on the development costs, and the owner a quick return on the investment costs. The product life cycle for consumer products continues to get shorter and shorter. The possibility of building machines in such a way that they can be reconfigured quickly and extensively,and thus adapted to new tasks, is critical for the competitiveness of these manufacturers today. Numerous machine manufacturers have therefore started to give their machines' mechanics a modular structure, and to use developed and tested modules over and over again with minimal adaptation.

The definition of a modular system demands extensive conceptual work. The machine modules are self-contained function blocks with defined interfaces. They can be exchanged without influencing the other modules of the machine. Modules for example can contain mechanical, pneumatic, and electrical elements, and of course also control functions.The control functions typically include motion control, logic control, technology functions(for example, temperature control), and HMI. When it comes to control design, every machine module has elements assigned to these four areas from a control-technical point of view.

At the moment, there are two basic topology structures for modular automation. The first is more suitable for compact machines with central control. With this structure, the automation functionality of the machine is already determined in the engineering. The control programs for motion control, logic control, technology, the user interface, and the appropriate hardware configuration are selected from modules of a library. This process can be implemented within the engineering system, or with the help of a master configuration database – even manually in simple systems. The basic program in the control is the same in every machine variant. Depending on the machine options used, extra program modules are loaded, and the appropriate faceplates are added to the user interface.

The second topology variant refers to a distributed automation structure with mechatronic function blocks. Here the modularization continues to be further developed using the new possibilities offered by modern industrial communication and Component Based Automation. The modules have their own intelligence and are connected with each other by clearly defined interfaces. The functionality of the modules is encapsulated inside of the module software.

The advantages are obvious: individual modules can be developed, produced, and commissioned independently; extensions to a module can be made largely without influencing the machine as a whole; modules can be exchanged without affecting adjacent sections of the machine; and multifunctional communication interfaces reduce wiring expenses(Siemens,2005).

3.4.3 Flexibility

Flexibility is used as an attribute of various types of systems. In the field of engineering systems design, one can define flexibility as the ability of a system to respond to potential internal or external changes affecting its value delivery, in a timely and cost-effective manner. Thus, flexibility for an engineering system is the ease with which the system can respond to uncertainty in a manner to sustain or increase its value delivery. It should be noted that uncertainty is a key element in the definition of flexibility. Uncertainty can create both risks and opportunities in a system, and it is with the existence of uncertainty that flexibility becomes valuable (Wikipedia,2009).

Time is absolutely crucial in today’s industrial production.Loss of time due to a machine changeover from one product to another is often a major cost factor. Here, the focus is on flexible, fast and easy changeover and affordable investment levels.

Dedicated(“hard”) automation is dying out due to: high variant floras(customer driven) and short product life-cycles(Onori,2003).

3.4.4 Turn-key

The term *turn-key*(also called *turnkey*) derives from the idea that the end user can just turn a key and the system is ready to go. Turnkey systems include all the hardware and software necessary for the particular application(Webopedia,2009).

Today's business climate has limited the engineer's ability to build most systems themselves, especially the larger and more complex systems.In particular, staffing cutbacks, expanding product variations and increasing system complexity—when coupled with shrinking implementation dates—have made manufacturers more reliant on the full turnkey services offered by an integrator. Turnkey systems are usually advantageous for highly specialized equipment designs. If a company does not have the specialized expertise inhouse, it makes a lot of sense to go turnkey.

By tapping outside expertise or purchasing equipment from one source, manufacturers can:

- Maximize productivity. If correctly specified, responsibility is clear and the buyer's employees can concentrate on their core business. The systems integrator or machine builder assumes day-to-day project management responsibilities.
- Provide for single-source accountability to assure that interaction between devices, components and machinery is one party's responsibility.
- Assure continuity in controls and mechanical design that provides for a smoother operating system.
- Minimize the risk requirements and management requirements for in-house engineering to bring the equipment online.
- Inject new ideas and concepts. Inhouse projects run the risk of using old ideas and old technology. For instance, designs tend to follow similar automation themes that are part of the culture of the company. By using outside services, technological advances as well as alternative automation approaches can be explored(Weber, 2004).

CHAPTER FOUR
COMPONENTS OF AUTOMATION SYSTEMS

4.1 Components for "Hard" Tasks

Components for "hard" tasks refers to the components that have a direct relationship with the physical process/procedure which is the subject of the automation.

4.1.1 Chasis(also called "machine frame")

Chasis refers to the assembled structural components that supports all the process/function related parts like actuators,machine elements, etc. Generally selected materials for chasis in automation applications are *steel* and *aluminum*.

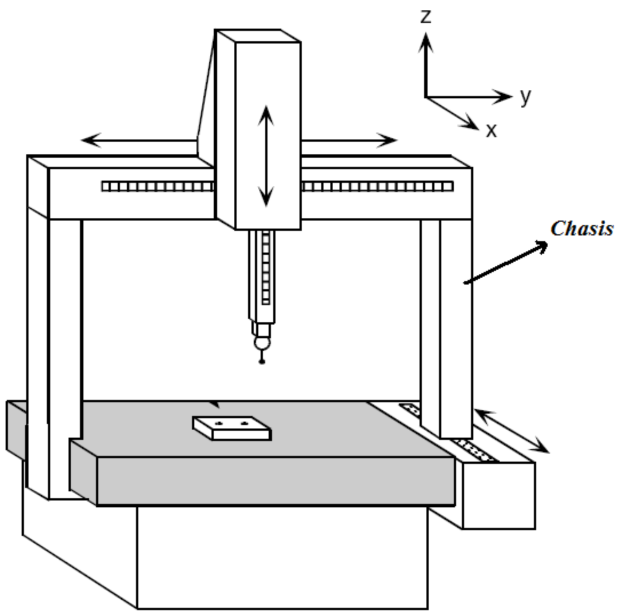


Figure 4.1 A typical chasis(Hurmuzlu, 2002)

4.1.2 Machine elements

Machine elements are the mechanical components used for fastening, bearing, power/motion transmission, energy storing, sealing, etc.

4.1.3 Actuators

The *actuator* provides the source of energy or motion in a system.

4.1.3.1 *Electrical*

Electrical actuators are electromechanical devices that convert electrical energy to motion.

4.1.3.1.1 *Solenoids*

Solenoids are electromechanical devices that use an electromagnet to produce short-stroke linear motion(Kilian,2005).

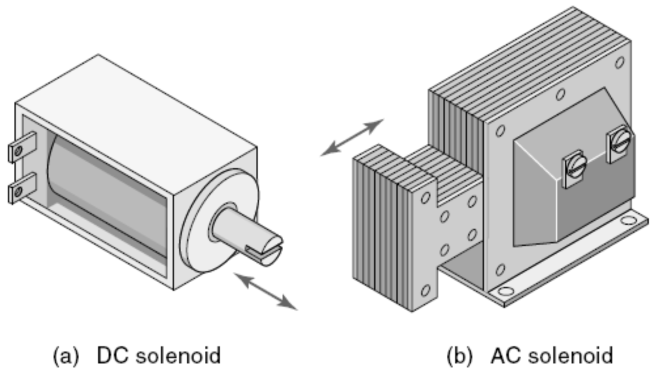


Figure 4.2 DC and AC type solenoids(Kilian, 2005)

4.1.3.1.2 *Electric motors*

It is important to remember at the outset that electric motors operate through the interaction of magnetic flux and electric current, or flow of charge. They develop force because a charge moving in a magnetic field produces a force which happens to be orthogonal to the motion of the charge and to the magnetic field. Electric machines also produce a voltage if the conductor in which current can flow moves through the magnetic field. Describing the interaction in a electric motor requires both phenomena, since the energy conversion typified by torque times *rotational speed* must also be characterized by *current* times *back voltage*.

Electric motors are broadly classified into two categories: AC and DC. Within these categories there are subdivisions(Beaty,2004).

4.1.3.1.2.1 *DC motors*

DC motors, as the name implies, operate with terminal voltage and current that is "direct", or substantially constant. While it is possible to produce a "true DC" machine in a form usually called "acyclic", with homopolar geometry, such machines have very low terminal voltage and consequently high terminal current relative to their power rating. Thus all application of DC motors have employed a mechanical switch or commutator to turn the terminal current, which is constant or DC, into alternating current in the armature of the machine. DC motors have usually been applied in two broad types of application. One of these categories is when the power source is itself DC. This is why motors in automobiles are all DC, from the motors that drive fans for engine cooling and passenger compartment ventilation to the engine starter motor. A second reason for using DC motors is that their torque-speed characteristic has, historically, been easier to tailor than that of all AC motor categories. This is why most traction and servo motors have been DC machines.

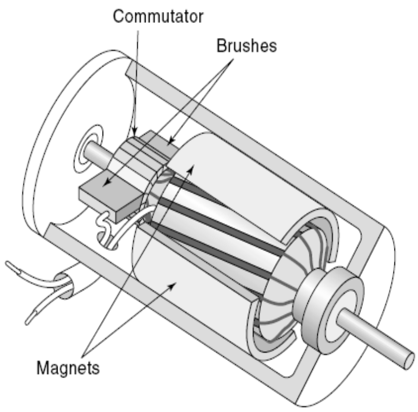


Figure 4.3 DC motor components(Kilian, 2005)

Brushless DC motors alters the main disadvantage of the classical design of brushed DC motors follows from brush-commutation. Brushless motors place permanent magnets on the rotor and wire windings on the stator. The interaction between the magnetic field and the electrical circuit, which forces the rotor to move, still exists. Brushes are not needed because there is no current in the rotor. To synchronize switching in the electrical circuit and the angular velocity, sensors are used. They give the information for the device called an electronic commutator. In this way the electronic commutator imitates the brush commutation(Kurfess,2005).

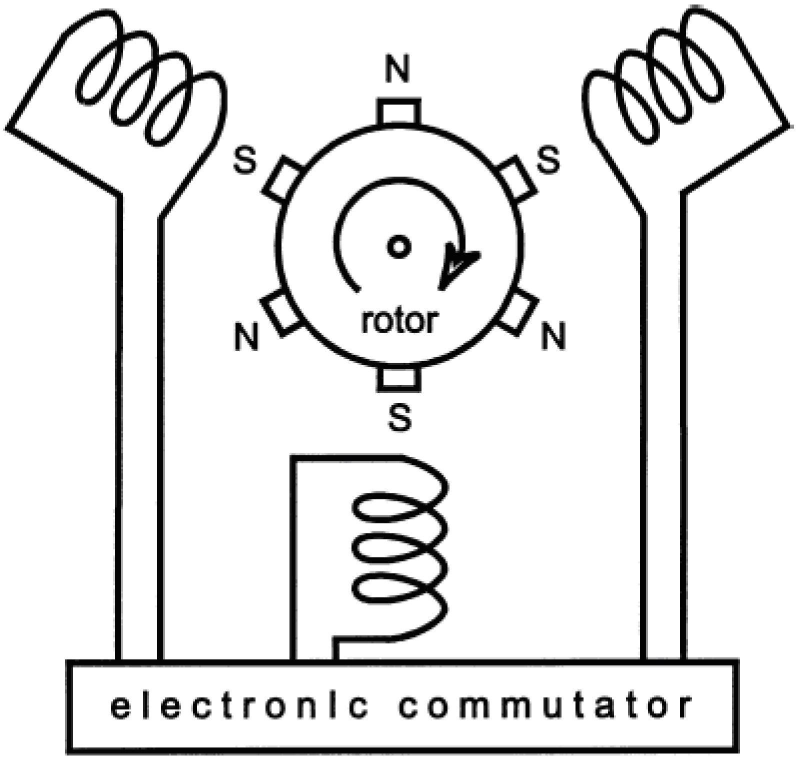


Figure 4.4 Scheme of a brushless motor(Hurmuzlu, 2002)

DC brushless motors use *Hall Effect sensor* signals for commutation feedback. The Hall Effect sensors(typically three) are built into the motor to detect the position of the rotor magnetic field. These sensors are mounted such that they each generate a square wave with 120-degree phase difference, over one electrical cycle of the motor. The amplifier drives two of the three motor phases with DC current during each specific Hall sensor state.

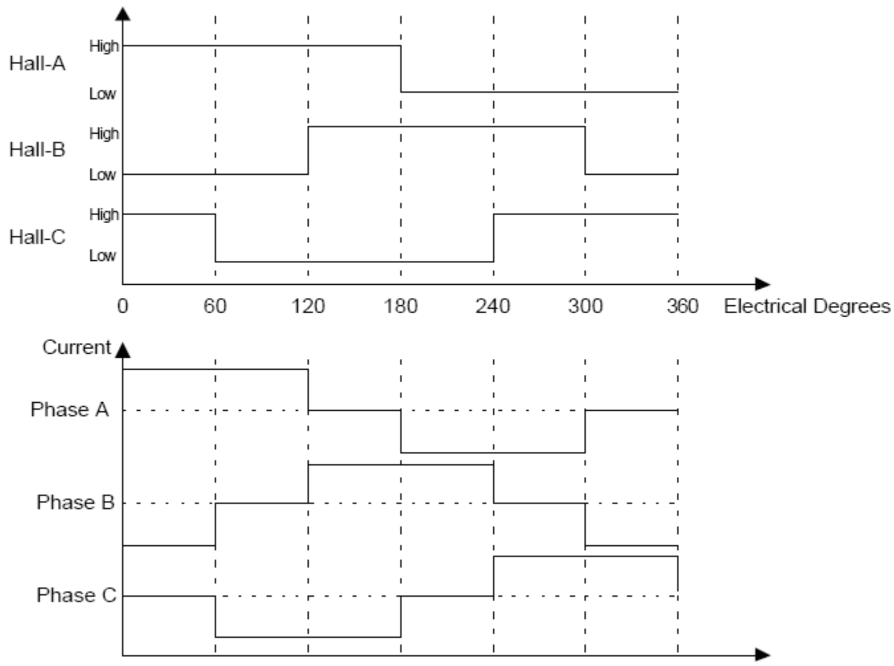


Figure 4.5 Hall sensor based commutation(Axsys Technologies inc.,2002).

This commutation technique results in a very cost-effective amplifier. When used with motors with sinusoidal back-EMF, the torque ripple is about 13.4%. The average torque is 5% lower compared to a sinusoidal(or AC brushless) system, the peak torque however is 10% higher(Axsys Technologies inc.,2002).

Stepper motors are devices that convert a dc voltage pulse train into a proportional mechanical rotation of their shaft. In essence, stepper motors are a discrete version of the synchronous motor. The discrete motion of the stepper motor makes it ideally suited for use with a digitally based control system such as a microcontroller. The speed of a stepper motor may be varied by altering the rate of the pulse train input. Thus, if a stepper motor requires 48 pulses to rotate through one complete revolution, then an input signal of 96 pulses per second will cause the motor to rotate at 120 rev/min. The rotation is actually carried out in finite increments of time; however, this is visually indiscernible at all but the lowest speeds. Stepper motors are capable of driving a 2.2-kW load with stepping rates from 1000 to 20,000 per second in angular increments from 180° down to 0.75°. There are three basic types of stepper motors:

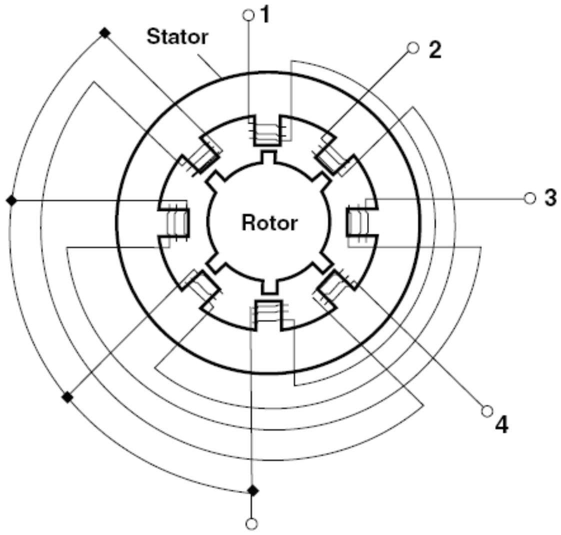


Figure 4.6 Variable reluctance stepper motor(Hurmuzlu, 2002)

- **Variable reluctance**: This type of stepper motor has a soft iron multi-toothed rotor with a wound stator. The number of teeth on the rotor and stator, together with the winding configuration and excitation determines the step angle. This type of stepper motor provides small to medium sized step angles and is capable of operation at high stepping rates.

- **Permanent magnet**: The rotor used in the PM type stepper motor consists of a circular permanent magnet mounted onto the shaft. PM stepper motors give a large step angle ranging from 45° to 120°.

- **Hybrid**: The hybrid stepper motor is a combination of the previous two types. Typically the stator has eight salient poles, which are energized by a two-phase winding. The rotor consists of a cylindrical magnet, which is axially magnetized. The step angle depends on the method of construction and is generally in the range 0.9°–5°. The most popular step angle is 1.8°.

The principle of operation of a stepper motor can be illustrated with reference to a variable reluctance, four-phase machine. This motor usually has eight stator teeth and six rotor teeth. If phase 1 of the stator is activated alone, two diametrically opposite rotor teeth align themselves with the phase 1 teeth of the stator. The next adjacent set of rotor teeth in the clockwise direction are then 15° out of step with those of the stator. Activation of the phase 2 winding on its own, would cause the rotor to rotate a further 15° in the anti-clockwise direction to align the adjacent pair of diametrically opposite rotor teeth. If the stator windings are excited in the sequence 1, 2, 3, 4, then the rotor will move in consecutive 15° steps in the anti-clockwise direction. Reversing the excitation sequence will cause a clockwise rotation of the rotor (Bishop,2008).

Voice-coil motors(VCM) were originally developed for loudspeakers. They are now extensively used in moving read/write heads in hard disk drives. Since the coil is in motion, VCM is also referred to as a *moving-coil* actuator. The VCM consists of a moving coil(armature) in a gap and a permanent magnet(stator) that provides the magnetic field in the gap. When current flows through the coil, based on the Lorentz law, the coil experiences electromagnetic(Lorentz) force F which *is* proportional to the applied current amplitude and the proportional constant K_F is often called the *force constant*.

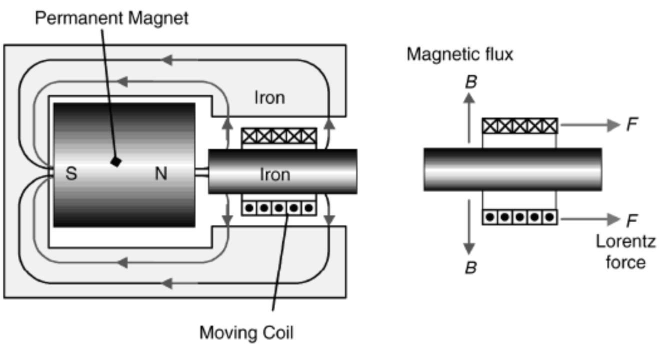


Figure 4.7 Voice-coil motor(Hurmuzlu, 2002)

The coil is usually suspended in the gap by springs and attached to the load such as the diaphragm of an audio speaker, the spool of a hydraulic valve, or the read/write head of the disk drive. The linear relationship between the output force and the applied current and the bidirectional capability makes the voice coil more attractive than solenoids. However, since the controlled output of the voice coil is force, some type of closed loop control or some type of spring suspension is needed (Bishop,2008).

4.1.3.1.2.2 *AC motors*

Electric motors designed to operate with alternating current(AC) supplies are themselves broadly categorized into two classes: induction and synchronous. There are many variations of synchronous machines. AC motors work by setting up a magnetic field pattern that rotates with respect to the stator and then employing electromagnetic forces to entrain the rotor in the rotating magnetic field pattern. Synchronous machines typically have a magnetic field which is stationary with respect to the rotor and which therefore rotate at the same speed as the stator magnetic field. In induction motors, the magnetic field is, as the name implies, induced by motion of the rotor through the stator magnetic field.

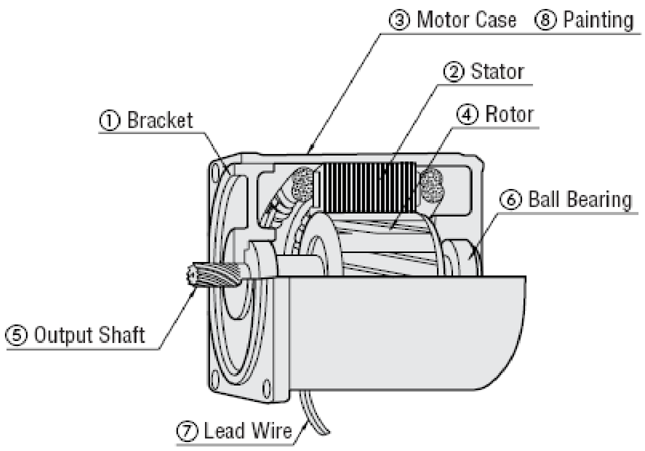


Figure 4.8 Components of the AC motors

Induction motors are probably the most numerous in today's economy. Induction machines are simple, rugged and usually are cheap to produce. They dominate in applications at power levels from fractional horsepower(a few hundred watts) to hundreds of horsepower(perhaps half a megawatt) where rotational speeds required do not have to vary.

Synchronous motors are not as widely used as induction machines because their rotors are more complex and they require exciters. However, synchronous motors are used in large industrial applications in situations where their ability to provide leading power factor helps to support or stabilize voltage and to improve overall power factor. Also,in ratings higher than several hundred horsepower, synchronous machines are often more efficient than induction machines and so very large synchronous machines are sometimes chosen over induction motors.

Operated against a fixed frequency AC source, both synchronous and induction motors run at(nearly) fixed speed. However, when coupled with an adjustable frequency AC source, both classes of machine can form adjustable speed drives. There are some important distinctions based on method of control:

- *Adjustable speed drives:* synchronous or induction motors coupled to inverters that generate variable frequency. The speed of the motor is proportional to the frequency.

- *Vector control:* also called *field oriented control,* is used to produce high performance servomechanisms by predicting the location of internal flux and then injecting current to interact optimally with that flux.

Figure 4.9 Frequency invertors for speed control

Universal motors are commutator machines, similar to DC machines,but are adapted to operation with AC terminal voltage. These machines are economically very important as large numbers are made for consumer appliances. They can achieve high shaft speed, and thus relatively high power per unit weight or volume, and therefore are economical on a watt-per-unit-cost basis. They are widely used in appliances such as vacuum cleaners and kitchen appliances.

Variable reluctance machines(VRMs) also called *switched reluctance machines,* are mechanically very simple, operating by the principle that, under the influence of current excitation, magnetic circuits are pulled in a direction that increases inductance. They are somewhat akin to synchronous machines in that they operate at a speed that is proportional to frequency. However, they typically must operate with switching power electronics, as their performance is poor when operating against a sinusoidal supply. VRMs have not yet seen wide application, but their use is growing because of the simplicity of the rotor and its consequent ability to operate at high speeds and in hostile environments(Beaty,2004).

Brushless AC motors use encoder or resolver signals for commutation feedback. The amplifier drives the motor with sinusoidal currents, resulting in smooth motion (no torque ripple). The amplifier is more complex than brushless DC type since it needs to accept high-resolution position feedback. Such amplifiers use a micro-controller implementation for the sinusoidal commutation. When encoder feedback information is used for commutation, Hall Effect sensors are still needed for startup since the encoder provides only incremental position information. Resolvers provide absolute position information and therefore no additional sensors are required.The commutation function can also be implemented in the motion controller. In such case, the amplifier merely amplifies the controller signals(2 analog sinusoidal signals that represent 2 of the 3 motor phase currents). The amplifier creates the third motor phase current(sum of the three currents must be zero). No position feedback needs to be wired into the amplifier. The motor current amplitude(Amperes) is proportional to the reference signal amplitude(Volts). The reference signal frequency depends on the motor velocity and the motor pole count. The phase angle is adjusted to obtain maximum torque. Amplifiers accepting 2 sinusoidal reference signals are sometimes also referred to as “noncommutating” or U-V amplifiers(Axsys Technologies inc.,2002).

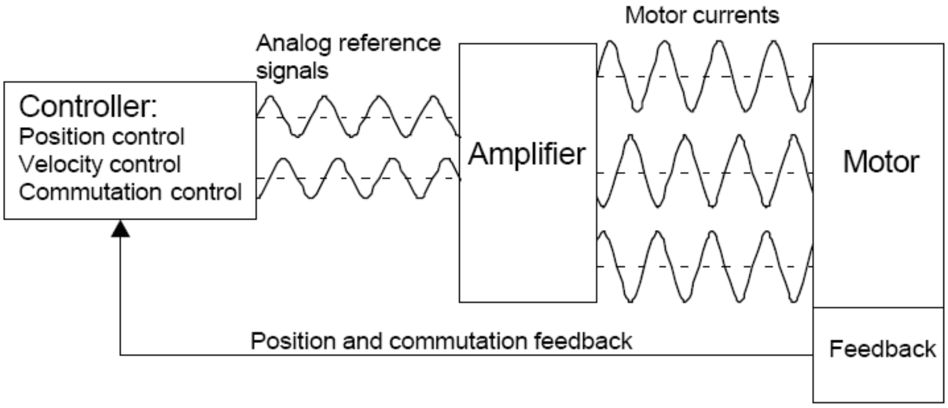


Figure 4.10 Controller-based commutation(Axsys Technologies inc.,2002).

4.1.3.1.3 *Linear motors*

One of the newer types of linear actuators is the electric linear motor. Basically, a linear motor is a rotary brushless DC motor(BLDC) that has been rolled out flat. Linear motors convert electric power directly into linear motion. They are capable of high speed(up to 10 m/s), high force and long travel(several meters), and, like a BLDC, they have no sliding contacts but do require an electronic drive unit. A linear motor consists of two parts: the base unit known as the *magnet way,* which consists of an iron plate with a row of alternate-pole permanent magnets, and the moving part known as the *slider,* which contains the coils. The slider is supported on linear ball bearings so that it can slide along over the magnet way(there is a small air gap between them). A flexible cable connects the slider to the drive unit.

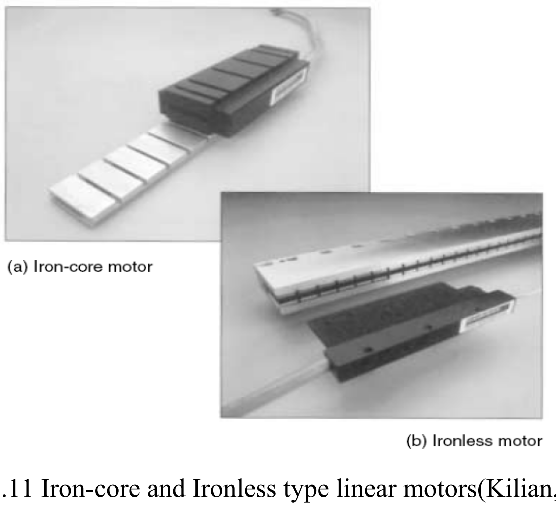


Figure 4.11 Iron-core and Ironless type linear motors(Kilian, 2005)

4.1.3.2 *Hydraulic*

Hydraulic actuators output mechanical motion through the control of incompressible fluid flow or pressure. Because incompressible fluid is used, these actuators are well suited for force, position, and velocity control. In addition, these actuators can be used to suspend a payload without significant power consumption. Another useful option when using hydraulics is that mechanical damping can be incorporated into the system design.

Working pressures for hydraulic actuators vary between 150 and 300 bar. When using these actuators,typical concerns include hydraulic fluid leaking and system maintenance. However, these can be mitigated through intelligent engineering design. Hydraulic actuators have been used in many factory automation problems and have also been used in mobile robotics. Figure 4.12 is a picture of the TITAN 3 servo-hydraulic manipulator system from Schilling Robotics. This is a remote manipulator that was originally developed for mobile underwater applications but is also being used in the nuclear industry(Kurfess,2005).

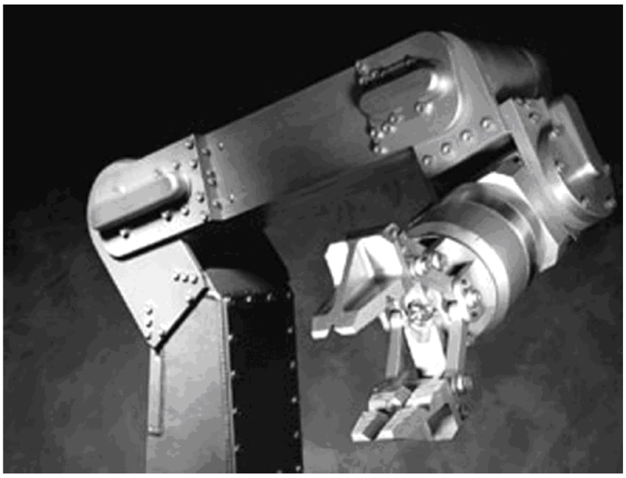


Figure 4.12 Titan 3 servo-hydraulic manipulator(Kurfess,2005)

The primary subsystems in hydraulic actuation include:

- Incompressible fluid—transfers power within the system
- A pump—converts input electrical power to hydraulic pressure

- Valves—to control fluid direction, flow, and pressure
- Filters, accumulator, and reservoirs
- Hoses, piping and fittings—used to transport fluids in the system

4.1.3.2.1 *Hydraulic cylinders*

A hydraulic cylinder is based on a rod connected to a piston which slides inside of a cylinder. The rod is connected to the mechanical load in motion. The cylinder may be single or double action. A single action cylinder can apply force in only one direction and makes use of a spring or external load to return the piston to its nominal position. A double action cylinder can be controlled to apply force in two directions. In this case, the hydraulic fluid is applied to both faces of the piston (Kurfess,2005).

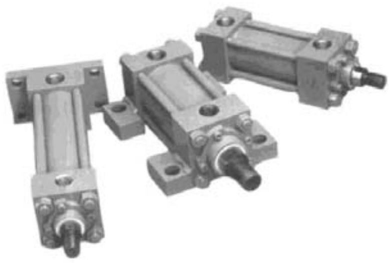


Figure 4.13 Hydraulic cylinders(Kurfess,2005)

4.1.3.2.2 *Hydraulic motors*

Hydraulic motors are similar to hydraulic pumps. Manufacturers offer *gear*, *vane*, and *piston* type designs. Another type of rotary actuator makes use of a rack and pinion design where a piston is used to drive the rack and the pinion is used for the output motion(Kurfess,2005).

4.1.3.3 ***Pneumatic***

Pneumatic actuators are similar to hydraulic actuators in that they are also fluid powered. The difference is that a compressible fluid, pressurized air, is used to generate output mechanical motion. Pneumatic actuators have less load carrying capability than hydraulic actuators because they have lower working pressure. However, pneumatic actuators have advantages in lower system weight and relative size. They are also less complex in part because exhausted pressurized air in the actuator can be released to the environment through an outlet valve rather than sent through a return line. Because compressed air is used, the governing dynamic equations of pneumatic actuators are nonlinear. In addition, compressed air adds passive compliance to the actuator.These two factors make these actuators more difficult to use for force, position, and velocity control.However, pneumatic actuators are frequently used in industry for discrete devices such as grippers on robotic end effectors.

Working pressures for pneumatic actuators are typically less than 10 bar. Installation for these types of actuators is facilitated by the availability of compressed air on the factory floor(Kurfess,2005).

The primary subsystems in pneumatic actuation include:

- Air—transfers power within the system
- A compressor—converts input electrical power to air pressure
- Compressed air treatment unit—includes filter, pressure regulator and lubricator
- Valves— to control compressed air direction, flow, and pressure
- Hoses, piping and fittings—used to transport air in the system

4.1.3.3.1 *Pneumatic cylinders*

A pneumatic cylinder is based on a rod connected to a piston which slides inside of a cylinder. The rod is connected to the mechanical load in motion. The cylinder may be single or double action. A single action cylinder can apply force in only one direction and makes use of a spring or external load to return the piston to its nominal position. A double action cylinder can be controlled to apply force in two directions. In this case, the air is applied to both faces of the piston(Kurfess,2005).

Figure 4.14 Pneumatic cylinders(Kurfess,2005)

4.1.3.3.2 *Pneumatic motors(also called "air motors)*

Pneumatic motors produces rotary motion with air pressure. Manufacturers offer *gear*, *vane*, and *piston* type designs.

Air motors should not be looked upon as a substitute for hydraulic or electric motors. They have their own characteristics which make them ideal in certain applications. They offer a compact and lightweight source of rotary power, reversible and easily adjustable in speed and torque. They possess characteristics similar to those of d.c. series wound electric motors.Air motors can be stalled indefinitely and start immediately with maximum torque. They can be designed to produce equal power in either direction of rotation, merely by reversing the supply and exhaust ports, although maximum efficiency is usually obtainable only when the rotation is uni-directional. They can operate at any speed throughout their design range, and are easily geared to produce maximum power at any required shaft speed. They can be run from any available compressed gas, *eg* from natural or a process gas. They can be run at any attitude.

When comparing pneumatic motors with the alternative using hydraulic or electric power, the following should be borne in mind:

- There is no heat build-up when continuously stalled. When the load is reduced to allow the motor to turn, it will resume normal operation. They can tolerate being driven counter to the applied pressure. The air flow through the motor acts as a self cooler.
- Maintenance is low compared with hydraulic motors.
- There is no sparking, so they are safe in explosive atmospheres. In wet conditions,there is no shock hazard.
- When compared with electric motors they have a higher power/weight ratio (for the same output, the weight is about one-third).
- The moment of inertia is lower than electric and hydraulic motors, so they reach maximum speed quickly and brake instantly.
- They can be installed and operated in any position from horizontal to vertical(Barber,1997).

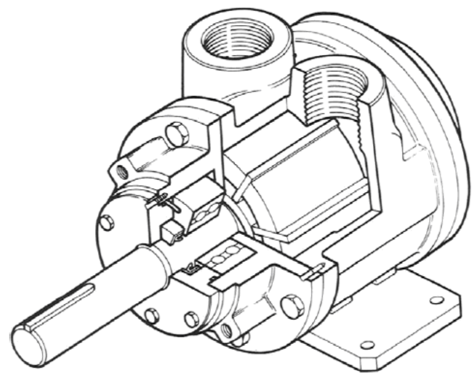


Figure 4.15 Reversible vane type pneumatic motor(Barber,1997)

4.1.4 Sensors

A sensor is a device that receives a stimulus and responds with an electrical signal. The term *stimulus*(also called "*measurand*") is the quantity, property, or condition that is sensed and converted into electrical signal.

The purpose of a sensor is to respond to some kind of an input physical property(stimulus) and to convert it into an electrical signal which is compatible with electronic circuits. We may say that a sensor is a translator of a generally nonelectrical value into an electrical value. When we say "electrical," we mean a signal which can be channeled, amplified, and modified by electronic devices. The sensor's output signal may be in the form of voltage, current, or charge. These may be further described in terms of amplitude, frequency, phase, or digital code. This set of characteristics is called the *output signal format*. Therefore, a sensor has input properties(of any kind) and electrical output properties.

The term *sensor* should be distinguished from *transducer*. The latter is a converter of one type of energy into another, whereas the former converts any type of energy into *electrical*. An example of a transducer is a loudspeaker which converts an electrical signal into a variable magnetic field and, subsequently, into acoustic waves. This is nothing to do with perception or sensing. Transducers may be used as *actuators* in various systems. An actuator may be described as opposite to a sensor—it converts electrical signal into generally nonelectrical energy. For example, an electric motor is an actuator—it converts electric energy into mechanical action.

Transducers may be parts of complex sensors. For example, a chemical sensor may have a part which converts the energy of a chemical reaction into heat (transducer) and another part, a thermopile, which converts heat into an electrical signal.The combination of the two makes a chemical sensor—a device which produces an *electrical* signal in response to a chemical reaction. Note that in the above example,a chemical sensor is a complex sensor; it is comprised of a transducer and another sensor(heat).

A sensor does not function by itself; it is always a part of a larger system that may incorporate many other detectors, signal conditioners, signal processors, memory devices, data recorders, and actuators. The sensor's place in a device is either intrinsic or extrinsic. It may be positioned at the input of a device to perceive the outside effects and to signal the system about variations in the outside stimuli. Also, it may be an internal part of a device that monitors the devices' own state to cause the appropriate performance. A sensor is always a part of some kind of a data acquisition system. Often, such a system may be a part of a larger control system that includes various feedback mechanisms.To illustrate the place of sensors in a larger system, Fig. 4.16 shows a block diagram of a data acquisition and control device. An object can be anything: a car, space ship,animal or human, liquid, or gas. Any material object may become a subject of some kind of a measurement. Data are collected from an object by a number of sensors.Some of them(2, 3, and 4) are positioned directly on or inside the object. Sensor 1 perceives the object without a physical contact and, therefore, is called a *noncontact* sensor. Examples of such a sensor is a radiation detector and a *TV camera*. Even if we say “noncontact”, we remember that energy transfer always occurs between any sensor and an object. Sensor 5 serves a different purpose. It monitors internal conditions of a data acquisition system itself. Some sensors(1 and 3) cannot be directly connected to standard electronic circuits because of inappropriate output signal formats. They require the use of interface devices(signal conditioners). Sensors 1, 2, 3, and 5 are passive. They generate electric signals without energy consumption from the electronic circuits. Sensor 4 is active. It requires an operating signal, which is

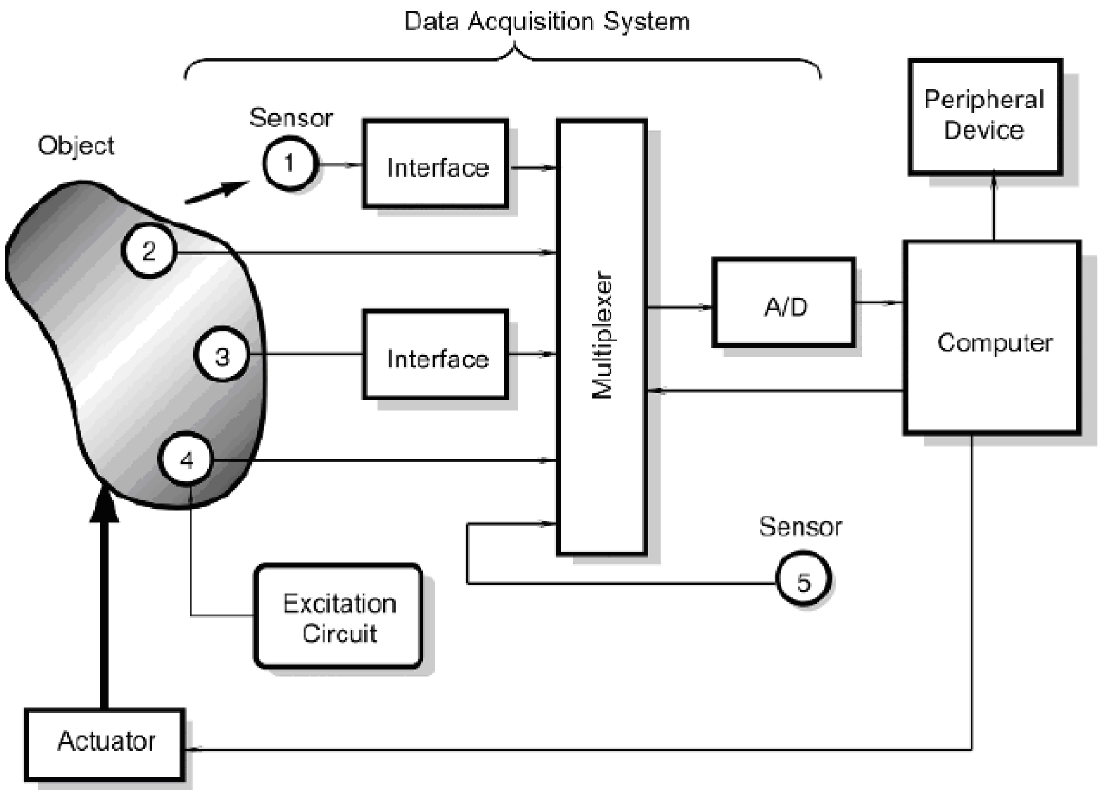


Figure 4.16 Positions of sensors in a data acquisition system.Sensor 1 is nocontact, sensor 2 and 3 are passive, sensor 4 is active, and sensor 5 is internal to a data acquisition system (Fraden, 2004)

provided by an excitation circuit. This signal is modified by the sensor in accordance with the converted information. An example of an active sensor is a thermistor, which is a temperature-sensitive resistor. It may operate with a constant-current source, which is an excitation circuit. Depending on the complexity of the system, the total number of sensors may vary from as little as one(a home thermostat) to many thousands(a space shuttle).Electrical signals from the sensors are fed into a multiplexer(MUX), which is a switch or a gate. Its function is to connect sensors one at a time to an analog-to-digital(A/D) converter if a sensor produces an analog signal, or directly to a computer if a sensor produces signals in a digital format. The computer controls a multiplexer and an A/D converter for the appropriate timing. Also, it may send control signals to the actuator, which acts on the object. Examples of actuators are an electric motor, a solenoid, a relay, and a pneumatic valve. The system contains some peripheral devices(for instance, a data recorder, a display, an alarm, etc.) and a number of components,which are not shown in the block diagram. These may be filters, sample-and-hold circuits, amplifiers, and so forth (Fraden,2004).

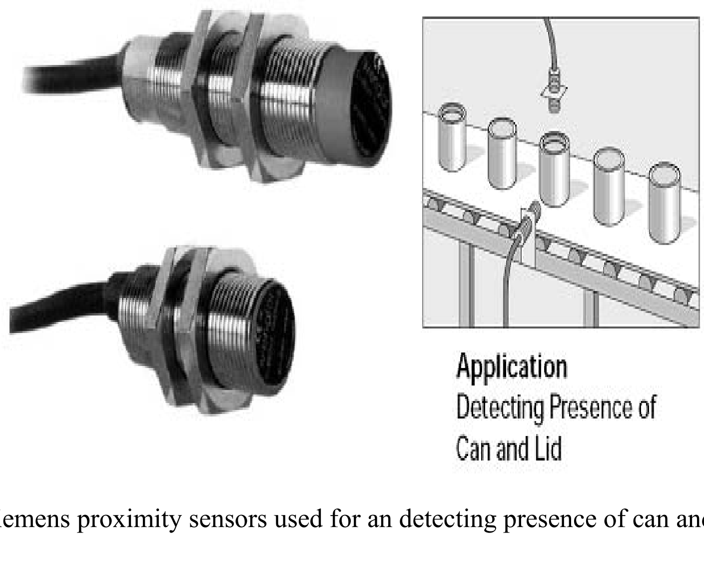


Figure 4.17 Siemens proximity sensors used for an detecting presence of can and lid application

4.2 Components for "Soft" Tasks

Components for "soft" tasks refers to the components that have an *in*direct relationship with the physical process/procedure which is the subject of the automation.

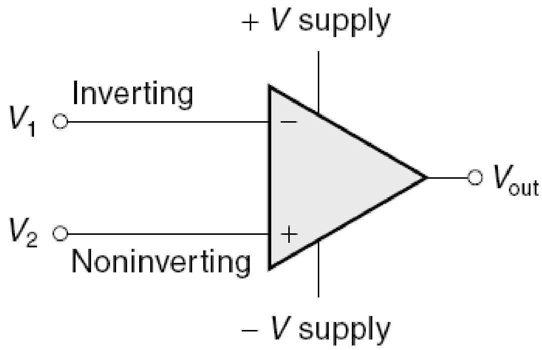
4.2.1 Signal conditioning/processing devices

The term signal(unless otherwise stated,electrical signal in the form of voltage or current) processing/conditioning refers to the manipulation of a signal to a desired form that is dictated from the process requirements.

Filters are used for the attenuation(lessening) of certain frequencies from a signal. This process can remove noise from a signal and condition the line for better data transmission. Filters can be divided into analog and digital types, the analog filters being further divided into passive and active types. Analog passive filters use resistors, capacitors, and inductors. Analog active filters typically use operational amplifiers with resistors and capacitors. Digital filters may be implemented with software and/or hardware. The software component gives digital filters the feature of being easier to change.Filters may also be differentiated by the type of frequencies they affect.

- Low-pass filters allow lower set of frequencies to pass through, while high frequencies are attenuated.
- High-pass filters, the opposite of low-pass, filter a lower frequency band while allowing higher frequencies to pass.
- Band-pass filters allow a particular range of frequencies to pass; all others are attenuated.
- Band-stop filters stop a particular range of frequencies while all others are allowed to pass(Bishop,2008).

Operational Amplifiers(op-amps) are the basis of many signal processing elements, the basic amplifier being supplied as an integrated circuit on a silicon chip. It has two inputs, termed the inverting input (-) and the non-inverting input (+) and is a high gain d.c. amplifier, the gain typically being of the order of 100 000 or more.



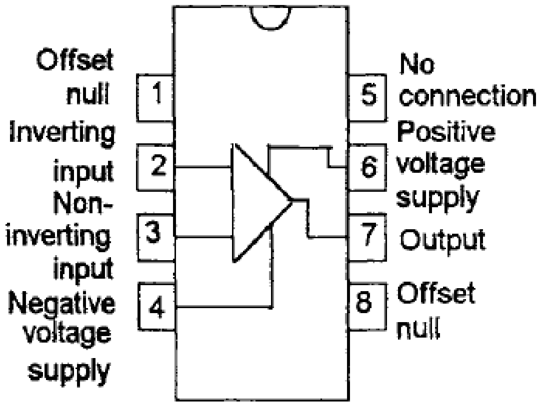


Figure 4.18 The op-amp symbol on the left and the 741 IC on the right(Kilian, 2005 and Bolton, 1992)

Analog-to-digital converters(ADCs) are circuits that converts an analog voltage into a digital word.The electrical output from sensors such as thermocouples, resistance elements used for temperature measurement, strain gauges, diaphragm pressure gauges, LVDTs, etc. is in analogue form. An analogue signal is one that is continuously variable, changing smoothly over a range of values. The signal is an analogue, i.e. a scaled version, of the quantity it represents. A digital signal increases in jumps, being a sequence of pulses, often just on-off signals. The value of the quantity instead of being represented by the height of the signal, as with analogue, is represented by the sequence of on-off signals. Microprocessors require digital inputs. Thus, where a microprocessor is used as part of a control system, the analogue output from a sensor has to be converted into a digital form before it can be used as an input to the microprocessor. Thus there is a need for an ADC. Analogue-to-digital conversion involves a number of stages. The first stage is to take samples of the analogue signal. A clock supplies regular time signal pulses to the analogue-to-digital converter and every time it receives a pulse it samples the analogue signal. The result is a series of narrow pulses with heights which vary in accord with the variation of the analogue signal. This sequence of pulses is changed into the signal form by each sampled value being held until the next pulse occurs. This holding is necessary to allow time for the conversion to take place at an analogue-to-digital converter. This converts each sample into a sequence of pulses representing the value. For example,the first sampled value might be represented by 101, the next sample by 011, etc. The 1 represents an 'on' or 'high' signal, the 0 an 'off' or 'low' signal. Analogue-to-digital conversion thus involves a sample and hold unit followed by an analogue- to-digital converter(Bolton,2003).

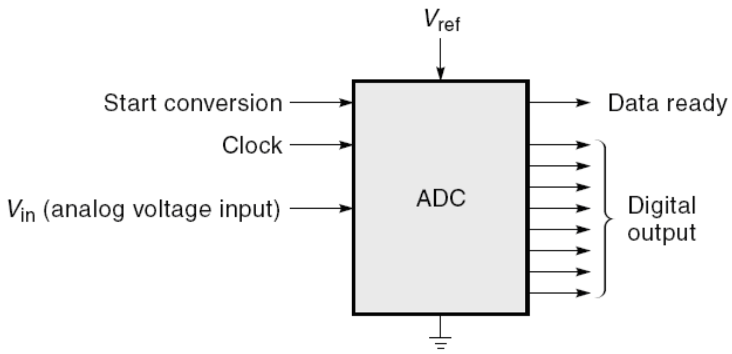


Figure 4.19 An analog to digital converter(ADC) block diagram(Kilian, 2005)

Digital-to-analogue converters(DACs) are circuits that converts an analog voltage into a digital word(Kilian,2005).

Rectifiers(AC-to-DC converters) are electronic circuits that convert bidirectional (AC) voltage to unidirectional(DC) voltage.This process can be accomplished either by mechanical means like in the case of DC machines employing commutators or by static means employing semiconductor devices. Static rectification is more efficient and reliable compared to rotating commutators. This section covers rectification of electric power for industrial and commercial use. In other words, we will not be discussing small signal rectification that generally involves low power and low voltage signals. Static power rectifiers can be classified into two broad groups. They are (1) uncontrolled rectifiers and (2) controlled rectifiers. Uncontrolled rectifiers make use of power semiconductor diodes while controlled rectifiers make use of thyristors (SCRs), gate turn-off thyristors (GTOs), and MOSFET-controlled thyristors (MCTs). Rectifiers, in general, are widely used in power electronics to rectify single-phase as well as three-phase voltages. DC power supplies used in computers, consumer electronics, and a host of other applications typically make use of single-phase rectifiers. Industrial applications include, but are not limited to,industrial drives, metal extraction processes, industrial heating, power generation and transmission, etc.Most industrial applications of large power rating typically employ three-phase rectification processes(Skvarenina,2002) .

Inverters(DC-to-AC converters) are used to create single or polyphase AC voltages from a DC supply. In the class of polyphase inverters, three-phase inverters are by far the largest group.A very large number of inverters are used for adjustable speed motor drives. The typical inverter for this application is a “hard-switched” voltage source inverter producing pulse-width modulated(PWM) signals with a sinusoidal fundamental.Recently research has shown detrimental effects on the windings and the bearings resulting from unfiltered PWM waveforms and recommend the use of filters. A very common application for single-phase inverters are so-called “uninterruptable power supplies” (UPS) for computers and other critical loads. Here, the output waveforms range from square wave to almost ideal sinusoids (Skvarenina,2002).

Transformers are devices which use the phenomenon of mutual induction to change the values of alternating voltages and currents.In fact,one of the main advantages of AC transmission and distribution is the ease with which an alternating voltage can be increased or decreased by transformers.Losses in transformers are generally low and thus efficiency is high.They range in size from miniature units used in electronic applications to the large power transformers used in power stations(Bird,2003).

Data acquisition(DAQ) boards/cards can generate analog input and multiplex multiple input signals onto a single bus for transmission to the PC.It can also come with signal conditioning hardware/software and an ADC. Some units have direct memory access (DMA), where the device writes the data directly into computer memory without using the microprocessors(Bishop,2008).

4.2.2 Switching devices

Roughly a *switch* can be defined as a device that can open or close, thereby allowing a current to flow or not. Switches come in many different shapes, sizes, and configurations.

Probably the most common switch type is the *toggle switch*, which is available in various contact configurations. Each switch consists of one or more *poles*, where each pole is actually a separate switch. The contact arrangement for the single-pole/single-throw switch (SPST), the simplest switch, is illustrated in Figure 4.20(a). Notice that it has a single set of contacts that can either open or close. Next, up the line of complication,is the single-pole/double-throw switch (SPDT) illustrated in Figure 4.20(b). Notice that the movable "arm" called the *common* (C), or wiper, can connect with either contact A or B. Figure 4.20(c) illustrates a double-pole/double-throw switch (DPDT), which consists of two electrically separate SPDT switches in one housing that operate together.In Figure 4.20(d), notice how the terminals are arranged on the back of the DPDT switch housing, with the three terminals for each pole running the "long way" on the switch body. Although not as common, switches with up to six poles are available.

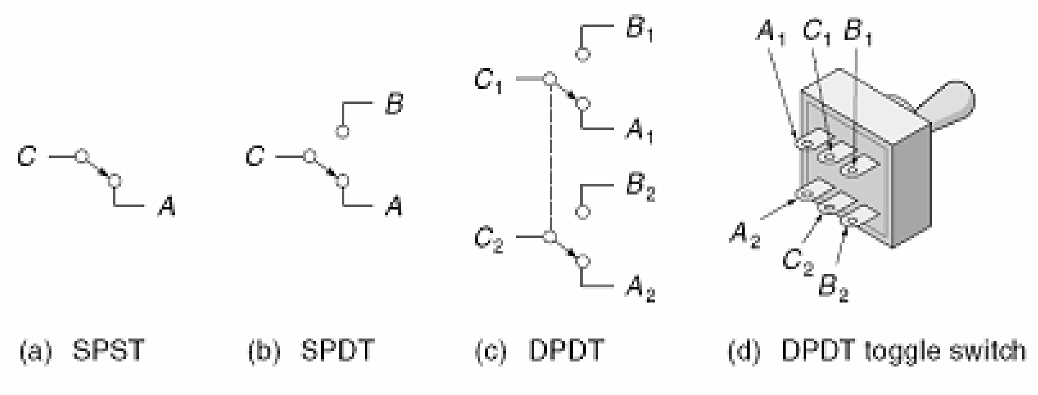


Figure 4.20 A Toggle switch(Kilian, 2005)

Closely related to the toggle switch is the *slide switch* illustrated in Figure 4.21. Although mechanically different internally, the slide switch performs the same functions as the toggle switch and is available in the same configurations. Slide switches tend to be less expensive but are not available with the high current rating of toggle switches.

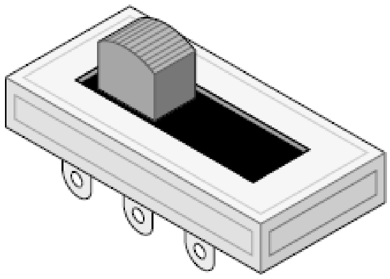


Figure 4.21 A slide switch(Kilian, 2005)

Push-button switches are almost always the momentary type—pressure must be maintained to keep the switch activated.There are two configurations possible: normally open(NO) and normally closed (NC). For the NO ,the contacts are open until the button is pushed; and for the NC switch, the contacts are closed when the switch is “at rest” and open when the button is pushed.

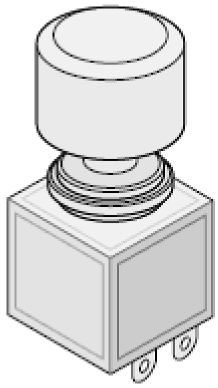


Figure 4.22 A push-button switch(Kilian, 2005)

A limit switch is a push-button switch mounted in such a position that it is activated by physical contact with some movable object. An example is a car door switch, which senses whether or not the door is closed. Limit switches are available with different kinds of actuator hardware, such as the “paddle” or roller. Often these are mounted on a small standard-sized switch body called a microswitch (developed by the MicroSwitch Company).

A DIP switch is a set of small SPST switches built into a unit shaped like an integrated circuit (IC) (DIP stands for dual in-line package). The DIP switch can be plugged into an IC socket or soldered into a circuit board. As shown in Figure 4.23,

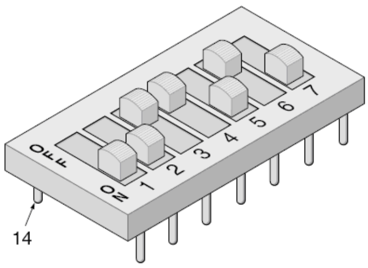


Figure 4.23 A DIP switch(Kilian, 2005)

each individual switch uses two pins directly across from each other; that is, switch 1 uses pins 1 and 14, switch 2 uses pins 2 and 13, and so on.

A rotary switch, considerably different from the switches discussed so far, can perform multiple, complicated switching operations. As shown in Figure 4.7, the rotary switch is constructed of switch wafers mounted along a single shaft. The inner part of each wafer rotates in steps with the shaft, and the outer part remains stationary.

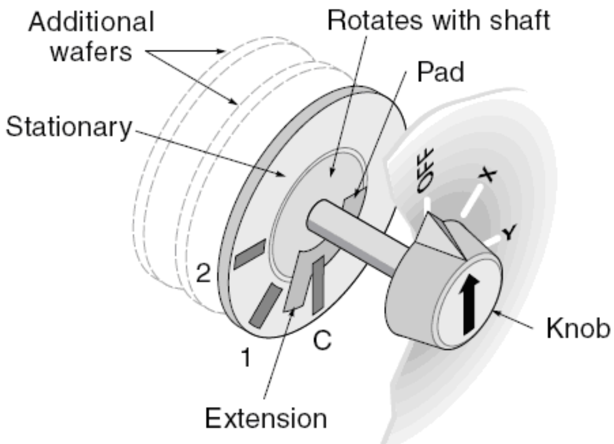


Figure 4.24 A rotary switch(Kilian, 2005)

A thumbwheel switch, a special type of rotary switch, is used to input numeric data.The operator selects a number by rotating the numbered wheel, and each number corresponds to a different switch setting. The switch schematic in Figure

4.25 shows that one of ten separate terminals is connected with the C terminal. Also available are thumbwheel switches that output 4-bit BCD(binary coded decimal) and other codes.

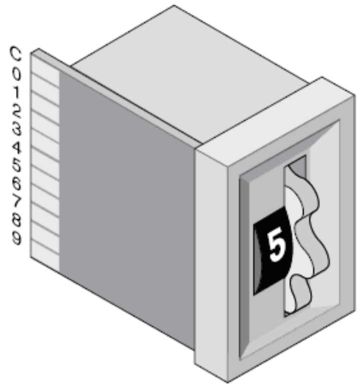


Figure 4.25 A thumbwheel switch(Kilian, 2005)

Another type of data-input device is the *membrane switch keypad*. This type of keypad consists of push-button switches built up from a number of layers, as shown in Figure 4.26. The bottom layer is usually a printed-circuit board with two nonconnecting pads

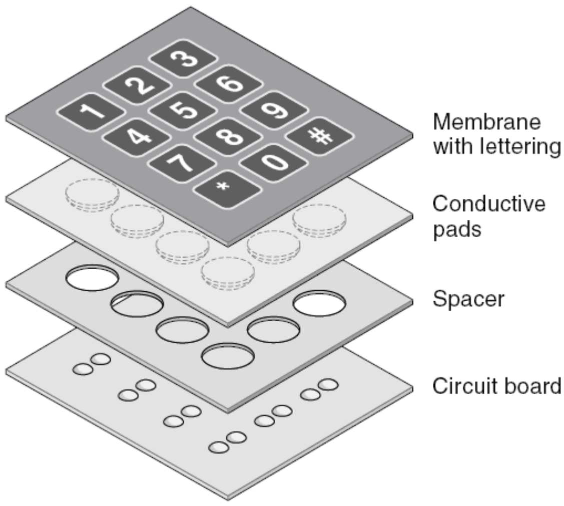


Figure 4.26 A membrane switch keypad(Kilian, 2005)

for each switch. Lying over the circuit board is a spacer layer with a hole over each switch position. The third layer is flexible and has a conductive pad over each switch. Overlying the whole thing is a flexible waterproof membrane, which has the key lettering.When a key is pressed, the conductive pad is forced into contact with the circuit board and provides a path for the current. Membrane switches are especially appropriate in dirty industrial environments because the membrane keeps dirt from getting into the switch assembly.

The electromechanical relay(EMR) is a device that uses an electromagnet to provide the force to close (or open) switch contacts, in other words, an electrically powered switch. When the electromagnet, called the *coil*, is energized, it pulls down on the spring-loaded *armature*. Relay contacts are described as being one of two kinds: normally open contacts (NO), which are open in the unenergized state, and normally closed contacts (NC), which are closed in the unenergized state. By convention, the symbol always depicts the relay in the unenergized state, so you can easily determine which are the NC and NO contacts from the schematic. This symbol is used in a type of drawing called a *ladder diagram*. In a ladder diagram, the relay coil and its contacts are separated on the drawing.The electrical specifications for the contacts are different than for the coil. For the contacts, the maximum current and voltage for DC and AC operation is specified. For the coil, the intended voltage and coil resistance are usually specified. The coil voltage and resistance can be used to calculate the steady-state coil current. Actually, it takes more voltage and current to pull in the relay contacts than it does to hold them there because the armature must be pulled in across an air gap. Hence, these quantities are called,respectively, pull-in voltage and pull-in current. For example, the contacts of a particular 6-V relay actually close at 2.1 V and stay closed until the voltage is decreased to 1 V. The values of voltage and current needed to keep the relay energized are called the minimum holding voltage and sealed current. Notice that the actual pull-in voltage is much less than the rated coil voltage. This is to guarantee that the relay will pullin quickly and reliably when operated at the rated voltage. Coil voltages are specified to be AC or DC. The difference is that AC coils are constructed with shaded poles to prevent “buzzing” with 60-cycle power. A shaded-pole relay has a metal ring around the pole face of the electromagnet.Magnetic flux induced into this ring keeps the relay closed when the AC cycles through 0 V.

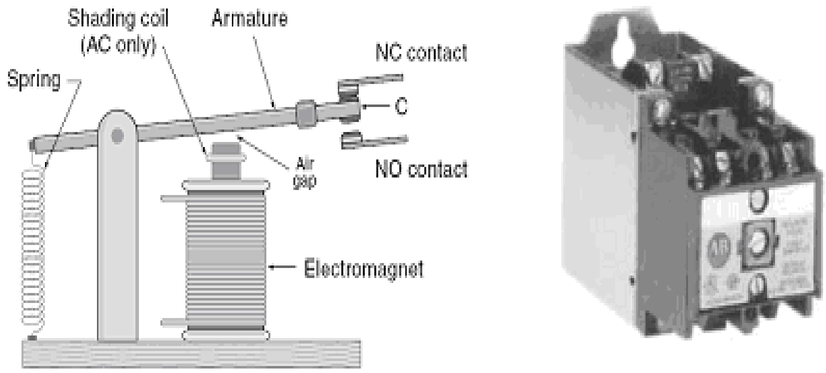


Figure 4.27 Electromagnetic relay(Kilian, 2005)

Relays are available in a variety of sizes, contact configurations, and power-handling capabilities. Some miniature relays can plug into an IC socket and be powered directly from a digital logic gate. On the other end of the spectrum, a power relay, often called a *contactor*, is used to switch the current directly to larger machines and may handle 50 A. It is well to remember that for two reasons, relays have a finite life. First, becauase the relay is a mechanical device, the moving parts eventually wear out, and second, the electrical contacts can become pitted because of arcing. The contact wear is very dependent on the electric current that is being switched. For example, a certain relay is rated for 9 million operations at 1.5 amps but only 2 million operations at 3 amps. Two million operations sounds like a lot, but if this relay were in a 24-hour factory being used in a repetitive operation every 10 seconds, it would have to be replaced every 8 months. Contact life also depends on the type of load being controlled. For example,inductive loads such as motors cause much more arcing and pitting than resistive loads such as lights and heating elements.

The reed relay is unique because the small reedlike contacts are encapsulated in a small sealed glass tube that is evacuated or filled with an inert gas like dry nitrogen. The contacts are activated by an external magnetic field, as shown in Figure 4.28. Contacts are either dry or mercury-wetted. Mercury-wetted contacts have a thin coating of mercury that fills in surface irregularities, making a larger conduction area, and reduces pitting. Generally, reed relays have a long life and low coil voltage (frequently TTL compatible), and are immune to dirty environments; however, they are generally low power (contacts rated at 2 A or less) and vibration sensitive.

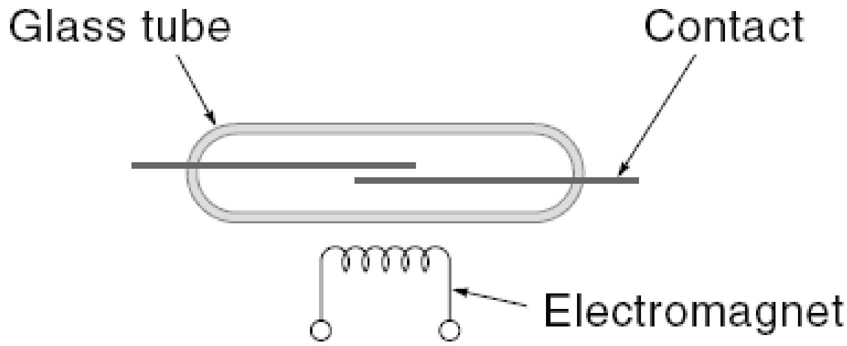


Figure 4.28 A reed relay(Kilian, 2005)

A solid-state relay(SSR) is a purely solid-state device that has replaced the EMR in many applications, particularly for turning on and off AC loads such as motors. Physically, the SSR is packaged in a box(about the same size as an EMR), with four electrical terminals, as shown in Figure 4.29. The two input terminals are analogous

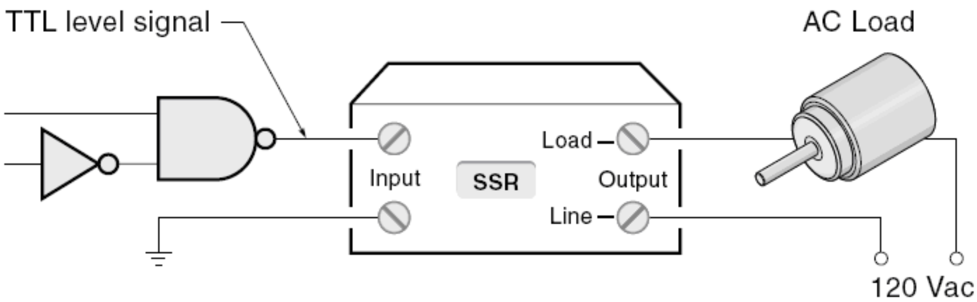


Figure 4.29 Using an SSR to drive a motor(Kilian, 2005)

to the coil of an EMR, and the two output terminals are analogous to the contacts of the EMR(usually SPST, normally open).The input or *control voltage* of the SSR is typically 5 Vdc, 24 Vdc, or 120 Vac.The 5-Vdc models are designed to be driven directly from TTL digital logic circuits.Turning our attention to the output side of the SSR, we see that the load is placed in series with the 120-Vac or 240-Vac power. The output current can be as high as 50 A in some models. Many SSRs incorporate a feature called zero-voltage switching: The line current is switched on at the precise time that the AC voltage is crossing 0 V. This eliminates sharp output voltage-rise times and so minimizes electromagnetic interference noise (EMI).

Solid-state relays have a number of important advantages over electromechanical relays. Having no moving parts means that(theoretically) they will never wear out and makes them practically immune to shock and vibration. Also, because of the built-in electronics, they can be driven with a low-voltage source (such as TTL) regardless of the output-current capability. The main disadvantages of the SSR are the following: (1) They can be “false triggered” by electrical noise; (2) even when on, the output resistance is not exactly 0 ohm, so there is some small voltage drop and consequent power loss within the relay, and when off they may have lethal levels of leakage current; (3) although they are long-lasting, unlike an EMR they do not fail predictably; (4) contact arrangements are limited, so they may not work for all relay applications.

The hybrid solid-state relay is similar to the SSR but uses a low-voltage, fast-acting reed relay instead of an LED to turn on the output triac. Using the reed relay provides good electrical isolation and may work better than the SSR in some situations.

4.2.3 PLCs

In the late 1960s the American motor car manufacturer General Motors was interested in the application of computers to replace the relay sequencing used in the control of its automated car plants. In 1969 it produced a specification for an industrial computer.Two independent companies, Bedford Associates (later called Modicon) and Allen Bradley, responded to General Motor’s specification.Each produced a computer system which bore little resemblance to the commercial minicomputers of the day.The computer itself, called the central processor, was designed to live in an industrial environment, and was connected to the outside world via racks into which input or output cards could be plugged.Each card would accept 16 inputs or drive 16 outputs. A rack of eight cards could thus be connected to 128 devices. It is very important to appreciate that the card allocations were the user’s choice, allowing great flexibility.

The most radical idea, however, was a programming language based on a relay schematic diagram, with inputs (from limit switches, pushbuttons,etc.) represented by relay contacts, and outputs (to solenoids,motor starters, lamps, etc.) represented by relay coils.These programs look like the rungs on a ladder, and were consequently called ‘ladder diagrams’.The program was entered via a programming terminal with keys showing relay symbols (normally open/normally closed contacts, coils,timers, counters, parallel branches, etc.) with which a maintenance electrician would be familiar.The program would highlight energized contacts and coils, allowing the programming terminal to be used for simple fault finding.The processor memory was protected by batteries to prevent corruption or loss of program during a power fail. Programs could be stored on cassette tapes which allowed different operating procedures (and hence programs) to be used for different products.The name given to these machines was ‘programmable controllers(Parr, 2003).

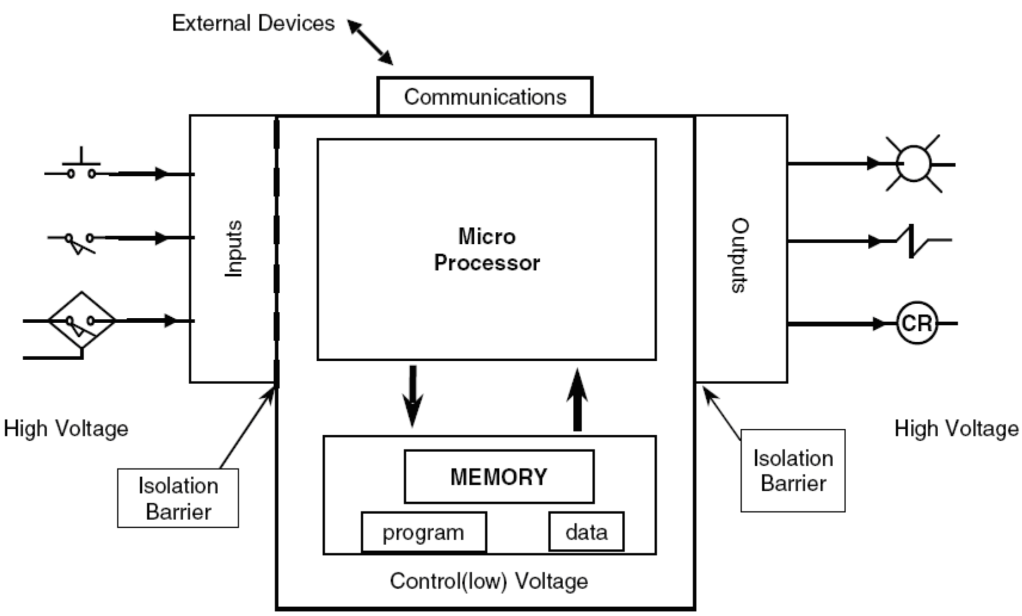


Figure 4.30 PLC Input/Output(I/O) structure(Parr, 2003)

The programmable logic controllers have been part of manufacturing automation for over two decades,replacing the hard-wired relay logic controllers.For smaller-scale, event-driven processes and machines with limited I/O points, stand alone PLCs are the controller of choice. PLCs are rugged,relatively fast, and low cost with excellent sequential control performance.In the last 10 years the functionality of the

PLC and systems using PLCs has been growing rapidly,with integration of networking, peripherals, and expanded programming options. The distinction between PLC systems and other more complex controllers (e.g.,DCS) is diminishing, as PLCs are moving up in function and connectivity. Advanced PLCs and DCSs overlap each other’s controller areas. Indeed, the networked PLC-SCADA systems are virtually equivalent to the larger DCS systems.Programming standards and networks have also removed the limitations of PLCs. In addition to the traditional ladder logic, four other standardized programming languages are available.

Figure 4.31 Siemens PLCs

4.2.4 Motion and Process controllers

Motion/Process controllers are implemented as machine controllers when position,velocity, or other servo-control loop critical functions must occur in a plant with limited I/O.These controllers have built-in servo control algorithms, typically PID.Motion and process I/O data are easily integrated into control loops, as they reside on the same CPU.Some manufacturers allow user-defined interrupt service routines (ISR) for advanced control algorithms.These controllers offer faster update rates for high bandwidth, servo-control loops.Motion/Process controllers can provide servo update rates greater than 1 kHz. However, as integration of motion/process control into PLCs advances with new control networks, the need of using a motion/process controller as a plant controller is diminishing for plants requiring high speed servo control with large amounts of process I/O.Motion/process controllers generally provide significantly fewer I/O points than PLCs or DCSs. PLC manufacturers have specific PLC/motor driver/high speed bus configuration for accessing and controlling motion/process within the PLC.A major limitation of motion/process controllers as plant controllers is their use of unique and proprietary programming languages. Most of these are textural languages, sometimes based on the C programming language. This limits the portability and maintainability of the controller programs(Kurfess,2005).

4.2.5 PCs and ICs(personal and industrial computers)

As personal computer (PC) operating systems have become more stable, the open architecture PC systems have made their way into factories. The drive for data automation and electronic commerce along with lower initial and operating costs, flexibility, and built-in networking ability are some of the reasons for pursuing this approach. PCs have an open systems advantage over both DCS and PLC approaches. PC deployment in control systems occurs in several different ways.In some applications PCs are used as HMIs linked to process controllers.For other applications the PC is the controller and HMI. A PC-based controller is an integrated package of software (operating system, programs, data structures, communication protocols) and hardware (CPUs, communication/network cards, I/O device networks, I/O modules,bus resident controllers, etc).

Another driving reason for PC-based control is the open architecture, allowing the linking and integration of different hardware, software, and networks.While individually excellent components can be purchased and assembled, the success of the system depends on the compatibility of both the hardware and software components.

Typically PC-based controls are built using fairly stable operating systems (OS), such as Windows NT/2000/XP/CE or Linux. There are three levels of control/operating systems interactions. First is relying completely on the OS for all levels of control. This is only acceptable in noncritical, low usage systems that do not require real-time control at regular update intervals. Second is the use of a real-time operating system or real-time kernel forWindows/DOS. This provides real-time control with easy access to all the standard PC components. These are sometimes referred to as software PLC applications. Both of these schemes should be avoided in critical applications including life safety systems, to avoid possible shutdowns from suspensions or system reboots.

The third PC-based control approach is the use of a separate controller card on the PC bus.Here the real-time control resides in the controller card, which takes its power fromthe bus. All control I/O are connected through the card. The advantage of this scheme is that the PC may be re-booted without affecting the controller operation. All three PC approaches have cost savings associated with using the PC as a database, communication host, and HMI.

Industrial PCs are x86 PC-based computing platforms for industrial applications.IBM released the 5531 Industrial Computer in 1984,arguably the first 'industrial PC'. The IBM 7531, an industrial version of the IBM AT PC was released May 21, 1985.Industrial Computer Source first offered the 6531 Industrial Computer in 1985. This was a proprietary 4U rackmount industrial computer based on a clone IBM PC motherboard.Industrial PCs are used primarily for process control and/or data acquisition. In some cases, an Industrial PC is simply used as a front end to another control computer in a distributed processing environment. Software can be custom written for a particular application or an off-the-shelf package such as Wonder Ware, Labtech Notebook or LabView can be used to provide a base level of programming.An application may simply require the I/O such as the serial port offered by the motherboard. In other cases, expansion cards are installed to provide analog and digital I/O, specific machine interface, expanded communications ports, and so forth, as required by the application.

Industrial PCs offer features different from consumer PCs in terms of reliability, compatibility, expansion options and long-term supply.Industrial PCs are typically characterized by being manufactured in lower volumes than home or office PC's. A common category of industrial PC is the 19" rackmount form factor. Industrial PCs typically cost considerably more than comparable office style computers with similar performance. Single-board computers and backplanes are used primarily in Industrial PC systems. However, the majority of industrial PCs are manufactured with COTS motherboards.A subset of industrial PCs is the Panel PC where a display, typically an LCD, is incorporated into the same enclosure as the motherboard and other electronics. These are typically panel mounted and often incorporate touch screens for user interaction. They are offered in low cost versions with no environmental sealing, heavier duty models sealed to IP67 standards to be water proof at the front panel and including models which are explosion proof for installation into hazardous environments. Makers can tailor-make industrial panel PCs to the performance requirements and budget considerations of buyers through the use of different processors and OS. Most entry-level models are designed with Via processors and Linux platforms. Midrange industrial panel PCs are mostly based on AMD processors. Models incorporating Intel processors and Microsoft Windows OS are typically positioned as the high end. Some suppliers said that Windows 2000 and Windows XP are the easiest to work with in terms of installing and developing applications, as these are stable despite their poor environmental adaptability. Meanwhile, Linux is not stable enough, but has better in environmental adaptability. Windows XP Embedded is hard to install, but it has better environmental adaptability. Interviewed makers claim that their industrial panel PCs can support Windows Vista(Wikipedia,2009).


Figure 4.32 Beckhoff rack mount and built-in panel type industrial computers

4.2.6 HMIs

An integral part of the modern industrial control system is the human-machine interface (HMI). Before the widespread use of microprocessor-based graphical displays, an HMI consisted of hardwired dial gauges, strip chart and servo recorders, light indicators, and various push buttons. Modern controllers and automation systems interact with people mainly through graphical user interfaces (GUI). These GUI interfaces most often appear as touch screens with a menu driven display. Minimally HMIs display process information and controls in real-time.

Figure 4.33 Beckhoff HMIs

A low-feature HMI (some are integrated with low cost PLCs) may simply display a current rung of the ladder logic diagram.With a PC-based HMI, powerful graphics can be used. Historical and real-time data can be displayed,using the databases, file structures, and graphics capabilities of a PC. The use of dynamic data exchange (DDE), multiple open windows, and other standard PC platform software components, such as OPC,augments its functionality.Control parameters and functions are integrated into the HMI screens for easy use by operators and control engineers. Some displays mimic the analog devices they replaced (dial gauges, LED displays, indicator lights, etc.). Other features include charting and trending of data for quality control. Animations are also available for better display process status. System status and other diagnostic tools are also presentable. Using data monitoring with alarms, an HMI may also serve as a supervisory control and data acquisition system (SCADA). HMIs can be devices connected directly to the controllers or to database servers that pass information back and forth to the process controller via several network protocols. In fact may HMIs are run in a Web-browser windows, allowing remote viewing and control(Kurfess,2005).

4.2.7 DCS

A *distributed control system(DCS)* refers to a control system usually of a manufacturing system, process or any kind of dynamic system, in which the controller elements are not central in location (like the brain) but are distributed throughout the system with each component sub-system controlled by one or more controllers. The entire system of controllers is connected by networks for communication and monitoring(Wikipedia,2009).

DCS typically uses custom designed processors as controllers and uses both proprietary interconnections and Communications protocol for communication. Input & output modules form component parts of the DCS. The processor receives information from input modules and sends information to output modules. The input modules receive information from input instruments in the process (a.k.a. field) and transmit instructions to the output instruments in the field. Computer buses or electrical buses connect the processor and modules through multiplexer or demultiplexers. Buses also connect the distributed controllers with the central controller and finally to the Human-Machine Interface (HMI) or control consoles.Elements of a distributed control system may directly connect to physical equipment such as switches, pumps and valves or may work through an intermediate system such as a SCADA system.

Distributed Control Systems (DCSs) are dedicated systems used to control manufacturing processes that are continuous or batch-oriented, such as oil refining, petrochemicals, central station power generation, pharmaceuticals, food & beverage manufacturing, cement production, steelmaking, and papermaking. DCSs are connected to sensors and actuators and use setpoint control to control the flow of material through the plant. The most common example is a setpoint control loop consisting of a pressure sensor, controller, and control valve. Pressure or flow measurements are transmitted to the controller, usually through the aid of a signal conditioning Input/Output (I/O) device. When the measured variable reaches a certain point, the controller instructs a valve or actuation device to open or close until the fluidic flow process reaches the desired setpoint. Large oil refineries have many thousands of I/O points and employ very large DCSs. Processes are not limited to fluidic flow through pipes, however, and can also include things like paper machines and their associated variable speed drives and motor control centers, cement kilns, mining operations, ore processing facilities, and many others.

A typical DCS consists of functionally and/or geographically distributed digital controllers capable of executing from 1 to 256 or more regulatory control loops in one control box. The input/output devices (I/O) can be integral with the controller or located remotely via a field network. Today’s controllers have extensive computational capabilities and, in addition to proportional, integral, and derivative (PID) control, can generally perform logic and sequential control.DCSs may employ one or several workstations and can be configured at the workstation or by an off-line personal computer. Local communication is handled by a control network with transmission over twisted pair, coaxial, or fiber optic cable. A server and/or applications processor may be included in the system for extra computational, data collection, and reporting capability(Wikipedia,2009).

4.2.8 Scada

SCADA stands for *Supervisory Control And Data Acquisition*. It generally refers to an industrial control system: a computer system monitoring and controlling a process. The process can be industrial, infrastructure or facility based as described below:

- Industrial processes include those of manufacturing, production, power generation, fabrication, and refining, and may run in continuous, batch, repetitive, or discrete modes.

- Infrastructure processes may be public or private, and include water treatment and distribution, wastewater collection and treatment, oil and gas pipelines, electrical power transmission and distribution, civil defense siren systems, and large -communication systems.
- Facility processes occur both in public facilities and private ones, including buildings, airports, ships, and space stations. They monitor and control HVAC, access, and energy consumption.

A SCADA System usually consists of the following subsystems:

- A Human-Machine Interface or HMI is the apparatus which presents process data to a human operator, and through this, the human operator, monitors and controls the process.
- A supervisory (computer) system, gathering (acquiring) data on the process and sending commands (control) to the process.
- Remote Terminal Units (RTUs) connecting to sensors in the process, converting sensor signals to digital data and sending digital data to the supervisory system.
- Programmable Logic Controller (PLCs) used as field devices because they are more economical, versatile, flexible, and configurable than special-purpose RTUs.
- Communication infrastructure connectin g the supervisory system to the Remote Terminal Units

Figure 4.34 SCADA systems

There is, in several industries, considerable confusion over the differences between SCADA systems and Distributed control systems (DCS). Generally speaking, a SCADA system usually refers to a system that coordinates, but does not control processes in real time. The discussion on real-time control is muddied somewhat by newer telecommunications technology, enabling reliable, low latency, high speed communications over wide areas. Most differences between SCADA and DCS are culturally determined and can usually be ignored. As communication infrastructures with higher capacity become available, the difference between SCADA and DCS will fade(Wikipedia,2009).

4.2.9 Data buses and Networks

Data communications is the transfer of information from one point to another. In automated systems,we are specifically concerned with digital data communication. In this context,'data' refers to information that is represented by a sequence of zeros and ones; the same sort of data that is handled by computers. Many communications systems handle analog data; examples are the telephone system, radio, and television. Modern instrumentation is almost wholly concerned with the transfer of digital data.

Any communications system requires a *transmitter* to send information, a *receiver* to accept it and a link between the two. Types of link include copper wire, optical fiber,radio, and microwave.Some short distance links use parallel connections; meaning that several wires are required to carry a signal. This sort of connection is confined to devices such as local printers. Virtually all modern data communication use serial links, in which the data is transmitted in sequence over a single circuit.The digital data is sometimes transferred using a system that is primarily designed for analog communication. A *modem*, for example, works by using a digital data stream to modulate an analog signal that is sent over a telephone line. At the receiving end, another modem demodulates the signal to reproduce the original digital data.The word 'modem' comes from modulator and demodulator.

There must be mutual agreement on how data is to be encoded, that is, the receiver must be able to understand what the transmitter is sending. The structure in which devices communicate is known as a *protocol*.Traditionally, developers of software and hardware platforms have developed protocols, which only their products can use. In order to develop more integrated instrumentation and control systems, standardization of these communication protocols is required.Standards may evolve from the wide use of one manufacturer's protocol (a *de facto* standard) or may be specifically developed by bodies that represent an industry.Standards allow manufacturers to develop products that will communicate with equipment already in use, which for the customer simplifies the integration of products from different sources(Park,2003).

There is a wide range of technologies in various stages of development and standardization, which address virtually all levels or layers of the ISO/OSI network reference model. One or more of the available technologies will probably suit almost any networking need. An analysis of the available technologies and their limitations will also be beneficial if it is deemed that a networking method must be designed to meet a particular application. The selection and description of technologies is by no means complete or exhaustive. The technologies presented are selected from several industries which make common use of networking to communicate sensor data.

4.2.9.1 *RS-232*

RS-232(ANSI/EIA/TIA-232-E-91) is a widely used method of communication, which has been standardized in a variety of places including the Electronics Industry Association [3]. RS-232 represents elements of layer 1 of the OSI model, for communicating between two (and only two) stations. RS-232 provides a separate wire for transmission of data in each direction between the two stations, and gives the two stations different designations — data terminal equipment (DTE), and data communications equipment (DCE) — so that a method exists to distinguish which station will use which wire to transmit and receive. The signal levels for RS-232 represent a digital 1 bit as a voltage in the range of 5 to 12 V on the wire, and a digital 0 bit as a voltage of negative 5 to 12 V on the wire. RS-232 is typically implemented in a full duplex fashion, since each station can transmit to the other simultaneously using separate wires. RS-232 can be made to operate at a variety of bit rates, but typically is used at bit rates from 300 bit/s up to 115,200 bit/s.

4.2.9.2 *RS-485*

EIA RS-485 was made a standard in 1983, derived from the RS-422 standard. RS-485 provides for differential transmission of data on a pair of wires among 32 or more stations. Like RS-232, the standard is a layer 1 specification. RS-485 provides for half duplex communication, since a station cannot simultaneously transmit and receive independent data streams. Each station in an RS-485 system can have either a transmitter or a receiver, or both (commonly called a transceiver). Most implementations provide a transceiver. When one transceiver is transmitting, all others should be receiving (i.e., not transmitting).Which station is allowed to transmit at which time is not specified in the standard, and must be covered by a higher layer protocol (e.g., Interbus-S, Profibus-DP)(Webster,1999).

4.2.9.3 *Seriplex*

Seriplex® is a digital, serial multiplexing system developed by Automated Process Control, Inc., in Jackson,MS. Square D Corporation purchased Automated Process Control and the rights to Seriplex in 1995,and subsequently launched Seriplex Technology Organization (STO) to manage the protocol. Seriplex is designed to be particularly efficient at handling large numbers of digital or on/off input and output points. Seriplex provides three communication wires, one for a clock signal, one for a data signal, and a ground reference. The system can be operated in two different modes (peer-to-peer and master–slave).In master–slave mode, one station is designated the master. The master synchronizes all data transmission among stations by driving a digital waveform on the clock line which all stations listen to and use for timing of transmit and receive operations. The master generates a repetitive pattern on the clock line which causes all stations to transmit and/or receive data on each cycle, or "scan" of the network. Each station is given an address, and uses the address along with the clock signal to determine when to drive the data line (in the case of an input point) or when to monitor the data line for valid output data (in the case of an output point). There are variations possible in implementation which allow for various clock speeds and bit rates (16, 100, and 200 kHz). Other protocol details allow for the handling of analog or multibit input and output points (by combining several bits on sequential scans together), bus fault detection, input redundancy, and communication error control using multiple scans of the network.Implementing the protocol in a sensor or other device typically requires using a Seriplex ASIC (Application Specific Integrated Circuit) which must be licensed from the STO.

4.2.9.4 *AS-i*

Actuator Sensor Interface, or AS-i, was developed by a consortium of primarily European companies interested in developing a low-cost, flexible method for connecting sensors and actuators at the lowest levels of industrial control systems. The system is managed by an independent worldwide organization.The AS-i system provides a two-wire, nontwisted cable for interconnection of devices. Devices may draw current from the two wires (nominally at 24 V dc) for powering circuitry, and the data communications are modulated on top of the nominal dc level at a bit rate of 167 kHz, under the control of the master. A single parity bit per station is used for error detection. Similar to Seriplex, an AS-i device is typically implemented using a special ASIC which handles the communication.

4.2.9.5 *Interbus-S*

Interbus-S was developed by Phoenix Contact and is controlled by the Interbus-S Club. The topology of the network is a ring, with data being sequentially shifted from point to point on the ring under the control of a network master. Each device in the ring acts as a shift register, transmitting and receiving data simultaneously at 500 kHz. The actual serial data transmission between stations conforms to RS-485.Interbus-S transmissions include a CRC for error detection. Interbus-S (Interbus-S Remote Bus) has also been extended to include a subprotocol called Interbus-Sensor Loop (or Interbus-S Local Bus). This subprotocol provides an alternate physical layer, with a single twisted pair carrying power and data on the same lines, and a reduction in the minimum size of the shift register in each station from 16 to 4 bits.Each Interbus sensor loop system can act as a single station on an Interbus-S network, or the sensor loop can be connected directly to a controller or master. Interbus-S devices are usually implemented with a special ASIC.

4.2.9.6 *CAN*

Controller Area Network (CAN) is a data link layer(layer 2) network technology developed by Robert Bosch Corporation, with an application target of onboard automotive networking. The technology is standardized in ISO 11898,licensed to all major integrated circuit manufacturers, and is widely available — both as separate CAN controllers as well as CAN controllers integrated with microprocessors.As a result, CAN has been used in a variety of industries. As a data link layer technology, it is not a complete network definition. A number of physical layer options are usable with CAN (e.g., twisted pair,fiber optic, radio frequency wireless) and some have been subject to standardization (e.g., ISO 11898).Also, a number of application layer protocols have been developed for use with CAN, such as DeviceNet,Smart Distributed System (SDS), CANOpen, and SAE J1939.Both DeviceNet and Smart Distributed System have developed systems for creating networks of industrial field devices for the factory floor, including sensors and actuators.

4.2.9.7 *4 to 20 mA Current Loop*

The 4 to 20 mA current loop is a widely used method for transferring information from one station (the transmitter) to another station (the receiver). Therefore, this system allows for only two stations. A typical current loop system assigns a sensing range (e.g., 0 to 100 °C) to the current range between 4 and 20 mA.A loop exists (i.e., two wires) between the transmitter and receiver. The transmitter can impress a certain current in the loop (using a controlled current source) so that the receiver can measure the current in the loop (e.g., by placing a small resistor in series with the loop and measuring the voltage drop across the resistor). After measuring the current, the receiver can then determine the present level of the sensed signal within the defined sensing range. This method uses current signaling, instead of voltage signaling,and therefore is relatively unaffected by potential differences between the transmitter and the receiver.This is similar to the benefit of differential (voltage) signaling, which also requires two wires. Another characteristic of this method is that it is not primarily digital in nature, as many other sensor communication systems are. The measured value can vary continuously in the range of 4 to 20 mA, and therefore can easily represent an analog sensing range, rather than a set of digital signals. Also, the signal is continuously variable and available. Another characteristic of this method is that the integrity of the loop can be verified. As long as the loop is unbroken and the transmitter is in good working order, the current in the loop should never fall below 4 mA. If the current approaches 0 mA, then the receiver can determine that a fault exists — perhaps a broken cable. These systems are widely used in various process control industries (e.g., oil refining) for connecting sensors (transmitters) with control computers. Because one station is always the transmitter and one station is always the receiver, this is a unidirectional, half duplex communication system.

4.2.9.8 *HART*

HART® is a protocol which builds upon 4 to 20 mA communication systems. The basic idea is that additional data (beyond the basic sensor signal being carried in the current loop) can be transmitted by modulating a signal on top of the current flowing in the loop. The actual modulation method conforms closely to the Bell 202 standard for analog modem communications on telephone lines at 1200 bit/s.Because a 4 to 20 mA current loop carries a relatively slowly varying signal, it is easy to separate the 4 to 20 mA signal from the digital signal using filters. The Bell 202 standard uses continuous-phase frequency shift keying between two frequencies at up to 1200 shifts/s to modulate digital ones and zeros onto the 4 to 20 mA current loop. This method allows for bidirectional, full duplex communication between the two stations, on top of the 4 to 20 mA signal. It is also possible to configure HART communications on a network that is not carrying a 4 to 20 mA signal, in which case up to 15 devices can be connected together on the network. HART was developed by Fisher-Rosemount Corporation, and has been transferred to an independent foundation for management. Because HART is compatible with U.S. telephone systems, it can theoretically be run over the telephone line and is therefore capable of running over arbitrarily long distances.

4.2.9.9 *Profibus*

Profibus (PROcess FIeld BUS) is one of three networks standardized by a European standard.Profibus is under the control of a global organization,PNO. Profibus is an umbrella network standard which encompasses three subnetworks within the Profibus family. Profibus-DP (Distributed Periphery) is the variant which is designed specifically for communication with field devices (sensors and actuators) at the device I/O level. Profibus-PA (Process Automation) is a variant which has more capabilities designed to support the needs of device-level networking for process industries, such as oil refining. One of the capabilities of Profibus-PA is its ability to be installed in an intrinsically safe way, thus providing a higher degree of safety in environments which may be explosive or otherwise hazardous. Profibus-PA typically uses a special physical layer specification standardized under IEC 1158-2, which is used by several network systems for process automation applications. IEC 1158-2 specifies a two-wire twisted pair implementation carrying both power and data on the same two wires at 31.25 kbit/s. Profibus-FMS (Fieldbus Messaging Specification) represents the highest level implementation, which is used to link together controllers (not field or I/O devices) in a factory.

Profibus-DP systems are typically master–slave systems, where usually a single network master (the host controller) communicates with a number of slave devices (remote I/O blocks and other I/O devices). The protocol provides for cyclic exchange of I/O information as well as on-demand exchange of other types of information.

Profibus-DP can be implemented on several different physical layers, including RS-485 and fiber optics, at various bit rates up to 12 Mbit/s. Profibus messages include a CRC for error detection.

4.2.9.10 *Foundation Fieldbus*

Foundation Fieldbus (FF) is a networking standard which has grown out of an effort within industry standards organizations, especially ISA-SP50, and IEC SC65C/WG6, to provide a replacement for the 4 to 20 mA analog sensor communication standard. FF provides two basic levels of networking:H1 and H2. H1 is a lower-speed system that can provide intrinsically safe(IS) operation and uses a single twisted pair to deliver both power and data communications to field devices, according to IEC 1158-2.Running at a bit rate of 31.25 kbit/s, H1 is very similar to Profibus-PA, when run on the IEC 1158-2 physical layer standard. The H1 system is designed to be able to connect hierarchically “upward” to an H2 system, which acts as the host. FF H2 can be run at either 1 or 2.5 Mbit/s on twisted pair wires, and also provides an IS option at the 1 Mbit/s rate. The H2 system can act as a network backbone in a factory environment, carrying data among various H1 systems.

4.2.9.11 *WorldFIP*

WorldFIP is another technology of the three that were standardized in the European standard EN 50 170, running on the IEC 1158-2 physical layer. Many of the proponents of WorldFIP have embraced FF, and contributed to the development of that standard. WorldFIP is a member of the FF, and FF has incorporated many of the capabilities of WorldFIP as a result. When run on the IEC 1158-2 physical layer, WorldFIP has similar capabilities to FF.

4.2.9.12 *LonWorks*

LonWorks® is a networking technology developed and controlled by the Echelon Corporation.LonWorks is designed to be a general-purpose networking technology suitable for a variety of industries.LonWorks has been applied extensively in the building automation and control industry, as well as a variety of other industries. The core LonWorks technology for devices is contained in special integrated circuits — called Neuron® chips — which combine several microprocessors to manage the network,communications, and provide a general-purpose control environment. These chips are available from Motorola, Inc., and the Toshiba Corporation, which are licensees of the LonWorks technology. Echelon has also announced the possibility to license the LonTalk® protocol to other manufacturers for implementation in other microprocessors. LonWorks networks can be implemented on a variety of physical layers, including twisted pair at several bit rates and wireless options at 4800 bit/s, but the most common is a differential twisted pair system running at 78 kbit/s. Most of the networking details (the LonTalk protocol) are hidden from the user, and are encapsulated as functions within the general-purpose control environment. The user programs (using a language like the C programming language) the Neuron chip for each station to behave in a certain way and communicate various data items to other stations. Then,specialized tools are used to tie all of the stations together (handling addressing and other network details) to yield a functioning network. The system combines flexibility with a certain amount of ease of implementation,and can easily be applied to a variety of applications.

4.2.9.13 Ethernet

With several integrated IP protocols, *Ethernet* is the most popular network at multiple system levels.Control manufacturers select Ethernet to avoid many of the proprietary or custom networks. Ethernet provides interoperability among products from various vendors. 100 Mbps Ethernet is becoming a logical choice for controller networks as well as for information networks. Ethernet provides high standard data transfer rates, efficient error correction, and industrial Ethernet switches for better determinism. Ethernet also brings with it a large available IT expertise.Many control manufacturer have selected Ethernet for connecting remote I/O rack locations to controllers, effectively making Ethernet a process control fieldbus. There is even a push downward for device-level Ethernet.

There are many competitors to Ethernet including *Modbus/TCP*, *ProfiNet*, *HSE Fieldbus*, and many other proprietary protocols.Arguments against using Ethernet in factory floor automation often stress that Ethernet lacks the level of robustness and determinism needed in control applications. However, recent developments of intelligent switches have largely discounted this argument.

Along with the high data transfer rates, Ethernet also provides superior technology compared with others networks, in terms of openness, ease of access to and from the Internet, ease of wiring, setup, and maintenance. A new open application layer protocol, Ethernet/IP, has been created for the industrial environment. It is built on the standard TCP/IP protocols and takes advantage of commercial off-the-shelf Ethernet integrated circuit sand physical media. IP stands for “industrial protocol.”Ethernet/IP is supported by several networking organizations: ControlNet International (CI), Industrial EthernetAssociation (IEA),Open DeviceNet Vendor Association (ODVA), and Industrial Open Ethernet Association (IOANA)(Kurfess,2005).

Table 4.1 Real-time Ethernet industrial interfaces(Roy,2006)

Name	**Organization/Main manufacturer**
EtherCAT (Ethernet for Control Automation Technology)	ETG / Beckhoff
Ethernet/IP mit CIP Sync	ODVA / Rockwell Automation
ETHERNET Powerlink (EPL)	EPSG / B&R
Precision Time Protocol (IEEE 1588)	IEEE / -
PROFINET	PNO / SIEMENS
RTPS (Real-Time Publish-Subscribe Protocol)	Modbus-IDA / Schneider Electric
SERCOS-III	IGS / -
SynqNet * (only Layer 1 based on Ethernet)	SynqNet User Group / Motion Engineering Inc. (MEI), USA
JetSync	– / Jetter, Germany

Table 4.1(Cont.)

PowerDNA (Distributed Network Automation and Control)	– / United Electronic Systems (UEI), USA
SynUTC	– / Oregano Systems, Austria
Switch mit Zeit-Server	– / Ontime Networks, Norway
RTnet (Open Source)	– / Real-Time Systems Group of University Hannover, Germany
Vnet/IP	– / Yokogawa, Japan
TCnet	– / Toshiba, Japan
EPA (Ethernet for Plant Automation)	– / ZHEJIANG SUPCON INSTRUMENT, China
SafetyNET p	SafetyBUS p Club / Pilz

4.2.10 Input/Output(I/O) devices

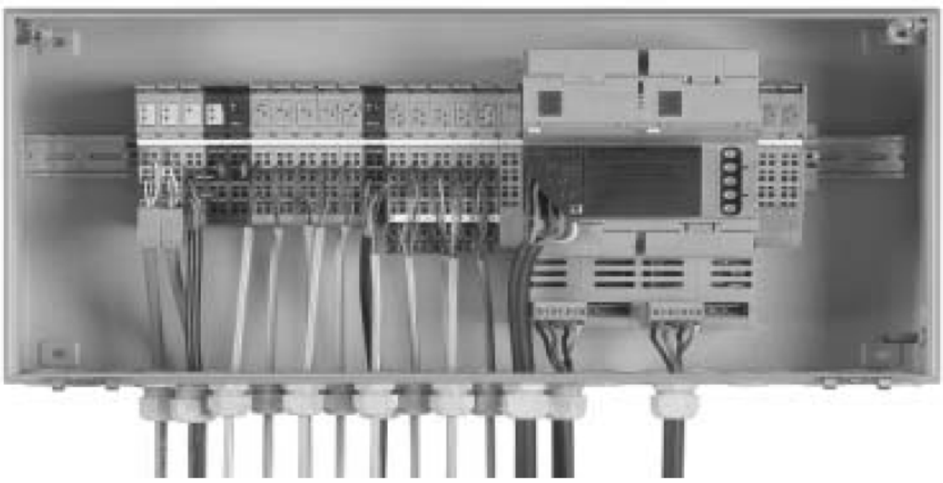


Figure 4.38 Combination of I/O devices

Terminal blocks are components and systems the main function of which is to ensure safe and secure electrical and mechanical conductor(wire and cables) connections.The term covers all conceivable types,designs and forms of connection. From the application point of view, the most important group of terminals is that of rail mounted modular terminal blocks(Klemsan,2009).

Figure 4.39 A terminal block

Fuses are overcurrent protection devices. Their typical component is a metal wire or strip (element) that melts when too much current flows, which interrupts (disconnects) the circuit in which it is connected. Circuit or device failure is often a reason for excessive current. A fuse blows (interrupts excessive current) so that further damage (ie. fire) is prevented. A fuse typically is not intended to protect from the initial cause of overcurrent.Overcurrent protection devices are an essential part of appliances and of power distribution systems to limit both threats to human life and damage. For example, too much current for too long may cause a wire to overheat, be damaged, or even start a fire. Wiring regulations often define a maximum fuse current rating. Fuses are selected to allow passage of normal current and of excessive current for short periods. And to interrupt what is called a short circuit, overload condition, or fault current.

Figure 4.40 Fuses

Wires and *cables* provide low-resistance pathways for electric currents. Most electrical wires are made from copper or silver and typically are protected by an insulating coating of plastic, rubber, or lacquer. Cables consist of a number of individually insulated wires bound together to form a multiconductor transmission line.

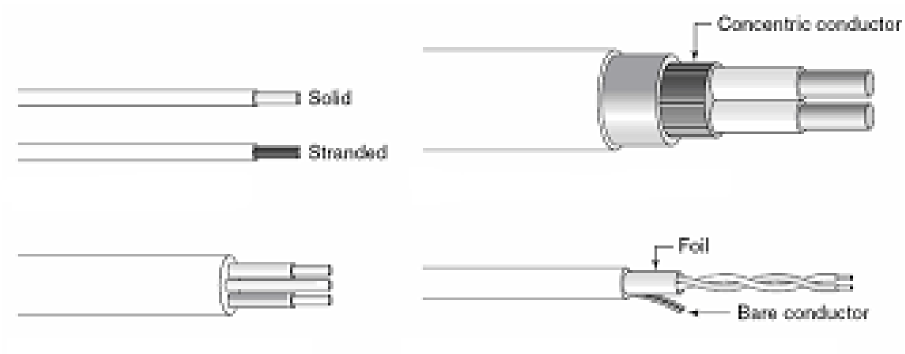


Figure 4.41 Cables(Kilian, 2005)

Connectors,such as plugs, jacks, and adapters, are used as mating fasteners to join wires and cable with other electrical devices.The connection may be temporary, as for portable equipment,or may require a tool for assembly and removal, or may be a permanent electrical joint between two wires or devices. There are hundreds of types of electrical connectors. In computing, an electrical connector can also be known as a physical interface (compare Physical Layer in OSI model of networking). Connectors may join two lengths of flexible wire or cable, or may connect a wire or cable to an electrical terminal.

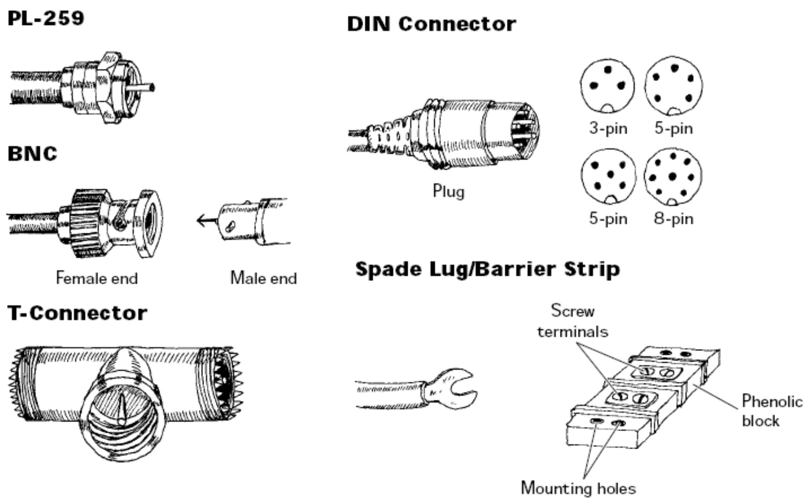


Figure 4.42 Connectors

Cable trays and *conduits*,according to the US National Electrical Code, are "a unit or assembly of units or sections and associated fittings forming a rigid structural system used to securely fasten or support cables and raceways." Cable trays are used to hold up and distribute cables.

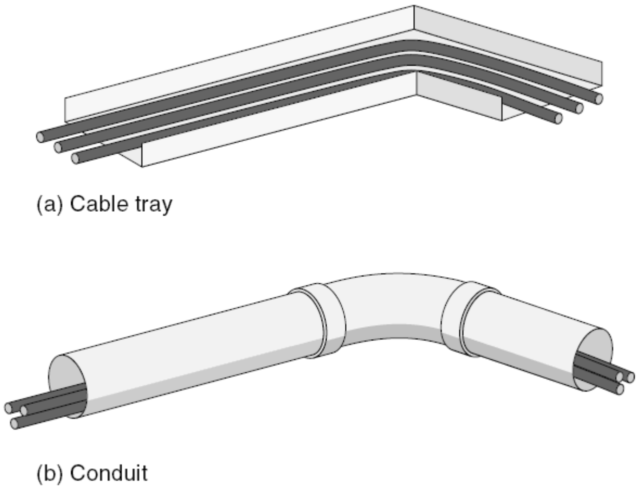


Figure 4.43 A cable tray and conduit(Kilian, 2005)

DIN rails are standardized 35 mm wide metal rails with hat-shaped cross section. It is widely used,especially in Europe, for mounting industrial control equipments inside equipment racks.

Figure 4.44 A 35 mm DIN rail with mounted circuit breaker

4.2.11 Power Supplies

Power supply is a reference to a source of electrical power. A device or system that supplies electrical or other types of energy to an output load or group of loads is called a power supply unit or PSU.

Linear power supplies are AC powered and usually uses a transformer to convert the voltage from the wall outlet(mains) to a different, usually a lower voltage. If it is used to produce DC, a rectifier is used. A capacitor is used to smooth the pulsating current from the rectifier. Some small periodic deviations from smooth direct current will remain, which is known as ripple. These pulsations occur at a frequency related to the AC power frequency (for example, a multiple of 50 or 60 Hz).The voltage produced by an unregulated power supply will vary depending on the load and on variations in the AC supply voltage. For critical electronics applications a linear regulator will be used to stabilize and adjust the voltage. This regulator will also greatly reduce the ripple and noise in the output direct current. Linear regulators often provide current limiting, protecting the power supply and attached circuit from overcurrent.

A *switched-mode power supply(SMPS)* works on a different principle. AC mains input is directly rectified without the use of a transformer, to obtain a DC voltage. This voltage is then sliced into small pieces by a high-speed electronic switch. The size of these slices grows larger as power output requirements increase.The input power slicing occurs at a very high speed (typically 10 kHz — 1 MHz). High frequency and high voltages in this first stage permit much smaller step down transformers than are in a linear power supply. After the transformer secondary, the AC is again rectified to DC. To keep output voltage constant, the power supply needs a sophisticated feedback controller to monitor current draw by the load.
Modern switched-mode power supplies often include additional safety features such as the crowbar circuit to help protect the device and the user from harm.In the event that an abnormal high current power draw is detected, the switched-mode supply can assume this is a direct short and will shut itself down before damage is done. For

decades PC computer power supplies have also provided a *power good* signal to the motherboard which prevents operation when abnormal supply voltages are present.Switched mode power supplies have an absolute limit on their minimum current output.They are only able to output above a certain power level and cannot function below that point. In a no-load condition the frequency of the power slicing circuit increases to great speed, causing the isolation transformer to act as a tesla coil, causing damage due to the resulting very high voltage power spikes. Switched-mode supplies with protection circuits may briefly turn on but then shut down when no load has been detected. A very small low-power dummy load such as a ceramic power resistor or 10 watt light bulb can be attached to the supply to allow it to run with no primary load attached.Power factor has become a recent issue of concern for computer manufacturers. Switched mode power supplies have traditionally been a source of power line harmonics and have a very poor power factor. Many computer power supplies built in the last few years now include power factor correction built right into the switched-mode supply, and may advertise the fact that they offer *1.0 power factor*.By slicing up the sinusoidal AC wave into very small discrete pieces, the portion of the alternating current not used stays in the power line as very small spikes of power that cannot be utilized by AC motors and results in waste heating of power line transformers. Hundreds of switched mode power supplies in a building can result in poor power quality for other customers surrounding that building, and high electric bills for the company if they are billed according to their power factor in addition to the actual power used. Filtering capacitor banks may be needed on the building power mains to suppress and absorb these negative power factor effects.

An *Uninterruptible Power Supply(UPS)* takes its power from two or more sources simultaneously. It is usually powered directly from the AC mains, while simultaneously charging a storage battery. Should there be a dropout or failure of the mains, the battery instantly takes over so that the load never experiences an interruption. Such a scheme can supply power as long as the battery charge suffices, e.g., in a computer installation, giving the operator sufficient time to effect an orderly system shutdown without loss of data. Other UPS schemes may use an internal combustion engine or turbine to continuously supply power to a system in parallel with power coming from the AC mains. The engine-driven generators would normally be idling, but could come to full power in a matter of a few seconds in order to keep vital equipment running without interruption. Such a scheme might be found in hospitals or telephone central offices.

High-voltage power supplies(High voltage refers to an output on the order of hundreds or thousands of volts) use a linear setup to produce an output voltage in this range.When choosing a high-voltage power supply, there are several options to consider. Some of these are maximum current, maximum power, maximum voltage, output polarity, user interface, and style. The first four of these characteristics of course depend upon the supply's intended application. There are many available types of user interfaces. For example, the interface may be local in the form of a digital meter, or analog meter. Also, the interface can be remote, as in a computer connection. Numerous styles of high-voltage power supplies are also manufactured. Available models come in printed circuit board mount, open frame (as designed to be incorporated into an instrument), and rack mount. Models with multiple outputs can also be found.

Dual Supplies have positive and negative outputs as well as zero volts (0V). This is called a 'dual supply' because it is like two ordinary supplies connected together as shown in the diagram.Dual supplies have three outputs, for example a ±9V supply has +9V, 0V and -9V outputs.

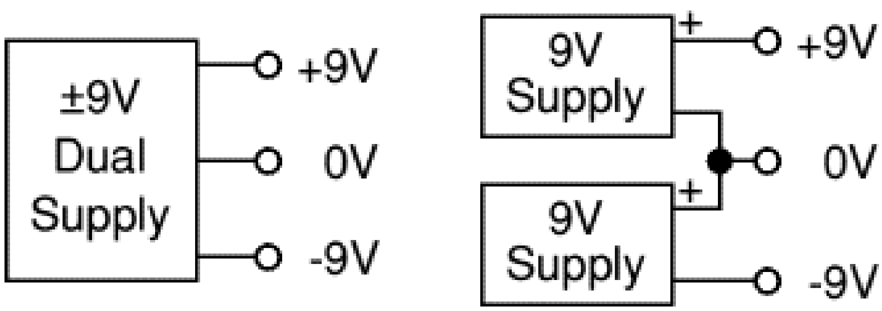


Figure 4.46 Dual supplies schematics

Power supplies can also be classified by their construction like:DIN Rail,Pan and PCB types.

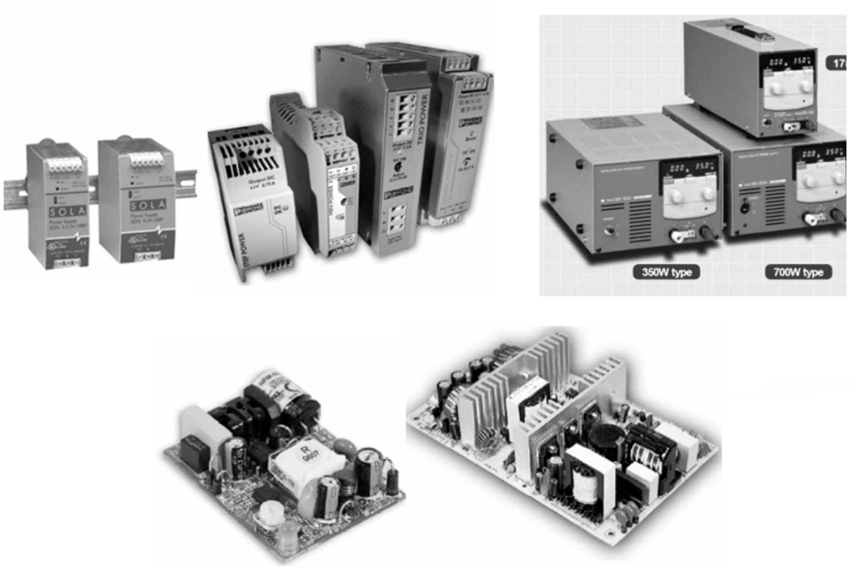


Figure 4.47 DIN rail,Pan and PCB type power supplies

4.2.12 Control cabinets

The control cabinets are enclosures for the components of “soft tasks” and sometimes for the hard tasks sub-systems like pneumatic valves etc.

They are used for protecting the devices from environmental effects,maintenance ease and clean-cut seen assemblies.

Figure 4.48 A control cabinet

CHAPTER FIVE
ROBOTIC SYSTEMS

5.1 Robotic Systems

Robotic systems are representative of mechatronics devices which integrate aspects of manipulation,sensing,control,and communication.Rarely have so many technologies and scientific disciplines focused on the functionality and performance of a system as they have done in the fields of robot development and application (Hurmuzlu,2002).

In 1999 some 940,000 industrial robots were at work and major industrial countries reported growth rates in robot installation of more than 20% compared to the previous year.The automotive,electric,and electronic industries have been the largest robot users;the predominant applications are welding,assembly,material handling,and dispensing.The flexibility and versatility of industrial robot technology have been strongly driven by the needs of these industries,which account for more than 75% of the world's installation numbers.Still,the motor vehicle industry accounts for some 50% of the total robot investment worldwide.Robots are now mature products facing enormous competition by international manufacturers and falling unit costs.A complete six-axis robot with a load capacity of 10 kg was offered at less than $60,000 in 1999.It should be noted that the unit price only accounts for about 30% of the total system cost.However, for many standard applications in welding, assembly,palletizing,and packaging,preconfigured,highly flexible workcells are offered by robot manufacturers,thus providing cost effective automation to small and medium sized operations.

A broad spectrum of routine job functions led to a robotics renaissance and the appearance of service robots.Modern information and telecommunication technologies have had a tremendous impact on exploiting productivity and profitability potentials in administrative, communicative,and consultative services. Many transportation,handling,and machining tasks are now automated.Examples of diverse application fields for robots include cleaning, inspection,disaster control,waste sorting,and transportation of goods in offices or hospitals. It is widely accepted that service robots can contribute significantly to better working conditions,improved quality,profitability,and availability of services.Based on sales figures from leading manufacturers,the total service robot stock can be estimated at a few thousand and certainly below 10,000 units.It is expected that within ten years, service robots may become commodities and surpass industrial robot applications (Hurmuzlu,2002).

The past two decades have seen the incorporation of robotics into medicine.From a manufacturing perspective,robots have been used in pharmaceuticals,preparing medications. But on more novel levels,robots have been used in service roles,surgery,and prosthetics.Not only are robots capable of much higher precision than a human, they are not susceptible to human factors,such as trembling and sneezing,that are undesirable in the surgery room(Kurfess,2005).

Space exploration has been revolutionized by the introduction of robotics,taking shape in many different forms,such as flyby probes,landers,rovers,atmospheric probes,and robot arms. All can be remotely operated and have had a common theme of removing mankind from difficult or impossible settings.It would not be possible to send astronauts to remote planets and return them safely.Instead, robots are sent on these journeys,transmitting information back to Earth,with no intent of returning home(Kurfess,2005).

Just as space programs have used robots to accomplish tasks that would not even be considered as a manned mission,military and law enforcement agencies have employed the use of robots to remove humans from harm’s way.Police are able to send a microphone or camera into a dangerous area that is not accessible to law enforcement personnel,or is too perilous to enter.Military applications have grown and continue to do so(Kurfess,2005).

In addition to their extensive application in manufacturing, space exploration, the military, and medicine, robotic systems can be found in a host of other fields, such as the ever-present entertainment market—toys,movies, etc.

5.2 Classification

Robotic systems can be classified with different classes based on different criterians.With the functionality base three categories can be stated: industrial, service, personel(Hurmuzlu,2002). If we take the decision-making capabilities base: programmable, intelligent/autonomous(Angales,2003). Or taking the controller/operator type base: PC operator and human/tele operator systems (Hurmuzlu,2002).

Figure 5.1 CyberKnife® stereotactic radiosurgery system(Kurfess, 2005)

In my thesis I preferred kinematic configuration based three major categories cause all the categories above can be regarded as the sub-categories of these configurations below.

5.2.1 Serial manipulators

Robotic manipulators deserve special attention,for various reasons.One is their relevance in industry.Another is that they constitute the simplest of all robotic mechanical systems,and hence,appear as constituents of other,more complex robotic mechanical systems.A manipu-lator,in general,is a mechanical system aimed at manipulating objects.Manipulating,in turn, means to move something with one's hand,as it derives from the Latin *manus*,meaning hand(Angeles,2003).

Hence,a manipulator is any device that helps man perform a manipulating task.Although manipulators have existed ever since man created first tool,only very recently,by the end of World War II,have manipulators developed to extent that they are now capable of actually mimicking motions of the human arm.In fact during WWII,the need arose for manipulating probe tubes containing radioactive substances,this led to the first six-degree-of-fredom(DOF) manipulators(Angeles,2003).

Shortly there after,the need for manufacturing workpieces for high accuracy arose in the aircraft industry,which led to the first numerically-controlled(NC) machine tools.The synthesis of the six-DOF manipulator and the NC machine tool produced what became the *robotic manipulator*.

A robotic manipulator is to be distinguished from the early manipulator by its capability of lending itself to computer control.The robotic manipulator can be programmed once and for all to repeat the same task forever.Programmable manipulators have existed for about 30 years,namely since the advent of microprocessors.

The fundamental structure of serial type manipulator is the open kinematic chain.From a topological viewpoint,a kinematic chain is termed open when there is only one sequence of links connecting the two ends of the chain.The mobility is ensured by the presence of joints.The articulation between two consecutive links can be realized by means of either a *prismatic* or a *revolute* joint.In an open kinematic chain,each prismatic or revolute joint provides the structure with a single degree of mobility.A prismatic joint realizes a relative translational motion between the two links,whereas a revolute joint realizes a relative rotational motion between the two links(Sciavicco,L.&Siciliano,B,2005).

The type and sequence of the arm's degrees of mobility,starting from the base joint,allows classifying serial manipulators as:*cartesian*,*cylindrical*,*spherical*, *SCARA*,and *anthropomorphic*.

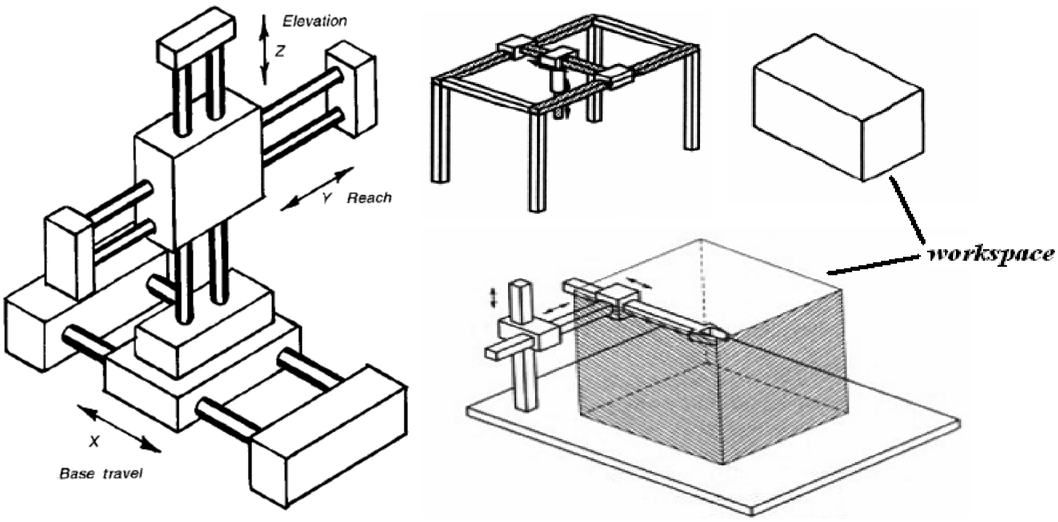


Figure 5.2 Cartesian/gantry/rectangular type serial manipulators(Sclater, 2006 and Özçelikyıldız, 2006)

Cartesian(or rectangular) type serial manipulators have prismatic joints whose axes are coincident with a Cartesian coordinate system.This configuration produces robots with very stiff structures.As a consequence,very large robots can be built (Craig,1989).Most cartesian robots come as gantries,which are distinguished framed structures supporting linear axes.*Gantry robots* are widely used for handling tasks such as palletizing,warehousing,order picking,and special machining tasks such as laser or water jet cutting where robot motions cover large surfaces.Gantry robots sometimes manipulate entire automobiles or inspect aircraft(Craig,1989).

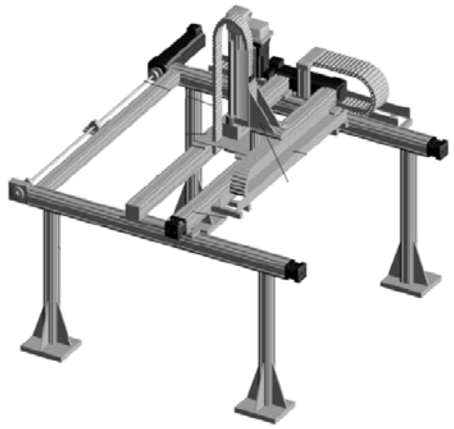


Figure 5.3 Parker Hannifin Corporation Gantry/cartesian type robot

Cylindrical type serial manipulators consist of a prismatic joint for translating the arm vertically,a revolute joint with a vertical axis,another prismatic joint orthonogal to the revolute joint axis,followed by a wrist of some sort.

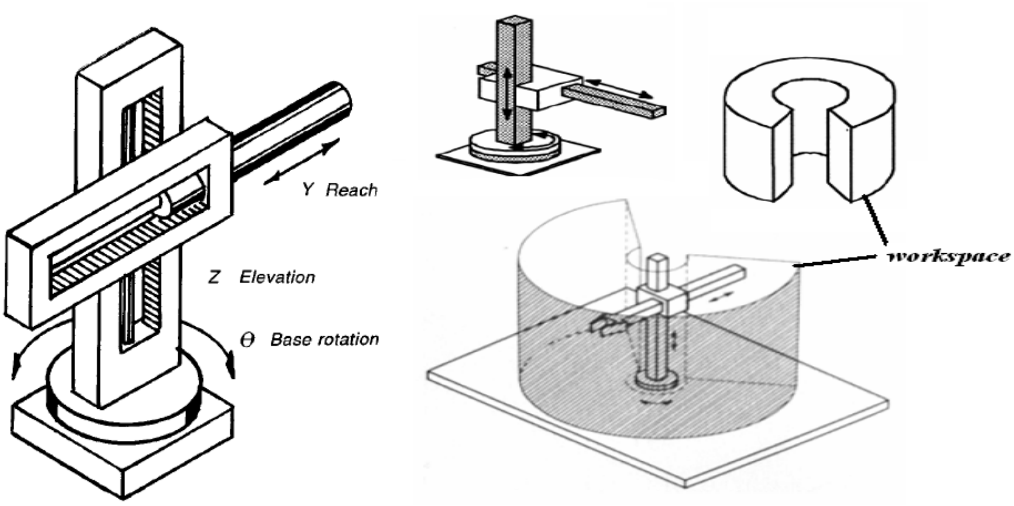


Figure 5.4 Cylindrical type serial manipulators(Sclater, 2006 and Özçelikyıldız, 2006)

Spherical(also called polar) type serial manipulators differ from the cylindirical one in that the second prismatic joint is replaced with a revolute joint.Each degree of mobility corresponds to a degree of fredom only if the task is described in spherical coordinates.

Today cylindrical and spherical type serial manipulators play only a minor role and are used for palletizing, loading,and unloading of machines.

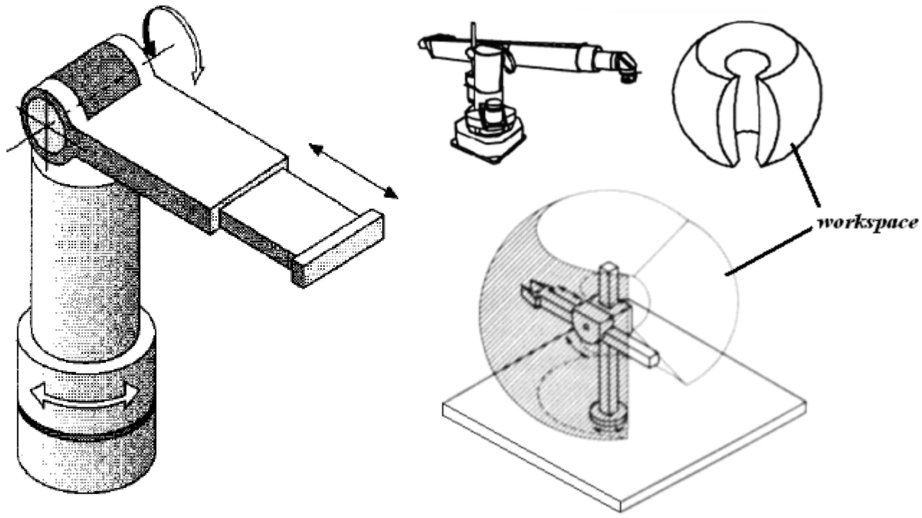


Figure 5.5 Spherical/polar type serial manipulators(Sclater, 2006 and Özçelikyıldız, 2006)

SCARA(Selective Compliant Articulated Robot for Assembly) type serial manipulators have three parallel revolute joints allowing it to move and orient in a plane,with a fourth prismatic joint for moving the end-effector normal to the plane. The chief advantage is that the first three joints don’t have to support any of the weight of the manipulator or the load.The SCARA was introduced in Japan in 1979 and has been adopted by numerious manufacturers.

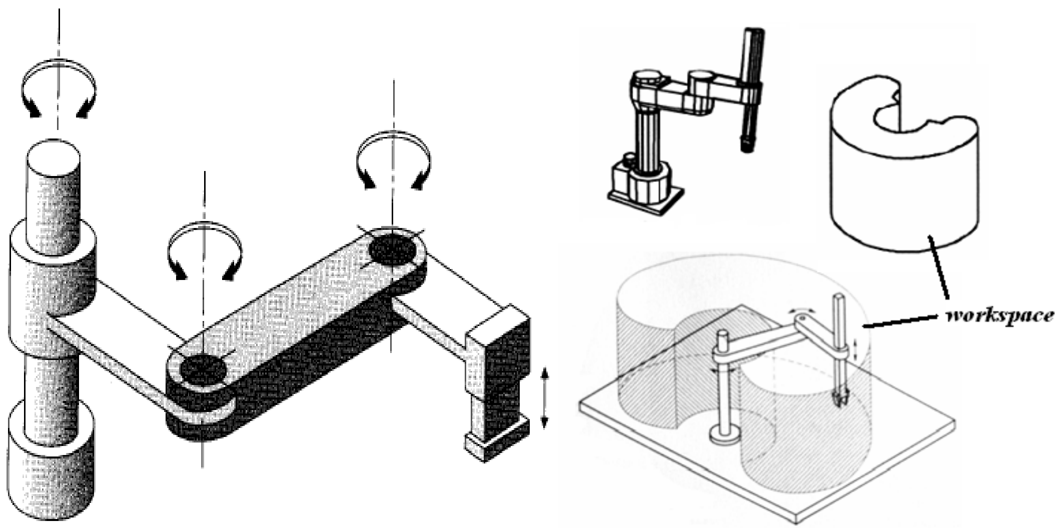


Figure 5.6 SCARA type serial manipulators(Sclater, 2006 and Özçelikyıldız, 2006)

Figure 5.7 Kuka Robotics 4 axes SCARA type robot

Anthropomorphic(also called jointed,elbow,or articulated) type serial manipulators are the most common kinematic configuration,consist of at least three rotary joints by definition. They typically consists of two “shoulder” joints,one for rotation about a vertical axis and one for elevation out of the horizontal plane,an “elbow” joint whose axis is usually parallel to the shoulder elavation joint,and two or three wrists joints at the end of the manipulator.

Anthropomorphic robots provide the least intrusion of the manipulator structure into the workspace,making them capable of reaching into confined spaces.This type is the most dexterous serial one,since all the joints are revolute.

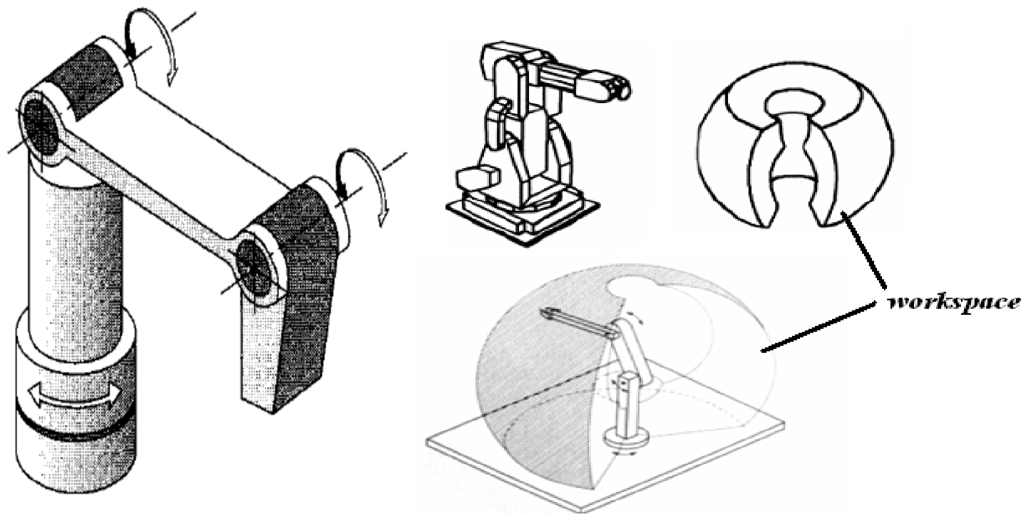


Figure 5.8 Articulated/anthropomorphic type serial manipulators(Sclater, 2006 and Özçelikyıldız, 2006)

5.2.2 Parallel manipulators

A parallel manipulator is one in which two or more series chains connect the end-effector to the base of the robot.Parallel manipulators can offer advantages over open-chain(serial type) manipulators in terms of rigidity of the mechanism and placement of the actuators. Parallel manipulators ara also called closed-chain manipulators,since they contain one or more closed kinematic chains(Murray,1994).

Because of the serial nature of the coupling of links in the serial type manipulators,even though they are supplied with structurally robust links,their load carrying capacity and stiffness is too low when compared with the same properties in other multiaxis machines,such as NC machine tools.Obviously,a low stiffness implies a low positioning accuracy.In order to remedy these drawbacks,parallel manipulators have been proposed to withstand higher payloads with lighter links.In a parallel manipulator,we distinguish one *base platform*,one *moving platform* and various *legs*(Angeles,2003).

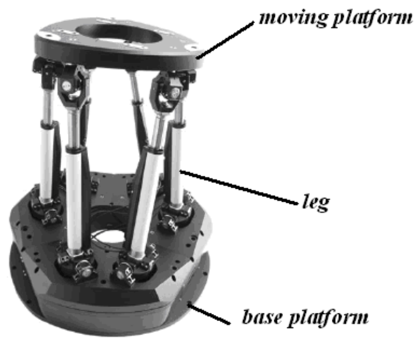


Figure 5.9 A hexapod

Contrary to serial type manipulators,all of whose joints ara actuated,parallel manipulators contain unactuated joints,which brings about a substantial difference between the two types. The presence of unactuated joints makes the analysis of parallel manipulators,in general,more complex than that of their serial counterparts (Angeles,2003).

Parallel manipulators are distinguished by concurrent prismatic or rotary joints.Two kinematic designs have been popular:

- The tripod with three translatory axes connecting end effector,base and moving platforms,and a two-DOF wrist
- The hexapod with six translatory axes for full spatial motion(also called "*Stewart platform*")

At the extremities of the link,we find a universal joint and a ball-and-pocket joint.Due to the interconnected links,the kinematic structure generally shows many advantages such as high stiffness,accuracy,load capacity,and damping.However kinematic dexterity is usually limited.

Parallel manipulators now work in many applications where conventional serial type manipulators reached shown their limits-machining,deburring,and part joining where high process forces at high motion accuracy are overwhelming.

Figure 5.10 ABB IRB940 Tricept parallel manipulator

Although parallel manipulators have been introduced recently and their designs are quite different from those of most classical(serial type) manipulators,their advantage for many robotics tasks is obvious,and they will probably become indispensable.

5.2.3 Mobile

A mobile robot is a navigated or autonomous system capable of traversing a terrain with natural or artificial obstacles.Its chassis is equipped with *wheels*, *tracks* or *legs*, and, possibly, a manipulator setup mounted on the chassis for handling of work pieces, tools,or special devices. Various preplanned operations are executed based on a preprogrammed navigation strategy taking into account the current status of the enviroment(Hurmuzlu,2002).

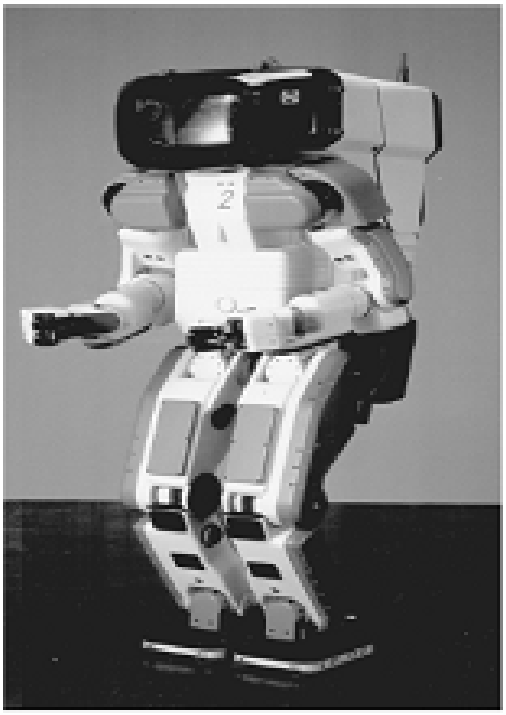


Figure 5.11 Honda’s P2 and Sony’s Aibo mobile robots

Thus mobile robots are very attractive engineering systems,not only because of many interesting theoretical aspects concerning intelligent behavior or autonomy,but also because of applicability in many human activities.Attractiveness from the theoretical point of view is evident because no firm fundamental theory covering intelligent control independent of human assistance exists.Also,because wheeled or tracked mobile robots are nonholonomic mechanical systems,they are attractive for nonlinear control and modeling research.

Figure 5.12 Irobot's Roamba vacuum cleaner

5.3 Wrists

A robot manipulator needs at least 6 degrees of freedom to manipulate an onject freely in space.Especially for serial type manipulators the lengths of the first three moving links are much longer than those of the last three links.An end effector is attached to the last moving link for grasping or fine manipulation of an object.Thus the first three moving links are used primarily for manipulating the position,while the last three links are used for controlling the orientation of the *end effector*.For this reason,the subassembly associated with the first three moving links is called the *arm*,and the subassembly associated with the last three moving links is called the *wrist*(Tsai,1999).

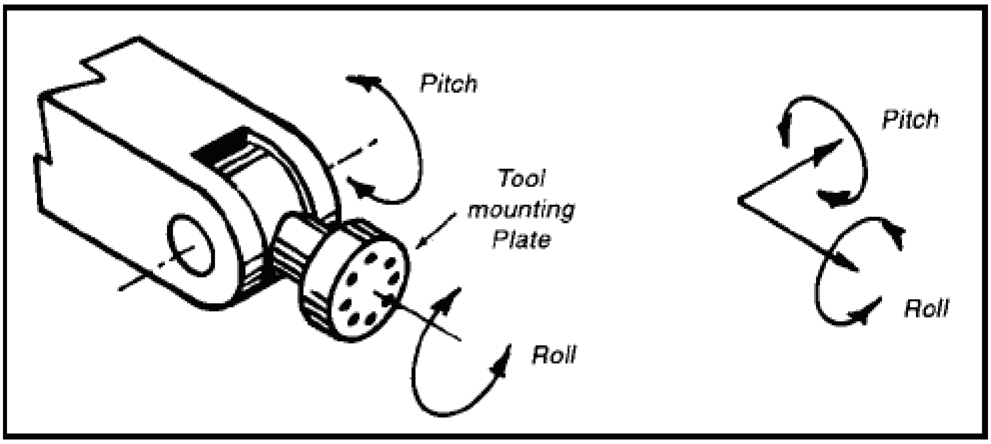


Figure 5.13 A two DOF robot wrist model(Sclater, 2006)

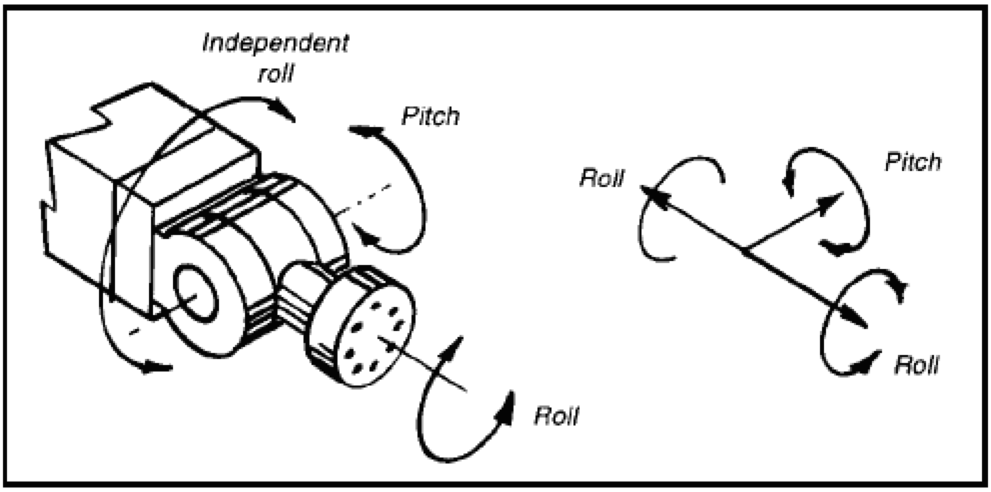


Figure 5.14 A two DOF robot wrist model(Sclater, 2006)

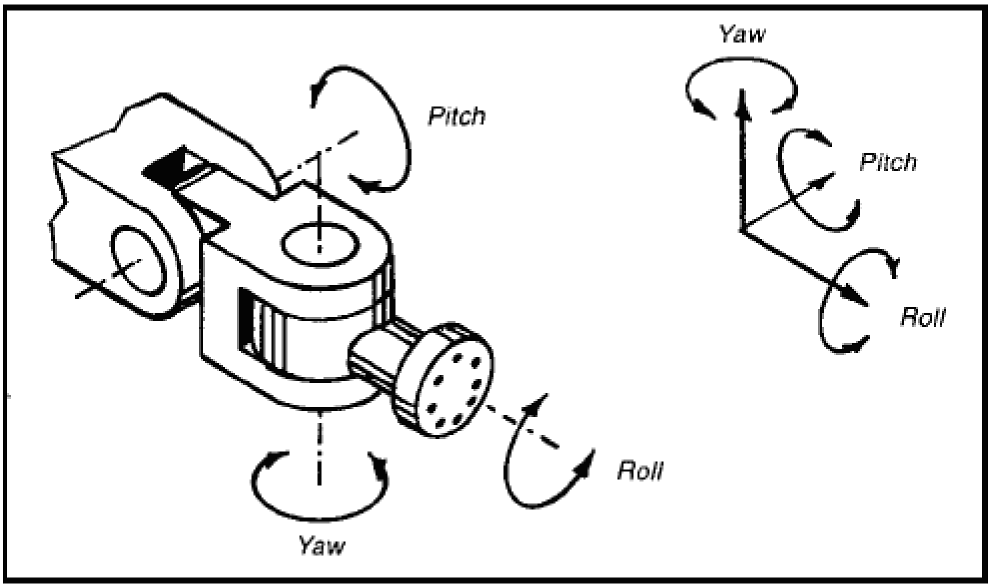


Figure 5.15 A three DOF robot wrist model(Sclater, 2006)

5.4 End Effectors

End effectors or end-of-arm tools are the devices through which a robot interacts with the world around it,*grasping* and *manipulating* parts,*inspecting* surfaces,and *working on* them.As such end effectors are among the most important elements of a robotic application-not "accessories" but an integral component of the overall tooling,fixturing,and sensing strategy(Kreith,1999).

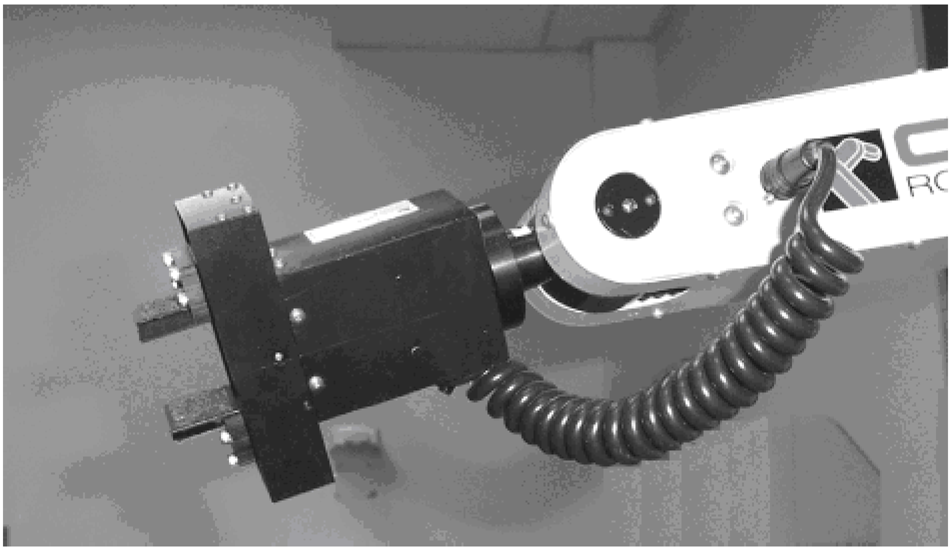


Figure 5.16 A robot end-effector integrated into arm controller(Kurfess, 2005)

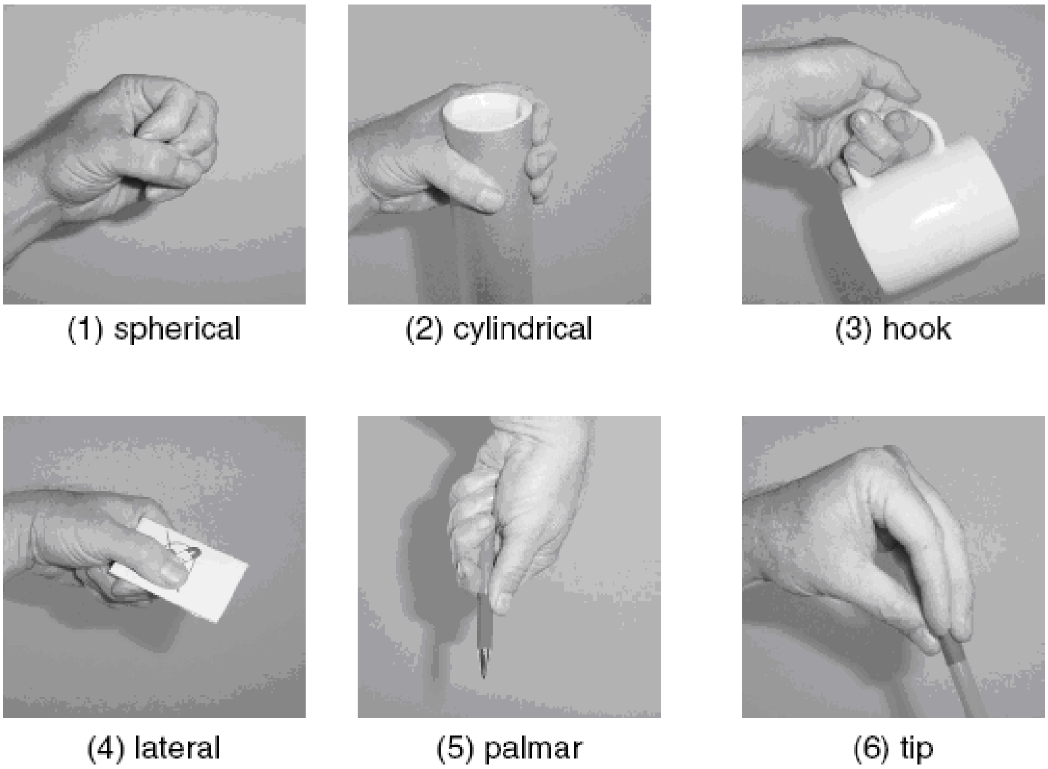


Figure 5.17 Grasp types for human hands(Kurfess, 2005)

Robotic end effectors today include everthing from simple two-fingered grippers and vacuum attachments to eleborate multifingered hands but they can be classified with three major categories(Kreith,1999).

5.4.1 Passive End Effectors

Passive end effectors can hold parts,but can not manipulate them or actively control the grasp force.Most end effectors in use today are passive; they emulate the grasps that people use for holding a heavy object or tool, without manipulating it in the fingers. However,a passive end effector may (and generally should) be equipped with sensors,and the information from these sensors may be used in controlling the robot arm.

5.4.1.1 *Non-prehensile*

Includes *vacuum*,*electromagnetic*,and *Bernoulli-effect* end effectors.Vacuum grippers,either singly or in combination, are perhaps the most commonly used gripping device in industry today. They are easily adapted to a wide variety of parts —from surface mount microprocessor chips and other small items that require precise placement to large,bulky items such as automobile windshields and aircraft panels. These end effectors are classified as “nonprehensile” because they neither enclose parts nor apply grasp forces across them. Consequently,they are ideal for handling large and delicate items such as glass panels.Unlike grippers with fingers,vacuum grippers to not tend to “center” or relocate parts as they pick
them up and this feature can be useful when initial part placement is accurate.

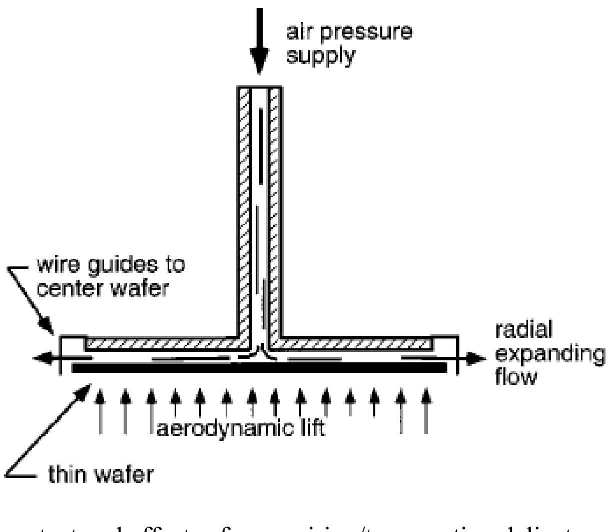


Figure 5.18 A non-contact end effector for acquiring/transporting delicate wafers(Kreith, 1999)

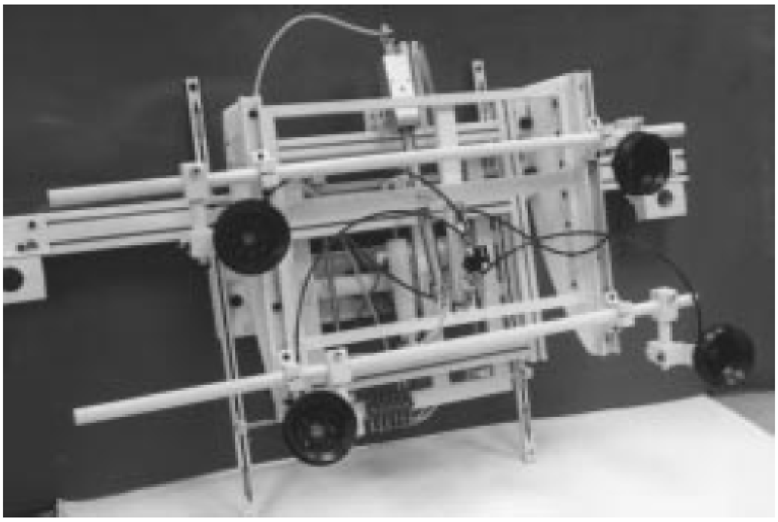


Figure 5.19 A large end effector for handling autobody panels with actuators for local motions(Kreith, 1999)

5.4.1.2 *Wrap*

The second branch of end effector taxonomy includes "wrap" grippers that hold a part in the same way that a person might hold a heavy hammer or a grapefruit. In such applications, humans use *wrap grasps* in which the fingers envelop a part, and maintain a nearly uniform pressure so that friction is used to maximum advantage. similar effect.

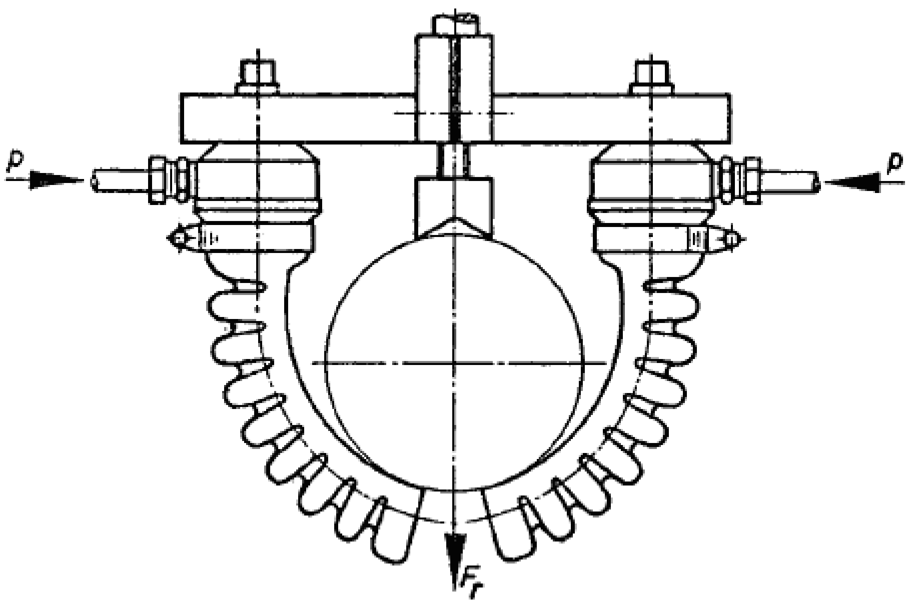


Figure 5.20 A compliant pneumatic gripper that executes a gentle wrap grasp(Kreith, 1999)

5.4.1.3 *Pinch*

The middle branch of the end effector taxonomy includes common two-fingered grippers. These grippers employ a strong “pinch” force between two fingers, in the same way that a person might grasp a key when opening a lock. Most such grippers are sold without fingertips since they are the most product-specific part of the design. The fingertips are designed to match the size of components, the shape of components (e.g., flat or V-grooved for cylindrical parts), and the material (e.g., rubber or plastic to avoid damaging fragile objects).

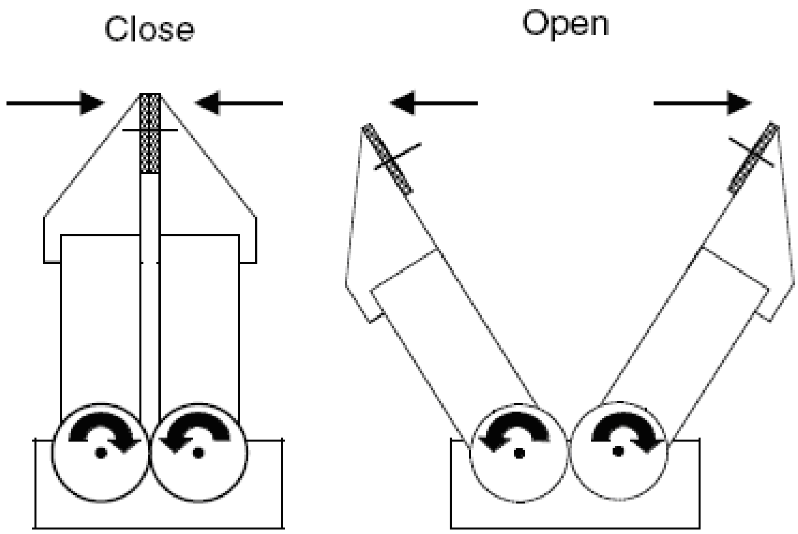


Figure 5.21 Rotating axes/pivoting jaws(Kurfess, 2005)

5.4.2 Active End Effectors

Includes servo grippers and dextrous multifingered hands.Here the distinctions depend largely on the number of fingers and the number of joints or degrees of freedom per finger.

Servo-controlled end effectors provide advantages for fine-motion tasks.In comparison to a robot arm,the fingertips are small and light,which means that they can move quickly and precisely.The total range of motion is also small,which permits fine-resolution position and velocity measurements.When equipped with force sensors such as strain gages,the fingers can provide force sensing and control,typically with better accuracy than can be obtained with robot wrist- or joint-mounted sensors.A servo gripper can also be programmed either to control the position of an unconstrained part or to accommodate to the position of a constrained part.The sensors of a servo-controlled end effector also provide useful information for robot programming.For example, position sensors can be used to measure the width of a grasped component, thereby providing a check that the correct component has been grasped. Similarly, force sensors are useful for weighing grasped objects and monitoring task-related forces.

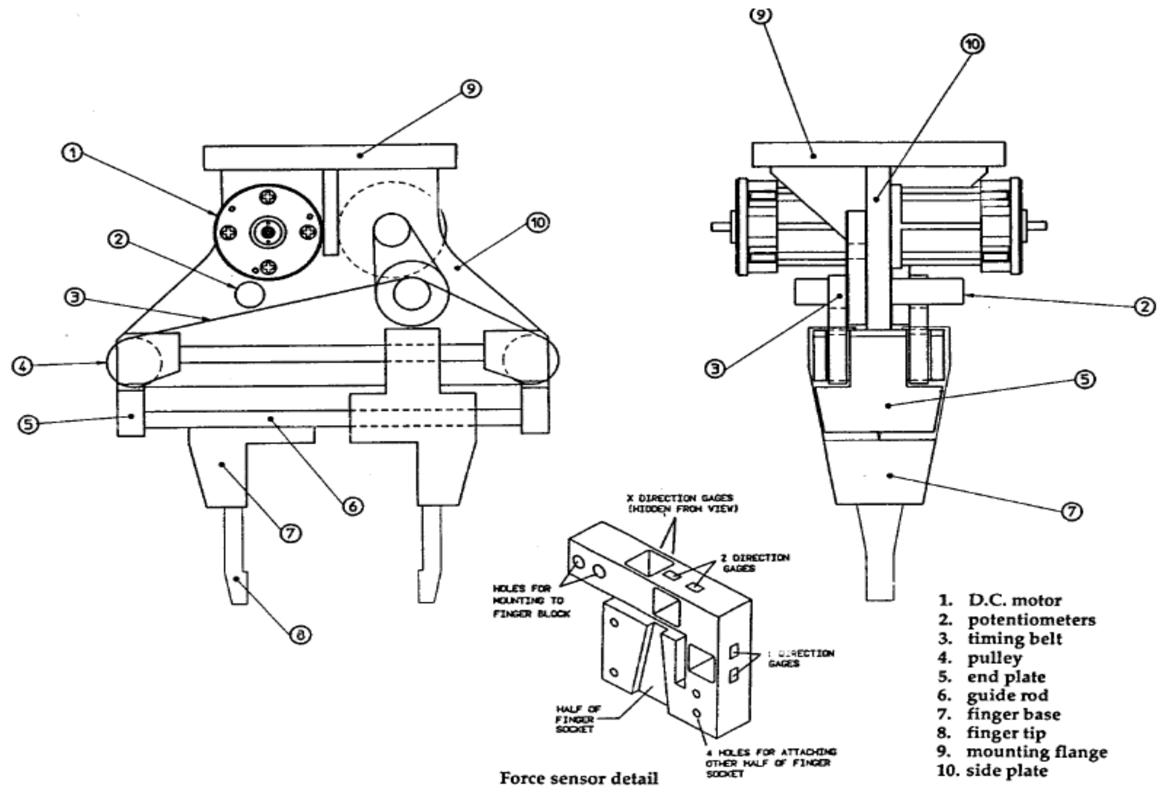


Figure 5.22 A two-finger servo gripper with force sensing and changeable fingertips(Kreith, 1999)

For applications requiring a combination of dexterity and versatility for grasping a wide range of objects,a dextrous multifingered hand is the ultimate solution.A number of multifingered hands have been described in the literature and commercial versions are available.Most of these hands are frankly anthropomorphic,although kinematic criteria such as workspace and *grasp* have also been used.

Despite their practical advantages,dextrous hands have thus far been confined to a few research laboratories.One reason is that the design and control of such hands present numerous difficult tradeoffs among cost,size,power,flexibility and ease of control.For example,the desire to reduce the dimensions of the hand,while providing adequate power, leads to the use of cables that run through the wrist to drive the fingers.These cables bring attendant control problems due to elasticity and friction.A second reason for slow progress in applying dextrous hands to manipulation tasks is the formidable challenge of programming and controlling them.The equations associated with several fingertips sliding and rolling on a grasped object are complex — the problem amounts to coordinating several little robots at the end of a robot.In addition,the mechanics of the hand/object system are sensitive to variations in the contact conditions between the fingertips and object(e.g., variations in the object profile and local coefficient of friction).Moreover,during manipulation the fingers are continually making and breaking contact with the object,starting and stopping sliding,etc.,with attendant changes in the dynamic and kinematic equations which must be accounted for in controlling the hand(Kreith,1999).

Figure 5.23 A three fingered hand(Kreith, 1999)

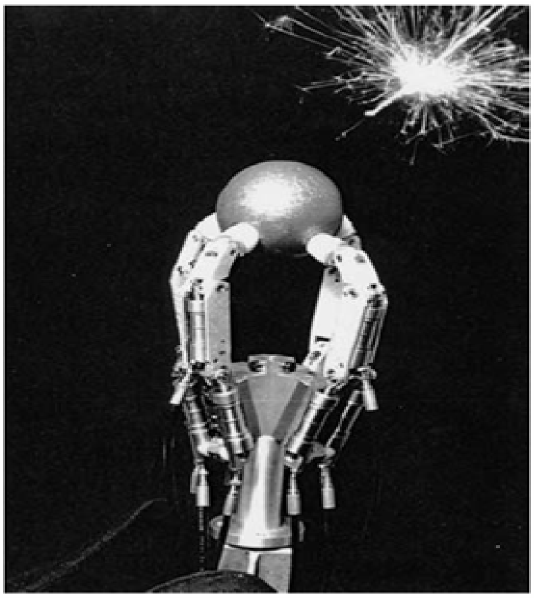


Figure 5.24 A four fingered hand(Kreith, 1999)

5.4.3 Special purpose

The end-effector of the robot manipulator can be specified according to the task. For material handling tasks, the end-effector is a gripper of proper shape and dimension determined by the object to grasp.For machining and assembly tasks,end effector is a tool or specialized device,e.g,a welding torch,a spray gun,a mill,a drill or a screw driver(Özçelikyıldız, 2006).

Figure 5.25 A welding torch as an end effector(Özçelikyıldız, 2006)

5.5 Vision Systems for Robots

Many industrial tasks require sophisticated vision interpretation, yet demand low cost, high speed,accuracy, and flexibility. To be fully effective, machine vision systems must be able to handle complex industrial parts. This includes verifying or recognizing incoming parts and determining the location and orientation of the part within a short cycle time. Typical video-based vision systems conform to the RS-170 standard established in the 1950s, which defines the composite video and synchronizing signal that the television industry uses. It specifies a standard frame rate for visual interpretation. The components required for building a video-based vision system generally include a video camera which outputs standard RS170 video signal, a frame grabber board which uses a flash analog-to-digital (A/D) converter to change the RS170 video signal into a series of n bit brightness values (gray levels) and fast memory components to store them, and a microcomputer which processes the images and computes the location and orientation of the part.In addition to the error resulting from the timing mismatching between image acquisition hardware and the computer hardware, the RS170 video signal limits the readout of a complete frame at a rate of 30 fps (frames per second). An image of m rows by n columns has $m \times n$ *pixels* and so requires a substantial amount of memory and loading time. Among these $m \times n$ pixels, only a few carry the information on which a vision system will base a decision. This generally makes “frame grabbing” inherently wasteful.Apart from the lack of appropriate hardware and the high equipment cost for robotic applications, a major problem often associated with the use of the RS170 video vision system is the excessive image processing time which depends on the illumination technique, the complexity of the geometry, and the surface reflectance of both the background and the objects to be handled(Kreith, 1999).

5.5.1 Flexible Integrated Vision System

To overcome these problems, several vision systems were designed for robotic applications. Among these is a Flexible Integrated Vision System (FIVS) developed at Georgia Tech,which offers performance and cost advantages by integrating the imaging sensor, control, illumination,direct digitization, computation, and data communication in a single unit. By eliminating the host computer and frame grabber, the camera is no longer restricted by the RS-170 standard and thus frame rate higher than 30 fps can be achieved.

Flexible Integrated Vision System Hardware. As shown in Figure 5.26, the central control unit of the flexible integrated vision system is a microprocessor-based control board. The design is to have all of the real-time processing performed using the microprocessor control board without relying on any other system or computer. Thus, it is desired to have the following features: (1) the microprocessor has an on-chip program memory and independent on-chip data memories. These memories must be externally expandable and accessible with zero wait states; (2) it has independent execution units which are connected by independent buses to the on-chip memory blocks. This feature provides the parallelism needed for high performance digital signal processing and high-powered computation of mathematically intensive algorithms. For these reasons, a digital signal processor (DSP) chip has been chosen.The DSP-based control board is designed to communicate with several option boards in parallel to tailor the system for a number of applications. Each of these option boards is controlled independently by a programmable logic device (PLD) which receives a peripheral select signal, a read/write signal,and an address signal from the microprocessor control board. Typical examples of the option boards for the FIVS are the digital video head, a real-time video record/display/playback board, and an expandable memory board.The video head consists of a $m \times n$ CCD array, the output of which is conditioned by high bandwidth amplification circuitry. The output is then sampled by a “flash” analog-to-digital converter (ADC). The DSP-based control board provides a direct software control of CCD array scanning and integration time,the intensity of the collocated illumination, and the real-time execution of a user-selectable vision algorithm imbedded in the EEPROM. In operation, the PLD decodes the control signals to initiate row shifts and column shifts in response to commands from the DSP-based control board. Particular row shifts and column shifts enable retrieving only a specific relevant area from an image. The PLD also provides control signals to ADC for performing the analog-to-digital conversion synchronized with row shifts, and enables the video buffer when the DSP reads or writes data to the VRAM.

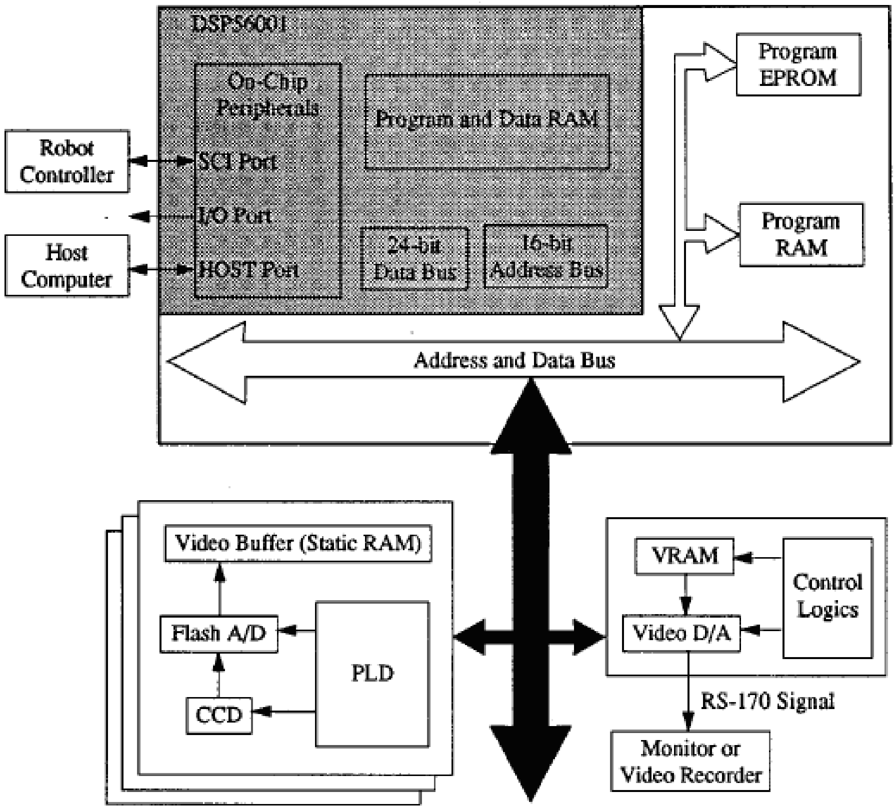


Figure 5.26 Schematic of a flexible integrated vision system(Kreith, 1999)

Unlike conventional RS170-based systems which require pixel data to be stored in a video buffer before processing of pixel data can commence, the FIVS design provides an option to completely bypass the video buffer and thus offers a means to process and/or to store the digitized pixel data by directly transferring the ADC output to the DSP. For real-time vision-based object tracking and motion control system applications, the scheme represents a significant saving in time and video buffer size required for processing an image.

Flexible Integrated Vision System Imbedded Software. The vision system imbedded software includes the following functions. The first function is to give users the flexibility to control the CCD array scanning, integration time, and the intensity of the illumination. With the CCD under software control,partial frames can be "captured" instead of the customary full frame, reducing the cycle time required to capture and process an image. The ability to shift out partial frames is ideal for high-speed tracking applications where the approximate location is known from a prior image. By reducing the time to capture an image, the effective frame rate is increased.The second function is to offer an option to process the pixel data from the ADC directly without having to store the pixel data prior to processing. Although windowing process methods have been suggested to perform object tracking under software control, these methods required that a partial window is stored before scanning can begin. The differences between the direct computation and the windowing process for object tracking are as follows: (1) in windowing process, the entire image must be stored and analyzed at least once before any subsequent windowing process can be performed in order to provide a reasonable estimate of the object location. Furthermore, if the initial field of view does not contain the object, this estimate must be repeated until an approximate area containing the object can be reasonably found. This prerequisite of storing the image is not necessary if the pixel data are directly processed; (2) after the initial estimate, a fixed window which must be sufficiently large in order to include the object in the field of view must be specified in the windowing process. In most conventional systems which output their ADC to the video buffer directly, a partial frame of the image as specified by the window must be stored. By providing a direct transfer the ADC output to the DSP and thus eliminating the windowing storing process, a significant fraction of time can be saved. This function provides an attractive feature to vision-based motion control applications.The third function allows image processing to be performed in real time without a host computer.The algorithm that allows the user to customize the system for a specified task is preprogrammed in the EEPROM (electrically erasable programmable read only memory). Because it is impractical to preprogram every possible vision processing algorithm into the FIVS camera, it is desirable that the system can be reprogrammed easily. The main kernel provides a user interface whereby the user can customize the real-time processing for a particular task, from a library of algorithms. This function also provides an effective means to resolve software implementation issues prior to an on-line application. By previewing images of a sample part, the user may select an appropriate vision algorithm for an accurate computation of the location and orientation in real time. Once the algorithms and data are downloaded into the on-board EEPROM, the FIVS can function as an intelligent sensor and communicate directly with the robot controller without a host computer.

The fourth function, which incorporates a real-time display, allows the process controller to set up,to calibrate the vision system, or to analyze a failure mode (if any).

5.5.2 Illumination Considerations

Imaging sensors are characterized by their specific bandwidths or wavelengths of light which maximize the response of the sensor and will provide it an optimum operating environment. It is desired that the photodetector responds only to the light from the illumination source structured for the object but not that of ambient lighting. Otherwise, software compensation must be considered. To accomplish the objective, a typical sensor/illumination system design must consider the spectral matching of the camera imaging sensor/filter and a spectral illuminator while minimizing the effect of the ambient lighting.

Spectral Responsivity of Sensor. The two most commonly used camera imaging sensors are the chargecoupled device (CCD) and the charge injection device (CID). The CCD is responsive to wavelengths of light from below 350 nm (ultraviolet) to 1100 nm (near infrared) and has a peak response approximately at 800 nm. The CID offers a similar spectral response and has a peak spectral response about 650 nm.The relative response of a vidicon camera, however, depends significantly on the materials.

Spectral Characteristic of Typical Ambient Lighting. Depending on the spectral emissions of illuminationsources used as general lighting in the factory environment, the influences of the ambient lighting can be effectively minimized or eliminated by means of spectral filtering. Gas discharge lamps generally have relatively high emission in the visible range and have little or no emission for wavelengths larger than 800 nm. Sun, tungsten lamps, and quartz-halogen-type lamps have a wide spectral emission.

Illumination Source. The spectral characteristics of three different spectral sources, namely, laser diodes, light-emitting diode (LED), and xenon strobes, are of particular interest since the spectral wavelengths of these sources well match the optimal response of the CCD and/or CID detectors. Pulsed GaAlAs laser diodes emit single frequency power in the 790- to 850-nm wavelength range. Irradiance at spectral wavelength in the range of 810 to 830 nm can also be produced from a xenon lamp. An AlGaAs LED is designed to concentrate the luminous flux into a narrow radiation pattern to achieve a narrow high peak intensity.

Object and Background Reflectance. If the orientation of the parts can be characterized by the twodimensional object silhouette and the environment can be structured, back lighting can be used to create silhouettes of the object. Alternatively, retroreflective materials can be used to create a unique background. Since most of the incident illuminance from the object is reflected or diffused away from the aperture, whereas that on the background surface is retroreflected, the object appears as a dark silhouette against a reliable bright-field background.Retroreflective materials can be used as background in part presentation or as a landmark on parts.The choice clearly depends on the part design and manufacturing process. The most common retroreflective surface is in the form of sheeting due to its reliability and ease of application. Flexible retroreflective sheeting is made of countless microcube-corners or spheres enclosed in a weather-resistant transparent plastic film. Pigment or dye can be inserted into the film or the reflecting surface to reflect color. Four typical retroreflective sheetings are described as follows: (1) cube-corner retroreflective sheeting, (2) exposed glass beads, (3) enclosed glass beads, and 4) encapsulated glass beads.

5.5.3 Vision Algorithms for Robotic Applications

Figure 5.27 illustrates a vision system for robotic part pickup applications.Here the camera is mounted along with the gripper on the end effector mount of the robot.

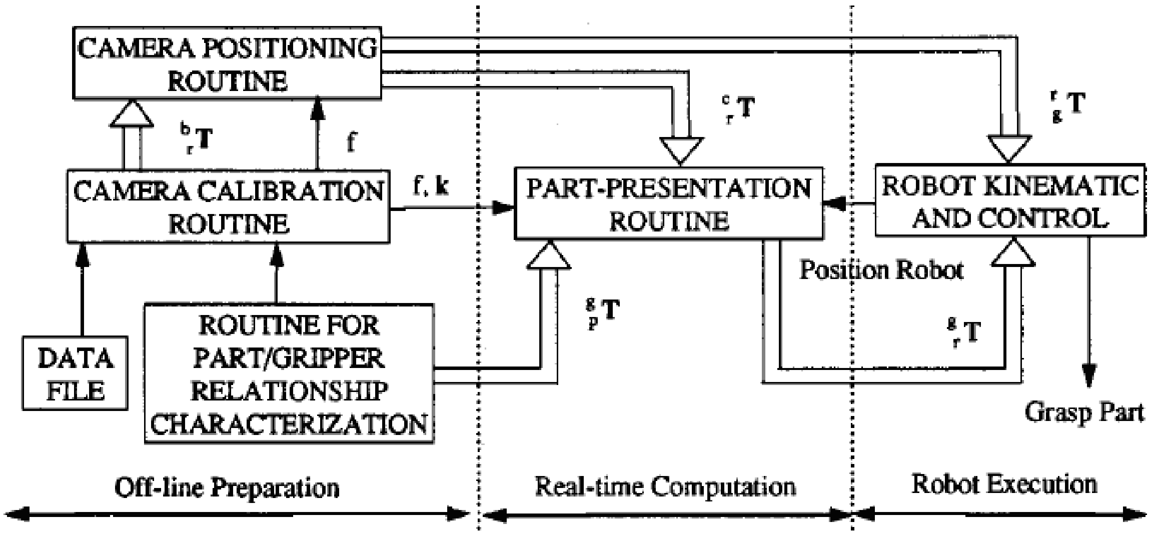


Figure 5.27 A vision system for robotic applications(Kreith, 1999)

This allows complete freedom in positioning and orienting the camera for viewing. Placing the camera on the last link of a six-DOF robot enables the machine vision to view objects (parts) individually. The camera is oriented so that its line of sight is perpendicular to the plane on which the part is placed. However, at each position, the 3D position and orientation of the feature measured by the vision system are only relative to the vision sensor. The robot is driven by sensory information from the vision system as well as inputs from the off-line calibration[8].

CHAPTER SIX

ROBOTIC SYSTEMS IN AUTOMATION

6.1 Industrial Applications of Robots

Replacing humans with robots to perform processes has often led to failure. The reason is that the robots are often mechanically capable of the manipulation while being incapable of process planning and control. Thousands of robot installations have failed because replacing the manual method with the automatic method lacked adaptability to process related variation. The human operators had been using their cognitive abilities to do the job. A vast majority of successful robot implementations past and present have a very important common aspect: repeated execution of fixed programs with little or no on-line modification of path or position.

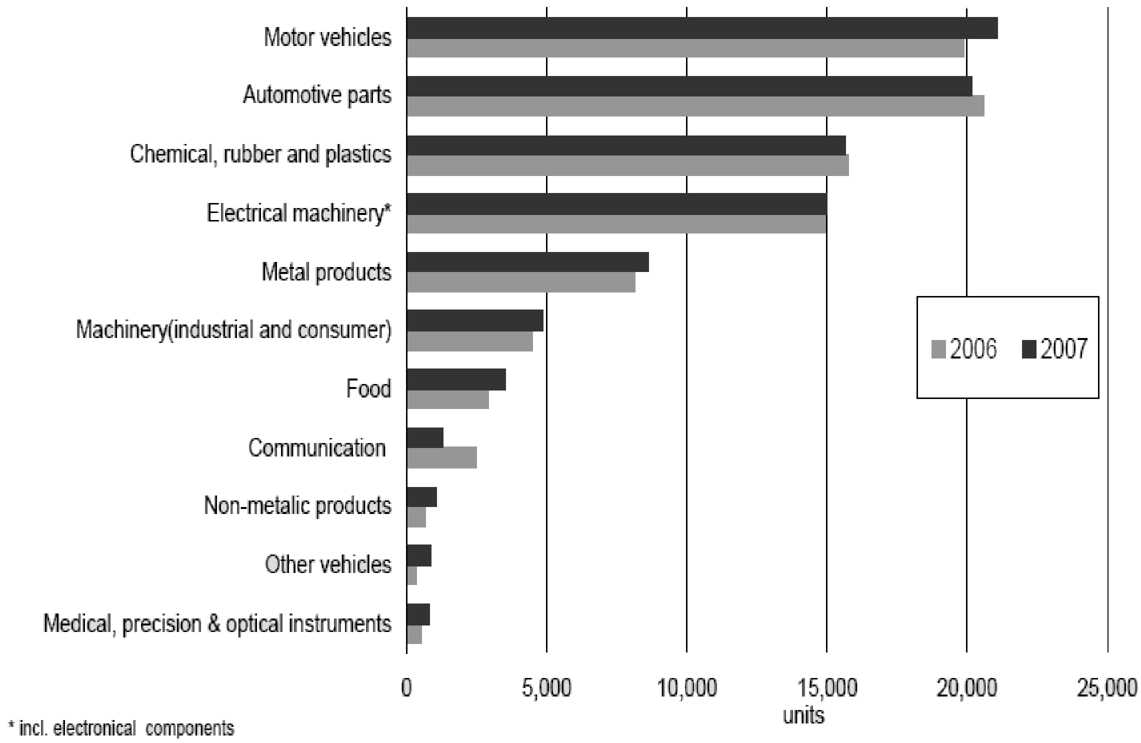


Figure 6.1 Estimated yearly supply of industrial robots at year-end in total world(World Robotics, 2008)

Process robot planning and programming still usually require the efforts of highly skilled technicians.Often, complex programs cost too much and take too long.

Continuously controlling and varying path manipulation parameters for real-time process control is difficult. Many processes are not known well enough to describe their control algorithmically. In a few applications sensors are becoming more common for adapting robot plans to changes in the environment. Setup, seam tracking, positioning,conveyor tracking, and now automatic programming for painting and finishing are becoming practical as sensor costs and computation costs continue to decline.In this section robotic material handling and process applications are presented from an automation system perspective focusing on the robot’s manipulation functions. Manipulation is considered a manufacturing material transformation and a transportation process factor. Programming and control are viewed as the means of integrating robot manipulation as part of the manufacturing process(Kreith,1999).

6.1.1 Manipulation as a Process Requirement

The starting point of automation system design is a thorough understanding of the process to be automated. Implementation of a process robot requires a focus on manipulation as a process factor. The pose and path requirements of the process are independent of the manipulator used.It is useful to conduct a static spatial analysis of manipulation requirements and then examine the mechanical and dynamic requirements when designing or selecting a process robot manipulator.A spatial description of the relative positions and orientations of the workpiece and tool during processing provides the basis for describing the required manipulation. *Tool poses* are graphed in an appropriate reference frame, usually the frame of the workpiece, or in the case of machine loading, the work holding fixture may be used. Path requirements are secondary for these applications.The path taken does not affect the process. For *continuous path processes* entire paths must be graphed or mapped.If continuous analytical descriptions of the path are not available, a sampling of discrete points along the required path can be used to represent the space occupied by the path. The result in both cases is a Cartesian mapping of spatial requirements of pose and path. A description of the pose and path precision requirements should be included. Next the mechanical and dynamic requirements are defined.Payload and force reactions at each position and along the path must be understood. Other important dynamic requirements such as acceleration and power should be quantified. The manipulation requirements are the basis for design and selection of both the robot arm and the controller.

6.1.2 Manipulation Capability of Process Robots

The basic mechanical capability of the robot mechanism to perform the manipulation work is determined by its mechanical structure, kinematic configuration,and drive mechanism. There are several applications including painting, palletizing, spot welding, and arc welding for which specific types of robot arm designs have evolved driven by process needs. Although predisposed by design to perform a particular process, these robots have no innate process capability and are not guaranteed to perform in a specific application. Specifications of gross robot performance characteristics such as reach, *repeatability,* accuracy,and payload are usually readily available from their manufacturers. A well-defined set of process manipulation requirements when compared with published robot specifications usually isolates the field of mechanically qualified candidates. It is more difficult to characterize and evaluate a robot's capability for complex motion. The exact working of the robot's trajectory generation software is usually not known by end users and can only be evaluated by indirect testing. Acceleration and load capacity are usually specified, and there are some standard methods for specifying path performance, but the robot's dynamic behavior and performance are difficult to measure. Specific performance testing is usually required to prove manipulability for process robot applications.

6.1.3 Integration of Manipulation Control and Process Control

Achieving manipulator and process control integration depends upon robot programming and external data access. For any given application the required motion execution may be possible, but programming may be too difficult to be practical. Establishing that the robot is capable of coordinated motion can be done by reviewing the specifications or by conducting motion tests. As an illustration of the importance of programmability consider, for example, a situation in which a complex series of twisted curves define a robot tool path. If two robots with identical kinematic structure and joint trajectory generation capability differ in their programming in that one is capable of executing paths following user-defined mathematical functions and the other is only capable of executing paths defined by closely spaced taught poses, the difference in programming effort could easily amount to hundreds of hours. For each application encountered the programming methods must be assessed to determine if the required motion is programmable in a practical sense.Access by process robot programs to external data is becoming more important. Although most process robots now work without any external process feedback, this is beginning to change rapidly with the development of improved low cost sensor systems and methods. Virtually all robots are capable of discrete digital and analog signal input and output. Most may also be equipped with standard serial and parallel communication capacity. If sensor information is to be used for set-up positioning or real-time path adjustment, the robot controller must have the communication and control to convert data into information that can be used to modify path and position commands. In cases of extreme path complexity,path planning systems external to the robot controller may be needed to create the paths. Testing will verify the ability of the robot controller to accept and execute externally generated motion sequence data.

6.1.4 Flexible-Link Robot Manipulators

Most robots used in today's manufacturing systems are rigid-link manipulators. Making the robot links and drives extremely stiff to minimize vibrations allows rigid-link robots to track a desired trajectory with very high degree of accuracy, often using standard classical (PID) control schemes. However, the price paid for this includes heavy manipulators, a low payload-weight-to-arm-weight ratio, high power consumption, and slow response rates to motion control commands.With the growing demand from industry automation for lower manufacturing costs, higher motion speeds, better performance, and easier transportation and setup, the rigid-link manipulators may, sooner or later, be replaced by some sort of lightweight mechanical structures, such as flexible-link robots.While lightweight flexible manipulators have certain inherent advantages over rigid-link robots, they impose more stringent requirements on system modeling and controller design because of the vibrations of the flexible modes.

6.2 Industrial Applications of Serial Manipulators

6.2.1 Assembly

Assembly is projected to be the largest area of growth for robots. Key design goals for robotic assembly are to ensure high-quality parts, minimize the use of fasteners and cables, and provide accessibility so that parts can be easily fed and oriented by automated equipment. Designing to facilitate the use of robotics requires a review of their capabilities. Although assembly robots are often shown as stand-alone equipment, they require considerable amounts of support tooling and auxiliary equipment. These include part feeders, end effectors, special fixturing, and a material handling system. Except in the case of robots with vision or special sensors, parts with which the robot will interact must be precisely located and oriented. This may require additional tooling or special vendor packaging.

Robot assembly requires the robot to go to a predefined location and grasp a part. The part may be positioned and oriented or it may not. Since a positioned and oriented part is preferred, part-feeding methods that can perform this task are desired. The most popular types are:

- Vibratory bowl feeders
- Pallets and trays
- Specialized feeders
- Special vendor packages
- Conveyors

Figure 6.2 ABB's assembly robots

When the part is not positioned or oriented, additional sensors must be added to the system. Commonly used sensors are:Machine/robotic vision,Simple sensors such as photodiodes and Tactile/touch sensors.Robotic vision is becoming more popular in assembly as their purchase, software integration, and installation costs continue to decrease. Although most robot manufacturers offer vision systems as an option, they are still an expensive addition to the system. Simple on/off sensors can be used in certain cases when only limited data are required. Tactile sensors can sometimes be used to touch/feel the part to identify specific features of the part or to recognize its location.

6.2.2 Palletizing and Depalletizing

Many products are packaged in boxes of regular shape and stacked on standard pallets for shipping.Robots are commonly used to palletize and depalletize boxes because they can be programmed to move through the array of box positions layer after layer. Although palletizing is more common than depalletizing,there is no major functional difference in the manipulation requirementsWhen standard servo-driven joint actuators are used accuracy and repeatability will usually be far better than the required box positioning precision.Palletizing typically requires four axes of controlled motion — three for translation and a fourth for yaw to orient the box. Cylindrical coordinate robots are favored in palletizing because they have large vertical lift and a compact footprint allowing more of the floor area in the workspace for conveyors and pallets. When larger workspace is needed gantry robots must be used. Continuous duty cycles are not uncommon and robot power is important for maximizing throughput.

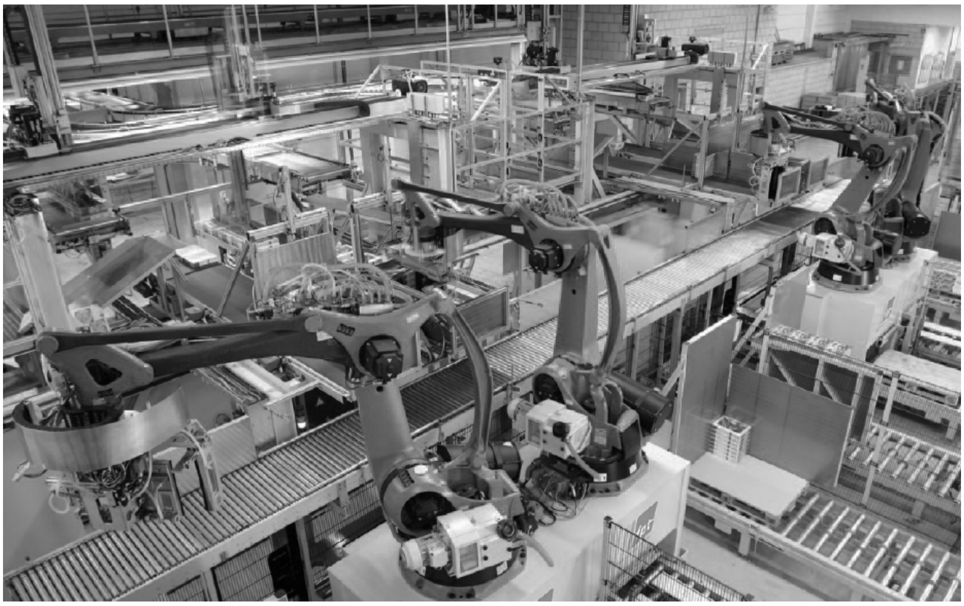


Figure 6.3 Kuka's palletizing robots

The most technically demanding aspect of system design is the gripper. Vacuum grippers are popular for lifting boxes by their tops,but other more complex gripping methods are sometimes needed. Payloads must be carefully positioned with respect to the robot’s wrist and other links to balance gravitational and dynamic loading. Load shifting during high acceleration moves can result in dropping or mislocating the box.Palletizing position arrays are usually taught or programmed relative to a corner or keystone box position as a reference so that the entire array can be shifted by redefining that one position. Programs are simple and easily modified to adapt to changes in box dimensions. Monitoring is done by checking the state of discrete proximity and vacuum sensors. A proximity sensor mounted on a gripper will indicate if an object is at an expected location; or the same simple proximity sensor may be used to stop the robot in the correct location to pick up a box from a stack of unknown height when the top of the box is encountered. Vacuum pressure switches are often used to verify acquisition by suction cup. A simple proximity switch can be used to signal the presence of an expected package at the pick-up point. With careful timing and additional sensor inputs, items can be transported to and from moving conveyors.

6.2.3 Packaging

Packaging is often a combination of palletizing and assembly-type actions. A collection of objects which may not be identical are inserted into a box or other container. The robot may also be required to assemble, place dunnage, seal, or mark the package. Insertion may simply require positioning the pack item over the opening of the package and dropping it. Boxes most often are supplied partially assembled, printed, and folded flat. Usually human operators or a special machine will open and prepare the box for packing; rarely will the robot be used for this purpose. Often the robot can be used to place cardboard layer separators, foam, or cardboard holding forms and other protective dunnage in the box. Finally,sealing and marking operations may be performed by the robot. Pack items may require complicated assembly-type motions such as rotations and curved moves to clear other packed items.Three to six axes of motion may be needed. Packing items with a variety of sizes, shapes, and other varying physical properties into one package have the potential to complicate motion and tooling requirements. Grippers can be designed with multiple functions or they can be designed to be exchanged by the robot at tool storage racks. When material throughput is high, a single robot may be dedicated to each pack item. Simple programming methods are employed such as teach programming. Discrete sensors are useful for monitoring grip status of pack items.

6.2.4 Machine Tending: Loading and Unloading

Forges, stamping process, some machine tools, and molding machines are now commonly tended by robots. Historically these types of machines have been loaded by human operators. Now these jobs are considered to be too arduous and hazardous. An important benefit of robotic machine loading is improved product quality resulting from consistent machine cycles. Robots eliminate the inconsistencies of humanpaced loading and as a result the cycle can be precisely repeated. For heated molding, stamping, and forging processes, part formation and release are sensitive to the thermal state of the machine. If a machine is left open for loading for differing amounts of time each cycle, significant cooling variations result in potential sticking and geometric flaws. When robots are used, the process can be tuned to the consistent robot loading cycle.Machine loading is usually more demanding than other material handling applications because part orientation and placement are critical and may require locating mechanisms such as tooling pins and pads and/or sensor logic to guarantee interface between the robot and the serviced machine. Accuracy is usually not an important factor because the loading stations are permanently located in the robot workspace, but repeatability requirements may be as small as several thousandths of an inch. Grippers for machine loading may also require tooling pins and pads to locate and orient parts and to mate precisely with the machine's part holding fixture. The gripper may dock with the holding fixture and then transfer the part when loading clearances are very tight.The entire range of robot types, sizes, and configurations is used for machine tending. Articulated arm robots are needed when dexterous manipulation is required to transport parts through the maze of clamps and spindles and other protrusions and obstacles found on some machines or when part orientation must change for loading. Applications where the robot is dedicated to loading a single part into a single machine in high volume production are not uncommon. Position programming is usually done by teaching. It is common to monitor discrete sensors in the gripper and the loaded machine to insure proper loading before cycling the process machine.

6.2.5 Sorting

Discrete parts are often sorted during production, usually as a condition of transfer to the next production station. The sort characteristics are usually distributed in some unpredictable manner so that individual inspection and handling are required. The diflference between sorting and other transfer or loading robot applications is that the disposition of the part is based on information gained during the sort. The robot must have the programming functions to support multiple preprogrammed path execution triggered by the logical sort outcome conditions.

6.2.6 Part Dipping

Many processes require controlled manipulation of parts temporarily submerged in some working fluid or coating material. Some common part dipping processes are the following.

- Investment Casting
- Solder Pretinning
- Conformal Protective Coating
- Quenching

6.2.7 Resistance Spot Welding

Robotic spot welding is the most pervasive robot application in the automotive industry. Resistance spot welds are formed by tightly clamping steel pieces together with opposing contact electrodes and then passing a large amount of current through the joint, welding the metal while producing a spray of molten sparks along with loud noise. Then the joint is held momentarily until the weld solidifies. Welds are made at discrete positions by moving the robot-mounted gun to pretaught poses. The spot welding process parameters, pressure and temperature, are controlled with the separate gun controller. Weld location and therefore positioning of the gun are critical.Dexterity, payload, and quickness are critical operational requirements for spot welding robots.Gun pose repeatability is critical for consistently locating weld joints. Access to joint locations is limited because both electrodes must reach the weld site while maintaining clearance between gun frame and workpiece edges. Large articulated arm robots are typically used for most spot welding applications because of the dexterity needed and because the weight of the welding gun and associated robot-mounted apparatus often exceeds 200 lb. Fixed cycle programs are typical which may require several man-months to develop and less than a minute to execute. The robot spot welding path position names, path order,and control logic can be developed off-line, but lack of robot positioning accuracy characteristic of large articulated robots requires the weld positions for each individual robot to be taught by posing and recording them manually. This takes advantage of the robot's repeatability which is often orders of magnitude better than its accuracy. Unfortunately, when a robot that has been teach programmed is replaced by another robot, even an identical model, hours or days of teaching will be required to bring the replacement robot on line. Practical new PC-based calibration methods which eliminate this problem by effectively improving accuracy are now becoming commercially available.

6.2.8 Drilling

Hole drilling is a precision machining process. Most robots cannot hold a drill spindle rigidly enough to overcome the drilling reactions and most robots cannot generally move in a precise enough straight line to feed the drill. Drilling robots use special drilling end effectors which locate and dock onto the work piece or a fixture. The robot wrist and arm must be compliant and forceful enough to hold the drilling end effector firmly into location against the fixture or workpiece. Drilling end effectors have a spindle motor and a feed mechanism which execute a separately controlled drilling cycle while the robot holds the end effector in position.
The robot's only contribution to the process is to move the drilling end effector into its docking or holding place. Drilling robots have been used most successfully in the aerospace industry because airframe structures require thousands of holes to be placed precisely and in complex orientations.Manipulability requirements for drilling are similar to those for spot welding. The drilling end effector weight will tend to be less than a welding gun but tool holding force and reach usually impose the requirement for large robots.

6.2.9 Fastening

Robots are commonly used for applying threaded fasteners in the automobile industry for fastening wheels, and in the electronics industry for screwing components to circuit boards and circuit boards into chassis. Robots are also used for riveting in airframe fabrication.Fastening is an end effector position-and-hold application. The robot does not follow the threaded fastener as it turns and travels into place; the end effector uses a slide or cylinder for that purpose.Automatic nut runners and screwdrivers and the associated hardware feeding apparatus are broadly available. Since a human is no longer operating the fastening tool other means of process control are needed. Usually fastener angular displacement, longitudinal displacement, and torque can be monitored and correlated with signatures or patterns characterized for specific fastener joints. Manipulator arm and control system requirements are similar to other position-and-hold applications. Very large torque may be encountered. Torsion bars or other static mechanisms are often needed to prevent the arm from beingtorque loaded.

6.2.10 Inspection

Robot inspection involves relative part/sensor manipulation to compare, measure, or detect a physical characteristic of the objective workpiece. Sensors used in robotic inspection include chemical detectors,computer vision systems, infrared detectors, sonar, laser radar, radiation detectors, capacitive proximity sensors, touch probes, X-ray cameras, particle/photon detectors, thread probes, and go-no go gauges.Robot inspection applications cover the range of manipulation from end effector position-and-hold to continues in-contact path motion. In some cases the kinematic structure of the robot is used as a spatial measuring device by incorporating surface sensors or probes in the last link as robot end effectors.The forward kinematic solution of the joint angle measurements sampled at a contact pose give the position in Cartesian space of the contact point. If the manipulator is stationary during the
measurement then the robot's Cartesian positioning error must be added. If the robot is calibrated the error may be almost as small as the repeatability (0.001 to 0.020 in. for most industrial servo-driven arms). If the arm is moving while measurements are made significant error may be added because of delay in sampling the manipulator joint positions.Programming considerations are critical because robot inspection often requires data collection at a huge number of discrete positions. When CAD data are available, off-line programming of inspection may be possible, particularly for position and sense-type inspections. Sensor tool pose requirements can be quickly

and accurately defined in the CAD environment and the pose data transformed into robot workspace coordinates. When hundreds or thousands of inspection poses are required manual teach programming may be too time consuming and cost prohibitive, especially when a mix of different parts must be inspected.

6.2.11 Paint and Compound Spraying

Paint spraying is a major application in the automotive industry. Painting booths are hazardous because the paint material is often toxic, carcinogenic, and flammable. Human painters often wear required protective clothing and breathing equipment. The paint fan projecting from the arm-mounted spray gun must be manipulated smoothly along paths that are often curved and complex.Most robots used for painting are especially designed for that purpose. They usually have large reach,small payloads, and repeatability is usually larger than that of other types of robots and may exceed ±0.010 in. Painting robots are typically six DOF articulated arms, often with supplemental axes to pitch the paint gun and to traverse alongside a moving line. The potential for ignition of solvents and suspended particles may require taking precautions to eliminate ignition sources associated with the sparking of motors and other electrical components. Until brushless DC motors became commonly available for robot actuation virtually all painting robots were hydraulic because of the motor sparking problem. Leadthrough teaching (also called teach-playback) is typical for painting. Off-line programming of painting is becoming more popular and some special software packages are available.Some compound spraying is done with smaller general-purpose robots, for example, spraying of protective coatings in the electronics industry. Circuit boards may require unexpected dexterity in order to point the spraying nozzle correctly to coat board features.

6.2.12 Compound Dispensing

Compound dispensing refers to laying a bead of fluid material on a surface. Application examples include caulking car bodies, sealing windshields, placing solder masking on circuit boards, gluing subassemblies,solder paste dispensing, and decorating candies and cakes. Precision of placement and amount is critical.Smooth controlled paths are often essential. Position accuracy and tool path velocity accuracy are both important requirements.All types and configurations of robots are used for dispensing. Many applications require only three DOF. When obstructions must be maneuvered around to gain access to the dispense locations, five or six DOF are needed. Payloads are usually small. Dispense speed may be limited by either the robot's ability to track a path at high speeds or by the dynamics of the dispensing process. In automotive applications the fixed cycle mode of operation is common. A robot program to lay a bead of sealer along the edge of a windshield is a taught path requiring good dynamic path repeatability of the robot. In electronic circuit board fabrication and decorating cakes, each workpiece may have a different dispense pattern; teaching paths are not practical in this situation. Some method of off-line programming must be used.

6.2.13 Cutting

Many engineering materials are produced and supplied as stacked or rolled flat plates or sheets. Further fabrication can require forming and/or cutting these materials into precise shapes. Robots are frequently used to manipulate a variety of cutting tools along paths that are often complex and curved. Many cutting processes are also used to produce fine features such as holes and slots. Common robotically manipulated cutting processes are listed below.

- Laser
- Waterjet
- Abrasivejet
- Plasma Arc
- Router
- Knife

The cutting tool path and pose must be precisely controlled to achieve accurately patterned piece parts. The demands on manipulator performance are primarily determined by the interaction of desired part geometry, material thickness, and material properties. Feed rate, tool stand-off, beam, jet, and arc angle are all cutting process control variables which must be adjusted to material characteristics for good results. An extreme case of cutting manipulator performance demand is the combination of thin easily cut material with complex shape, and small geometric tolerance. This requires high speed coordinated motion of five or more axes which must be kept on track. This translates to a requirement for high performance servo-control elements in order to achieve high rates of mechanical response and joint angle position and velocity precision.

6.2.14 Arc Welding

Arc welding is a metal joining process that uses intense heat produced by an electric arc between an electrode and the metal parts being welded. The weld pool and arc are always shielded by inert gas or a chemical vapor. In gas metal arc welding (sometimes called metal inert gas welding), which is the most common robotic arc welding, an electrode of filler metal wire is fed through a gun into the weld pool site as the robot manipulates the gun along the weld path. The hazards of arc welding include:intense ultraviolet, visual band and radio frequency radiation, toxic fumes, and noise. The pose (position and orientation) of the welding gun with respect to the joint or seam is a major arc control parameter.The feed rate of the gun is important in control of penetration and other weld characteristics. Unlike spot welding, manipulation is an arc welding process control variable.Most arc welding robots operate in fixed cycle mode, which means they execute or play back a programmed sequence. If assemblies are presented to the robot with consistent seam geometry, then the path can be taught once, stored, and then executed repeatedly for each assembly. Given that all other relevant process variation is within accepted limits, the system will produce satisfactory output. However,weld seam position and seam shape variations may influence the process, especially in larger assemblies. When there is variation in the upstream sizing, cutting, fit-up, and jigging of weld assemblies, the location and orientation of the weld seam will vary. Also, as the weld progresses, localized thermal expansion and residual stresses can force seam distortion. A range of methods for adapting the robot system to these variations exists, from correcting pretaught path plans at setup time, through actively altering robot motion in “real time.” A sustained high level of academic and commercial research and development effort has resulted in practical methods of automatic weld seam tracking and process control.Rapid deployment in recent years is a direct result of sensor integration for seam tracking Seam tracking methods correct the path to compensate for errors in location and orientation of the welding tip based on sensor data. Commonly used sensors include mechanical probes, computer vision, laser edge detection and ranging, and arc current and voltage. Because of the extreme environment of the region surrounding an active welding tip, sensors are often housed in protective chambers. Typically the errors are measured and calculated in a convenient reference frame in the three-dimensional workspace of the robot system, the same space in which the tool path is described. In some cases the error is measured by tool-mounted sensors relative to the moving reference frame of the tool. The preprogrammed path is then shifted by mathematical transform in the reference frame of the tool. An important aspect of seam tracking is the use of sensors to detect the sides of the weld channels as boundaries for automatic side-to-side weaving. This is usually done with “through-the-arc” sensing in which arc current is monitored as an indicator of clearance between the welding tip and the channel edge. While tracking in the direction of the seam, transverse motion commands are given so that the tip approaches one edge until the edge is sensed and then the motion is commanded in the direction of the other edge. Weld penetration, filler deposit amount, and weld bead shape can be controlled in-process by variable control of the welding speed or feed rate. Arc welding robot systems which use sensors to adjust the robot path in real time (computation is fast enough to respond to sensor data with useful path adjustments) are among the most advanced or intelligent robotic applications found in practical industrial use.Robots used for arc welding must be capable of precisely executing taught paths. Motion must be smooth and precisely controlled. Velocity control is important but the speeds required are not high, 2 in./sec, while welding is faster than most applications require. Higher velocities are important to reduce cycle time for applications with lengthy arc-off motion. Welding robots must have good reach and dexterity. Five DOF is required as a minimum and six DOF adds to gun maneuverability. There is normally no forced contact with the weld seam and the welding gun's weight is usually less than 20 lb,so robot payload requirements are light. If real-time path altering is required, the robot's motion generation functions must have programmable interfaces with the sensor systems. The robot's controller must have a means of accepting data and manipulating it for use with high level functions in the robot's native programming language.

Figure 6.4 Kuka Robotics arc welding robots

6.2.15 Finish Machining

Few material-forming processes produce finished parts. Most machining operations leave burrs and sharp edges. Large aircraft wing skins are milled by three-axis terrace cutting leaving small steps which must be blended to prevent fatiguing stress concentrations. Complex curved surfaces like ship propellers and aircraft landing gear are machined with rounded milling tools which leave a pattern of tool marks which must be ground off. Cast parts require gate and sprue removal and deflashing. Many parts must have their surfaces conditioned for appearance or subsequent plating and coating operations. Stamping and forging of automobile door panels and engine components leave "imperfections" which are finished out by hand. Die cast surfaces of hardware for door handles, faucets, furniture, and appliances are ground and polished. Finishing removes material to reduce waviness, reduce roughness, remove burrs and sharp edges, and to remove flaws. Manipulation is a finish machining process control variable. Tool pose,applied pressure, feed rate, and tool path must be controlled. Smaller parts are finished using fixed-floor or bench-mounted tool stands. For larger work pieces the finishing tool is mounted on the robot. Finish machining is very demanding of the manipulator because continuous path control is required while maintaining contact between part and tool.Medium- to large-sized robots are usually required for surface finishing because end effector weight and tool reaction force are additive when calculating payloads. A further margin of payload is usually required to offset the fatiguing effects of vibration and cyclic loading from tool reactions. Tool point positioning accuracy is less important than tool orientation and feed rate. In general, higher rates of surface curvature will require greater robot path precision. Six DOF robots are often required. Edge machining tool paths are constrained by burr geometry, finishing tool characteristics, end effector geometry, and part geometry. A single part may have edge features in several directions and orientations.The robot may require an assortment of different tools and a tool changer to reach all edges. If these measures do not allow access then multiple setups may be needed to present all features for finishing.Most robotic surface finish machining applications use compliant abrasive processes. Force control is required in some applications to keep tool pressure constant. Force controllers are most often incorporated in the end effector or in the tool stand. Through-the-arm robot force-control is available from some robot manufacturers, but its usefulness is limited to applications requiring slow feed rates because of slow mechanical response.Path planning and programming of edge and surface finishing for complex-shaped parts can be very difficult and time consuming. Both tool position and tool pose are critical in obtaining the correct tool contact area. Tedious paths programmed using the teach method require hundreds of hours to develop because of the large number of taught points. Generating the path control sequence is a major problem in manufacturing operations which produce a variety of complex-shaped parts. An example is in polishing large asymmetric-shaped aircraft skin panels. A more difficult automation problem is robotic spot finishing of flaws and other anomalous regions of the part surface when their location and extent are not known before set-up time. The reason is that the paths must be planned, generated, and executed on-line. This type of motion generation system requires part modeling and computational functions not available on most robot controllers.

6.3 Industrial Applications of Parallel Manipulators

By far the most widely used commercial robots are the serial-link manipulators, whose links and joints alternate with one another in an open kinematic chain. This serially connected configuration is similar to that of the human arm, with each link connecting only to two neighboring links through either prismatic or revolute joints, except for the last link which attaches to the end effector and the robot base which attaches to the floor. The advantage of the serial chain structural arrangement is that it provides a large work volume and dexterous manipulability; however, it suffers from a lack of rigidity and from accumulated actuator errors. Especially at high speed and high dynamic loading operating conditions, the serial-link manipulators show poor dynamic performance. To improve the dynamic performance and achieve high precision operations, the robot links must be made with high rigidity, which results in heavy robots with low force-output-to-manipulator-weight ratio. On the other hand, if the links can be arranged parallel to one another in a closed kinematic chain structure such that the major force components add together, then high precision operations and high force-output-to-manipulator-weight ratios can be achieved.

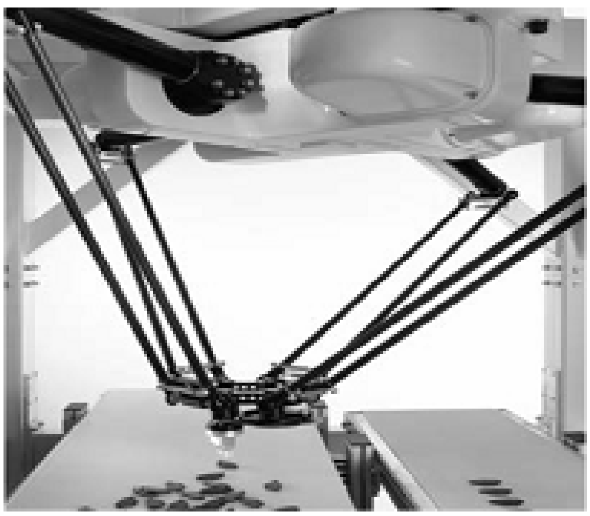


Figure 6.5 Adept's four-arm "Delta" robot

The most popular and successful parallel mechanical structure is the so-called Stewart platform, which was first proposed by Stewart (1965) in 1965. As a manufacturing manipulator, the Stewart platform has two fundamental characteristics which set it apart from machine tools and industrial robots — it is a *closed kinematic system* with *parallel links.* The Stewart platform link ends are simply supported, making the manipulator system far more rigid in proportion to size and weight than any serial link robot.Furthermore, the links of the Stewart platform are arranged so that the major force components of the six actuators add together, yielding a force-output-to-manipulator-weight ratio more than one order of magnitude greater than most industrial robots.The original Stewart platform was designed for an aircraft simulator and consisted of six linear hydraulic actuators acting in parallel between the base and the upper platform.All the links are connected both at the base and at the upper platform. Thus, by changing the length of each link, the position and orientation of the upper platform are able to be controlled.Some nice features of the original Stewart platform include:

- The manipulator design has six degrees of freedom, three for position and three for orientation.
- The six linear actuators are driven by six motors with each motor reacting on the base to avoid interaction between motors. Actually the manipulator can move when five of the jacks are locked merely by adjustment of the remaining jack.
- To achieve the maximum performance for a given power source, each motor operates directly on the same load (the upper platform). This makes a high payload-to-structure-weight ratio that at certain points of the workspace amounts to nearly six times the lifting capability of each individual actuator.
- Having low friction losses, with a powerful hydraulic system the manipulator can respond to commands very quickly.

It is interesting to note that the Stewart platform was not the first parallel link mechanical structure used in industry. As early as the 1950s, McGough devised a similar device for studying tire-to-ground forces and movements. The system had been in operation since 1955, but was never made known to the public until 1965 when Stewart published his journal article.

The Stewart platform appears simple and refined to the point of elegance. The performance mentioned above can be achieved using relatively inexpensive commercially available servo-actuator technology.The Stewart platform uses a closed kinematic chain which is structurally extremely strong and rigid,and is capable of distributing loads throughout the system. The actuator errors are not cumulative,allowing for high precision operations. However, the same closed kinematic structure that provides mechanical stiffness also complicates the forward kinematics analysis. This problem is an impediment to the derivation of dynamic equations and hence control schemes for real-time trajectory generation,which is necessary for industrial application of the manipulator (e.g., surface finishing applications).It is known that in the case of fully parallel structures, the inverse kinematics (that is, solving for the corresponding lengths of the links given the position and orientation of the upper platform in Cartesian space) is relatively straightforward. However, the forward kinematics analysis for the fully parallel mechanism (e.g., given the length of each link, solve for the position and orientation of the upper platform in Cartesian space) is very challenging. The reason is that the kinematic equations are highly coupled and highly nonlinear.Much effort has been devoted to finding an efficient algorithm for computing an accurate kinematic solution. To solve for the Cartesian position of the upper platform in terms of the given link lengths,thirty (30) nonlinear algebraic equations must be solved simultaneously, or polynomials of order 16 in a single variable must be solved. Due to the time-consuming nature of these procedures, it is difficult to compute the kinematic solutions on-line in real time. Since the Stewart platform requires complex kinematics computations for trajectory following control, it is difficult to achieve real-time control capable of supporting high bandwidth motion.The common feature of the forward kinematics analyses mentioned above is that there is no explicit analytical solution.Since there is no explicit expression available for the forward kinematics,deriving the Jacobian matrix and dynamic equations directly in link space and studying the singularity become impossible.

It is known that the Jacobian provides a transformation path which allows a two-way transformation between the link space and Cartesian space. If the Jacobian is not singular, then velocity in link space can be uniquely transformed to the corresponding velocity in Cartesian space. Particularly, if there is no movement in link space, then there is no movement in Cartesian space, so that the Stewart platform will remain rigidly fixed. However, at singular configurations, the transformation path from link space to Cartesian space is blocked. In this case, even though there is no movement in link space, the upper platform can lose rigidity, still possibly moving along some directions. In other words, at singularities,the Stewart platform may gain extra degrees of freedom. The problem becomes even worse in that, in this situation, forces or torques in Cartesian space cannot be transformed to link space, that is, at singular positions the Stewart platform cannot be controlled to move in all directions and cannot exert force in all directions. From the applications viewpoint, investigating the conditions under which there will be
singularities is important.Thus, while the parallel link manipulators afford structural advantages, they also present severe difflculties for controller design. The control problems associated with such structures are not easy, as the systems do not satisfy most of the assumptions made in the controls literature (e.g., linearity in the parameters and feedback linearizability). Therefore, most existing control algorithms do not work well.

Since proposed by Stewart in 1965, various applications of the Stewart platform have been investigated for use as aircraft simulators, as robot wrists, in mechanized assembly, and in active vibration control. As a manufacturing manipulator, the Stewart platform has great potential in automating many light machining applications such as surface finishing, edge finishing, routing, and profile milling. New manipulator applications to manufacturing processes requiring high force and power output such as combined assembly pressing are also possible.

Figure 6.6 McMaster University's Steward Platform as an flight simulator

There are several light machining applications that a Stewart platform manipulator would perform with less set-up complexity and tooling cost than a serial link robot or a standard machine tool.Many applications of robotic manipulators to high precision routing can be found in the aerospace industry. A common application is trimming wing skin edges. The precision is usually achieved through the employment of expensive templates that provide a precise guide bearing for the tool to follow as it is held in the naturally compliant grip of a robotic manipulator. The major advantage for using a Stewart platform as a routing machine is that it can follow the contours of many aerospace parts without the need for a tool guide; it is stiff enough to track the part precisely while withstanding the router cutting reactions. The cost of this contouring capability as compared to a standard five- or six-axis routing machine would be much lower.The Stewart platform would be superior to any serial link robot as a drilling head manipulator. Virtually all applications of drilling robots in aerospace manufacturing require the use of expensive and complex end effectors of part jigs to compensate for the inaccuracy and lack of stiffness of the robots. Drilling jigs for some parts can cost as much as ten times more than the robot itself. Special end effectors are often used to apply preloads to prevent the drill from “walking” and chattering. The Stewart platform could perform many drilling tasks unaided by special tooling because of its stiffness and precision.The industrial robot has generally not been considered to be a good milling manipulator. The Stewart platform could potentially perform contour milling of some materials with near-machine-tool accuracy.A Stewart platform milling machine with stiffness and dexterity characteristics intermediate between a large serial link robot and a five-axis mill could be built at or below the cost of a commercial serial link robot.When a direct contact tool like a grinder is used it is important to control both the tool position and the forces involved so that the substrate is not damaged. For example, when grinding mold scale a very aggressive tool may be needed, and the normal force applied can be large so long as the penetration into the surface is precisely controlled. The reactions in the surface tangent plane can be very large and could cause oscillations if not held rigidly. A Stewart platform with a constant force suspension for its tool could apply very large force with very high stiffness in one direction while being compliant and forceful in the normal direction.

6.4 Industrial Applications of Mobile Robots

Traditionally, standard robots are fixed in position. They are mounted on a rigid base and bolted to the floor so that they can withstand the forces and torques applied when the arm manipulates objects.However, fixed-base robots cannot cope with a large variety of applications in which a robot will operate in large and unstructured domains. A special type of manipulator, that is, a mobile robot, is often required in these applications.In tomorrow’s flexible manufacturing system (FMS) environment, mobile robots will play an important role. They will transport parts from one workstation to others, load and unload parts, remove undesired objects from floors, and so on. In addition to indoor mobile robots, there are some other outdoor occasions where mobile robots may take on heavy responsibilities. Examples include construction automation,military missions, handling of harmful materials, hazardous environments, interplanetary exploration, and so on.

Mobile robots can be classified by driving mechanism as wheeled mobile robots, legged mobile robots,and treaded mobile robots. Some other types of mobile robots, for instance, the *underwater mobile robots,* the *autonomous aerial mobile vehicle,* and so on, are also available but are not included in this discussion.

Wheeled Mobile Robots. Mobile robots using wheels for locomotion are called *wheeled robots.* Two driving configurations are used in today's wheeled mobile robot — steer-drive and differential-drive.The former uses two driving wheels to make the vehicle move forward and backward. The heading angle is controlled by an independent steering mechanism. Since the driving action is independent of the steering action, the motion control of the vehicle is somewhat simplified. However, due to physical constraints, this configuration cannot turn in a very small radius. This shortcoming makes it less attractive in some industrial applications. Differential-drive configuration mobile robots, on the other hand, have two independent driving wheels positioned at opposite sides of a cart base, arranged parallel to one another. Their speeds can be controlled separately. Thus, by appropriately controlling the speed of each driving wheel, this mechanism is able to drive the vehicle forward and backward, as well as steer its heading angle by differential speed commands. Even though this configuration requires a somewhat more complex control strategy than the steer-drive configuration, its capability of making small-radius turns, even making turns on-the-spot, makes it the first choice in many industrial applications. Some commercial wheeled mobile robots include the *CyberGuard Autonomous Survelliance Robot* manufactured by Cyberworks Inc., Canada; *B12 Mobile Robot Base* manufactured by Real World Interface, Inc., Dublin, NH; *LabMate Mobile Robot Platform* manufactured by Transitions Research Corporation, Danbury, CT; and *R-20 Mobile Robot* manufactured by Arrick Robotics, Euless, TX.

Legged Mobile Robots. While most mobile robots use wheels for locomotion because of the simplicity of the moving mechanism design and control, some other mobile robots use legs for locomotion. These types of mobile robots are called *legged robots.* The primary advantages of legged robots include their ability to traverse rough terrain with good body stability and minimal ecological damage. In order to maintain good stability, it is sufficient that at any time there are three points in contact with the ground.Therefore, most legged robots use at least four legs, or even six or eight legs. As long as the legged mobile robots' center of gravity is within the triangle formed by the three contact points, stability is guaranteed. Compared with the wheeled robots, the control of legged robots is much more difficult.Much has been learned about multilegged locomotion from studies of balancing and hopping on a single leg. In particular, biped running can be viewed as successive hopping on alternating legs, since both legs never contact the ground simultaneously.Some examples of legged mobile robots include *ODEX I* manufactured by Odetics and *BigDog* manufactured by Boston Dynamics.

Figure 6.7 Boston Dynamics “BigDog” billed as the most advanced quadruped robot on Earth,which is able to carry up four packs of military equipmant on awkward terrain unsuitable for vehicles.BigDog is powered by an engine that drives a hydraulic actuation system

Treaded Mobile Robots. Another type of mobile robot, the treaded robot, moves much like a tank. An example of the treaded robot is the *ANDROS MARK V* manufactured by REMOTEC, Inc. at Oak Ridge, TN. It is something of a hybrid between a walking and a rolling vehicle. *ANDROS* can ascend/descend 45° stair/slopes by lowering its front and rear auxiliary tracks. It has all-terrain capabilities that are ideal for performing missions in rough outside terrain or in rubble-strewn, damaged buildings.

To navigate in unknown and unstructured areas, the mobile robot must have the capability of sensing the real world, extracting any useful information from the data acquired, and interpreting the information to understand the environment surrounding it, especially the situation in front of it. Several sensor systems for mobile robot navigation have been reported in the literature.Of these, stereo vision systems and active rangefinding devices are the most used sensor systems. The former extracts range information from pairs of images to build a 3D world map. However, due to the high computational expense — a 3D map may require 1 min to generate — stereo vision systems have not to date been generally used for real-time navigation control. Active rangefinding devices do not suffer from this problem because they can deliver range information directly Two kinds of rangefinding devices are available: laser rangefinders and ultrasonic range transducers.Even though laser rangefinders can provide fast response with high resolution, a relatively long measurement range, and high measurement precision, the required systems structure and configurations are very complicated, which makes the system itself very expensive. On the other hand, sonar systems are simple and low cost (probably orders of magnitude less expensive than laser-based systems), though the measurements have lower resolution and lower precision.Determining range by means of sonar systems is a simple process. A short burst of ultrasonic sound is first transmitted by an ultrasonic range transducer, then an echo is expected to be received by the same transducer. If in a reasonable time period no reflected signal is detected, it is assumed that there are no objects in the area of interest. Otherwise, the time for round-trip propagation is determined and the distances to any objects are calculated. The transducer yields a 3-dB full angle beamwidth of 50 KHz at approximately 12 to 15°, depending on the signal frequency and transducer diameter. Thus, to scan the whole area surrounding the mobile robot, at least 24 to 30 transducers, of which the transmit/receive axis lies in the same horizontal plane, are needed.Vision systems, also sometimes useful in robot sensing, usually consist of one or more video cameras and an image processor. The vision system can provide the richest source of information, which is, in fact, needed in certain applications such as road following, object identification, and so on.Feedback from rotary and linear actuators used in wheeled and/or legged mobile robots is provided by position sensors and/or velocity sensors. This information is then processed for estimating position and orientation of the mobile robot in world coordinates.By far the most commonly used position sensor is the *optical encoder,* which uses marks to indicate position. The typical encoder has a track for each binary digit of information. The encoder is mounted on the servo motor. When the motor rotates certain degrees, the absolute rotation position of the axis can be read from the digital output of the encoder. The resolution of the encoder is equal to (360/2*n*) degree, where *n* is the number of tracks. If an 8-track encoder is used, then a 1.4°/step resolution can be attained.Other types of position sensors used in mobile robot systems include synchros, resolvers, potentiometers,linear variable differential transformers (LVDT), rotary variable differential transformers (RVDT),amplitude-modulated laser radars, and laser interferometers.Conventional servo design requires that the servo controller include a "velocity term" in its transfer function. Without the velocity term, a servo system will usually exhibit an undamped, resonant behavior and can be highly unstable. In principle, the signal from a joint position sensor can be electronically differentiated to obtain joint velocity. However, if the joint position sensor has a noisy output, differentiating the position sensor signal can effectively magnify the noise sufficiently to make the servo system unstable or unreliable. To overcome this difficulty, several velocity sensors are available for directly measuring the joint velocity. A *DC tachometer* system consists of a voltage meter (or a current meter) and a small DC generator (sometimes called a "speed-measurement generator"). The latter is usually constructed with a permanent-magnet stator and a multipole wound armature. The armature is connected directly to the rotating shaft of the servo motor which is used to drive the manipulator joint. When the small permanent magnet DC generator rotates with the servo motor, its output voltage (when driving a high-impedance load) varies in proportion to the rotation speed of the armature. Voltage output variations can then be translated into speed changes or used as a feedback signal to control the robot arm velocity.Supplementary position and orientation information can also be supplied by inertial guidance sensors,terrestrial magnetic field sensors, or inertial reference systems (IRS).Autonomous navigation of mobile vehicles has been studied by many researchers. In Elfes (1987), a sonar-based navigation system for an autonomous mobile robot working in unknown and unstructured environments was developed. The workspace is classified into “probably empty regions,” “somewhere occupied regions,” and “unknown regions” based on the interpretation of the data obtained from the sonar system. In this scheme, as more and more data are received, the first two regions may increase,and the uncertainty of these regions also decreases. It is reported that after a few hundred readings, a sonar map covering a thousand square feet with up to 0.1-ft position accuracy can be made.

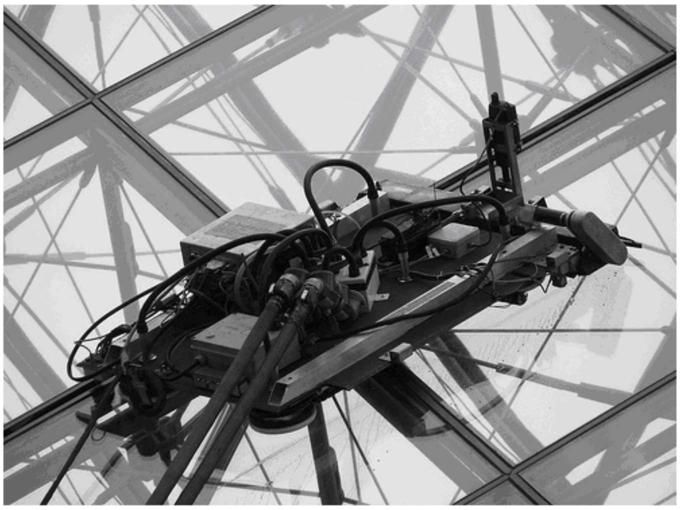


Figure 6.8 Glass cleaning robot at Musee du Louvre, Paris

Another navigation scheme uses a stereo vision system to control a mobile base autonomously operating in a complex, dynamical, and previously unknown environment. A pair of stereo cameras is mounted on the mobile base to generate a symbolic world model. Based on this model, the desired trajectories are specified for the driving motors.Although the schemes described above work well in specific environments, path planning and navigation control are always separated into two isolated issues. The path planning mechanism designs a smooth path from an initial position to a goal position by providing profiles of position and velocity, or profiles of position and heading angles, in Cartesian space. It assumes that perfect knowledge of the system dynamics and the environments is always available and that the position and orientation of the vehicle are measurable absolutely. After the desired trajectories have been designed, the navigation mechanism will take charge of driving the mobile robot to follow the prescribed trajectory as closely as possible.

Even though each mechanism may work well through closed-loop control, the whole navigation system is an open-loop system. Static path planning strategies do not provide the essential adaptability necessary for coping with unexpected events. The success of navigation control depends mostly on the accuracy of absolute measurements of position, velocity, orientation, and their rates of change. All of these must be measured in (or transformed to) Cartesian space. This is a very expensive and difficult job.Other possible closed-loop navigation control schemes use intelligent control techniques, for instance,fuzzy-logic control. In such a control scheme, the path-planning mechanism and trajectory-following mechanism are often integrated, not separated. The path is planned dynamically and is always up-todate.All the information that the system needs to know such as “where is the goal (the dock),” “what is the required final orientation (the docking angle),” “what is the present orientation (the present heading angle),” “what is the present distance between the car and the goal,” “what is the present distance between the car and any obstacles,” “what is the safe turning radius (the minimum curvature radius),” and so on is easily captured through sensing the environment surrounding the car using onboard sensors (e.g., sonar) that yield relative information.The advantages of such intelligent control strategies are evident. They unite navigation and maneuvering into a single set of algorithms. Full and accurate knowledge of the system dynamics is not required.The only knowledge needed are the correlations between the control actions (acceleration, steering, etc.) and the performance (“behaviors”) of the system. The absolute measurement of the position and velocity in Cartesian space is not required. Only information about relative locations is necessary, and this is always available. Tight coupling between sensor data and control actions provides the adaptability necessary for coping with unexpected events. Actually, there is no path planning to be performed; the driving mechanism reacts immediately to perceived sensor data as the mobile robot navigates through the world.

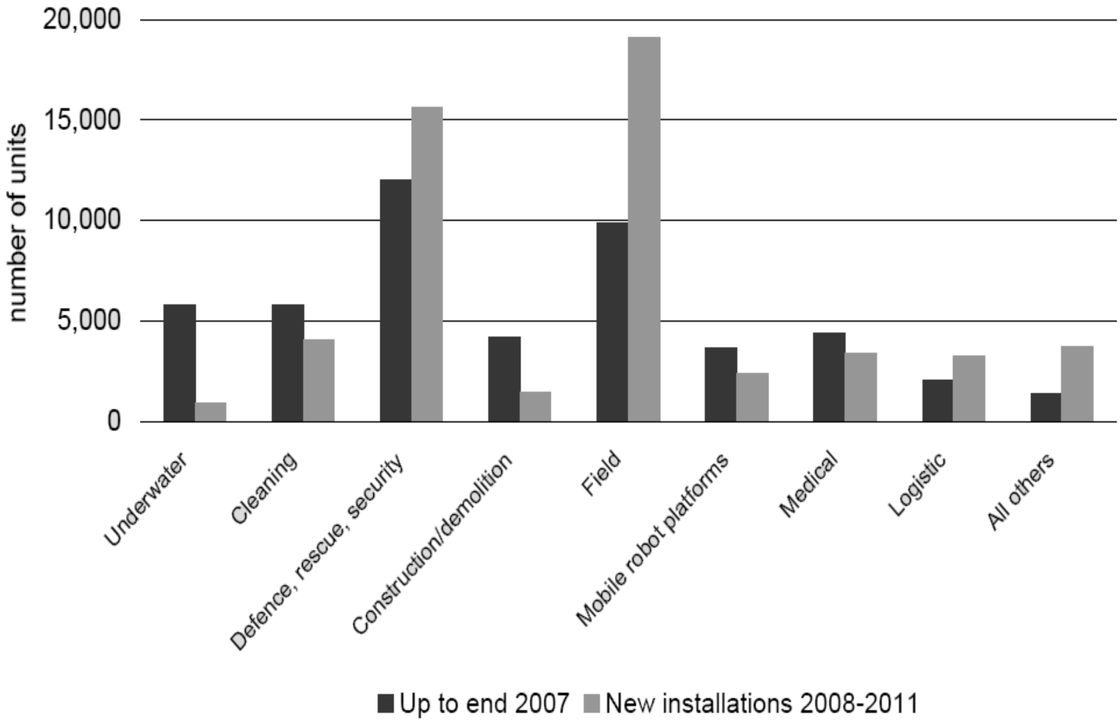


Figure 6.9 Service robots for professional use stock at the end of 2007 and projected installations in 2008-2011(World Robotics, 2008)

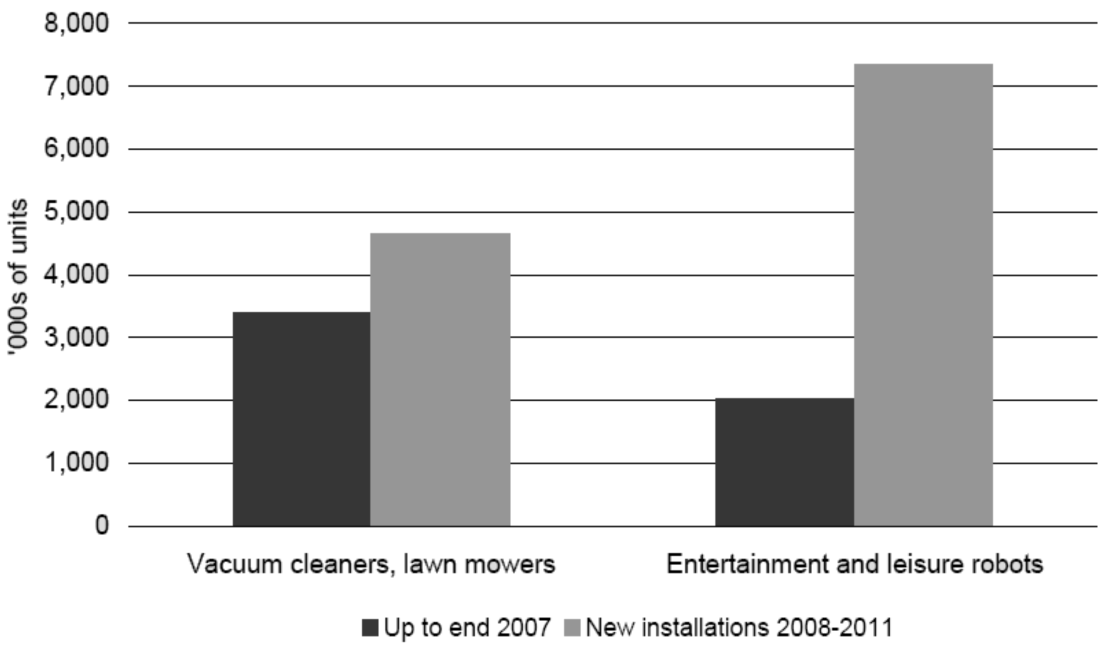


Figure 6.10 Service robots for personnel/domestic use stock at the end of 2007 and projected installations in 2008-2017(World Robotics, 2008)

CHAPTER SEVEN
CONTROL SYSTEMS

7.1 Control Systems

Machines are dynamic systems that are designed for special purposes.If purposes defined as the outputs and the directives that are causing the purposes inputs, generally any machine can be defined with the following block diagram.

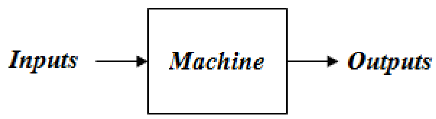


Figure 7.1 Machine operations in a general manner

A control system is a combination of components that act together in such a way that the overall machine/system behaves automatically in a prespecified desired manner.

7.2 Types of Control

7.2.1 Open-loop control

An open-loop system is a system whose input does not depend on the output.In open-loop systems,if the performance of the system is not satisfactory, the controller (due to the lack of feedback action) does nothing to improve it (Paraskevopoulos,2002).

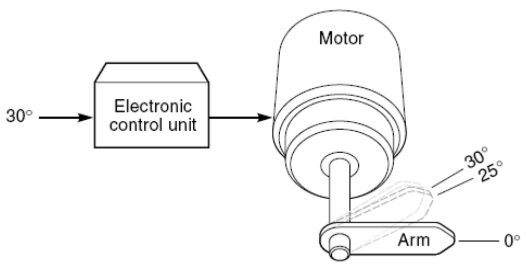


Figure 7.2 An open-loop system(Kilian, 2005)

7.2.2 Closed-loop control

A closed-loop system is a system whose input depends on the output.Closed-loop systems differ from open-loop systems, the difference being whether or not information concerning the system's output is fed back to the system's input. This action is called *feedback* and plays the most fundamental role in control systems.In closed loop systems the controller acts in such a way as to keep the performance of the system within satisfactory limits(Paraskevopoulos,2002).The term *control system design* is especially used for designing closed-loop control systems.

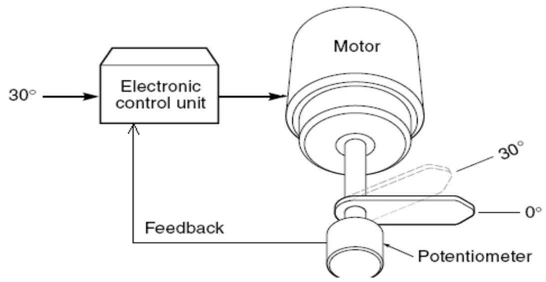


Figure 7.3 A closed-loop system(Kilian, 2005)

7.3 Types of control systems

7.3.1 Process control systems

Control systems that are used for controlling the thermal/chemical industrial processing variables like temperature,pressure,volume,etc. are called process control systems.

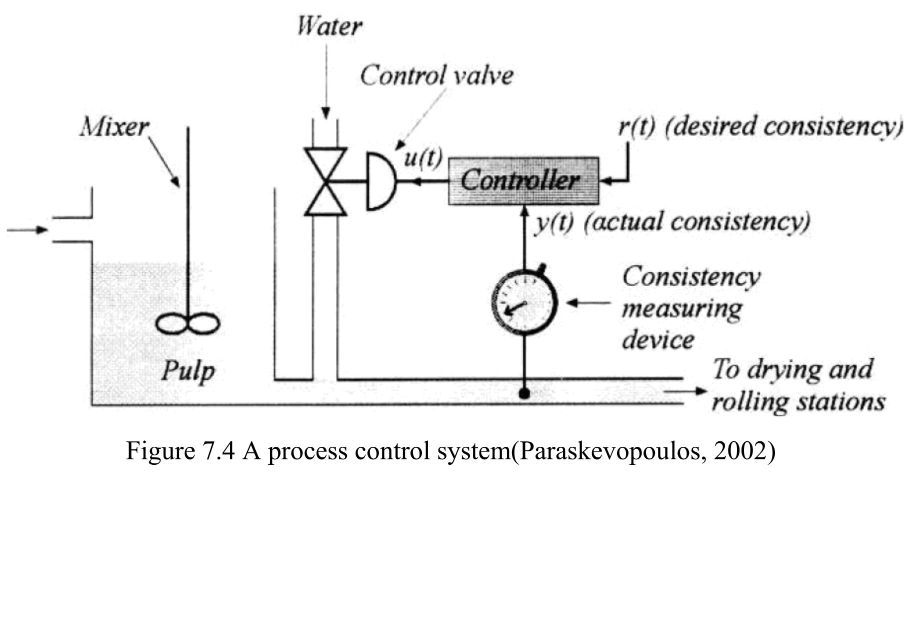


Figure 7.4 A process control system(Paraskevopoulos, 2002)

7.3.2 Motion control systems

Control systems that are used for controlling the motion variables like position, velocity, force,etc. are called motion control systems.

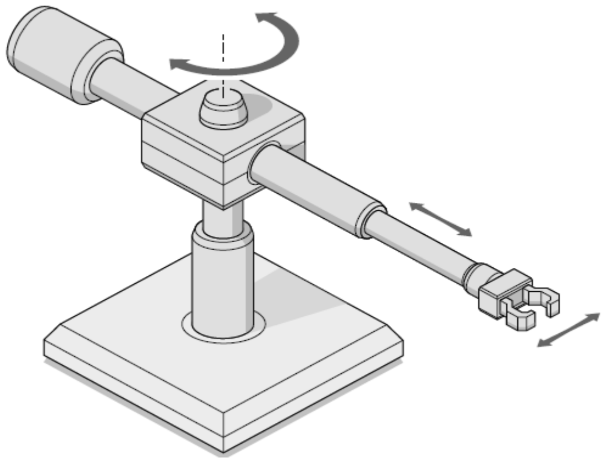


Figure 7.5 A motion control system(Kilian, 2005)

7.4 Control Systems Elements

7.4.1 Controller

The element which is dedicated for correcting the *error* with the desired and the measured output is defined as *controller*.It can be *analog*(resistance,capacitor and amplifier based ICs) or *digital*(microcontrollers,PCs,etc.).

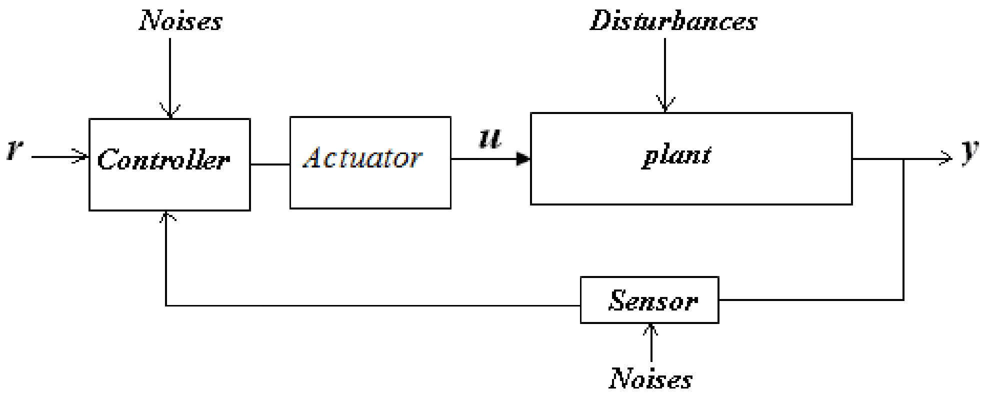


Figure 7.6 Control systems elements block diagram representation

7.4.2 Actuator

The *actuator* is the device that can influence the controlled variable of the plant.

7.4.3 Plant

The controlled physical system is defined as *plant*.

7.4.4 Sensor

The sensing element that is feeding back the output variables to the controller is defined as *sensor*.

7.4.5 Disturbance

The external effects which are acting to the system but contrary to the control input do not have a correcting effect are defined as disturbance.Disturbances can be classified as *deterministic* and *stochastic* disturbances.

Deterministic disturbances are the external effects which can be modelled with step,ramp, sinuzoidal,etc. like known functions.

Stochastic disturbances are the external effects which have random values and can be modelled with the probability functions.

7.4.6 Noise

Noise is a kind of disturbance which only has effect on the process if it is fed back to the controller.Noises can also be classified as *deterministic* and *stochastic* noises.

7.5 Linear and Non-linear Systems

A linear system is described by linear algebraic and differential equations.By contrast,a nonlinear system has nonlinear combinations of the variables and their derivatives(Wood,1997).

7.6 Linearization

Linearization is a process of finding a linear model that approximates a nonlinear one.The linearization approach is used to consider the relationship between incremental variables around an equilibrium state, but it requires continuity and differentiability in the non-linearities.Although this technique is not always applicable,in many cases it provides good insight into the process behaviour and can be used in the design of a suitable controller.

An alternative approach to obtain a linear model for use as the basis of the control system design is to use the part of the control effort to cancel the nonlinear terms and design the remainder of the control based on linear theory.This approach-*linearization by feedback*-is popular in robotics(known as *computed torque* control),aerospace,etc.

Finally,some nonlinear functions are such that an *inverse nonlinearity* can be found to be placed in series with it so the combination is linear.This method is often used to correct mild nonlinear characteristics of a sensor or actuator that have small variations in use(Franklin,2002).

7.7 SISO and MIMO Systems

The simplest feedback control system, a single-input-single-output(*SISO*) system, has one input and one output. In a SISO system, a sensor measures one signal and the controller produces one signal drive an actuator.

Control systems with more than one input or output are called multiple-input-multiple-output(*MIMO*) systems.

7.8 Performance Criterians for the Control Systems

7.8.1 Stability

A general definition of stability should be applicable to any dynamic system and it would appear as: *a system is stable if it presents bounded outputs for bounded inputs.*

Generally speaking:

If $\lim_{t \to \infty} e(t) = 0$ →System is stable (7.1)

Where $e(t) = y_d(t) - y(t)$ (7.2)

y_d:*Desired output*
y:Measured output

7.8.2 Steady-state error(steady state response)

The steady state error is the error between steady state value and desired value of step response output.

7.8.3 Settling time(transient response)

Settling time is the time at which the step response input stays within some small percentage range of the steady state value.Typically, a percentage of 2% or 5% is chosen to determine the settling time.

7.8.4 Robustness

Availability for maintaining the *above* criterians under changes and/or uncertainties in modelled plant parameters or disturbances/noises.

7.9 Controller Design Methods

7.9.1 Conventional controller design

Linear conventional controllers like *PID* and its variants *PI* and *PD* are suitable for decoupled dynamics so the motion controller can be designed with the transformation-based(*s or z*) conventional methods that are useful for single-input/single-output(*SISO*) systems(Kurfess,2005).

Transformation-based conventional controllers are appealing because of their efficiency in tuning and low computational costs.However,if high quality motion control performance is needed,conventional controllers may lead to unsatisfactory results.Use of these controllers means making serious tradeoffs among feasible static accuracy,system stability,and damping of high frequency disturbances.

7.9.2 Optimization-based controller design

Stability robustness,disturbance rejection,and controlled transient responce can be jointly and directly imposed using feedback schemes based on H_α(*H_2 and H_∞*)(*H_2 is the mathematical generalization of the LQR and LQG controller types*) control theory. These schemes enable quantitative prediction of motion performance,given bounds on modelling uncertainty and disturbances.Moreover,with the avaible knowledge of the system dynamics,parasitic effects(*noises*) and disturbances,motion performance can be optimized.These are the reasons that make H_α controllers appealing solutions for practical problems and motivate their applications(Kurfess,2005).

7.9.3 Sliding mode controller design

The most salient feature of this method is the ability to change the controller structure in accordance with the plant state.Associated with this change of structure,control actions lead the plant into the so called *sliding mode*.While the system remains in the sliding mode,it is insensitive to disturbances and parameter variations.Besides,the dynamic characteristics of the sliding mode are imposed by the controller designer and are independent of the plant dynamics.Such properties make this technique ratter attractive for control:insensitivity to disturbances(*while in sliding mode*) eliminate link interactions,therefore allowing a decentralized controller structure and simple models for controller design.

Unfortunately there are still practical problems that must overcome.The first concerns the reaching phase;in fact convergence in only ensured when he system enters the sliding mode,but there is no guarantee that the system will always reach it.The second arises when the system is in the sliding mode:unless the dynamic characteristics of the sliding mode coincide with one of the system's natural modes,the controller has to change it structures infinitely often.Because,in practice,only a finite number of switches is possible in a finite time interval,the system will not follow exactly the desired trajectory;instead it will exhibit high frequency oscillations around it.This phenomenon,also known as "*chattering*" may excite undesirable resonances in the mechanical structure[9].The thirth,the nonlinearity of this method does not facilitate a quantitative prediction of system performance for a given robustness level,where it is often very important to know in advance worst-case motion accuracy for a given bandwidth of reference trajectories.These are the limiting factors for the method's widespread application in practice(Kurfess,2005).

7.9.4 Adaptive controller design

The fundamental difference beetween fixed feedback control systems and adaptive control systems resides in the fact that the later “adapt” their characteristics to the changing dynamics of the controller process.

General purpose adaptive algorithms can be classified as model reference adaptive control (*MRAC*) and self-tuning adaptive control(*STAC*).The basic idea of MRAC is to synthesize the control inputs which force the system to behave in a desirable manner as prescribed by a reference model.In STAC the system is modelled as a linear,time-varying,discrete time process, which is updated(identified) at every sampling period,on the basis of which the controller is designated to achieve a prescribed goal(Tzafestas,1991).

Although,adaptive control method,can improve system performance in the presence of uncertainty in the system dynamics and external disturbances(*e.g. variable load*),the nonlinearity of this method(*like sliding mode method*) does not facilitate a quantitative prediction of system performance for a given robustness level.This is the limiting factor for the method’s widespread application in practice,where it is often very important to know in advance worst-case motion accuracy for a given bandwidth of reference trajectories(Kurfess,2005).

7.9.5 Learning/intelligent controller design

Systems that perform various tasks in an intelligent and autonomous manner are required in many contemporary technical systems.Autonomous systems have to perform various anthropomorphic tasks in both unfamiliar or familiar working environments by themselves much like humans.They have to be able to determine all possible actions in unpredictable dynamic environments using information from various sensors.In advance, human operators can transfer to systems the knowledge, experience, and skill to solve complex tasks.In the case of a system performing tasks in an unknown enviroment, the knowledge may not be sufficient.Hence, system have to adapt and be capable of acquiring new knowledge through learning.The basic components of system intelligence are actuation,perception,and control.Significant effort has been attempted to make systems more intelligent by integrating advanced sensor systems as vision,tactile sensing,etc.

Intelligent control is a new discipline that has emerged from the classical control disciplines with primary research interest in specific kinds of technological systems(systems with recognition in the loop, systems with elements of learning and self-organization, systems that sometimes do not allow for representation in a conventional form of differential and integral calculus).Intelligent control studies high-level control in which control strategies are generated using human intelligent functions such as perception,simultaneous utilization of a memory, association, reasoning,learning,or multi-level decision making in response to fuzzy or qualitative commands.Also,one of the main objectives of intelligent control is to design a system with acceptable performance characteristics over a very wide range of structured and unstructured uncertainties.

Efficient intelligent control systems must be based on the following features:

- robustness and great adaptability to system uncertainties and environment changes
- learning and self-organizing capabilities with generalization of acquired knowledge
- real-time implementation on controllers using fast processing architectures

The fundamental aim of intelligent control represents the problem of uncertainties and their active compensation..Hence, it is very important to include learning capabilities in control algorithms,i.e.,the ability to acquire autonomous knowledge about systems and their environment.In this way,using learning active compensation of uncertainties is realized, which results in the continous improvement of system performances.Another important characteristic that must be included is knowledge generalization,i.e.,the application of acquired knowledge to the general domain of problems and work tasks.

Few intelligent paradigms are capable of solving intelligent control problems:

- Symbolic knowledge-based systems(*expert systems*)
- Neural networks(*connectionist theory*)
- Fuzzy logic
- Evolutionary computation theory(*genetic algorithms*)

are very important in the development of intelligent control algorithms.Also, important in the development of efficient algorithms are hybrid techniques based on integration of particular techniques such as *neuro-fuzzy networks*,*neuro-genetic*,and *fuzzy-genetic* algorithms(Hurmuzlu,2002).

CHAPTER EIGHT
PACKAGING MACHINES

8.1 A Brief History of Packaging

From the very earliest times, humans consumed food where it was found. Families and villages made or caught what they used. They were also self-sufficient, so there was little need for packaging of goods, either for storage or transportation. When containers were needed, nature provided gourds, shells, and leaves. Later, containers were fashioned from natural materials, such as hollowed logs, woven grasses and animal organs. As ores and chemical compounds were discovered, metals and pottery were developed, leading to other packaging forms.Packaging is used for several purposes(Welt,2005):

- Contain products, defining the amount the consumer will purchase.
- Protects products from contamination, from environmental damage and from theft.
- Facilitate transportation and storing of products.
- Carry information and colorful designs that make attractive displays.

8.1.1 Paper and Paper Products

One way of placing packages into categories is to describe them as flexible, semi-flexible, or rigid.Flexible packaging includes the paper sacks that dog food comes in, the plastic bags that hold potato chips,and the paper or plastic sacks in which we carry home our purchases. An example of semi-flexible packaging is the paperboard boxes that cereal, many other food products, small household items, and many toys are packaged in. For many non-food items, the packaging is made more rigid by formed packing materials that slip inside the box and hold the product and its accessories or components in place.Forms of rigid packaging include crates, glass bottles,and metal cans.Cloth or paper may be the oldest forms of flexible packaging. Flexible packaging is the most "source-reduced" form of packaging, that means that a flexible package has the least amount of material compared to other forms of packages that would hold the product. This also means that flexible packaging adds very little weight to the overall product, and there is very little to discard when the package is empty.The use of flexible packaging materials began with the Chinese, They used sheets of treated mulberry bark to wrap foods as early as the first or second century B.C. During the following centuries,the Chinese also developed and refined the techniques of paper making. Knowledge of how to make paper gradually moved west across Asia and into Europe. In 1310, paper making was introduced to England. The technique arrived in America in Germantown, Pennsylvania, in 1690.Paper is basically a thin sheet of cellulose.Cellulose is a fibrous material derived from plants.Early paper was made from cellulose fibers derived from flax, the plant that also gives fibers for linen cloth. As demand for paper grew, old linen rags were sought as a source of fiber.In 1867, the process for deriving useful cellulose fiber from wood pulp was developed. Because wood was so cheap and plentiful, this fiber source rapidly replaced cloth fibers as the primary source of paper fiber.Today, virtually all paper has wood pulp as the source of cellulose fiber.An important step for the use of paper in packaging came with the development of paper bags.Commercial paper bags were first manufactured in Bristol, England, in 1844. Shortly thereafter, in 1852,Francis Wolle invented the bag-making machine in the United States. Further advancements during the 1870s included glued paper sacks and the gusset design, producing the types of paper bags used today.In 1905, machinery was invented to automatically produce in-line printed paper bags.With the development of the glued paper sack,the more expensive cotton flour sacks could be replaced. But a sturdier multiwalled paper sack for larger quantities did not replace cloth until 1925,when a means of sewing the ends was finally invented.Another important use of paper in packaging came with the development of paperboard -- the kind of paper that packages a box of cereal. The first paperboard carton -- often called a cardboard box --was produced in England in 1817, more than two hundred years after the Chinese invented cardboard or paperboard.Another common form of "cardboard" based on corrugated paper appeared in the 1850s. Basically,this form of cardboard is made from thin sheets of paperboard that are molded into a wavy shape and then "faced" or sandwiched between two flat sheets of paperboard. The strength, lightness, and cheapness of this material make it very useful for shipping and storing. However, replacing wooden crates with the new paper alternative would prove to be something of a battle. Nevertheless, about 1910, after much litigation between manufacturers and the railroads,shipping cartons of faced corrugated paperboard began to replace self-made wooden crates and boxes used for trade. Today, cardboard boxes – more accurately called "C-flute corrugated paperboard cartons" -- are used almost universally for product shipping.As with many innovations, the development of the carton was accidental. Robert Gair was a Brooklyn printer and paper-bag maker during the 1870s. While he was printing an order of seed bags, a metal rule normally used to crease bags shifted in position and cut the bag. Gair concluded that cutting and creasing paperboard in one operation would have advantages; the first automatically made carton, now referred to as "semi-flexible packaging," was created.Such folding cartons or "tubular cartons" dominate the dried, processed food market.The development of flaked cereals advanced the use of paperboard cartons. The Kellogg brothers were first to use cereal cartons. The Kelloggs operated a sanatorium at Battle Creek, Michigan. They developed flaked cereals as a health food for their patients, but soon began marketing this new food product on a mass scale. Their original packaging was a waxed, heat-sealed bag of Waxtite wrapped around the outside of a plain box. The outer wrapper was printed with the brand name and advertising copy.Today, of course, a plastic liner protects cereals and other products within the printed carton. Some cereal manufacturers have attempted to sell cereal in flexible pouches, like snack foods. However, U.S. consumers have only marginally accepted cereals in a pouch only, so we continue to see a bag-in-box format for cereals.Paper and paperboard packaging increased in popularity throughout much of the 20th century.Then with the advent of plastics as a significant player in packaging (late 1970s and early 1980s),paper and its related products were replaced in many uses. Lately that trend has slowed as designers have tried to respond to the perception that plastic is environmentally unfriendly. The fact is that decreasing that amount of material in packaging is usually more important than the composition of the package to get the most environmentally friendly form of packaging.

8.1.2 Glass

Although glass-making began in 7000 B.C. as an offshoot of pottery, it was first industrialized in Egypt in 1500 B.C. Made from base materials (limestone,soda, sand and silica), which were in plentiful supply,all ingredients were simply melted together and molded while hot. Since that early discovery, the mixing process and the ingredients have changed very little, but the molding techniques have progressed dramatically.At first, ropes of molten glass were coiled into shapes and fused together. By 1200 B.C., glass was pressed into molds to make cups and bowls. When the blowpipe was invented by the Phoenicians in 300 B.C., it not only speeded production but allowed for round containers. Colors were available from the beginning, but clear, transparent glass was not discovered until the start of the Christian Era. During the next 1000 years, the process spread steadily, but slowly, across Europe.The split mold, which was developed in the 17th and 18th centuries, further provided for irregular shapes and raised decorations. The identification of the maker and the product name could then be molded into the glass container as it was manufactured. As techniques were further refined in the 18th and 19th centuries, prices of glass containers continued to decrease. Owens invented the first automatic rotary bottle-making machine, patented in 1889. Suddenly, glass containers of all shapes and sizes became economically attractive for consumer products, and from the early 1900s until the late 1960s glass containers dominated the market for liquid products. A typical modern bottle-making machine automatically produces 20,000 bottles per day.While other packaging products, such as metals and plastics, were gaining popularity in the 1970s,packaging in glass tended to be reserved for highvalue products. As a type of "rigid packaging," glass has many uses today. High weight, fragility and cost have reduced the glass markets in favor of metal and plastic containers. Still, for products that have a high quality image and a desire for high flavor or aroma protection, glass is an effective packaging material.The packaging glass used today is the only type of glass accepted in US recycling programs.

8.1.3 Metals

Ancient boxes and cups, made from silver and gold, were much too valuable for common use. Metal did not become a common packaging material until other metals, stronger alloys, thinner gauges and coatings were eventually developed.One of the "new metals' that allowed metal to be used in packaging was tin. Tin is a corrosion-resistant metal, and ounce-for-ounce, its value is comparable to silver. However, tin can be "plated" in very thin layers over cheaper metals, and this process made it economical for containers.The process of tin plating was discovered in Bohemia in 1200 A.D., and cans of iron coated with tin were known in Bavaria as early as the 14th century. However, the plating process was a closely guarded secret until the 1600s. Thanks to the Duke of Saxony, who stole the technique, it progressed across Europe to France and the United Kingdom by the early 19th century. After William Underwood transferred the process to the United States via Boston, steel replaced iron, which improved both output and quality. The term 'tin can' referred to a tin-plated iron or steel can and was considered a cheap item. Tin foil also was made long before aluminum foil. Today many still refer to metal cans as 'tin cans' and aluminum foil as 'tin foil', a carryover from times well past.In 1764, London tobacconists began selling snuff in metal canisters, another type of today's "rigid packaging." But no one was willing to use metal for food since it was considered poisonous.The safe preservation of foods in metal containers was finally realized in France in the early 1800s. In 1809, General Napoleon Bonaparte offered 12,000 francs to anyone who could preserve food for his army. Nicholas Appert, a Parisian chef and confectioner, found that food sealed in tin containers and sterilized by boiling could be preserved for long periods. A year later (1810), Peter Durand of Britain received a patent for tinplate after devising the sealed cylindrical can.Since food was now safe within metal packaging,other products were made available in metal boxes.In the 1830s, cookies and matches were sold in tins and by 1866 the first printed metal boxes were made in the United States for cakes of Dr. Lyon's tooth powder.The first cans produced were lead-soldered by hand, leaving a 1 1/2-inch hole in the top to force in the food. A patch was then soldered in place but a small air hole remained during the cooking process.Another small drop of solder then closed the air hole.At this rate, only 60 cans per day could be manufactured.In 1868, interior enamels for cans were developed, but double seam closures using a sealing compound were not available until 1888.Aluminum particles were first extracted from bauxite ore in 1825 at the high price of $545 per pound. When the development of better processes began in 1852, the prices steadily declined until 1942, when the price of a pound of aluminum was $14.Although commercial foils entered the market in 1910, the first aluminum foil containers were designed in the early 1950s while the aluminum can appeared in 1959.The invention of cans also required the invention of the can opener! Initially, a hammer and chisel was the only method of opening cans. Then in 1866, the keywind metal tear-strip was developed. Nine years later (1875), the can opener was invented. Further developments modernized the mechanism and added electricity, but the can opener has remained, for more than 100 years, the most efficient method of retrieving the contents of a can. In the 1950s, the pop top/tear tab can lid appeared and now tear tapes that open and reseal are popular. Collapsible, soft metal tubes, today known as "flexible packaging," were first used for artists paints in 1841. Toothpaste was invented in the 1890s and started to appear in collapsible metal tubes. But food products really did not make use of this packaging form until the 1960s. Later, aluminum was changed to plastic for such food items as sandwich pastes, cake icings and pudding toppings.

8.1.4 Plastics

Plastic is the newest packaging material in comparison with metal, glass, and paper. Although discovered in the 19th century, most plastics were reserved for military and wartime use. Plastics have become very important materials and a wide variety of plastics have been developed over the past 170 years.Several plastics were discovered in the nineteenth century: styrene in 1831, vinyl chloride in 1835, and celluloid in the late 1860s. However, none of these materials became practical for packaging until the twentieth century.Styrene was first distilled from a balsam tree in 1831, but the early products were brittle and shattered easily. Germany refined the process in 1933 and by the 1950s styrofoam was available worldwide.

Insulation and cushioning materials as well as foam boxes, cups and meat trays for the food industry became popular.Vinyl chloride, discovered in 1835, provided for the further development of rubber chemistry. For packaging, molded deodorant squeeze bottles were introduced in 1947 and in 1958, heat shrinkable films were developed from blending styrene with synthetic rubber. Today some water and vegetable oil containers are made from vinyl chloride.Celluloid was invented during the American Civil War. Due to a shortage of ivory, a United States manufacturer of billiard balls offered a $10,000 reward for an ivory substitute. A New York engineer,John Wesley Hyatt, with his brother Isaiah Smith Hyatt, experimented several years before creating the new material. Patented in 1870, "celluloid" could not be molded, but rather carved and shaped, just like ivory.Cellulose acetate was first derived from wood pulp in 1900 and developed for photographic uses in 1909. Although DuPont manufactured cellophane in New York in 1924, it wasn't commercially used for packaging until the late 1950s and early 1960s. In the interim, polyethylene film wraps were reserved for the military. In 1933, films protected submarine telephone cables and later were important for World War II radar cables and drug tablet packaging.Other cellophanes and transparent films have been refined as outer wrappings that maintain their shape when folded. Originally clear, such films can now be made opaque, colored or embossed with patterns.One of the most commonly used plastics is polyethylene terephthalate (PETE). This material only became available for containers during the last two decades with its use for beverages entering the market in 1977. By 1980, foods and other hot-fill products such as jams could also be packaged in PETE.Current packaging designs are beginning to incorporate recyclable and recycled plastics but the search for reuse functions continues.

8.2 Packaging Machinery and Automation

Any finished consumer product of any value gets packaged in one of many different types of packages. It can be bags, boxes, cartons, SUPs, aseptic boxes, and more. None of these packages significantly improves the performance of the product inside, but the packaging does help the consumer understand the product,differentiate the product from the competition, and improve sales dramatically.

The packaging machinery focus in the early-to-mid-2000s was on new and diverse products to meet the individual needs and desires of the market. According to the Packaging Machinery Manufacturers Institute(PMMI), companies in 2003 wanted ''quick changeover capabilities,flexibility, and fast speeds'' more than any other features.Consequently, the industry was expecting continued growth to meet demands for newer and better packaging machinery, replacing older equipment with newer, faster,more efficient, and more automated machines. Trends toward lightweight, individually designed, flexible, and reusable packaging increased demand for the design of machines that could manufacture such packaging (Pearce,2005).

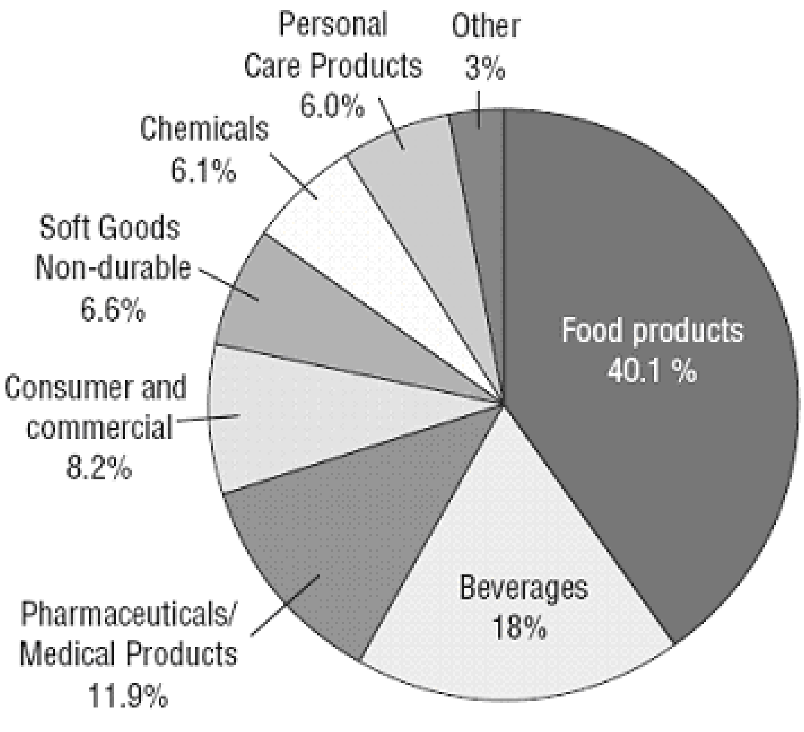


Figure 8.1 Packaging machines market shares(Market Share Reporter, 2004)

Packaging operations are one of the most important facets in effecting new product innovations, increasing speed-to-market and achieving sustainability goals. Properly selected and deployed packaging automation and innovative machine designs enable marketing,supply chain, sustainability and lean manufacturing strategies,and ensure customer satisfaction(Blanchard,2008).

Over the last 10 years, innovative packaging machine designs incorporating mechatronic solutions have inspired a culture of rapid innovation by packaging machinery builders that are break-ing barriers in design by combining functions once considered the domain of standalone systems. Now, integral robotics and purpose-built solutions can accommodate package designs and product mix in ways unachievable a generation ago.Automation technology and building blocks are in place for the next level of alignment of operations with business initiatives. Machinery designs allow for incremental increases in functionality, and builders are developing cost-effective ways to upgrade machines in the field when requirements change or there is a need for production flexibility. Some manufacturers consider this type of automation to be a luxury. However,progressive manufacturers consider TCO a requirement.In addition, packaging machinery automation systems that support the accurate collection and storage of real-time performance information, along with precise closed-loop machine control in critical aspects of the machine, are essential for operations management. For example, bottle-capping machinery using servo mechanisms delivers more precise torque control than machinery with traditional closed loop control techniques.Precise control combined with accurate data collection ensures continuous quality verification on every bottle.

Packaging line designs that utilize the improved capabilities of robotics are reinventing the status quo, and packaging machine builders and robotics suppliers are playing a major role in the buildup of highly flexible packaging lines. While robotic lines operate at a slower pace, their overall production output is often greater because robotic packaging lines are digitally reconfigurable and never need to stop for changeovers. Going forward, the industry challenge will be to determine the optimal combination of rapid changeover and slower robotic lines that create a balance with dedicated high-speed lines.While traditional six-axis and Cartesian robots have dominated end-of-line packaging operations, the Delta-style robot is the incipient robotic configuration being utilized for picking individual products, primarily due to its exceptional speed. Adept's Quattro parallel robot has taken the Delta concept one step further by using a four-arm rotational platform that achieves rotation without an extra telescoping joint. Both Adept's and Elau's robotic solutions are self-contained systems that incorporate embedded amplifiers and compact controls, consistent with the concept of modular machine design.The concept of integrating product design with the entire manufacturing process is now achievable with the implementation of highly flexible robotic packaging lines. In the future, digital designs of packages will drive digital reconfiguration of robotic packaging lines; robotics will add flexibility to add leaflets, gadgets or other types of promotional materials to late-stage packaging processes; and top-loading of cartons and wallet packs will be achievable, enabling end-users to tackle pressing customization demands.

8.3 Packaging Machines

Packaging can be defined as "the science, art and technology of enclosing or protecting products for distribution, storage, sale, and use". Packaging also refers to "the process of design, evaluation, and production of packages".

Packaging can be regarded as different types. The single item such as a bottle containing soft drink can be regarded as the item that a consumer would purchase known as "primary" packaging. Where as a pack of bottles, shrink wrapped, would be regarded as the transport package used within the distribution chain is known as "secondary" packaging.

Primary packaging is the material that first contains the product. This is usually the package which is in direct contact with the contents. For example, this could be a bottle or carton for liquids; or a packet for various snack foods.

The secondary packaging is outside the primary packaging, perhaps used to group primary packages together. For example, this could be a tray and shrink film.

Secondary packaging is mainly used as a means of transporting the primary packs or product from producer to retailer. This is usually removed and recycled once the pack has reached its destination. Secondary packaging can also be retained to enable the product to be purchased in bulk.

The choice of packaging machinery for primary & secondary packaging can depend on various situations. These can include available budget, payback period, integration, associated running costs, machine technology and available floor space.

Packaging machines can be of the following general types given below(PPMA,2009):

8.3.1 Cartoning

Cartoning machines are packaging systems which erect, close and/or erect, fill and close carton blanks or folded and side seam sealed cartons.

Cartons are one of the commonest forms of packaging. But while they almost all end up in a regular six-sided square or rectangular shape there are a number of different styles which are dictated by the filling and closing method. For example, some cartons are filled and closed via the end flaps; others are filled vertically and closed with a fold over 'lid'. Other important differences include the means of securing the carton in its erected form. Some are glued using adhesive; others have pre-cut tabs and slots, or are pre-coated with a heat sensitive material. Some applications use window cartons - a carton with a pre-cut area behind which transparent film has been fixed to allow the contents to be viewed.

Cartoners which erect, fill and seal on one machine are sometimes called Carton Form, Fill, Seal machines.

Some cartoning machines and systems are patented like the Tetra Brik and "Combibloc" for liquids which can only be produced on those companies' machines, while other patented designs like 'crashlock' cartons can be automatically erected on a wide range of machines.

Cartons are made from cartonboard which is a semi-flexible paper material 250µ to 1,000µ in thickness. They should not be confused with Cases which are made from rigid corrugated board and are larger, often containing a number of cartons for transit.

Cartons can come in the form of blanks, which are flat, pre-printed and cut to size and shape, with slots and tabs pre-cut if necessary. These are then folded or 'erected' to form the carton in the machine.

However the majority of cartons are delivered folded and side seam sealed to form what is sometime known as a skillet. On the cartoning machine these skillets are erected and then filled with product before the end flaps are folded and closed.

To add something extra to presentation, cartons come in a wide variety of shapes including hinged lids, triangular, hexagonal, octagonal, double-wall, frame-wall, wave-shaped cartons; and tapered trays.

At their simplest cartoners can be semi-automatic machines which close the flaps of manually erected and filled cartons at low speeds, but at their most sophisticated cartoners are fully automatic machines incorporating pick-and-place product loading or stacking devices, leaflet inserters and coding devices and run at several hundred cartons a minute.

Modern cartoners have benefited from the introduction of servo driven subassemblies, programmable logic controllers and even computers which allow the machines to be size changed automatically and synchronised using software rather than mechanical transmission components. However all these features come at extra cost and often a combination of old and new technology can achieve the desired performance.

Cartoning machines are used in all fast moving consumer goods sectors but especially food, pharmaceutical, toiletry, cosmetic, household products, and DIY and recorded media industries.

Cartoning machines are particularly important in the non-carbonated beverages industry but it is important to recognise that while the Combibloc carton is produced on a variant of a mandrel cartoning machine the apparently similar Tetra Brik cartons are produced on special vertical form fill and seal machines.

8.3.2 Cleaning

Machines which clean, sterilise, pasteurise, cool or dry containers or filled packages.

8.3.3 Closing

Packaging machines which seal or close filled packages.

8.3.4 Coding and Marking

Machines which apply a code, (including bar codes), dates and other variable or unique information to a package or transit container. There are two basic methods: contact or non-contact; and programmable and non-programmable.

There is a whole range of machines and equipment carrying out these functions, from simple mechanical stamps or overprinters to sophisticated ink jet and laser coders applying computer generated data. These machines are usually attached to a larger packaging machine such as a cartoner, filler or wrapper.

Modern *ink jet* and *laser coders* can be programmed to carry a large amount of variable information such as lot number, date code; sequential coding based on a unique serial number which is recorded in a secure database. A range of styles, typefaces and character sizes can be used and changed easily especially in comparison with older mechanical devices.

Sophisticated software means coders can be programmed to create a different mark for every product to create a track-and-trace feature on a pack. This helps to prevent counterfeiting. Track-and-trace features can also be used to ease product recall, monitor product quality and track products internally. Examples include sequential or non-sequential codes, a covert code or a machine-readable code.

Both small and large character ink jet coding machines are available. The former tend to be used for individual pack information and can be effective at high speeds, such as drink can lines. The latter tends to be used in warehousing and distribution on transit packages and pallets.

8.3.5 Conveyors

Conveyors are machines and equipment which carry ingredients, products, containers, packs or packaging components from one place to another.

There are a large number of different types of conveyor, designed to convey different types of product or to perform particular tasks. They can be divided into four main groups:

- Conveyors for bulk products e.g. powders or free flowing solids
- Conveyors for both bulk products and small unit loads
- Conveyors for small unit loads e.g. bottles or cartons
- Conveyors for large unit loads e.g. pallets or kegs

In their simplest form conveyors are mechanical assemblies which can be demountable and easy to move. In their most sophisticated form conveyors can be complex machines with drives, controls and sensors. In this form they undertake complex tasks or those needing highly accurate sorting, ordering or distribution of the items or products being conveyed.

Common forms of belt and slat band conveyors are used for all types of semi-automated or automated processing and packaging functions. They facilitate different requirements during production, and enable different products and packaging functions to be handled.

Some machines, such as large bakery ovens, include conveyors as part of the process, while high speed wrapping machines require in-feed and out-feed conveyors to be built in to operate at the speeds required.

Different consistencies of products, (soft, delicate, sticky, hot, chilled, frozen), require different handling techniques and so different designs of conveyor. The ability to clean conveyors is an important requirement particularly in food or pharmaceutical plants where rigorous clean-in-place and wash-in-place regimes exist. These conveyors are often made of wire mesh, plastic mesh or stainless-steel and some can be dismantled or moved for ease of cleaning.

Packaging containers and components also need to be sorted or orientated, combined, indexed or unscrambled prior to being presented to the packaging machine, or to bring products packed on different lines together and specific types of conveyor have been designed to achieve all of these functions.

8.3.6 Filling

Filling and dosing machines are packaging machines which measure out a product from a bulk supply by some predetermined value, e.g. volume, level in a container, mass or count. The filling method used is influenced largely by the nature of the product e.g. liquid, gas, piece goods, powder, free flowing solids or sticky paste, but also by the measure for selling the product e.g. by weight, by volume or by count.

However, it does not necessarily follow that products which are sold by volume have to be measured by volume, for example oils which are sold by volume are frequently filled by weight because the density of the oil varies significantly with temperature; conversely products like rice or frozen peas which are sold by weight may actually be filled by volume because this can be done at higher speed and lower cost. In fact it is not uncommon for products sold by count to be filled by weight.

Filling machines may comprise of one or a number of dosing devices that may be arranged with or without a mechanism to control containers or packages as they are filled.

Fill & Seal machines undertake the filling function as described above, but incorporate a sealing mechanism to close the container in a variety of ways (see Sub Pages). These machines are distinguished from Form Fill and Seal machines (see Form Fill Seal Pages) in that they fill and seal pre-made packages or containers. A separate Page covers dedicated Closing machines.

Volumetric and level filling is typically associated with liquid or gas products, but a whole range of products also use this technology including dry products such as powders and granules, pet foods, through to semi-liquids such as gels and pastes, or even products which are normally solid at room temperature like fats, lipstick and stick deodorants.

Different methods of filling have been developed not only to accommodate the different characteristics of the product but also to achieve various accuracies of fill, because while for a low value product there may be no incentive to fill more accurately than the statutory requirements, for high value product increased accuracy can represent a considerable saving in product "giveaway".

The filling of powders and free flowing solids poses particular problems because of the generation of dust and variations in bulk density. Very dusty products are typically filled using auger fillers or vacuum fillers, but where the bulk density of product varies significantly it will usually be necessary to combine this with a weight correction mechanism like a checkweigher because typically these products are sold by weight.

The filling of carbonated drinks like soft drinks or beer and products like liquid detergents which have a tendency to foam also poses significant problems which are typically solved using a technique called "bottom up filling", where the filling nozzle is inserted into the container and slowly raised during the filling process so that the mouth of the filling nozzle is always kept below the level of the liquid.

At their simplest filling machines can be single head bench mounted devices that are manually operated and at their most sophisticated rotary fillers which can incorporate scores of filling heads and be able to fill and seal thousands of cans every minute.

The two most common arrangements of fillers with multiple filling heads are 'in line' where the filling heads are fixed and containers are moved under the heads and then removed when filled in an intermittent process, and 'Rotary' where several filling heads are mounted on a rotating carousel and containers are fed onto the carousel, filled and then discharged continuously.

Figure 8.2 A filling operation

Some weigh filling machines for filling liquids like oils look remarkably similar to their volumetric or level equivalent, however, large machines for filling sacks or bags have little physical resemblance to liquid fillers, but the techniques of weighing, dosing or counting, etc, remain broadly similar.

Fill & Seal machines are specific to a particular type of container or package but can incorporate different types of filling heads and different closing mechanisms depending on the type of closure or method of closing the package e.g. cap, cork, heat seal, crimp or fold.

8.3.7 Food Processing

Can be defined as "the set of methods and techniques used to transform raw ingredients into food for consumption by humans or animals".Common food processing techniques include:

- Removal of unwanted outer layers, such as potato peeling or the skinning of peaches
- Brine mixing & storage equipment
- Chopping or slicing e.g. diced carrots.
- Mincing and macerating
- Liquefaction, such as to produce fruit juice
- Fermentation e.g. in beer breweries
- Emulsification
- Cooking, such as boiling, broiling, frying, steaming or grilling
- Deep frying
- Baking
- Mixing
- Addition of gas such as air entrainment for bread or gasification of soft drinks
- Proofing
- Spray drying
- Pasteurisation

When designing processes for the food industry the following performance parameters may be taken into account:

- Hygiene, e.g. measured by number of micro-organisms per ml of finished product
- Energy consumption, measured e.g. by “ton of steam per ton of sugar produced”
- Minimization of waste, measured e.g. by “percentage of peeling loss during the peeling of potatoes'
- Labour used, measured e.g. by ”number of working hours per ton of finished product”
- Minimisation of cleaning stops measured e.g. by “number of hours between cleaning stops”

8.3.8 Form Fill Seal

Form Fill Seal (FFS) machines are packaging machines that form fill and seal a package on the same machine.

The main types are vertical form fill seal (VFFS) and horizontal form fill seal (HFFS) machines – a term often used in the market place to cover horizontal versions of flow-wrappers, sachet machines, blister pack machines, four side seal machines and thermoform fill and seal machines.; in both cases packaging material is fed off a roll, shaped, and sealed. The bags/packs are then filled, sealed and separated.

Today many FFS systems are highly sophisticated featuring computer interfaces and control networks. Greater speed and versatility are the major benefits of FFS systems for user companies. For example snack producers demand systems that have the versatility to provide fast changeover between many different packaging formats to meet growing demand for single serve packs. Here VERTICAL FFS is capable of creating virtually any size or shape ranging from the standard pillow pack to bags sealed on all four sides.

The multiplicity of FFS machines employ a wide range of material types and are used across numerous markets including food, drinks, cosmetics, electronics, stationary, tobacco, chemical, medical, and pharmaceuticals.

Form fill seal machines are often divided into the types of packs they produce:

- Bags and Pillow packs:flow-wrapper; lower reel flow-wrapper; vertical form fill and seal; stickpack machines; mandrel form fill seal.
- Bottles/vials :blow fill seal.
- Cartons :vertical carton board form fill seal.
- Pots trays and blisters :cold form fill seal; thermoform fill seal; blister form fill seal.
- Sachets and Envelopes:edge seal machine; horizontal form fill seal; vertical sachet form fill seal.
- Sacks and Bags:tubular sack form fill seal and vertical form fill seal.

However, each type is introduced individually on the following pages to ensure that browsers are able to access information on easily.

Products commonly associated with form/fill/seal include:Crisps; Nuts; Sugar; Rice; Pulses; Sweets & Confectionery; Sauces & Soups; Pet Foods; Grain; Jams & Preserves; Cakes; Bread; Biscuits; Tea Bags; Condiments; Tablets, Capsules and Pills, Greetings cards; Phone cards.

8.3.9 Handling

Packaging machines which arrange, dispense or accumulate packages or packaging components.

8.3.10 Inspection

Inspection Machines are a series of machines including manual, mechanical and computerised electronic systems which inspect products, packages or packaging components to ensure they conform to specification. For example colour, size, mass, the presence of foreign bodies in a product or package, pack integrity, missing labels or items, or incorrect data; any items which fall outside the pre-set values are rejected.

The most common forms of inspection machines are *checkweighers* and *metal detectors* but the range of inspection equipment available has grown hugely in recent years driven by the need to automate production and to remove the people from the line who as well as carrying out manual tasks also inspected products and packs visually.

Advances in technology have also increased the range of inspection tasks which can be performed. For instance while conventional metal detectors were limited to detecting ferrous metal, using different technologies it is now possible to detect bone, glass, wood, fibres and most non-ferrous metals in products as well.

Verification of the weight of a filled package using a checkweigher is an important legal metrology process but in addition the checkweigher may be an integral part of a labelling or product filling system.

Other inspection machines carry out functions such as checking pack integrity for leaks, checking fill levels and even checking the temperature of a product in the pack without destroying the pack.

Inspection machines are used in all end user sectors, including food, beverage, pharmaceutical, toiletries & cosmetics, and household chemicals. Some kinds of inspection are more common in some sectors than others or even unique to a particular industry (for example missing or broken pill detectors in the pharmaceutical sector).

In the pharmaceutical industry a range of inspection systems have also been developed to check that batch codes are present and legible and to check that every packaging component is correct for the product being packed.

Inspection is also undertaken in many sectors outside the mainstream areas of use, for example, the garment industry is a major user of detection equipment for pre-packed items such as shirts.

8.3.11 Labelling

Labelling Machines apply labels and decoration onto all types of packaging containers, display, point-of-sale and transit packs.

Labels are used on every kind of product to brand, decorate or provide information for the consumer. Many labels do all three functions and can contain, for example, pre-printed bar codes supplying, batch, stock and price information to the retailer and consumer.

Other machines provide print on demand and weigh/price labels, usually for fresh or perishable products where the weight of item varies from pack to pack or for transit purposes. Many of these labels are printed and applied in the store or warehouse.

Labels are also used to provide protection against tampering (tamper evident) to ensure the product reaches the consumer without interference and unopened. Sleevers or sleeving equipment that apply a sleeve of thermoformable or stretch material to the neck or body of the container, are generally used to apply tamper evident labels. Shrink sleeve labels are also used on products which do not have surfaces suitable for a conventional label.

A growing market is security labelling to counter fraud and theft, and give brand protection and authentication. These include RFID and smart labels, holographic labels, tamper evidence, counterfeit deterrence and source tagging. Other machines are used to apply Leaflet labels – multi-page labels that provide space for large amounts of consumer information e.g. in pharmaceutical applications.

Figure 8.3 A labelling operation

Other types of labelling include in-mould labelling a technique that applies labels to blown bottles, injection moulded containers, and thermoform fill seal machines for yoghurt pots as they are formed on equipment.

There are two principal types of labelling machine: Wet Glue and Pressure Sensitive (Self Adhesive) applicators.

8.3.12 Packing

Packaging machines which group together a collation of products for transit purposes. Group packages include cases, trays, crates and cartonboard sleeves.

8.3.13 Palletising & Depalletising

Pallet Forming, Dismantling and Securing machines are packaging machines that assemble or dismantle pallet loads of products, groups of packages or rigid containers on a pallet, with little or no manual intervention, and secure the load on the pallet for security and stability during transportation.

Modern warehousing and distribution methods mean just about every sector uses pallets for storage and transport of their products. It is now common to see bricks and sacks of sand and cement being transported to their point of use on a pallet secured by a plastic film stretched or shrunk around the load.

A recent application for this type of machinery has been to form the retail-ready pallets, mini-pallets and dollies which supermarkets are now demanding for fast-moving product lines not only to minimize the use of transit packing materials but also reduce the amount of labour needed in store to prepare products ready for sale.

Just as technology has been developed to load and secure pallets in high volume environments, machines to de-palletise or unload full pallets of rigid containers or crates have also been developed to automate the front of end of production lines.

For safety, brand image, security and weather protection reasons, various kinds of pallet load securing systems have been created. So, for example, corrugated cases of whisky or other high value spirits are secured by an all-enveloping film of plastic material, including a top sheet to make it as hard as possible to break into the load and to ensure that products are not spoiled if they are left out in the rain; while other, less valuable and more durable products can be secured by a simple horizontal strap.

8.3.14 Pharmaceutical Processing

Cosmetic processing and packaging is market driven and therefore demands for high quality products and packaging is high.As batch runs have been exhausted to their optimum, flexible process parameters are needed to meet the latest processing trends. The combination of vessel and agitator system developed by various manufacturers offer high productivity, quality and yield.As well as the processing units themselves, deaerators, heat exchangers, mills and continuous manufacturing plants are also part of the primary processing line.Processing lines will always contain the basic requirements of filling, labelling, packing and palletising. Incorporated into the processing lines will be inspection at varying stages plus associated services such cleaning.

Aerosols are a dispensing system which creates a mist of liquid. An aerosol can contain a liquid under pressure or can be operated mechanically by hand.Aerosol processing machines can be single station, automatic indexing machines or automatic rotary machines. All processing machines also require a crimping section.

The compressed *tablet* is the most popular way of supplying dosages. Tablets can be made into virtually any shape but the most common are round or oval in shape that are easy for a patient to swallow.It is important that during the tablet pressing process, all ingredients are dry and are of a uniform grain size. There are two basic techniques used to prepare powders for granulation into tablets; wet granulation and dry granulation. Powers that are mixed well don't require granulation and therefore can be compressed into a tablet by Direct Compression.Tablet coating is the last stage and is carried out to protect the tablet from temperature and humidity and to hide the taste. The most common forms of tablet coating are sugar & film coating.

8.3.15 Wrapping

Wrapping Machines wrap a flexible packaging material, (e.g. paper, aluminium, plastic film), around a product or group of products. Other common descriptions of this style of packaging are Flow-wrapping, Overwrapping and Horizontal Form Fill Seal.

There are many distinct styles of wrapping and these are described in the sub-pages below. A major application is in the field of shrink wrapping where heat is applied by various means to a thermoplastic material already loosely wrapped around the product or group of products, which then shrinks around them to form a tight wrap. This method is often used for transit wrapping and protective packaging of larger item such as doors or even bricks on a pallet.

Because wrapping is so versatile it is used in many sectors, however, it is most common in food, bakery and confectionery for single items which can range from confectionery (count line), bars and cakes through to cheese and sausages.

There are so many applications of this packaging technique for single items it would be difficult to exclude any particularly for some products in daily use items, DIY or toiletries and cosmetics. Some techniques are used in very particular product areas e.g. skin packaging for DIY products and high quality fold wrapping for cosmetics, CDs or cigarettes.

Many single item wrappers can handle products at very high speeds, particularly in the confectionery sector.

When wrapping is used for larger items or units or for grouping single products in multipacks for point of sale, or in larger numbers for transportation, then speeds tend to be slower. However some applications in the beverage sector can achieve reasonable speeds to match demand from the speed of other machines in the line.

Machines have been specifically designed to wrap very large items and pallets for both protection and security reasons. These have found many applications in the building and beverage industries, but can be used in many other sectors.

These machine types are very general indeed. Each area or sector of packaging equipment can be expanded upon to reveal the various applications that are available today.

As technology advances, packaging machines are becoming more and more advanced to not only meet the current demands but to try and "future proof" the packaging equipment and product development within an organisation. This can have a bearing on machine costs plus the interchangeability of operators and training.

Packaging machines can be integrated into an existing line. For example, a new labelling machine within an existing line. Interfaces between new and old machines have to be considered as well as ingress and egress routes for the equipment. Downtimes of the line and surrounding lines should also be taken into account.

From single machines, as just discussed, to small systems or complete lines containing more than one new or existing / reconditioned packaging machines can be installed. Depending on the size of the installation, project management methods should be employed.

CHAPTER NINE
DESIGN OF AN AUTOMATED PACKAGING MACHINE

9.1 Concept for the Automated Process

The automated process that the machine performs can be reviewed as: Take the part(can be regarded as egg,chocolate, etc.) which is the subject of the packaging from 1(designed as a rotary/indexing table), place it to the suitable locations on 2(the package) and transfer the package when completely filled to 3.

The designed machine can be thought as a stand-alone automated system due to the the function it performs, but actually in an industrial environment it will be a sub-system of a packaging solution due to the fact that the feeding(e.g. a conveyor) and related transfer mechanisms(after 3) for the part and the package did not designed and integrated.

The weight of the packaged part is taken as *0.25 kg* and space limitation is *0.5x0.5x0.5 m* as *widthxlengthxheight*.

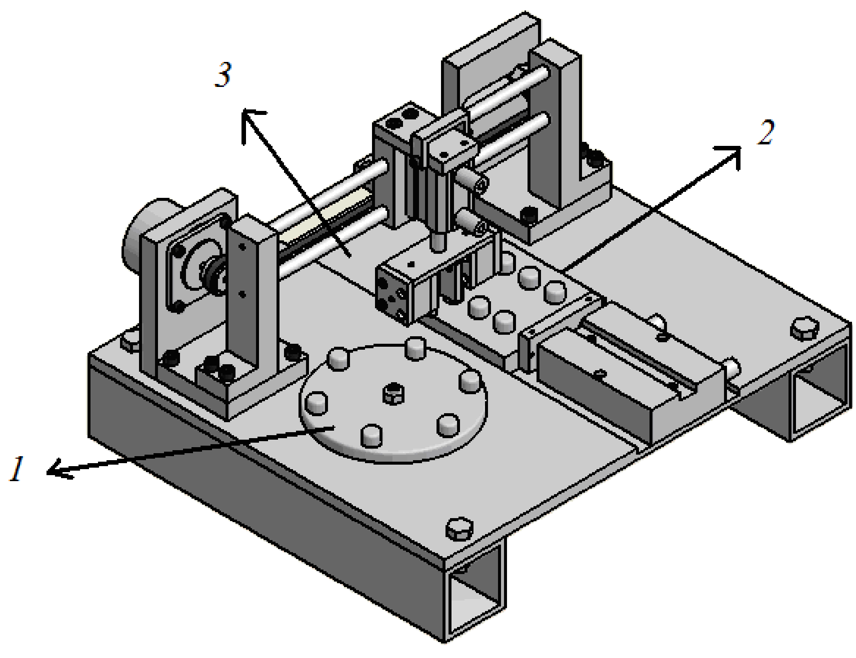


Figure 9.1 Designed CAD model for the packaging machine

9.1.1 Benefits

The advantages(so expectations) from automated systems have given in previous chapters. All of these previously stated factors are important but generally speaking the most will be the cost factor especially for the customer who will be the target of the automation systems solution providers,so first of all the cost advantages should be analysed and reported.

Roughly the cost of packaging operation can be approximated with the equation below

$$C_{asm} \cong \alpha . t + \frac{\beta}{n} \tag{9.1}$$

where

C_{asm}(€/package):Cost of one package
α(€/sec):Unit time cost of labour/machine
t(sec):Time for one package packaging
β(€):Investment cost for the machine
n:Number of packages which expected to be packaged during the assumed machine life-time

For the manual operation case:

$$\alpha = \frac{400}{60.60.8.24}.10 = 5.78.10^{-4}$$
$$t = 10$$
$$\beta \cong 0$$

Here 400 € taken for labour salary and assumed that he/she can package one package in 10 seconds.

For the automated case:

$$\alpha = 0.072.\frac{1}{60} = 0.0012$$
$$t = ?$$
$$\beta \cong 1000$$
$$n = \frac{60.60.8.24.12.3}{t} \cong \frac{25.10^6}{t}$$

Here an "educated guess" routed for power supply capacity and 24 Volt DC/3 A thought will be appropriate. The power need will be 0.072 kW. 1 € taken as the electric kW.h cost. The selling price will be the investment cost for the customer and taken as 1000 €. Finally the assumed machine life-time is 3 years.

The target operation time for one package can be derived from the formulae given below

$$0.0012.t + \frac{1000.t}{25.10^6} \leq 5.78.10^{-4}.10 \quad \rightarrow t \leq 4.66 \text{ sec}$$

If the design based on the operation time for 3 seconds, the customers cost benefits can be analysed as given in the table below. Annual production of packages will be approximately 8 million for the automated case.

Table 9.1 Cost benefits

	Manual case	**Automated case**	**Benefit**
One package cost	$5.78.10^{-3}$ €	$3.72.10^{-3}$ €	$2.06.10^{-3}$ €
1th year(8 million package)			16480 €
2nd year			32960 €
3th year			65920 €

The payback period will be (1000/16480) approximately 22 days.

9.1.2 Goals

The performed analysis in the previous section would be the "ideal" basis for further design efforts if it were an real industrial application, but this chapter actually aims to show a design approach which is demonstrating the integration process of the automation system components for a real life situation, so in further sections, the design efforts will be performed for the target operation time of 3 minutes for a package.

9.1.3 Duty-cycle

Duty-cycle operation sequence can be given below that based on the fact that a package which contains 6 parts will be packaged in 3 minutes.

0-Take the head above the rotary table
5-Lower the head cylinder
10-Close the gripper(part no 1)
15-Lift the head cylinder
20-Take the head above the package
25-Lower the head cylinder
30-Open the gripper(packaged part no 1)
35-Lift the head cylinder
40-Feed the 2nd part with rotary table

45-Take the head above the rotary table
50-Lower the head cylinder
55-Close the gripper(part no 2)
60-Lift the head cylinder
65-Take the head above the package
70- Lower the head cylinder
75-Open the gripper(packaged part no 2)
80- Lift the head cylinder

85-Feed the package to the 2nd section with cylinder on plate

90-Feed the 3th part with rotary table

***

95-Take the head above the rotary table

100-Lower the head cylinder

105-Close the gripper(part no 3)

110-Lift the head cylinder

115-Take the head above the package

120-Lower the head cylinder

125-Open the gripper(packaged part no 3)

130-Lift the head cylinder

135-Feed the 4thd part with rotary table

140-Take the head above the rotary table

145-Lower the head cylinder

150-Close the gripper(part no 4)

155-Lift the head cylinder

160-Take the head above the package

165- Lower the head cylinder

170-Open the gripper(packaged part no 4)

175- Lift the head cylinder

180-Feed the package to the final section with cylinder on plate

185-Feed the 5th part with rotary table

***

190-Take the head above the rotary table

195-Lower the head cylinder

200-Close the gripper(part no 5)

205-Lift the head cylinder

210-Take the head above the package

215-Lower the head cylinder

220-Open the gripper(packaged part no 5)

225-Lift the head cylinder

230-Feed the 6th part with rotary table

235-Take the head above the rotary table

240-Lower the head cylinder

245-Close the gripper(part no 6)

250-Lift the head cylinder

255-Take the head above the package

260- Lower the head cylinder

265-Open the gripper(packaged part no 6)

270- Lift the head cylinder

275- Take the head above the rotary table

There are 58 operations for duty-cycle of the automated system. So, an operation will be performed approximately in 3 seconds. The final/actual values for every operation will be determined after a calibration process that will be based on the engineering calculations and experimental studies on the assembled system.

9.2 Components for "Hard" Tasks

Components for "hard" tasks refers to the components that have a direct relationship with the physical process/procedure which is the subject of the automation.

9.2.1 Actuators selection

Chasis and related machine elements can be designed/selected only after the selection of the appropriate actuators for the system. So first of all we selected the actuators based on the related concepts and calculations given below.

A step motor with a *timing belt* selected for the head which is holding the gripper and allowing the linear motion. For selection,motor power capacity should be determined.

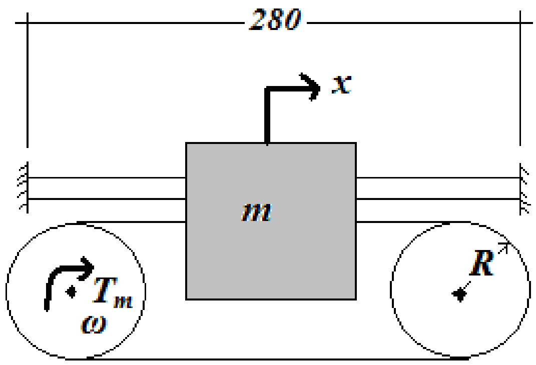


Figure 9.2 Model for the head linear motion

Equivalent inertia at motor shaft can be determined with the Lagrange method.

$$\frac{1}{2}.J_{eq}.\omega^2 = \frac{1}{2}.J_m.\omega^2 + \frac{1}{2}.m.\omega^2.R^2 \tag{9.2}$$

$$J_{eq} = J_m + m.R^2$$

$$T_m = J_{eq}.\alpha + T_f \tag{9.3}$$

With assuming a trapezoidal velocity profile for the head will as given below

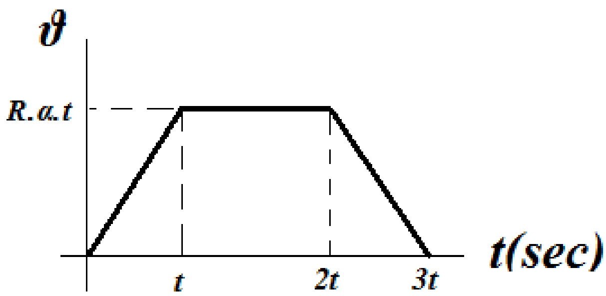


Figure 9.3 Trapezoidal velocity profile for the head's linear motion

$$x(t) = 2.(\frac{1}{2}.R.\alpha.t^2) + R.\alpha.t^2 = 2.R.\alpha.t^2 \quad (9.4)$$

By taking *x=140 mm*, *R=20 mm* and *t=1.5 sec*

$$\alpha(rad/sn^2) \cong 1.5$$

With assuming $J_m \cong 0$ and *m=2.5 kg* with pneumatic cylinder, gripper and related holding elements and Coulomb friction coefficient *μ=0.2*.

$$T_f(Nt.mm) = R.F_f = 20.(0.2.25) = 100$$

$$T_m(Nt.mm) = (2.5.20^2).1.5 + 100 = 1000.1.5 + 100 = 1600 \rightarrow T_m = 1.6 \text{ Nt.m}$$

$$\omega_{\max}(rad/sn) = \alpha.t = 1.5.1.5 = 2.25$$

$$P_m(W) = T_m.\omega_{\max} = 1.6.(2.25) = 3.6$$

We have selected a 6V/1 A stepper with a resolution of 1.8 deg/pulse and selected driver current capacity is max 0.5 A. Due to this fact, the available power will be 3 W. So the times for head's movement will be reconfigured and overall system's duty-cycle will be tuned according to this situation.

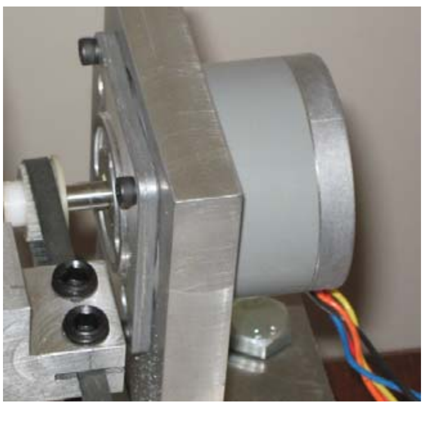


Figure 9.4 Selected step motor for the head's linear motion

A step motor selected for the rotary table which is functioning as the part feeder. For selection, motor power capacity should be determined as in the previous section.

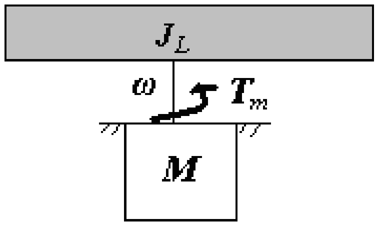


Figure 9.5 Model for the rotary table

Equivalent inertia at motor shaft can be determined with the Lagrange method.

$$\frac{1}{2}.J_{eq}.\omega^2 = \frac{1}{2}.J_m.\omega^2 + \frac{1}{2}.J_L.\omega^2 \tag{9.5}$$

$$J_{eq} = J_m + J_L$$

$$T_m = J_{eq}.\alpha + T_f \tag{9.6}$$

With assuming a trapezoidal velocity profile for the head will as given below

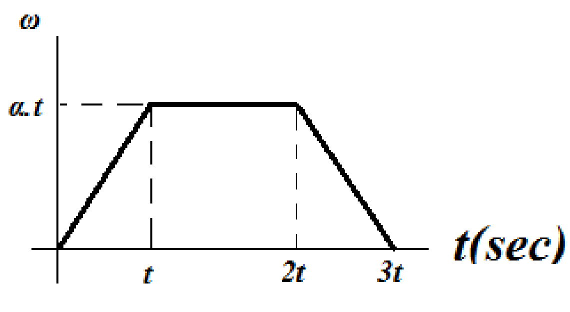


Figure 9.6 Trapezoidal velocity profile for the rotary table

$$\theta(t) = 2.(\frac{1}{2}.\alpha.t^2) + \alpha.t^2 = 2.\alpha.t^2 \tag{9.7}$$

By taking $\theta=2.\pi/6$ *rad*,*R=20 mm* and *t=1.5 sec*

$\alpha(rad/sn^2) \cong 0.25$

With assuming $J_m \cong 0$ and the Coulomb friction is zero.

$$J_L(kg.mm^2) = \frac{1}{2}.m.r^2 = \frac{1}{2}.(\frac{\pi}{4}.130^2.10.10^{-9}.2700).65^2 = \frac{1}{2}.(0.35).65^2 \cong 740$$

$$T_f(Nt.mm) \cong 0$$

$$T_m(Nt.mm) = (740).0.25 = 185 \rightarrow T_m = 0.2 \text{ Nt.m}$$

$$\omega_{\max}(rad/sn) = \alpha.t = (0.25).1.5 = 0.375$$

$$P_m(W) = T_m.\omega_{\max} = (0.2).0.375 = 0.075$$

We have selected a 24V/0.18 A stepper with a resolution of 7.5 deg/pulse and selected driver current capacity is max 0.5 A. Due to this fact,the available power will be 4.32 W. The times for head's movement will be reconfigured and overall system's duty-cycle will be tuned according to this situation.

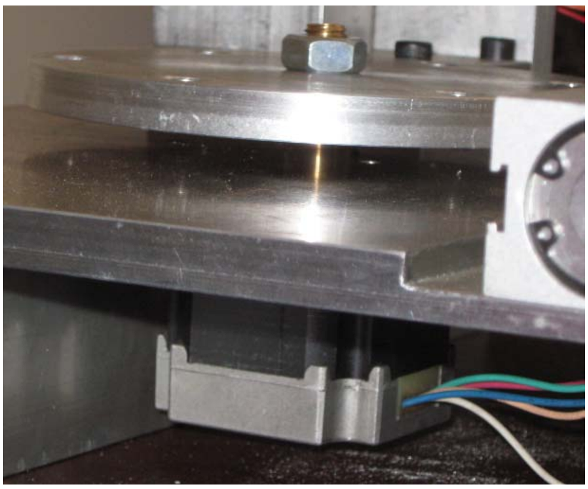


Figure 9.7 Selected step motor for the rotary table

A pneumatic cylinder selected for the package linear motion and finally transfer to 3. For selection, cylinder and rod diameters should be determined.

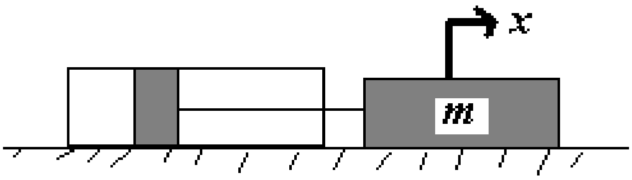


Figure 9.8 Model for the pneumatic cylinder

$$F = m.\ddot{x} + T_f \qquad (9.8)$$

By taking *m=0.5 kg* and Coulomb friction coefficient *μ=0.2*. Supplied pressure(*p*) will be *6 bar* as an industrial standart. Linear acceleration *a* taken as *1 m/sn*^{2}.

$$F = (0.5).1 + 5.(0.2) = 1.5$$

$$1.5 = p.A = p.(\frac{\pi}{4}.D^2) = (0.6).(\frac{\pi}{4}.D^2)$$

→ $D \cong 2\ mm$

So, Ø25/Ø111, Strok=50 mm double-acting pneumatic cylinder selected.

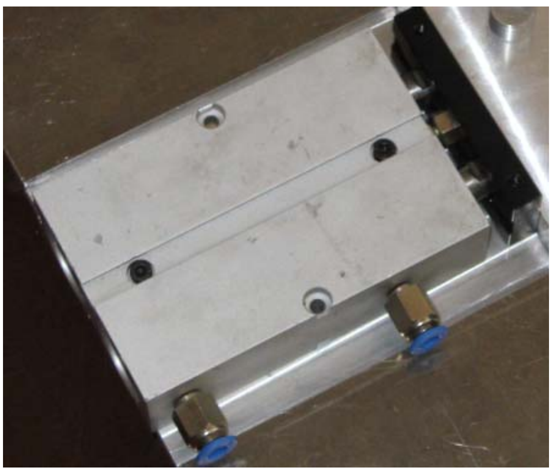


Figure 9.9 Selected pneumatic cylinder for package linear motion

A pneumatic cylinder selected for horizontal motion of the gripper on the linear head. For selection, cylinder and rod diameters should be determined.

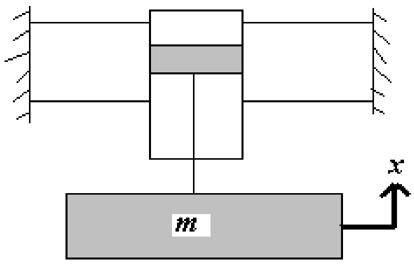


Figure 9.10 Model for the gripper holding cylinder

$$F = m.\ddot{x} + m.g + T_f \qquad (9.9)$$

By assuming *m=1 kg* and Coulomb friction zero. Linear acceleration *a* taken as *1 m/sn*^{2}.

$$F = 1.1 + 1.(9.81) \cong 11$$

$$11 = p.A = (0.6).(\frac{\pi}{4}.D^2)$$

$$D = 4.83\,mm$$

So,Ø20/Ø10,Strok=25 mm double-acting pneumatic cylinder selected.

Figure 9.11 Selected pneumatic cylinder for gripper holding

9.2.2 Gripper Design

Parts that will be packaged should be taken from the rotary table and located on the package. This task needs a mechanism that allows picking and placing. So a pneumatic gripper designed for the task, and related concepts and calculations are given below.

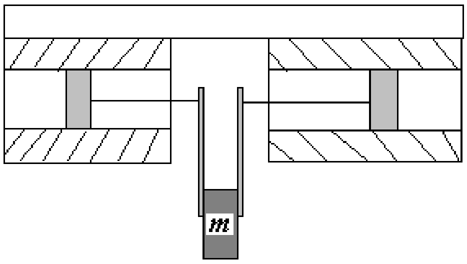


Figure 9.12 Model for the designed gripper

$$F_f = m.g = 2.\mu.N = 2.\mu.p.A \tag{9.10}$$

With taking *m=0.25 kg*, and Coulomb friction *μ=0.2*.

$$F_f = 0.25.(9.81) = 2.(0.2).(0.6).(\frac{\pi}{4}.D^2)$$

$$D = 3.6\,mm$$

So, two Ø12/Ø8, Strok=7 mm double-acting pneumatic cylinders based gripper designed to allow to pick-and-place mechanism.

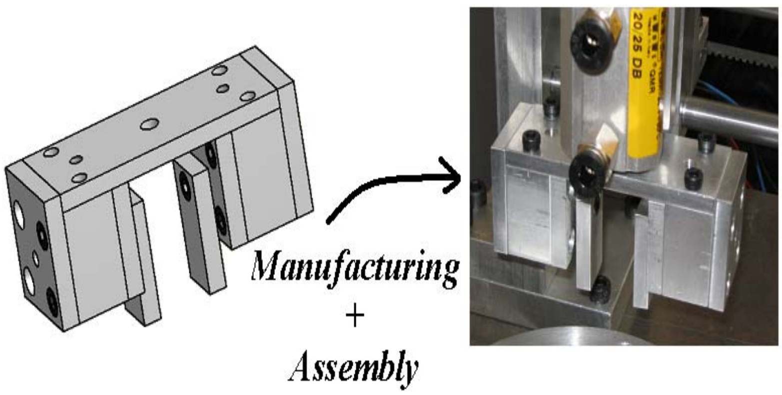


Figure 9.13 Designed gripper for the application

9.2.3 Pneumatic system

The pneumatic actuators and the gripper needs a pneumatic system that will allow the functions which the system should route. Related circuit and valve images are given below.

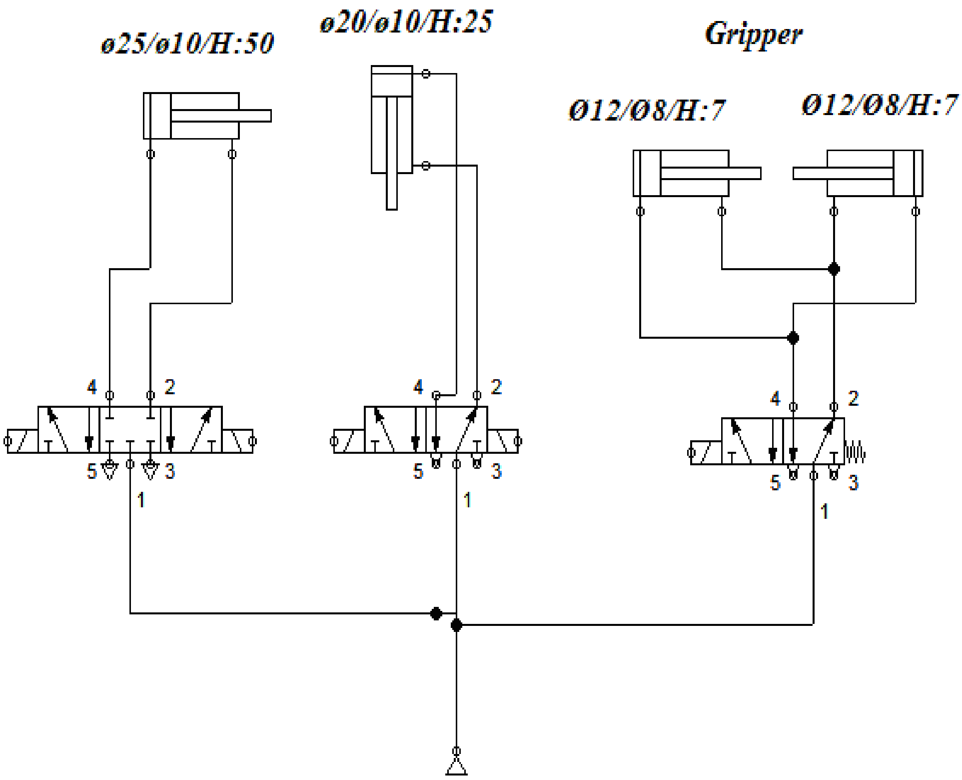


Figure 9.14 Pneumatic system's circuit diagram

Figure 9.15 Selected pneumatic valves for the application

9.2.4 Chasis and related machine elements design

Chasis and related machine elements can be designed/selected due to the fact that all the actuators and related sub-systems have determined. Chasis and related machine elements should be designed first of all based on the safety. So, for the selected critical elements stress analysis are performed that the concepts and calculations are given below.

Shafts that are holding and allowing the head which includes the gripper and related parts to slide should be dimensioned based on the stress analysis. Selected material is Ck45 chromed steel.

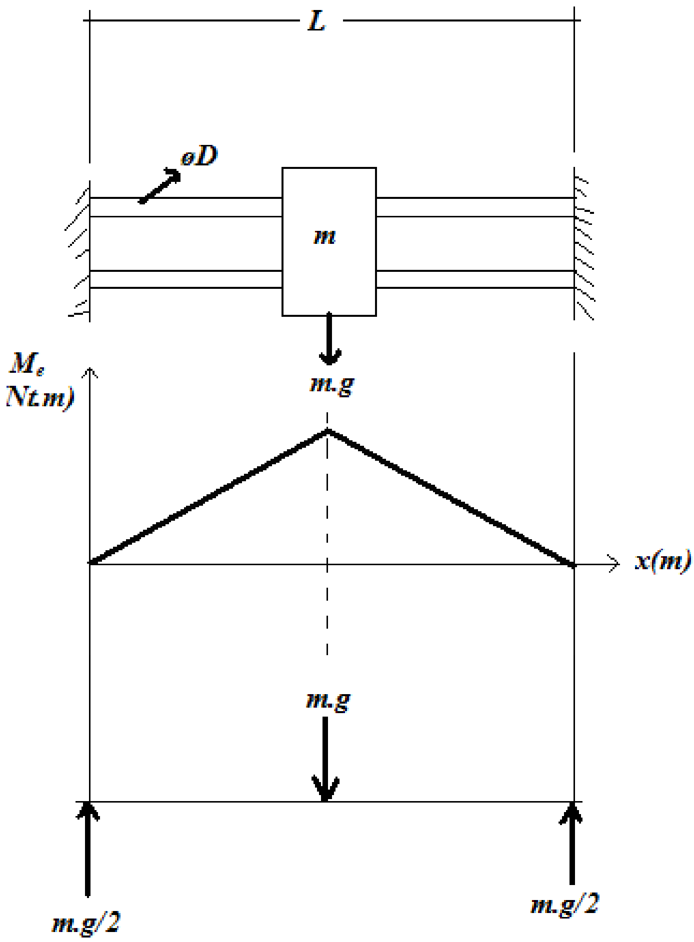


Figure 9.16 Head holding shaft's bending model

By writing the bending stress expression for one shaft

$$\sigma_e(Nt/mm^2) = \frac{M_e}{W_e} = \frac{\frac{1}{2}(\frac{m.g}{2}).\frac{L}{2}}{\frac{\pi.D^3}{32}} \leq \frac{\sigma_{Ak}}{s} \tag{9.11}$$

$$\sigma_e(Nt/mm^2) = \frac{M_e}{W_e} = \frac{\frac{2.5.(9.81)}{4}.140}{\frac{\pi.D^3}{32}} \leq \frac{400}{3}$$

$\rightarrow 4.03 \leq D(mm)$

So, shaft's diameters are taken as *10 mm*.

Head elements for holding the pneumatic cylinder should be dimensioned based on the stress analysis.

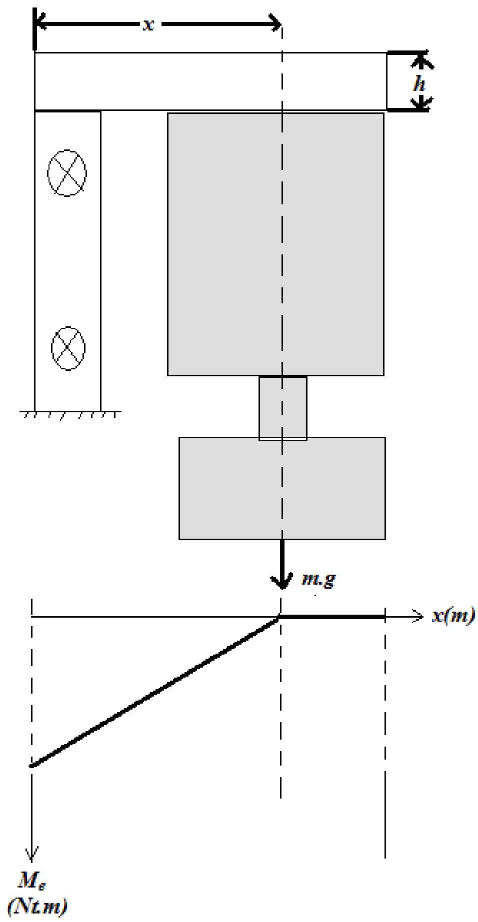


Figure 9.17 Gripper holding elements bending model

The bending stress expression can be written like

$$\sigma_e(Nt/mm^2) = \frac{M_e}{W_e} = \frac{m.g.x}{\frac{b.h^2}{6}} \leq \frac{\sigma_{Ak}}{s} \qquad (9.12)$$

With taking b as 36 *mm* according to pneumatic cylinder width and x approximately *45 mm*, we can determine h. Selected material is Al so yield strength can be taken as 100 MPa.

$$\sigma_e(Nt/mm^2) = \frac{M_e}{W_e} = \frac{2.5.(9.81).45}{\frac{36.h^2}{6}} \leq \frac{100}{3}$$

$\rightarrow 2.35 \leq h(mm)$

So,h taken as *10 mm*.

FEA results with *Autodesk Inventor* can be seen below

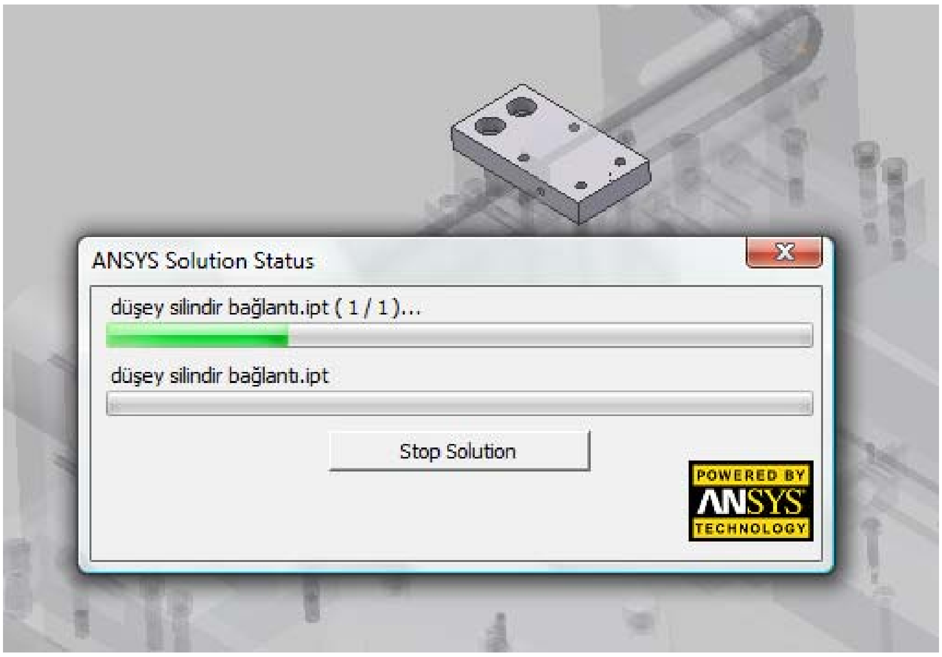


Figure 9.18 Inventor’s embedded FEA module by ANSYS

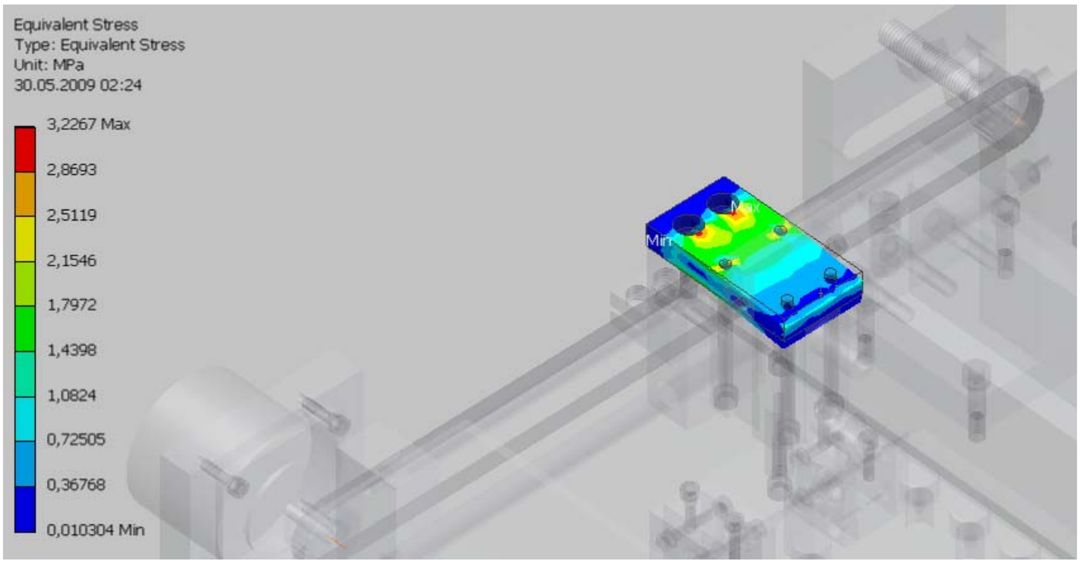


Figure 9.19 Equivalent stress for gripper holding element

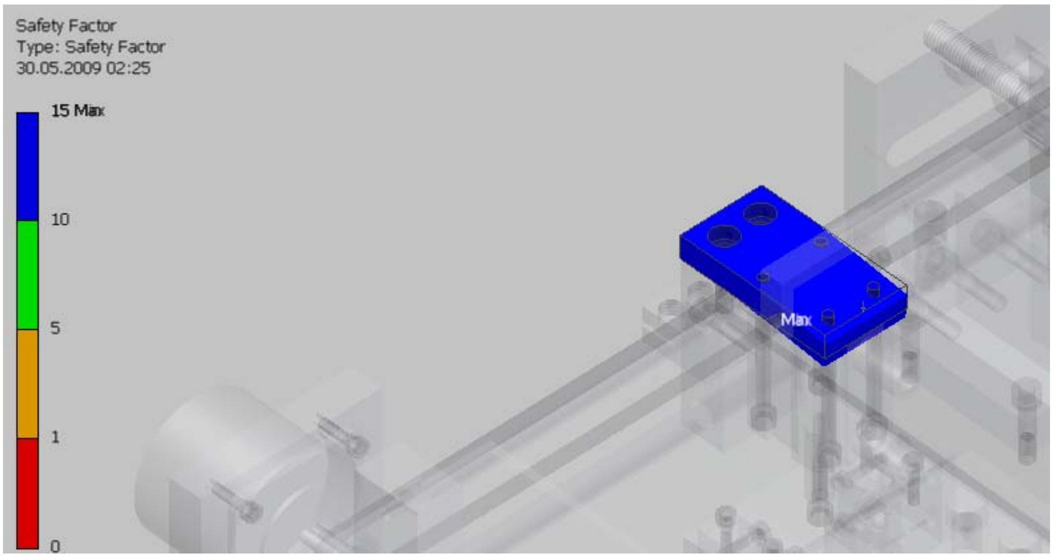


Figure 9.20 Safety factor for gripper holding element

The timing belt that is transforming the step motors rotary motion to head's linear motion should be checked based on the stress analysis.

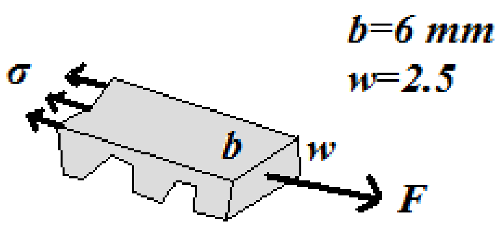


Figure 9.21

$$\sigma = \frac{F}{A} \cong \frac{F}{b.w/2} \le \sigma_{em} = \frac{\sigma_{Ak}}{s} \tag{9.13}$$

By taking $F(Nt) = T_{\max} / R = 1500/20 = 75$ and for elastomers 25 MPa as yield strength

$$\sigma \cong \frac{75}{6.(2.5)/2} = 10 \le \sigma_{em} = \frac{25}{2} = 12.5 \rightarrow \text{Safe}$$

The colums that will hold the shaft and the head assembly should be dimensioned based on the stress analysis.

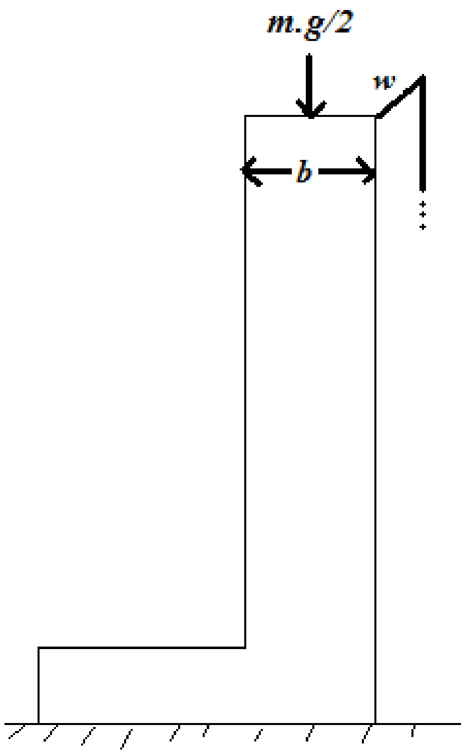


Figure 9.22 Head assembly holding columns loading model

$$\sigma = \frac{F}{A} = \frac{m.g/2}{b.w} \le \sigma_{em} = \frac{\sigma_{Ak}}{s} \tag{9.14}$$

By taking the yield strength for Al as 100 MPa and w=30 mm according to the shaft diameter that will support

$$\sigma = \frac{2.5.(9.81)/2}{b.30} \leq \sigma_{em} = \frac{100}{3}$$

$$\rightarrow 0.012 \leq b(mm)$$

b will be taken as *20 mm*. This value will guarantie the safety but also allow to the related sensor assembly modifications if needed in further studies.

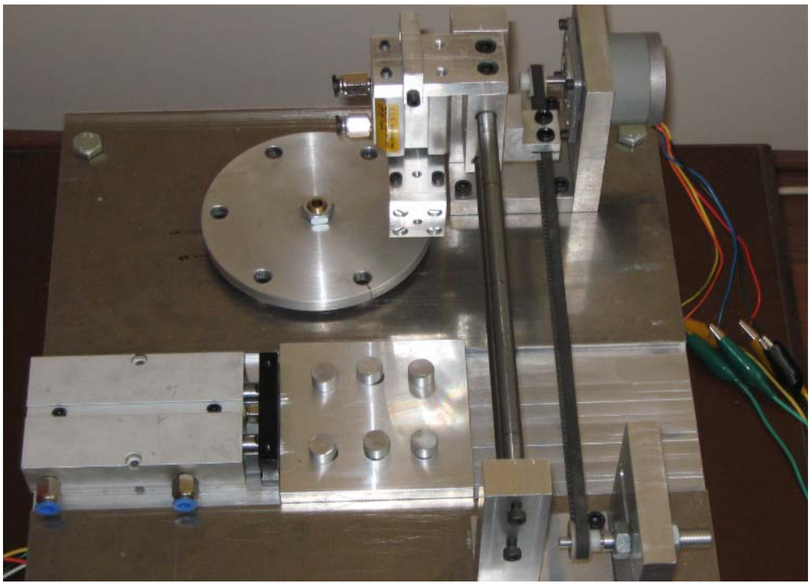


Figure 9.23 Designed packaging machine

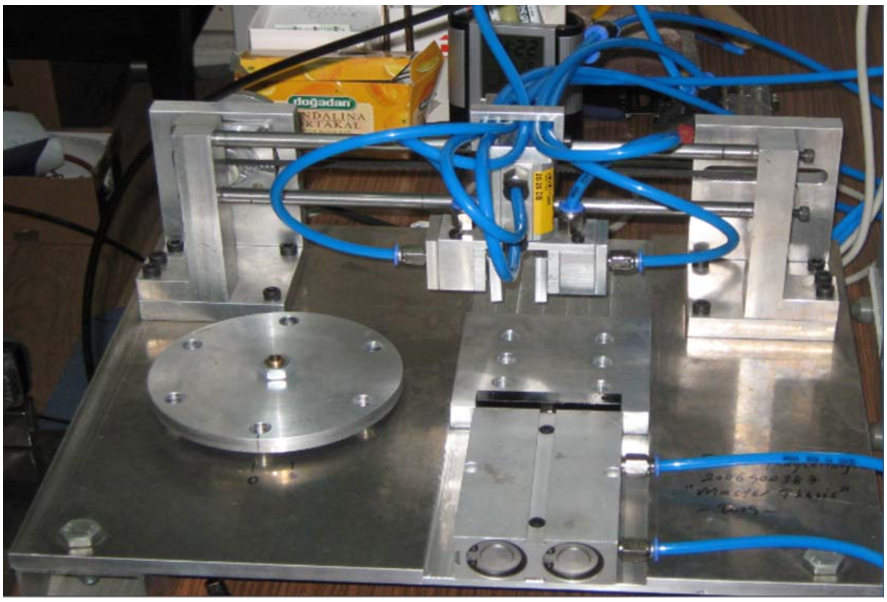


Figure 9.24 Designed packaging machine after the pneumatic fittings and hoses assembly

9.3 Components for "Soft" Tasks

Components for "soft" tasks refers to the components that have an *in*direct relationship with the physical process/procedure which is the subject of the automation.

The layout for the automated system can be given below.

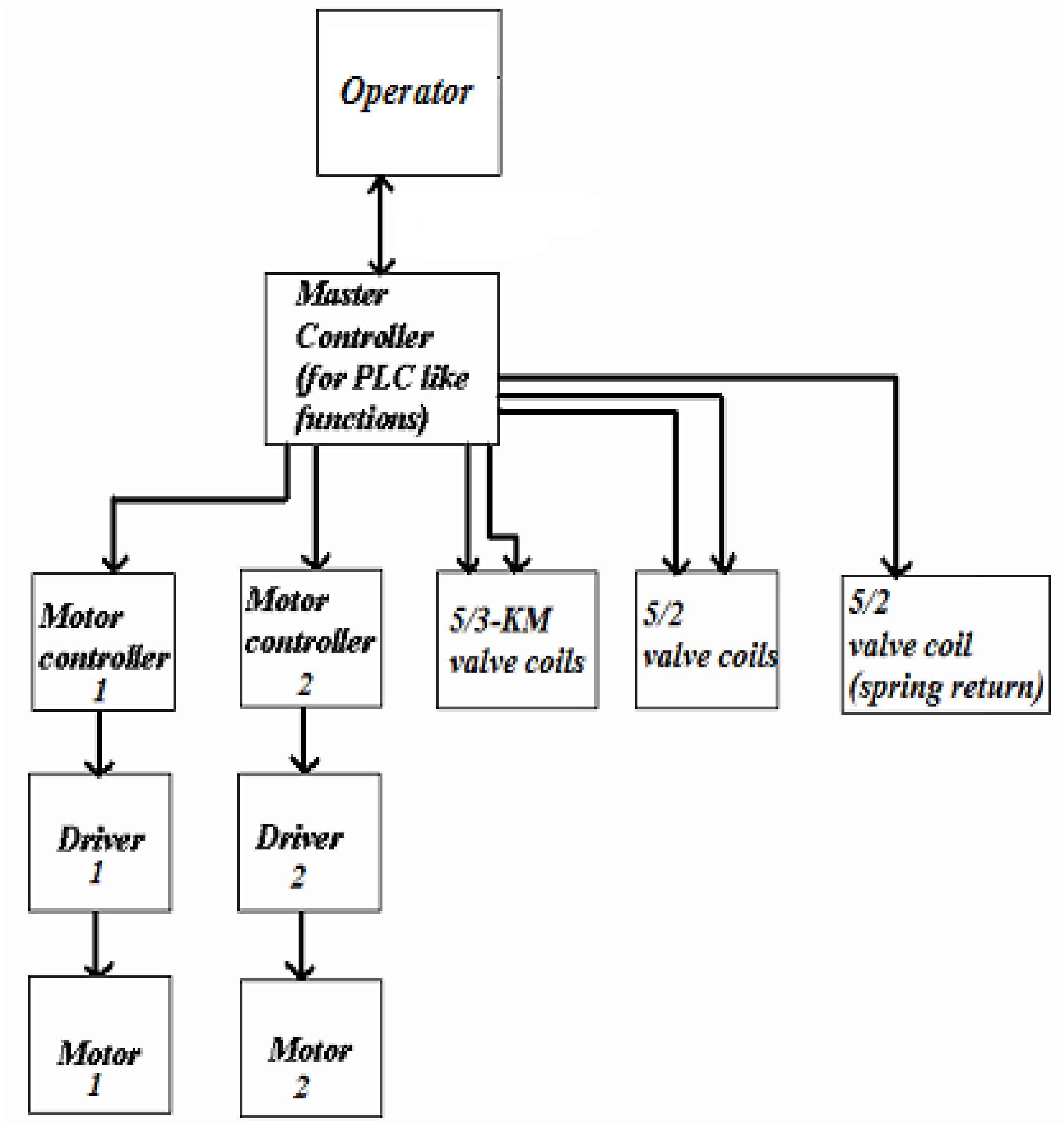


Figure 9.25 The layout of the automated packaging machine

9.3.1 Master Controller

Master controller selected and implemented to perform PLC like functions. It will communicate with and control the motor controllers and pneumatic valves.

Microchip's PIC 16F877 has selected as the master controller. It has 40 pins totally and built in RS-232 data transfer pin. The pin diagram for PIC 16F877 has given below.

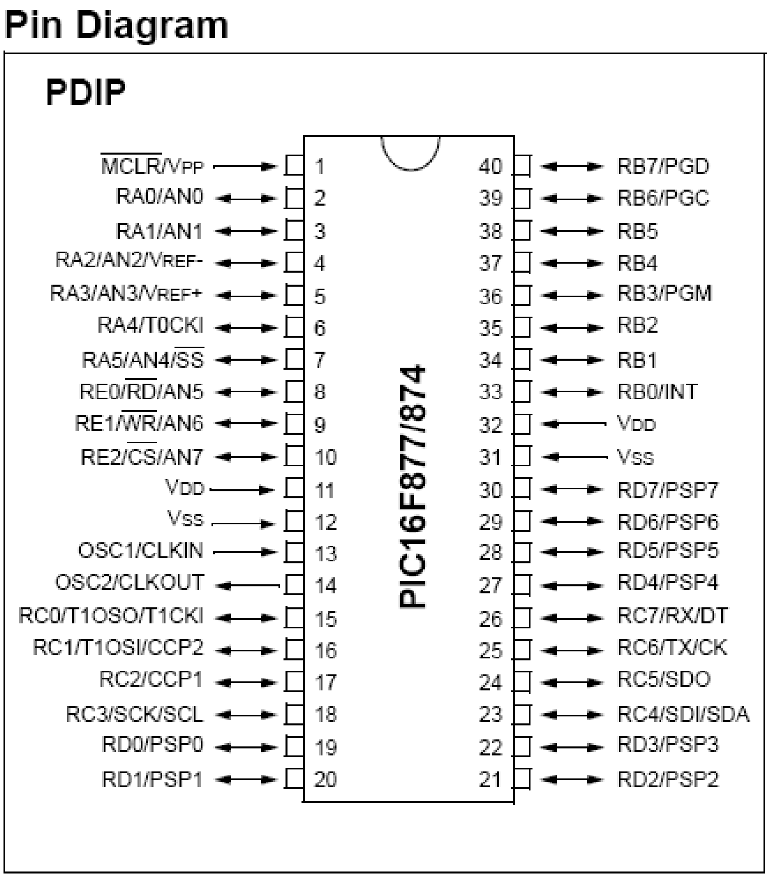


Figure 9.26 Pin diagram of the PIC 16f877

The designed boards for performing the master controller functions and pneumatic valves driver relays which are related with other devices can be seen below.

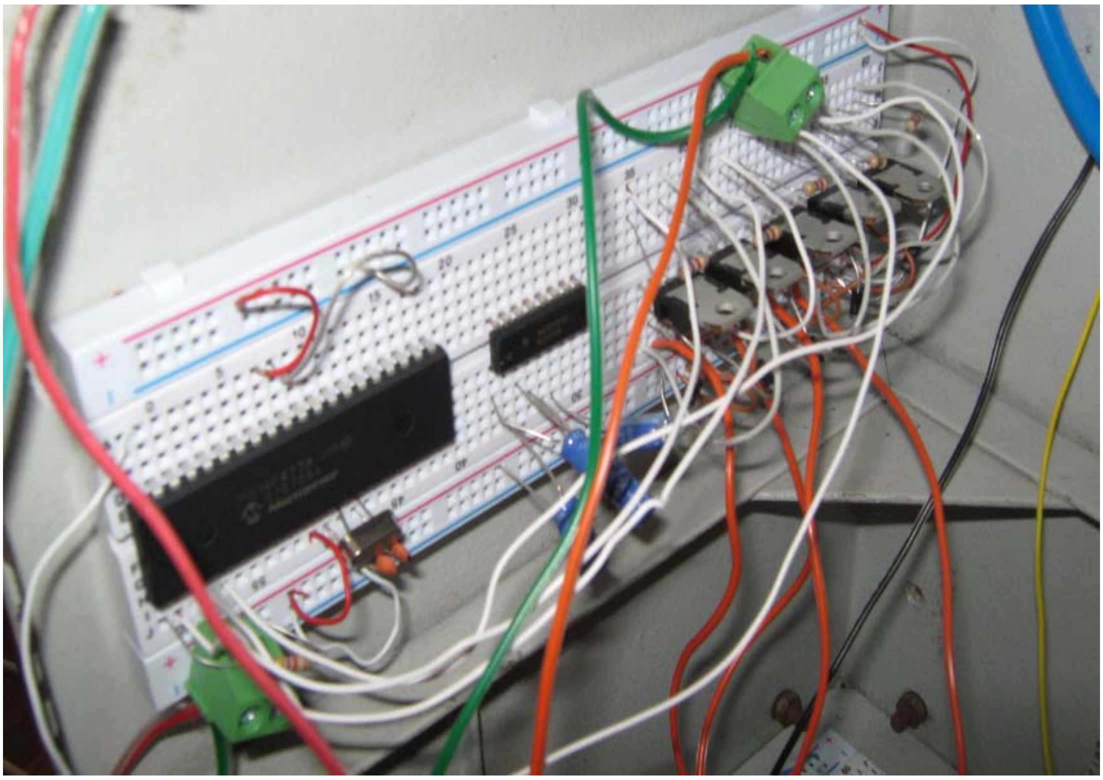


Figure 9.27 The designed board for the master controller and pneumatic valves

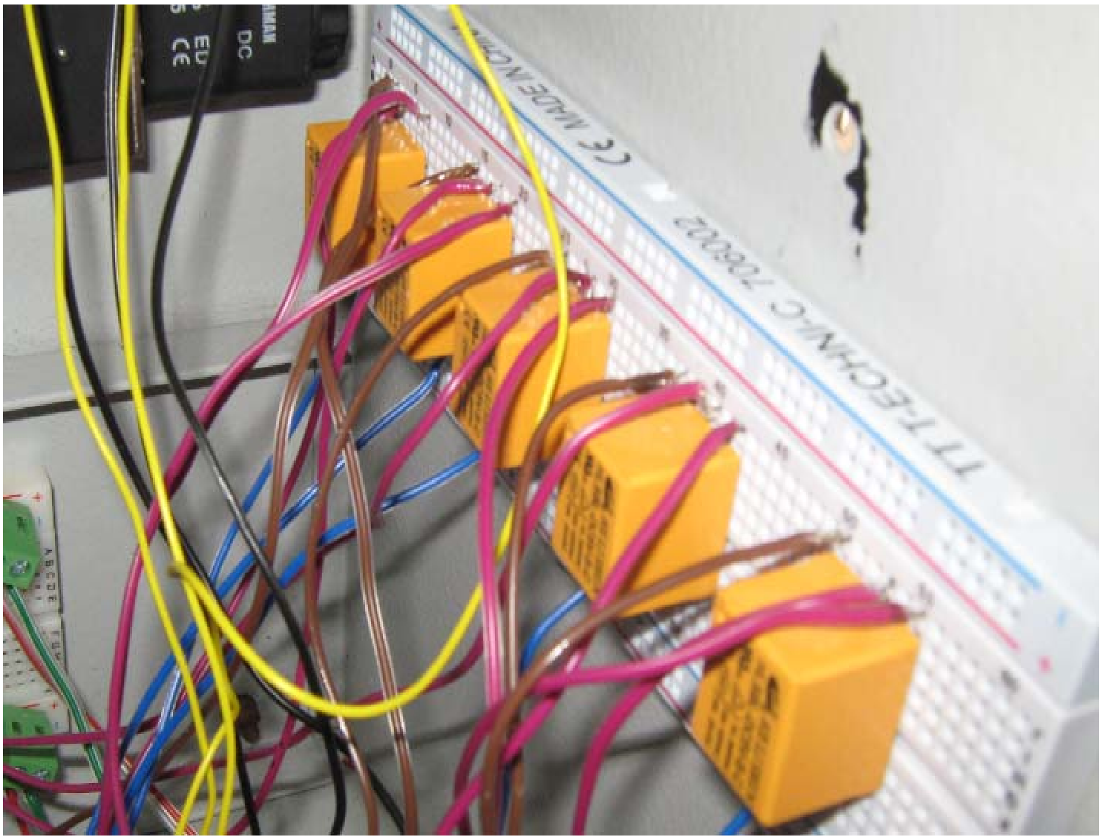


Figure 9.28 5V relays for the pneumatic valves

9.3.2 Motor Controllers and Drivers

Motor controllers and related motor drivers are selected for the system based on the related concepts and calculations that are given below.

Microchip's PIC 16F84A has selected as the motor controller. It has 18 pins totally and the pin diagram for PIC 16F84A has given below.

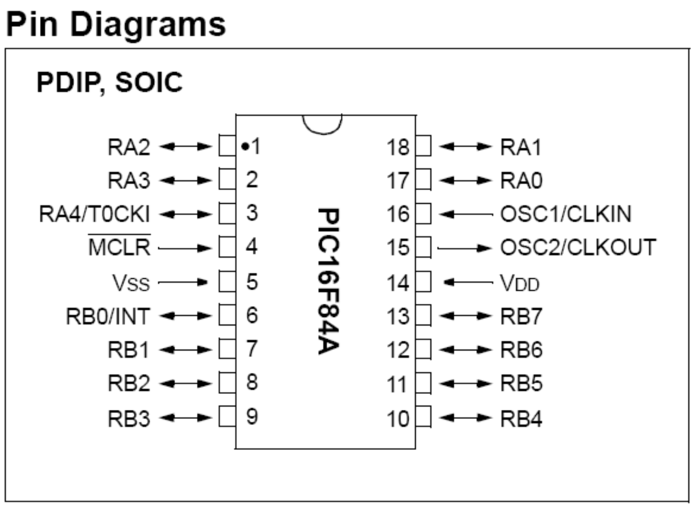


Figure 9.29 Pin diagram of the PIC 16f84

Texas Insturement's ULN2003A has selected for the motor driver. It has 0.5 A rated collector current capacity and can be used for driving max 50 V step motors. It's pin diagram can be seen below

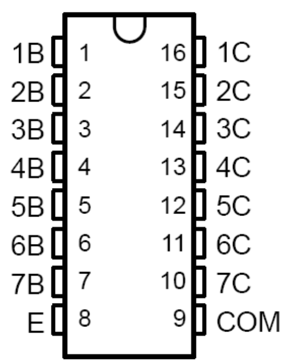


Figure 9.30 Pin diagram of the ULN2003A

The designed board for performing the motor controller and driver functions related with other devices can be seen below

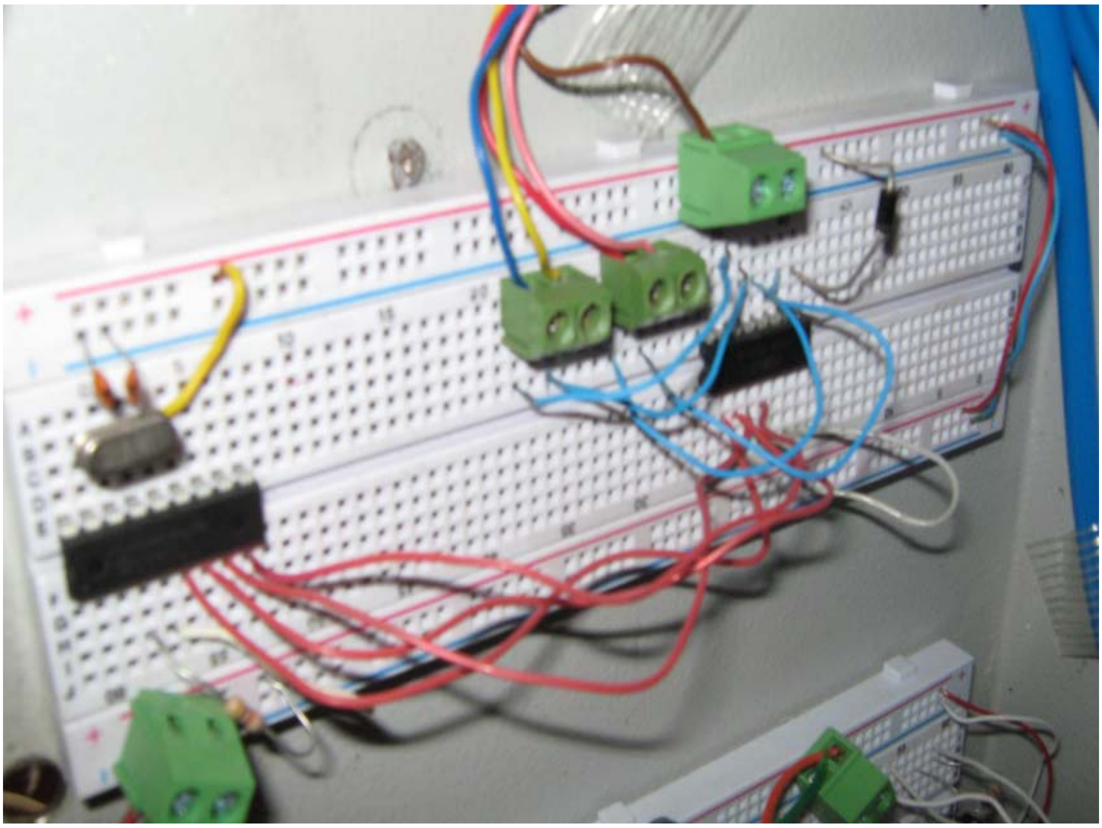


Figure 9.31 The designed board for motor controller

9.3.3 Power supply

The Power supply selected based on the system's voltage and current requirements that the related concepts and calculations are given below.

Step motor used for gripper holding head linear motion is 6V supply voltage and maximum 1 A current capacity. Used motor driver ULN2003 A has max 0.5 A pin capacity, so we will use 0.5 A. Step motor used for rotary/indexing table is 24 V/0.18 A. The valve coils of pneumatic valves are standartized for the PLC outputs and 24 V/0.2 A driven and totally 5 valve coils that the system will have.

To sum up, we can figure out the table below for assuming that all the actuators will driven at the same time. Actually,this will not be the fact but choosing the power supply capacity much then the real need will allow us to increase the system capabilities for further studies.

Table 9.2 Actuators power consumptions

Actuator	**Volt**	**A**
Step motor 1	6	0.5
Step motor 2	24	0.18
Pneumatic valve coils(x5)	24	5x0.2=1
Total	----	1.68

Finally, a Pan type power supply that can be seen below selected for the system. For 5 V supply voltages, we can use a regulator IC or an another power supply.

Figure 9.32 Used power supply for the application

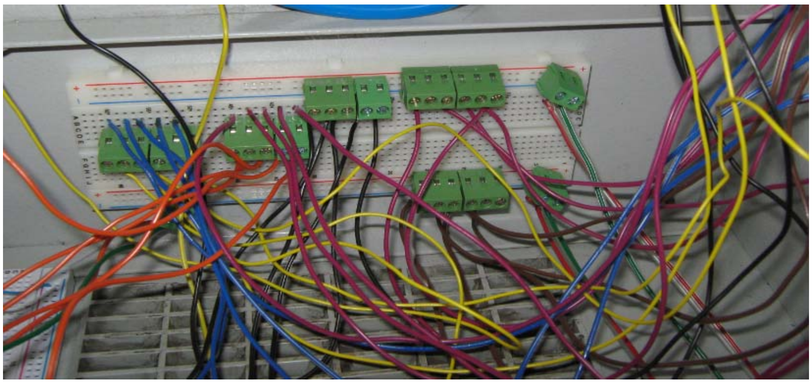


Figure 9.33 Designed terminal blocks for the application

9.3.4 Control cabinet

The control cabinet assembly for the system can be seen below. It will serve as an enclosure for the pneumatic valves, master and motor controller boards and the power supply.

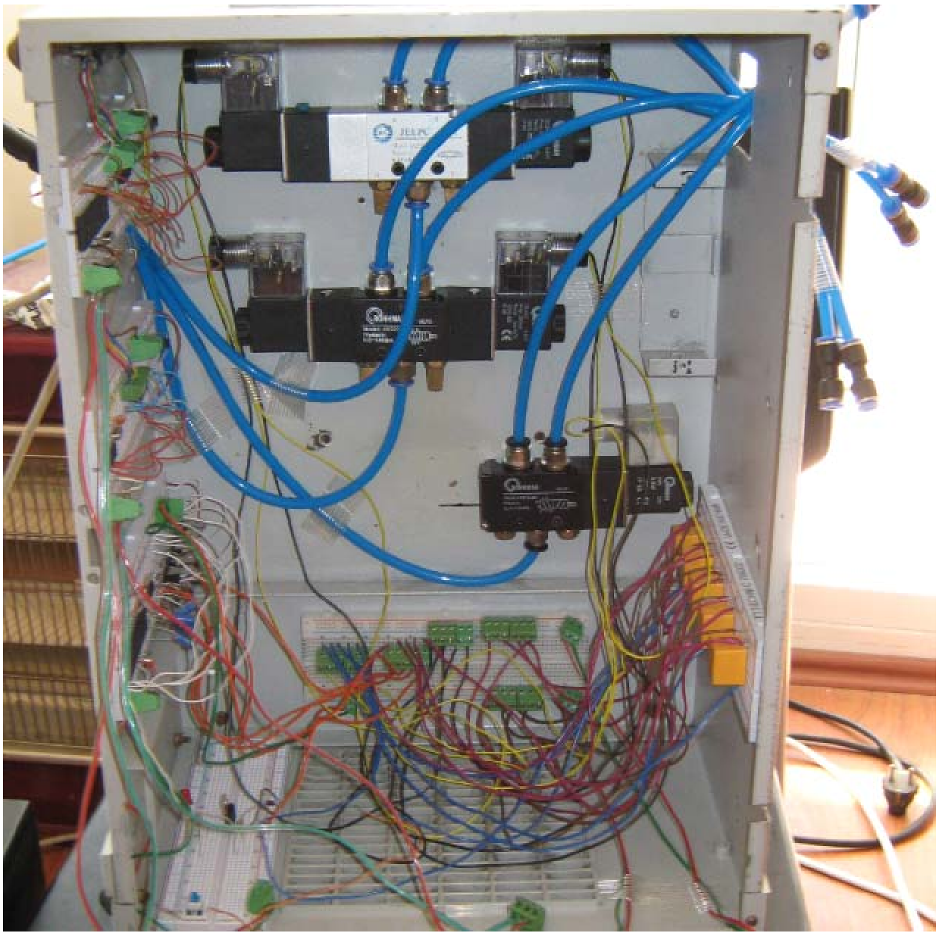


Figure 9.34 Designed control cabinet for the application

9.4 Cost Analysis

Up to now, we have designed and selected the related parts for the system.The further section will be the "performance analysis", but a cost analysis can be routed to base on the further analysis results on a "solid" ground cause it will determine the feasibility of the related and required modifications. The related concepts and calculations are given below.

Table 9.3 Costs for the selected/used components for the packaging machine

No	**Part**	**Note**	**Unit price**	**Count**	**Total price**
1	Chasis+Related machine elements+Gripper (*material(Al)+manufacturing*)				310 €
2	Ck45 chromed shaft	Second hand	3 €	2	6 €
3	Timing belt+pulleys	Second hand			10 €
4	Step motors	Second hand	2,5 €	2	5 €
5	Step motor drivers	ULN200A	5 €	2	10 €
6	Motion controller	PIC 16F84	3 €	2	6 €
7	Master controller	PIC 16F877	10 €	1	10 €
8	Pan type power supply	24 Volt/~3 A		1	
9	Control cabinet	Second hand		1	10 €
10	Control cabinet assembly	Performed by myself			0 €
11	Pneumatic components (*Valves+cylinders+hoses +fittings*)				230 €
12	Fasteners(*bolts+nuts+etc.*)				5 €
13	Electric/electronic components (*terminal blocks+ boards+etc.)*				50 €

We had been set the selling price 1000 €. If we assume %10 profit, that will mean the total cost of the machine should be 910 €. We have 258 €(910-652) for using in performance improvements. But it must be stated that if servo motors based improvements are being thought, it will not be realistic due to the fact that servo prices are nominally starting from 500 € and upper. So, if machine performance is not satisfactional, material and/or constructional based solutions should be thought first. Otherwise the selling price of the machine should be increased.

9.5 Performance Analysis

Performance criterians for the automated machines/systems had been given in previous chapters as *accuracy*, *repeatability* and *resolution*.These criterians all can be related with our packaging machine by analysing the tracking performance of the selected components motional parameters namely position, velocity and accelaration, but in our system we will limit our analysis especially on packaged part's *positional accuracy*. Positional resolution will be dictated by the actuator and/or feedback sensor capabilities, so we will not give special attention to this criterian due to the fact that it should be regarded actually as a financial issue. Finally, the positional repeatability criterian can be related with the control systems design concept "robustness", so it will be analysed in further section cause our automated machine is an open-loop system.

9.5.1 Vibration analysis

The torque expression of the stepper motors can simply be written as (Skvarenina,2002 and de Silva,2005)

$$T_m = -T_H.\sin(n_r.\theta) = -i_o.K_m.\sin(\frac{2.\pi}{p.\Delta\theta}.\theta) \tag{9.15}$$

where

T_H:*Holding torque*

n_r:*Number of rotor teeth*

i_o:*Current in phase*

K_m:*Torque constant*

p:Number of phases

θ_o:*Step angle*

θ:*Angular position of the rotor*

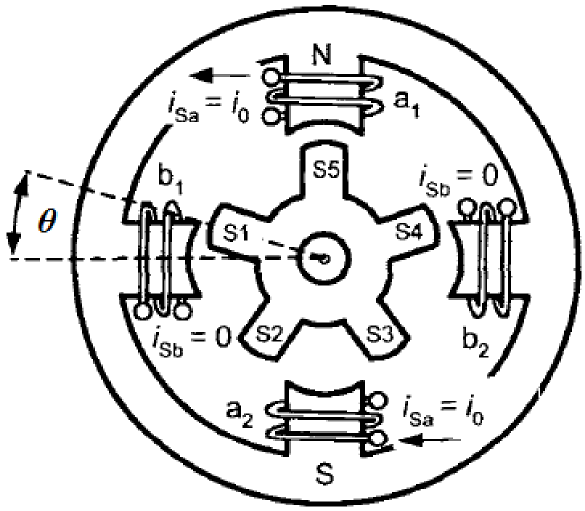


Figure 9.35 A step motor's actuation layout

For small angular rotations(like step angles), this expression can be approximated as

$$T_m \cong -i_o.K_m.n_r.\theta \qquad (9.16)$$

By putting this expression into the gripper(and so packaged part) holding head and motor's dynamic motion equations

$$T_m = J_{eq}.\ddot{\theta} + b_{eq}.\dot{\theta} \qquad (9.17)$$

with $j_{eq} = J_m + m.R^2$ and $b_{eq} = b_m + b.R^2$

where

J_m:Step motor's rotor angular inertia

m:Head assembly mass

R:Pulley

b_m:Viscous friction coefficient for step motor

b:Viscous friction for the head and slider shaft assembly

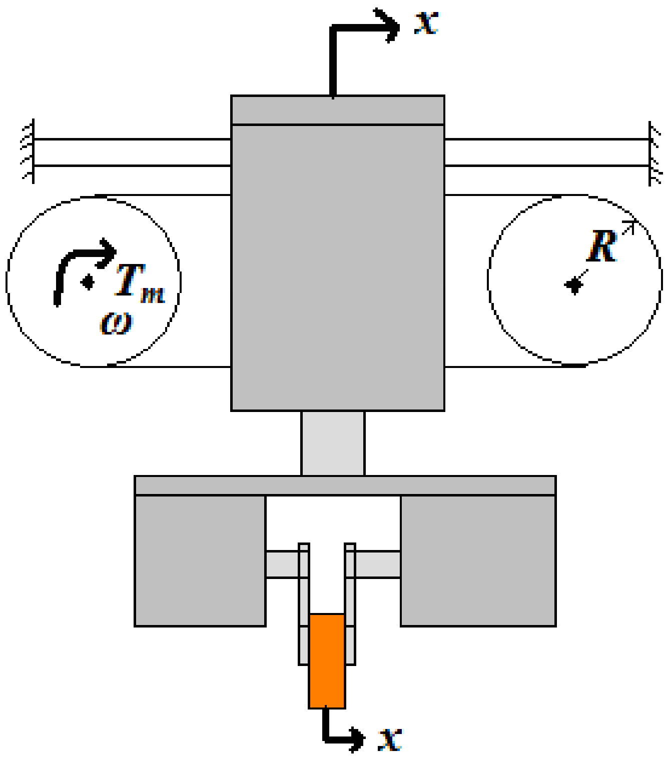


Figure 9.36 1-DOF model for the head's linear motion

Rearranging the equation

$$J_{eq}.\ddot{\theta} + b_{eq}.\dot{\theta} + i_0.K_m.n_r.\theta = 0 \tag{9.18}$$

with $2.\zeta.\omega_n = b_{eq} / J_{eq}$ and $\omega_n^{\ 2} = i_o.K_m.n_r / J_{eq}$, this may be rewritten as

$$\ddot{\theta} + 2.\zeta.\omega_n.\theta + \omega_n^{\ 2}.\theta = 0 \tag{9.19}$$

This is simply the equation of simple viscous damped free vibration, so the positional responce will be oscillatory like given in figure 9.37 for every step of the stepper.

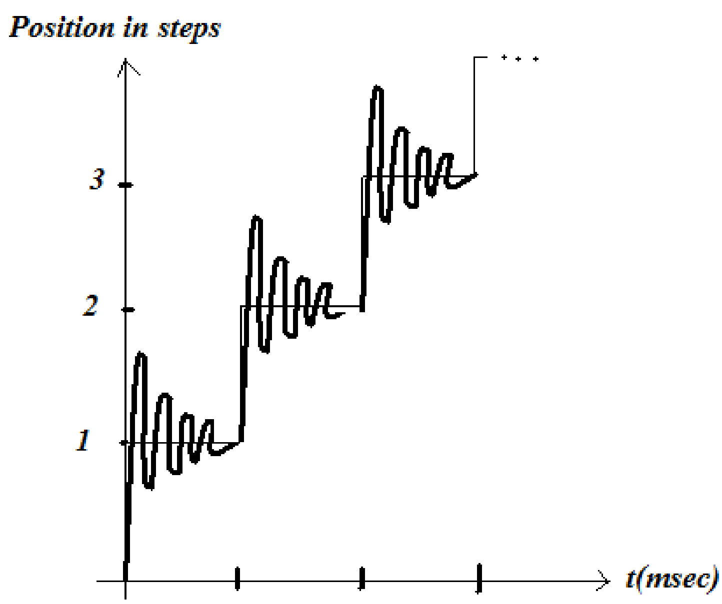


Figure 9.37 Expected positional responce of the stepper

By using the kinematic relationships $x(t)=\theta(t).R$, we can say that this oscillary motion will effect the head's positional accuracy by adding oscillations after every step of the stepper like given in the figure below.

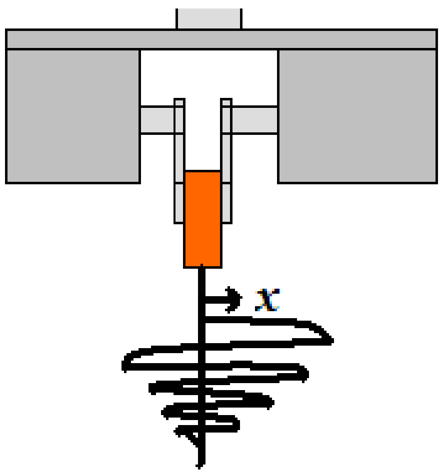


Figure 9.38 Expected positional responce of the packaged parts

We have used second hand steppers for the application, so we don't have any datasheet that will include the motor coefficients like torque constant, viscous friction coefficient and rotational inertia. The approximate values can be determined by exprerimental studies and, if the results are not acceptable, the performance improvements stated below can be preferred.

- Mechanical solutions(using torsional dampers like couplings)
- Electronic solutions(using "*electronic switching control*" or "*multiple phase enegization*" methods)

In the thesis, we preferred none these cause of the time and budget limitations. Also, machine operation practices showed that results can be stated acceptable if the parts which are being packaged are not very fragile for the vibrational effects and the machine noise can be assumed in acceptable levels due to the fact that it will perform the packaging operation in an industrial facility.

A more accurate analysis can be routed by modelling the system with the belt stiffness.

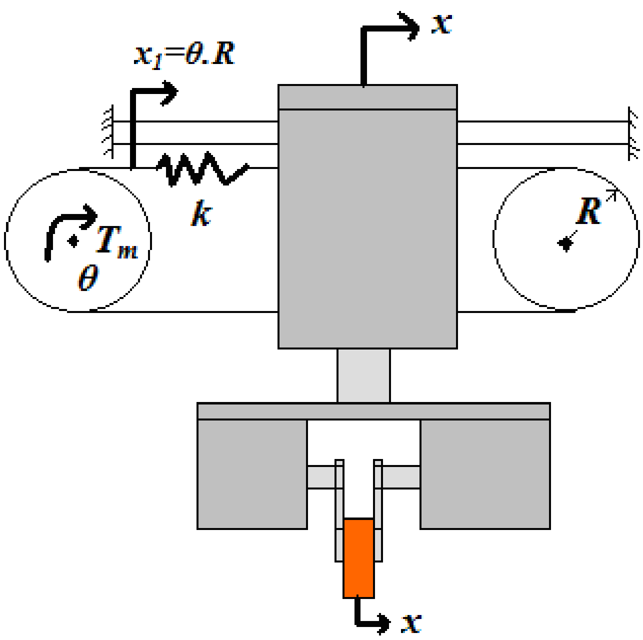


Figure 9.39 2-DOF model for the head's linear motion

With $q=[\theta\ x]^T$ are generalized coordinates, $Q=[T_m\ 0]^T$ are generalized loads and using Lagrange's Method

$$\begin{aligned}
&\frac{1}{2}.M.\dot{q}^2 = \frac{1}{2}.J_m.\dot{\theta}^2 + \frac{1}{2}.m.\dot{x}^2 \\
&\frac{1}{2}.B.\dot{q}^2 = \frac{1}{2}.b_m.\dot{\theta}^2 + \frac{1}{2}.b.\dot{x}^2 \\
&\frac{1}{2}.K.\dot{q}^2 = \frac{1}{2}.k.(\theta.R - x)^2 = \frac{1}{2}.k.\theta^2.R^2 - \frac{1}{2}.k.2.\theta.R.x + \frac{1}{2}.k.x^2
\end{aligned} \tag{9.20}$$

So

$$M = \begin{bmatrix} J_m & 0 \\ 0 & m \end{bmatrix}$$
$$B = \begin{bmatrix} b_m & 0 \\ 0 & b \end{bmatrix}$$
$$K = \begin{bmatrix} k.R^2 & -k.R \\ -k.R & k \end{bmatrix}$$

And so the system dynamic equations will be in compact form

$$M.\ddot{q} + B.\dot{q} + K.q = Q(t) \tag{9.21}$$

which states the form below

$$\begin{aligned}
&J_m.\ddot{\theta} + b_m.\dot{\theta} + k.R^2.\theta - k.R.x = T_m(t) \\
&m.\ddot{x} + b.\dot{x} - k.R.\theta + k.x = 0
\end{aligned} \tag{9.22}$$

Natural frequencies for the system can be found by solving the eigenvalues equation

$$\det(K - \omega^2.M) = 0 \tag{9.23}$$

where

J_m=55 kg.mm^2(“educated guess”)
b_m=0(neglected)
m=2.5 kg
b=0(neglected)
R=20 mm
k=A.E/L=135 Nt/mm

with the taken values for the timing belt as

$$A(mm^2) = b.\frac{w}{2} = 6.\frac{2.5}{2} = 7.5$$

$E(MPa) \cong 5.10^3$ assumed for elastomers

$$L(mm) = 280$$

```
In[13]:= Jm = 55; bm = 0; k = 135; R = 20; m = 2.5; b = 0;
         K = {{k R^2, -k R}, {-k R, k}}; MatrixForm[K]

Out[14]//MatrixForm=
         ( 54000  -2700 )
         ( -2700    135 )

In[15]:= M = {{Jm, 0}, {0, m}}; MatrixForm[M]

Out[15]//MatrixForm=
         ( 55   0  )
         (  0  2.5 )

In[16]:= Solve[Det[K - w^2 M] == 0, w] // N

Out[16]= {{w → -32.1841}, {w → 0.}, {w → 0.}, {w → 32.1841}}
```

Figure 9.40 Mathematica solution for finding the natural frequencies

Zero natural frequency is expected due to the fact that the head is unrestrained. So, the critical driving frequency will be *32 rad/sn* for the head operation.

9.5.2 Deflection analysis

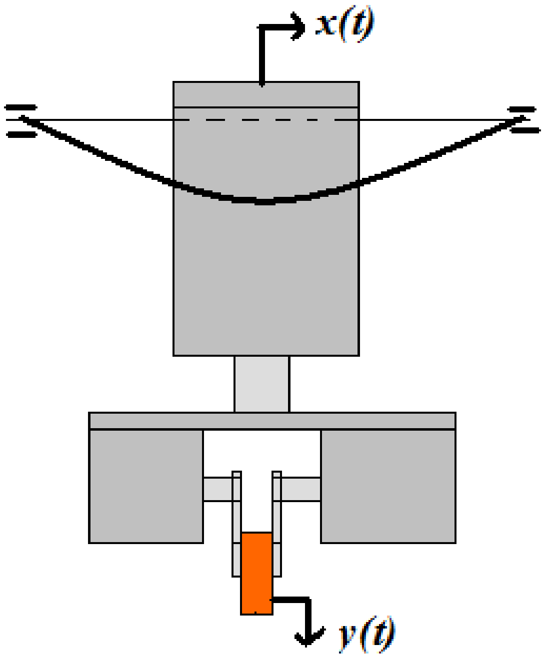


Figure 9.41 Deflection model for head

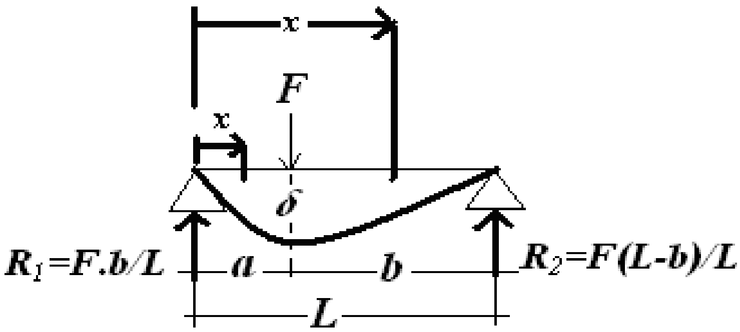


Figure 9.42 Model used for generalizing the deflection equations

$$(0 \rightarrow a) M_{e1} = \frac{F.b}{L}.x$$
$$(a \rightarrow L) M_{e2} = \frac{F.b}{L}.x - F(x-a) \qquad (9.24)$$

With Castigliano's first theorem:

"If the total strain energy expressed in terms of the external loads is partially differentiated with respect to one of the loads the result is the defection of the point of application of that load and in the direction of that load"

$$\delta = \int_{x=0}^{a} \frac{(\frac{Fbx}{L})(\frac{bx}{L})dx}{EI} + \int_{x=a}^{L} \frac{(\frac{Fbx}{L} - Fx + F.a)(\frac{bx}{L} - x + a)dx}{EI} \tag{9.25}$$

so the deflection will be

$$\delta = \frac{F.a^2.b^2}{3.E.I.L} \tag{9.26}$$

With $a = x$, $b = L - x$ and $F = m.g/2$, we can rewrite the equation as

$$\delta = \frac{(m.g).x^2.(L-x)^2}{6.E.I.L} \tag{9.27}$$

With *Mathematica* the deflection variation can be plotted as given below

where

m=2.5 kg
L=280 mm
E=200.10^3 MPa
d=10 mm

with

$$I(mm^4) = \frac{\pi.D^4}{64}$$

```
In[1]:= m = 2.5; g = 9.81; L = 280; e = 200 10^3; d = 10; i = π d^4 / 64;

In[2]:= δ = m g (L - x) ^2 x^2 / (6 e i L);

In[3]:= Plot[Evaluate[-δ], {x, 0, 280}, AxesLabel → {"x(mm)", "delta(mm)"}]
```

Figure 9.43 Mathematica solution for deflection

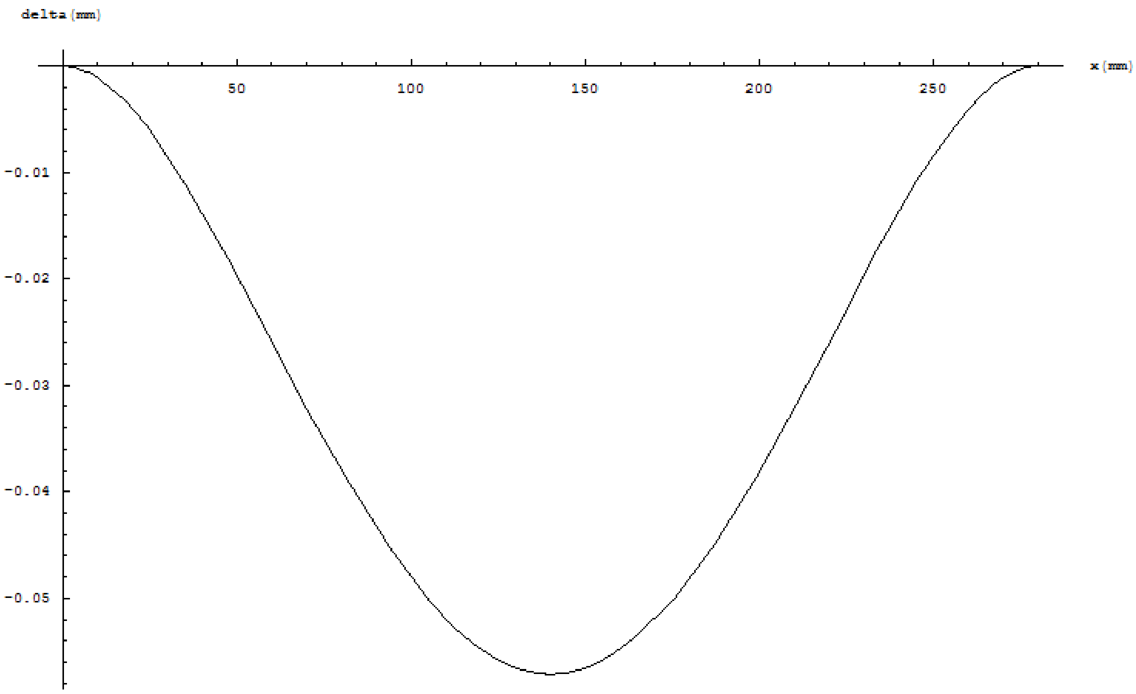


Figure 9.44 Deflection curve for the head holding shaft with Mathematica

9.6 Performance Improvements

In previous section, we have analysed our open-loop automated packaging machine performance by especially focusing on the gripper holding head linear positional accuracy. The results may be regarded satistactory or not, but if the second is the issue, we will face to the fact to make some modifications on the system. These modifications may be constructional, dimensional and/or material based, but if we directly speak the “ideal” case, none of these can incapsulate the performance criterians satisfactorily due to fact that the outputs of our system are not being fed back. This fact is the weak point of open-loop systems and under the case that luckly the performance is satisfactory after the modifications above, the sustainability of this performance is not obvious cause the system robustness can not be guarantied.

So,in this section, we will directly focus on the "control system design" based performance improvements.

The 1 and more accurate 2 DOF system models have been developed in previous sections, so the further analysis will be based on these expressions

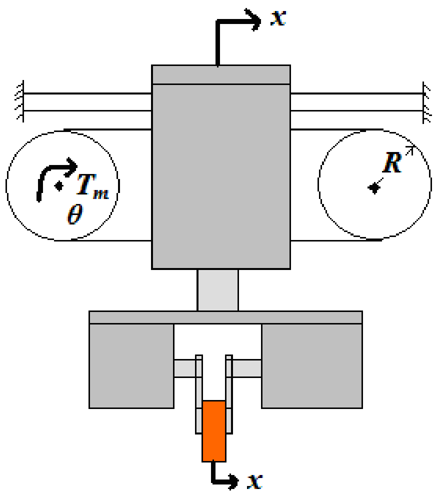


Figure 9.45 1-DOF model for the head's linear motion

$$J_{eq}.\ddot{\theta} + b_{eq}.\dot{\theta} = T_m(t) \tag{9.28}$$

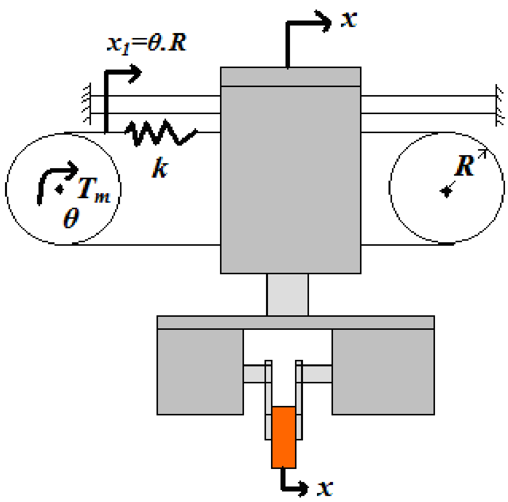


Figure 9.46 2-DOF model for the head's linear motion

$$\begin{aligned} &J_m.\ddot{\theta} + b_m.\dot{\theta} + k.R^2.\theta - k.R.x = T_m(t) \\ &m.\ddot{x} + b.\dot{x} - k.R.\theta + k.x = 0 \end{aligned} \tag{9.29}$$

All of the analysis below will be routed for the case that gripper holding head's step motor changed with a servo motor(PMDC,BLDC or BLAC types) and appropriate sensors(encoders and/or LVDTs) can be used for feeding back the head's linear motion related variables.

Selected servo is Baldor's MT-2250A.It's a PMDC type servo and related performance spesifications can be seen from the manufacturer's datasheet given below.

Figure 9.47 Selected DC servo motor for performance improvement

Model Number		MT-2240-A	MT-2240-B	MT-2250-A
General				
Continuous Stall Torque	lb-in	1.88	1.88	3.13
	N-m	0.21	0.21	0.35
Continuous Current	amps	2.05	3.33	3.42
Peak Torque	lb-in	13	13	19
	N-m	1.4	1.4	2.1
Peak Current	amps	12.3	20	18.5
Viscous Damping	lb-in/krpm	0.01	0.01	0.01
	Nm/krpm	7.1 E-04	7.1 E-04	1.4 E-03
Thermal Resistance	°C/watt	5	5	4.2
Mechanical Time Constant	msec	20	20	9.5
Electrical Time Constant	msec	7.8	9	2.52
Rated Speed	rpm	3500	3000	3500
Rated Voltage	volts	50	30	50
Electrical				
Torque Constant	lb-in/amp	1.012	0.625	1.0125
	N-m/amp	0.115	0.071	0.115
Voltage Constant	Vpk/krpm	12	7.4	12
	Vrms/krpm	0.115	0.071	0.115
Resistance	ohms	4.0	1.6	2.3
Inductance	mH	7.7	3.3	5.8
Mechanical				
Inertia	lb-in-s²	0.00031	0.00031	0.00048
	Kg-cm²	0.35	0.35	0.54
Maximum Speed	rpm	5000	5000	5000
Weight	lbs/Kg	3.2/1.5	3.2/1.5	3.5/1.6

Figure 9.48 Selected motor datasheet

9.6.1 PD controller

For PD controller,1 DOF system model will be taken for analysis, so the controlled system will be SISO.

By Laplace Transform

$$J_{eq}.s^2.\theta(s)+b_{eq}.s.\theta(s)=T_m(s) \tag{9.30}$$

By rearranging the expression

$$\frac{\theta(s)}{T_m(s)}=\frac{1}{J_{eq}.s^2+b_{eq}.s} \tag{9.31}$$

with the parameters given below,equivalent rotational inertia will be $J_{eq}=1054$ *kg.mm*^{2} and viscous coefficient $b_{eq}=13.3.10^{-3}$, following block diagram can be configured with *Matlab* module *Simulink*.

$J_m=54$ *kg.mm*^{2}

$b_m=(60/2\pi).1.4.10^{-3}=13.3.10^{-3}$ *Nt.mm.sn/rad*

m=2.5 kg

b=0(neglected)

R=20 mm

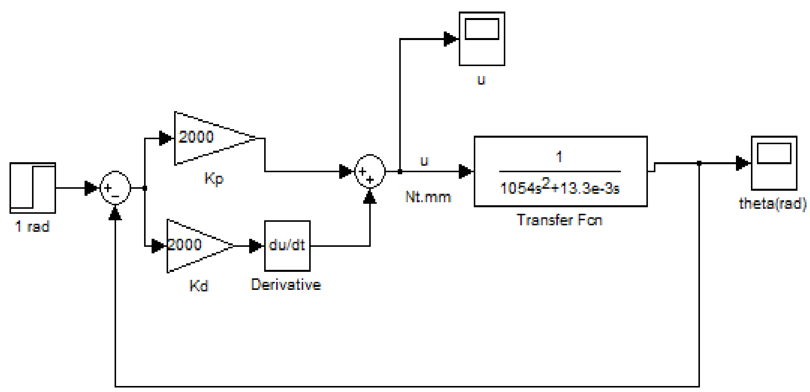


Figure 9.49 Simulink model for PD controller

Proportional and derivative constants(K_p and K_d) selected arbitrary. Test signal is 1 rad step and the theta output can be shown in the figure given below. Stabilization have been achived and overshoot is less than %5. But settling time is not satisfactory cause it's much bigger than targeted with approximatelly 5 seconds, but it should be approximatelly 1.5 seconds. So,control constants should be tuned until the targeted results have been achived. Finally, the control signal have to be checked for saturation due to the fact that if saturation occurs, actuator can not drive the system as if desired.

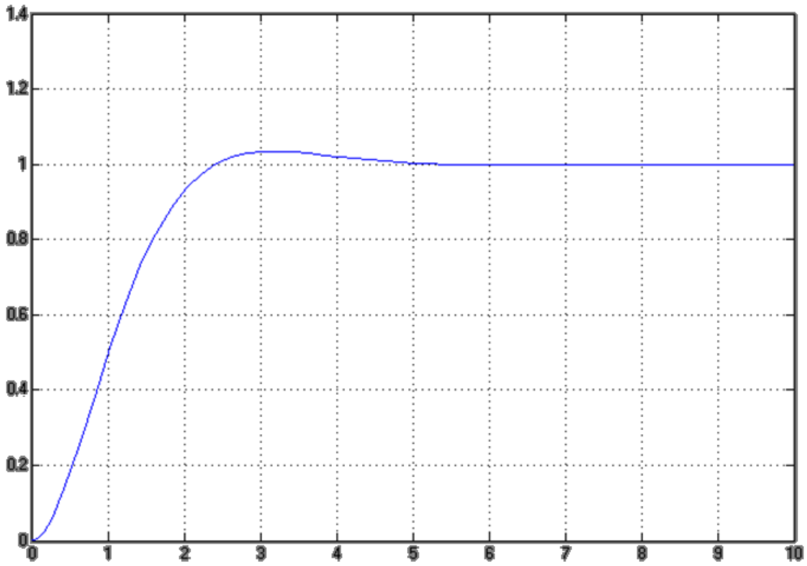


Figure 9.50 theta responce

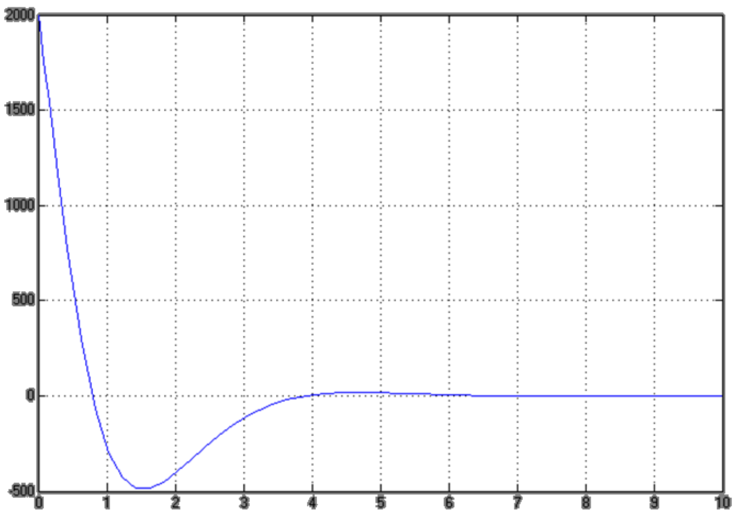


Figure 9.51 Control input in Nt.mm

9.6.2 PID controller

For PID controller, 1 DOF system model will be taken for analysis, so the controlled system will be SISO.

By Laplace Transform

$$J_{eq}.s^2.\theta(s) + b_{eq}.s.\theta(s) = T_m(s) \quad (9.32)$$

By rearranging the expression

$$\frac{\theta(s)}{T_m(s)} = \frac{1}{J_{eq}.s^2 + b_{eq}.s} \quad (9.33)$$

with the parameters given below,equivalent rotational inertia will be $J_{eq}=1054\ kg.mm^2$ and viscous coefficient $b_{eq}=13.3.10^{-3}$, following block diagram can be configured with *Matlab* module *Simulink*.

$J_m=54\ kg.mm^2$

$b_m=(60/2\pi).1.4.10^{-3}=13.3.10^{-3}\ Nt.mm.sn/rad$

$m=2.5\ kg$

$b=0(neglected)$

$R=20\ mm$

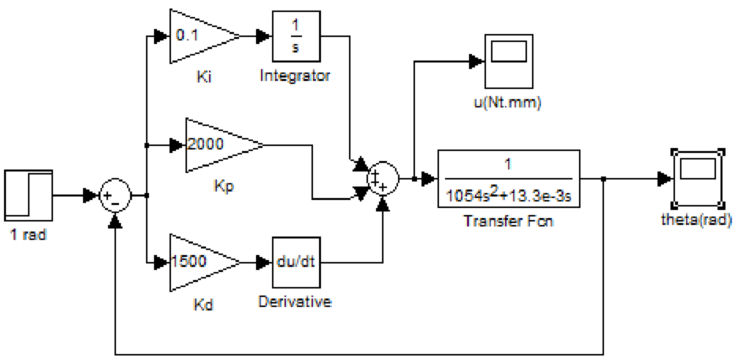


Figure 9.52 Simulink model for PID controller

Proportional, integral and derivative constants(K_p ,K_i and K_d) selected arbitrary. Test signal is 1 rad step and the theta output can be shown in the figures given below. Stabilization have been achived and overshoot is less than %20.But settling time is not satisfactory cause it's much bigger than targeted with approximatelly 5 seconds, but it should be approximatelly 1.5 seconds. So,control constants should be tuned until the targeted results have been achived. Finally,the control signal have to be checked for saturation due to the fact that if saturation occurs, actuator can not drive the system as if desired.

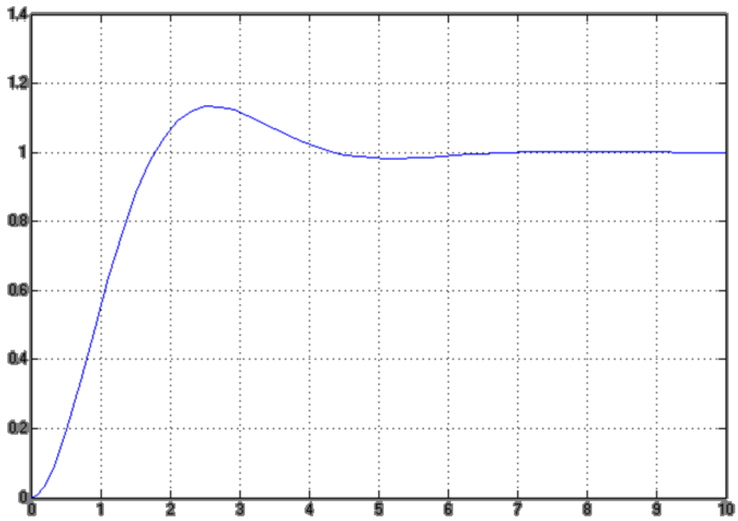


Figure 9.53 theta responce

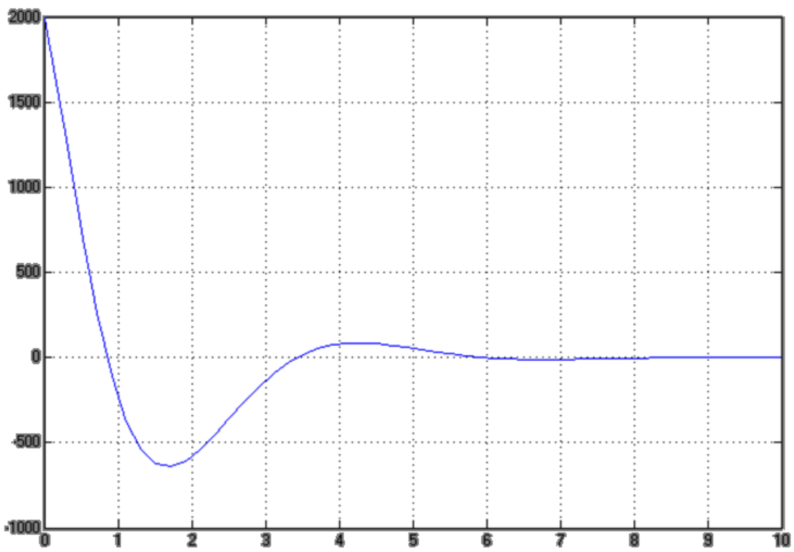


Figure 9.54 Control input in Nt.mm

9.6.3 LQR and LQG controllers

For LQR(*linear system+quadratic optimization(also called "cost") function*) and LQG(*linear system+quadratic optimization function+gaussian disturbance/noise*) controllers, 2 DOF system model will be taken for analysis, so the controlled system will be MIMO.

First of all, system's state-space model should be structured. 2 DOF MIMO model was like given below. There are 2 second order differential equations so, we will take 4 state-variables like *x1*, *x2*, *x3* and *x4*.

$$\begin{aligned} &J_m.\ddot{\theta}+b_m.\dot{\theta}+k.R^2.\theta-k.R.x=T_m(t)\\ &m.\ddot{x}+b.\dot{x}-k.R.\theta+k.x=0 \end{aligned} \tag{9.34}$$

Assigning the state-variables as

$$\begin{aligned} x_1 &= \theta\\ x_2 &= \dot{\theta}\\ x_3 &= x\\ x_4 &= \dot{x} \end{aligned}$$

With rearranging the system equations, we can write

$$\begin{aligned} &\ddot{\theta}=\frac{T_m(t)}{J_m}-\frac{b_m}{J_m}.\dot{\theta}-\frac{k.R^2}{J_m}.\theta+\frac{k.R}{J_m}.x\\ &\ddot{x}=-\frac{b}{m}.\dot{x}+\frac{k.R}{m}.\theta-\frac{k}{m}.x \end{aligned} \tag{9.35}$$

So, finally we can write

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= \frac{T_m(t)}{J_m} - \frac{b_m}{J_m}.x_2 - \frac{k.R^2}{J_m}.x_1 + \frac{k.R}{J_m}.x_3 \\
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= -\frac{b}{m}.x_4 + \frac{k.R}{m}.x_1 - \frac{k}{m}.x_3
\end{aligned} \tag{9.36}$$

In matrix form

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -k.R^2/J_m & -b_m/J_m & k.R/J_m & 0 \\ 0 & 0 & 0 & 1 \\ k.R/m & 0 & -k/m & -b/m \end{bmatrix} . \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 1/J_m & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} . \begin{bmatrix} T_m(t) \\ 0 \end{bmatrix} \tag{9.37}$$

And the outputs matrix(*assuming that linear displacement can be measured with a LVDT*)

$$y = \begin{bmatrix} \theta \\ x \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} . \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \tag{9.38}$$

So, system's state-space model will be in closed-form

$$\begin{aligned}
\dot{x} &= A.x + B.u \\
y &= C.x + D.u
\end{aligned} \tag{9.39}$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -k.R^2/J_m & -b_m/J_m & k.R/J_m & 0 \\ 0 & 0 & 0 & 1 \\ k.R/m & 0 & -k/m & -b/m \end{bmatrix} \tag{9.40}$$

$$B = \begin{bmatrix} 0 \\ 1/Jm \\ 0 \\ 0 \end{bmatrix} \tag{9.41}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{9.42}$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{9.43}$$

For the states that are not being fed back with sensors, we should use an estimator(also called observer) and the standart expression for the estimated states can be written like given below where “*L”* is the estimator gain that should be tuned. ”^” means the parameter is the estimated one.

$$\dot{\hat{x}} = A.\hat{x} + B.u + L(y - \hat{y}) \tag{9.44}$$

So, system with *LQR* controller simulink model and the results for the set-point tracking values as $\theta_{ref}=1\ rad$ and $x_{ref}=20$ mm are like given below with

$J_m=54\ kg.mm^2$

$b_m=(60/2\pi).1.4.10^{-3}=13.3.10^{-3}\ Nt.mm.sn/rad$

m=2.5 kg

b=0(neglected)

R=20 mm

k=A.E/L=135 Nt/mm

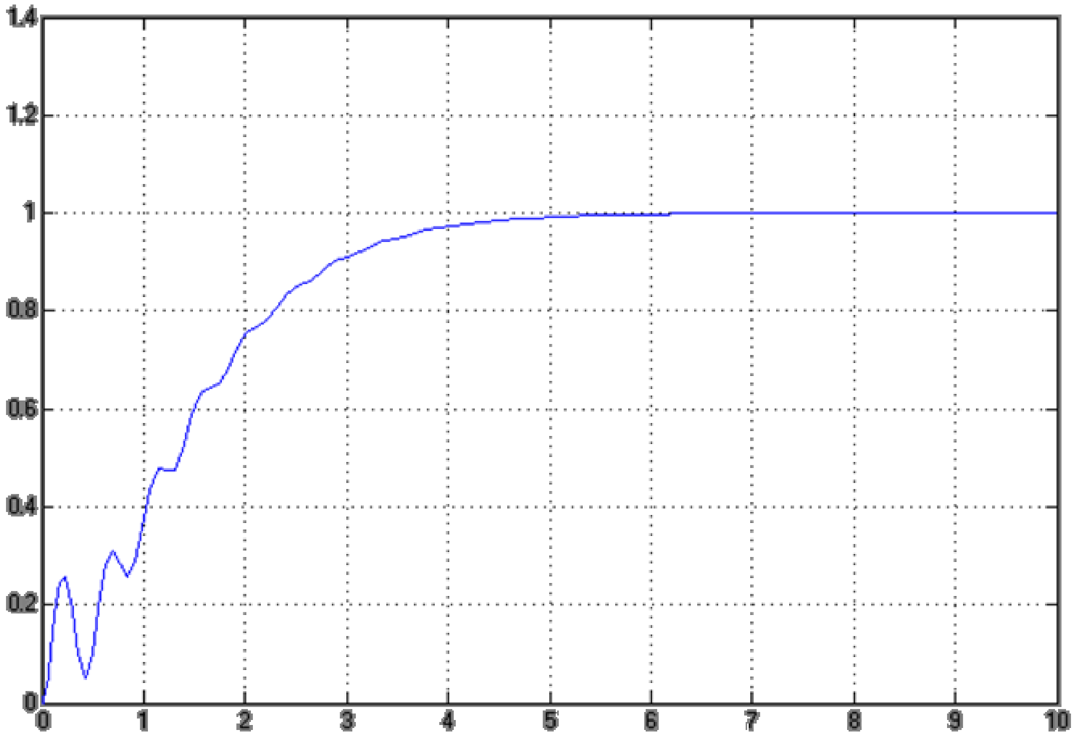


Figure 9.55 theta responce

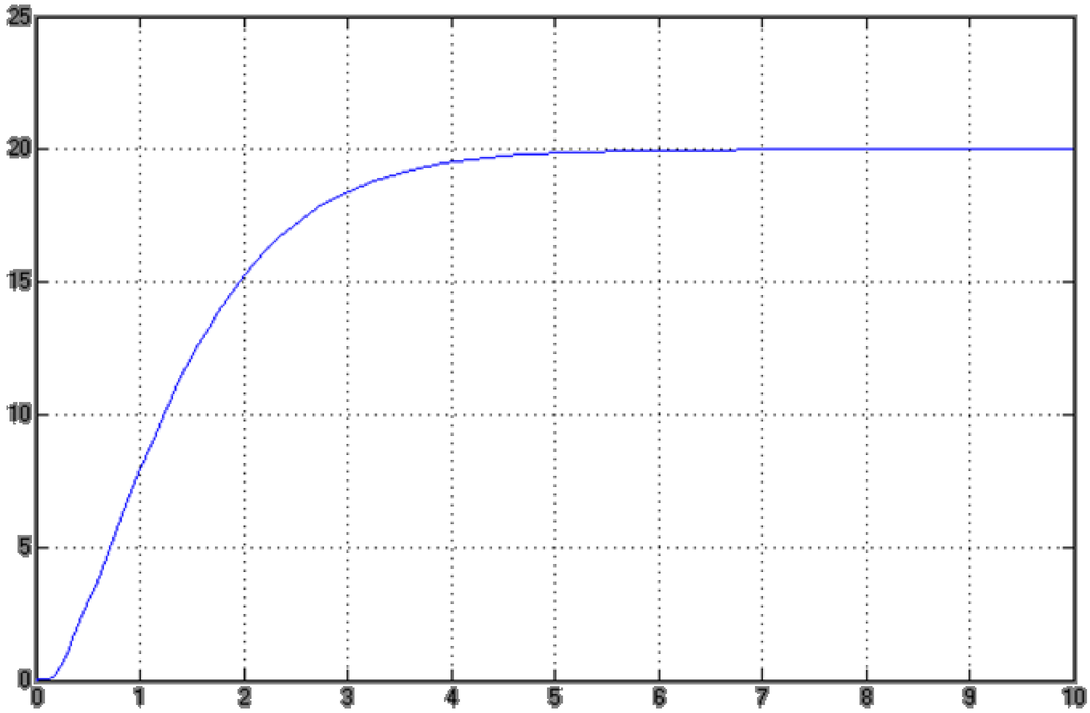


Figure 9.56 x responce

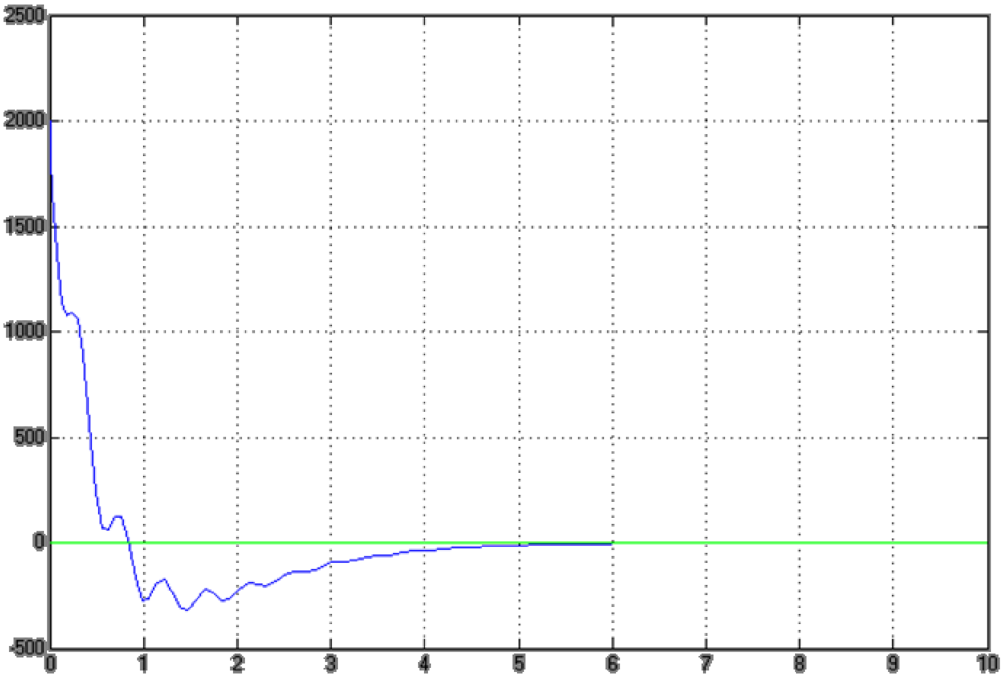


Figure 9.57 Control inputs

Controller parameters can be re-tuned until the results are satisfactory. Finally, the control inputs should be checked for saturation.

LQR controller will fail if the system is being effected by plant disturbances (e.g.friction) and/or sensor noises(e.g.quantization errors) due to the fact that estimated values is being corrupted. Rudolf Emil Kalman(1930) derived a filtering theorem around 1960 that could be used for filtering the corrupted data with Gaussian type disturbance and/or noises. We will not give the details cause there are dozens of reference books(like Grewall,2001) which are exracting the ideas behind the theorem and using the technics. LQG type controller is the generalization of the LQR type controllers with the augmented plant model with gaussian type disturbances and/or noises and using a Kalman filter for estimating the the states from the corrupted sensor data.

We first used used the system with standart estimator for comparison which is being effected by a white-noise signal added to the sensor input. The *Simulink* model, added white-noise and the results are like given below

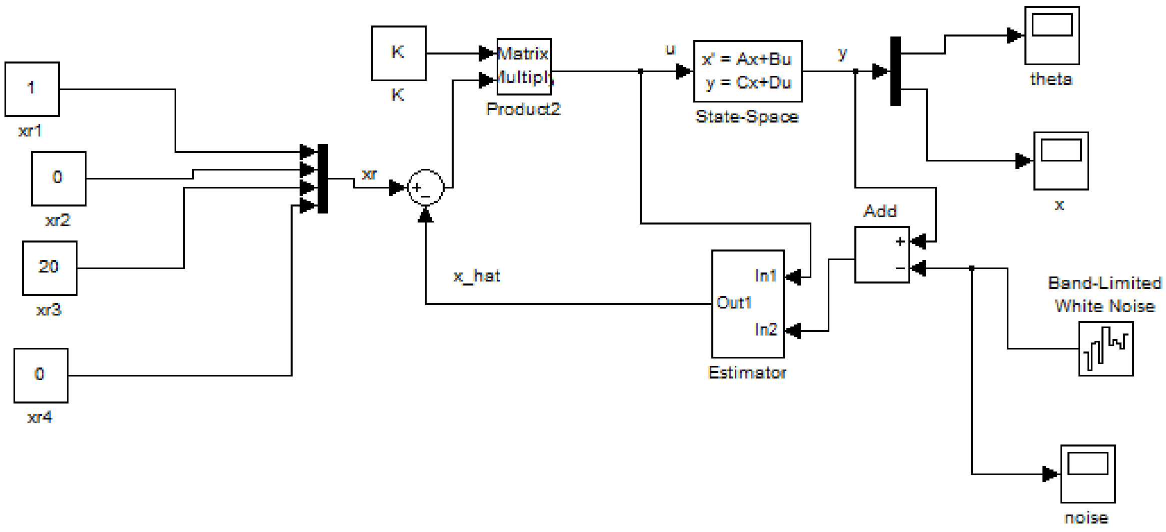


Figure 9.58 Simulink model with standart estimator

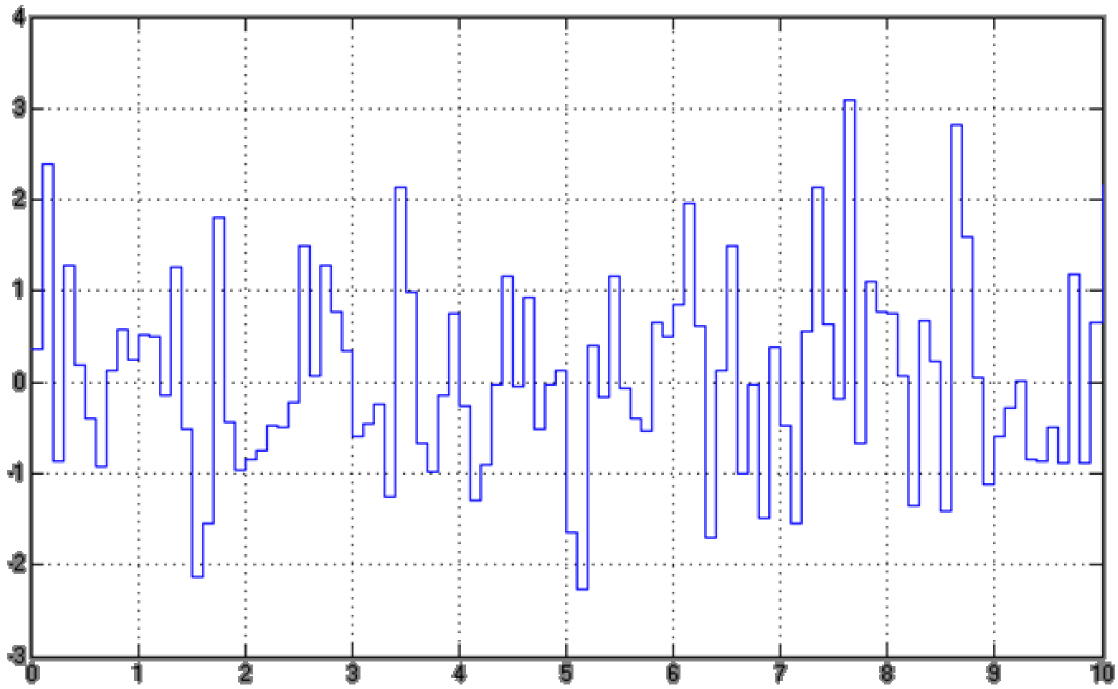


Figure 9.59 Added white-noise to the sensor input

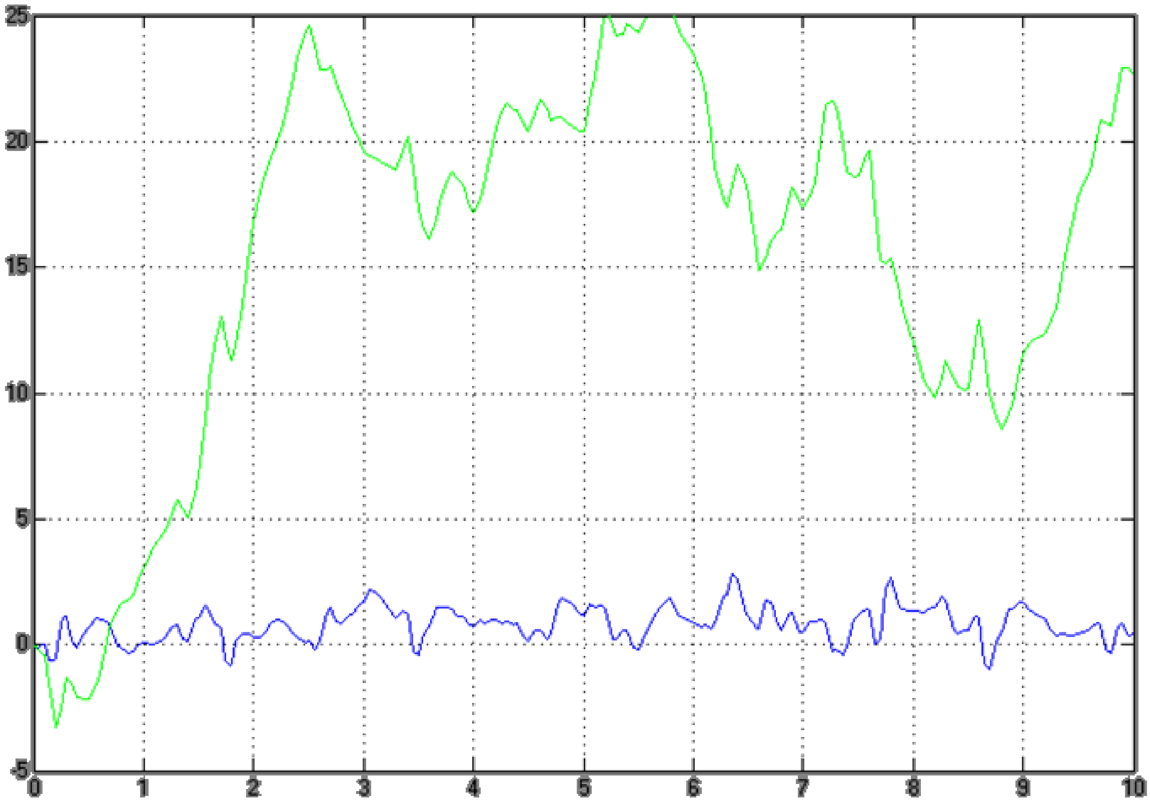


Figure 9.60 Estimated outputs with white-noise

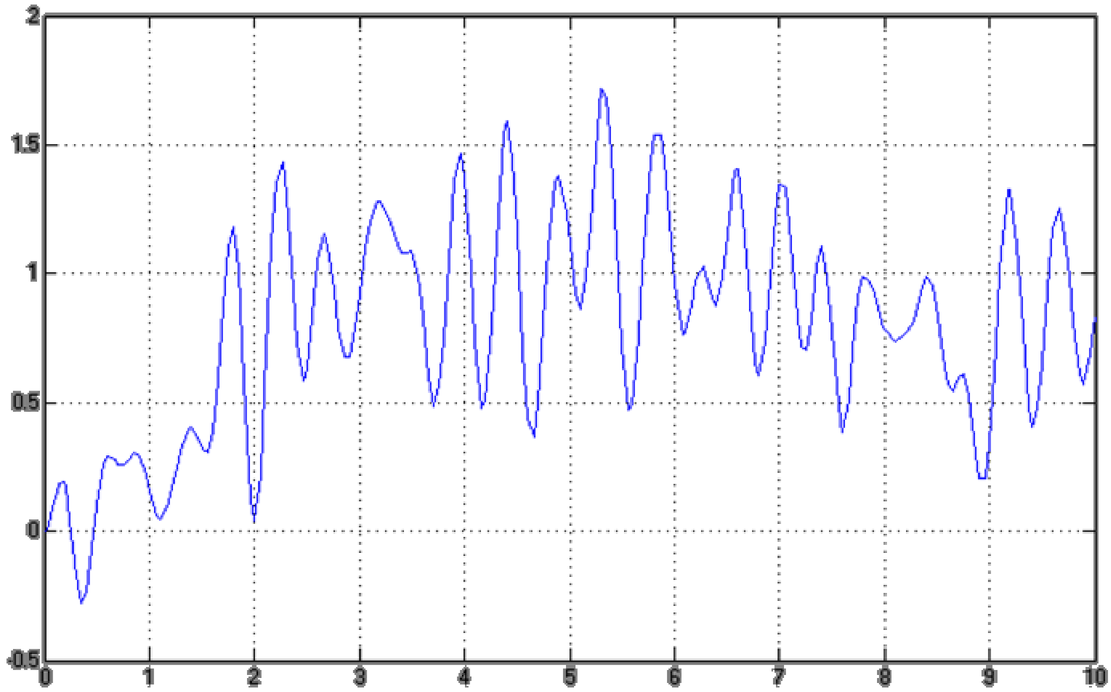


Figure 9.61 theta responce

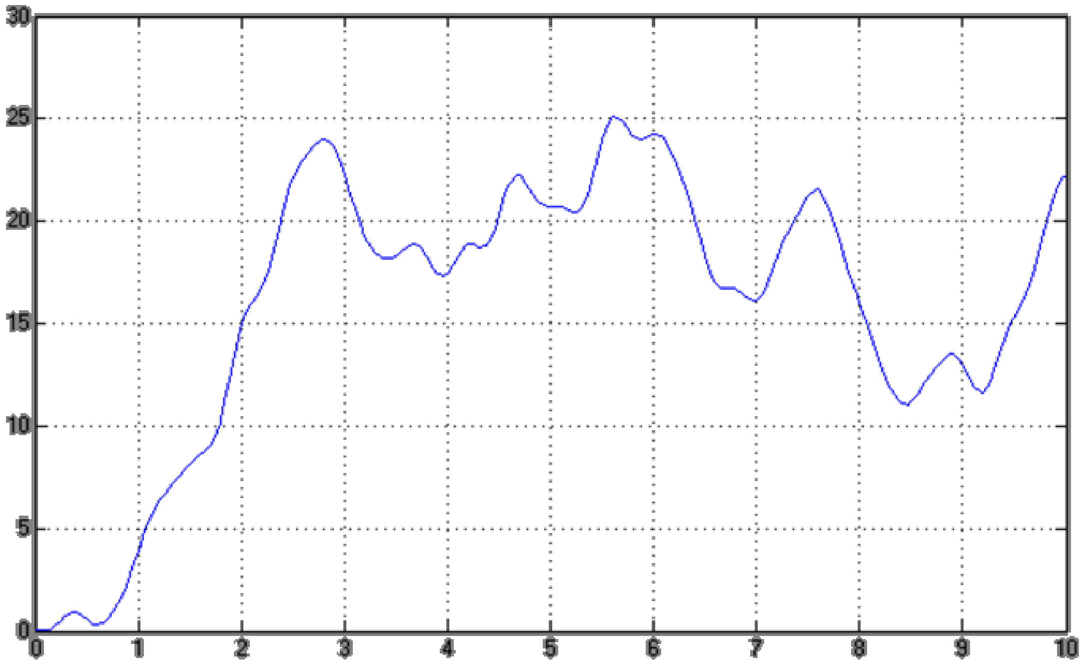


Figure 9.62 x responce

It’s clear that LQR type controller is failling with the sensor noise so, we should use LQG type controller. The Simulink model and the results are like given below. In figure x, the corrupted and filtered sensed variables can be seen. The parasitic effects have been filtered with the Kalman filter, so the outputs are under control again.

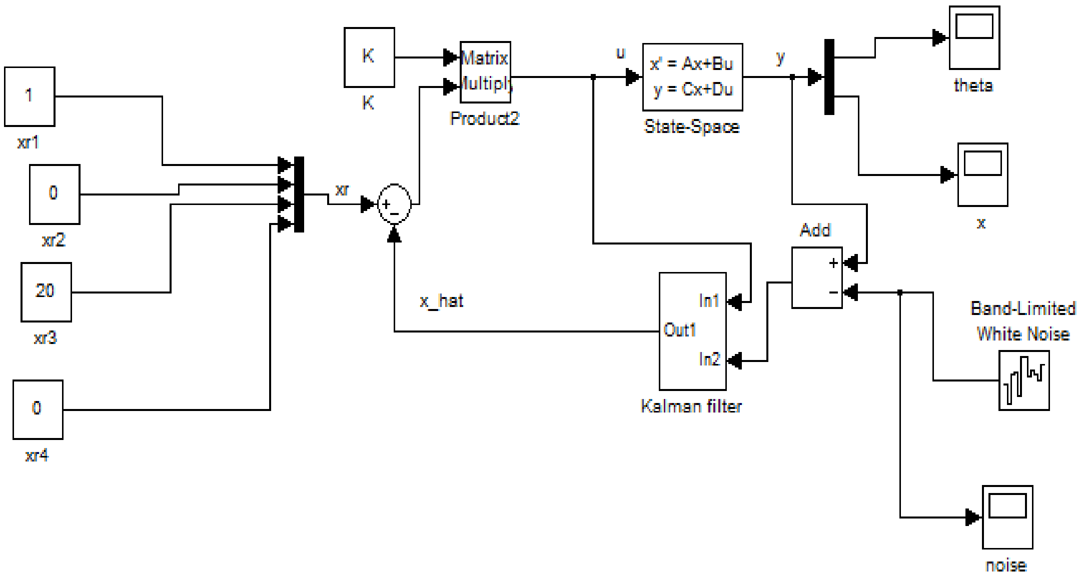


Figure 9.63 Simulink model with Kalman filter

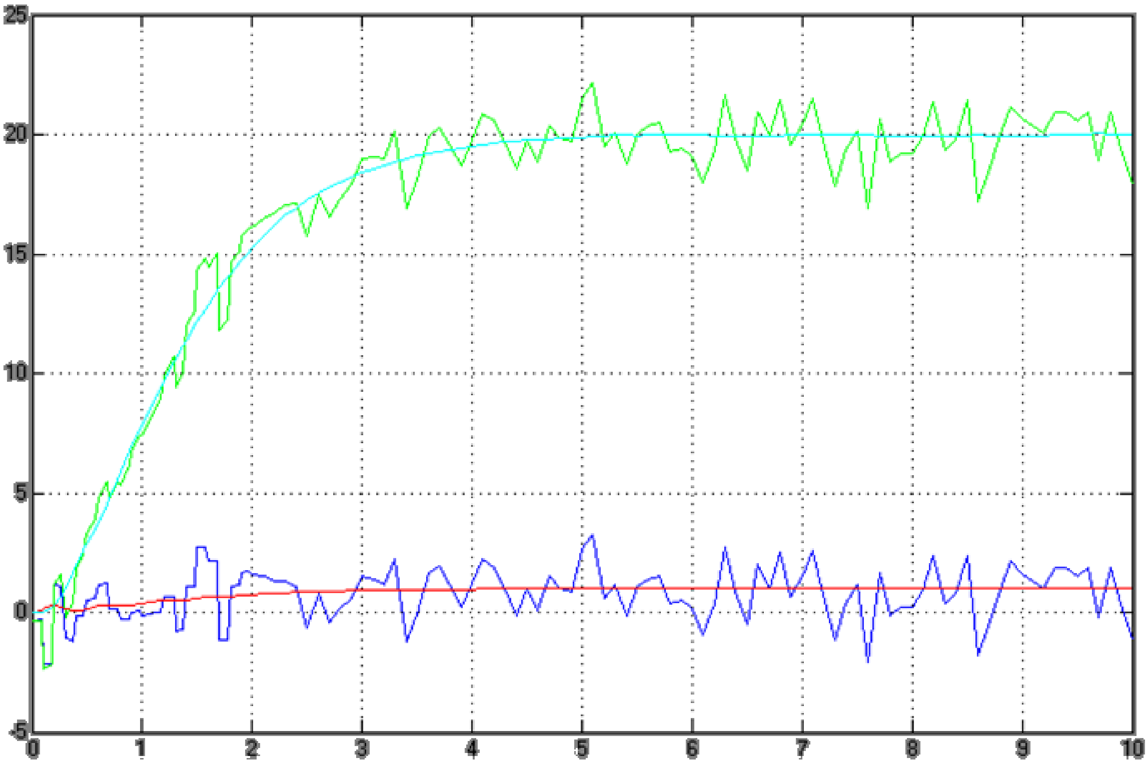


Figure 9.64 y with noise and estimated y with Kalman filter

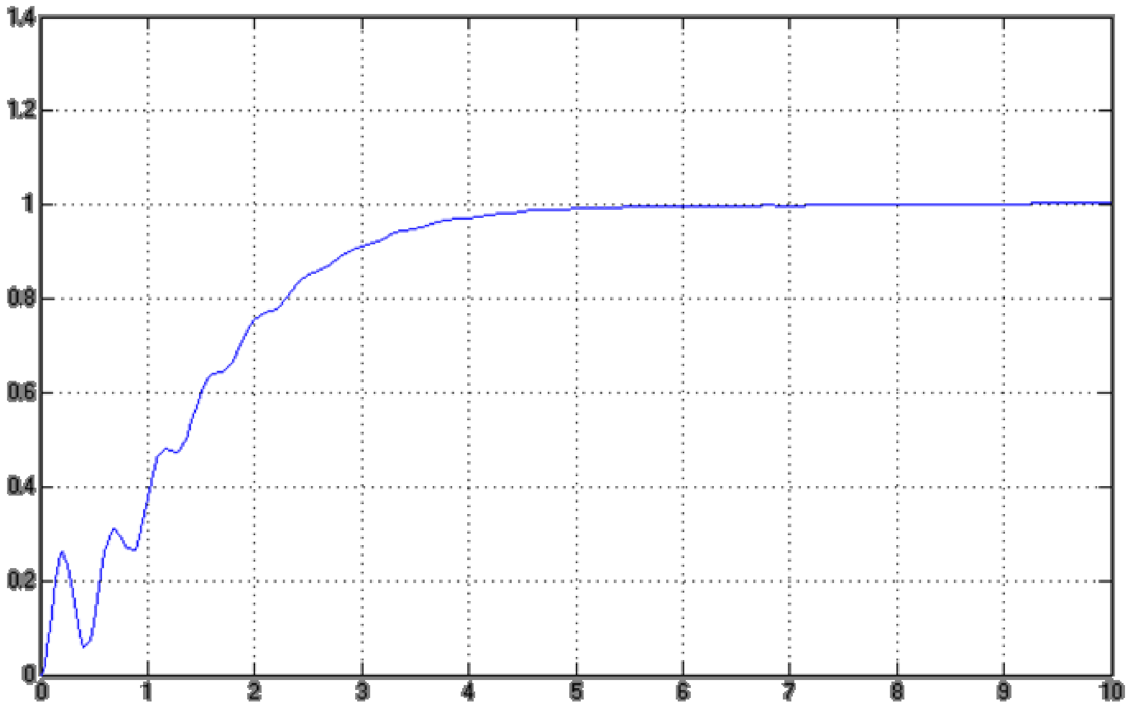


Figure 9.65 theta responce

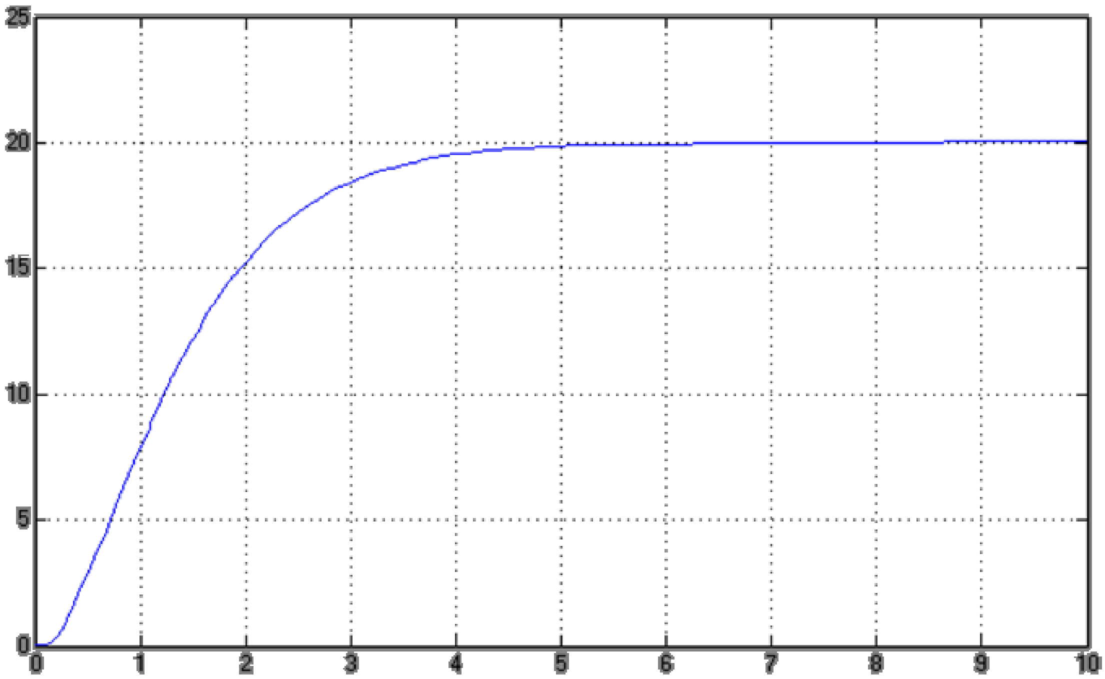


Figure 9.66 x responce

CHAPTER TEN
CONCLUSIONS

10.1 Overview of the Thesis

Thesis structured with two major modules. ”Automation systems” is the first and “design of an automated packaging machine” second.

In the first module:

- Industries that are using the automated solutions explained.
- Automation concepts in manufacturing explained.
- Automation system’s layout explained by using the building blocks approach, performance criterians for automated machines and trends in automation industry are given.
- Components for automation systems explained.
- Robotic systems explained in a general concept.
- Robotic applications in automation explained.
- Control systems and related concepts explained.
- Packaging machines and related automation solutions explained.

In the second module:

- Design concepts like the cost benefits, performance goals, etc. determined for the packaging machine.
- “Hard” components like actuators, mechanical elements, chasis, etc. designed and/or selected.
- “Soft” components like motion/motor controllers, power supply, control cabinet, etc. designed/selected and/or implemented.
- A cost analysis routed to base on the performance improvements on a “solid” ground cause it would determine the feasibility of the related and required modifications.

- Analytical performance analysis routed for preparing the observer for the expected machine operation.
- Control systems based performance improvements simulated.

10.2 Comments for the Designed Packaging Machine Operation

Designed machine have been manufactured/assembled/implemented and the operation performance observed. Machine operation practices showed that gripper holding head operation is vibrational as expected after the performance analysis section, but we did not preferred to realize any performance improvements cause of the time and budget limitations. Also,thought that results can be stated acceptable if the parts which are being packaged are not very fragile for the vibrational effects and the machine noise can be assumed in acceptable levels due to the fact that it will perform the packaging operation in an industrial facility.

10.3 Scope for the Further Studies

Further studies can include:

- Implementing/testing the controllers that have been designed in the performance improvements section
- Implementing/testing other controller types like sliding mode, adaptive and fuzzy logic.
- Augmenting the automated packaging solution by integrating related sub-systems, e.g. conveyors for feeding parts, vision systems for inspection,etc.

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APPENDIX A.1
INDUSTRIES

A.1 Agriculture

Agriculture refers to the production of food and goods through farming and forestry. Agriculture was the key development that led to the rise of civilization, with the husbandry of domesticated animals and plants(i.e. crops) creating food surpluses that enabled the development of more densely populated and stratified societies (Wikipedia,2009).

A.2 Forestry

Modern forestry industry generally concerns itself with: assisting forests to provide timber as raw material for wood products, wildlife habitat, natural water quality management, aesthetically appealing landscapes, biodiversity management, watershed management, erosion control and a 'sink' for atmospheric carbondioxide (Wikipedia,2009) .

A.3 Fishing

The fishing industry includes any industry or activity concerned with taking, culturing, processing, preserving, storing, transporting, marketing or selling fish or fish products(Wikipedia,2009) .

A.4 Livestock

Livestock industry includes any industry or activity concerned with production of meat, milk, fiber(sheep and goats produce wool and mohair; cows, deer, and sheep can make leather; and bones, hooves and horns) and fertilizers(Manure can be spread on fields to increase crop yields. This is an important reason why historically, plant and animal domestication have been intimately linked. Manure is also used to make plaster for walls and floors and can be used as a fuel for fires. The blood and bone of animals are also used as fertilizer)(Wikipedia,2009).

A.5 Quarries

A quarry is a type of open-pit mine from which rock or minerals are extracted. Quarries are generally used for extracting building materials, such as dimension stone. Types of rock extracted from quarries include: Cinder, Chalk, China Clay, Clay, Coal, Coquina, Construction aggregate(sand and gravel), Globigerina Limestone(Malta), Granite, Gritstone, Gypsum, Limestone ,Marble ,Ores ,Phosphate rock, Sandstone and Slate(Wikipedia,2009) .

A.6 Mining

Mining industry includes any industry or activity concerned with the extraction of valuable minerals or other geological materials from the earth, usually from an ore body, vein or coal seam. Materials recovered by mining include base metals, precious metals, iron, uranium, coal, diamonds, limestone, oil shale, rock salt and potash(Wikipedia,2009) .

A.7 Petroleum

The petroleum industry includes the global processes of exploration, extraction, refining, transporting(often by oil tankers and pipelines), and marketing petroleum products. The largest volume products of the industry are fuel oil and gasoline (petrol). Petroleum is also the raw material for many chemical products, including pharmaceuticals, solvents, fertilizers, pesticides, and plastics(Wikipedia,2009) .

A.8 Aerospace

Aerospace industry includes the activities for producing aircraft(An aircraft is a vehicle which is able to fly by being supported by the air, or in general, the atmosphere, of a planet. Examples include balloons, airplanes and helicopters. Objects which fly but which are not supported by the air, such as most rockets and missiles, are not aircraft), guided missiles, space vehicles, aircraft engines, propulsion units, and related parts. Most of the industry is geared toward governmental works(Wikipedia,2009) .

A.9 Automotive

The automotive industry designs, develops, manufactures, markets, and sells the world's motor vehicles(Wikipedia,2009) .

A.10 Basic&Fabricated metals

The basic&Fabricated metals industry includes establishments that smelt and/or refine ferrous and nonferrous metals from ore, pig or scrap, using electrometallurgical and other process metallurgical techniques. Establishments in this industry also manufacture metal alloys and superalloys by introducing other chemical elements to pure metals. The output of smelting and refining is used in rolling, drawing, and extruding operations to make sheet, strip, bar, rod, or wire, and in molten form to make castings and other basic metal products(Texas Office of the Governer,2009 and Holzner,2006)

A.11 Building materials

Building materials industry includes the activities for production of building materials namely cement, concrete, aggregates, gypsum, bricks and roof tiles(Moody’s Investors Service,2006).

A.12 Chemicals

The chemicals industry comprises the companies that produce industrial chemicals by the methods involves the use of chemical processes such as chemical reactions and refining.

Sales of the chemical business can be divided into a few broad categories, including basic chemicals(about 35 to 37 percent of the dollar output), life sciences (30 percent), specialty chemicals (20 to 25 percent) and consumer products (about 10 percent)(Wikipedia,2009).

A.13 Computer

Computer industry is a collective term used to describe the whole range of businesses involved in developing computer software, designing computer hardware and computer networking infrastructures, the manufacture of computer components and the provision of information technology services(Wikipedia,2009) .

A.14 Construction

The construction industry is divided into three major segments. The *c*onstruction of building segment includes contractors, usually called general contractors, who build residential, industrial, commercial, and other buildings. Heavy and civil engineering construction contractors build sewers, roads, highways, bridges, tunnels, and other projects. Specialty trade contractors perform specialized activities related to construction such as carpentry, painting, plumbing, and electrical work (BLS,2009).

A.15 Electronics

Electronics industry includes the activities for the production of electronic devices and components like semi-conductors, ICs, PCBs, microprocessors, microcontrollers, DSPs,etc.(Wikipedia,2009) .

A.16 Food&Beverage processing

Food&Beverage processing industry includes methods and techniques used to transform raw ingredients into food&beverage for human consumption. Food&beverage processing takes clean, harvested or slaughtered and butchered components and uses them to produce marketable food&beverage products (Wikipedia,2009).

A.17 Glass&Ceramics

The glass industry consists of four major segments: container glass(bottles,jars, etc.); flat glass(windows, windshields,mirrors, etc.); fiberglass(building insulation and textile fibers); and specialty glass(cookware, flat panel displays, light bulbs, fiber optics, medical equipment, etc.).

Ceramics industry includes the activities for the production of ceramics by consisting of four major segments: Monolithic ceramics(aluminum oxide (Al_2O_3), silicon nitride(Si_3N_4), silicon carbide(SiC), zirconium oxide(ZrO_2), transformation-toughened zirconia(TTZ), transformation-toughened alumina(TTA), and aluminum nitride(AlN), coatings, refractories and composite ceramics(Wikipedia,2009).

A.18 Furniture

Furniture is the mass noun for the movable objects which may support the human body(seating furniture and beds), provide storage, or hold objects on horizontal surfaces above the ground. Storage furniture(which often makes use of doors, drawers, and shelves) is used to hold or contain smaller objects such as clothes, tools, books, and household goods(Wikipedia,2009) .

A.19 Heavy machinery

Heavy machinery industry includes the activities for the production of machines and equipments for the “heavy” industries that are more capital intensive or as requiring greater or more advanced resources, facilities or management like agriculture, construction, mining,etc.(Wikipedia,2009 and Norteast Iowa Business Network,2004).

A.20 Home appliances

Appliance may refer to a device with a narrow function. Home appliances industry includes activities for the production of the home appliances that are electrical/mechanical appliances which accomplish some household functions, such as cooking or cleaning. Traditionally, home appliances are classified into: Major appliances(or "White goods") as CD and DVD players, televisions, video game consoles, etc. and Small appliances(or "Brown goods") as air conditioner, dish washer, refrigerator, microwave oven, etc.(Wikipedia,2009) .

A.21 Paper

Paper industry includes the activities for the production of paper and paper related products.

There are five major steps to the papermaking process: mechanical preparation of the wood into wood chips, wood digestion(pulping) to form pulp, pulp whitening (bleaching), pulp stock preparation, and finally paper formation(Emerson,2004).

A.22 Pharmaceuticals

The pharmaceuticals industry develops, produces, and markets *drugs* licensed for use as medications. Pharmaceutical companies can deal in generic and/or brand medications. They are subject to a variety of laws and regulations regarding the patenting, testing and marketing of drugs(Wikipedia,2009).

A.23 Plastics

The plastics industry manufactures polymer materials and offers services in plastics important to a range of industries, including: aerospace, building and construction, electronics, packaging, and transportation(Wikipedia,2009) .

A.24 Publishing

Publishing industry includes: the stages of the development, acquisition, copyediting, graphic design, production – printing (and its electronic equivalents), and marketing and distribution of newspapers, magazines, books, literary works, musical works, software and other works dealing with information, including the electronic media(Wikipedia,2009) .

A.25 Textile&Apparel

The textile industry(also known in the United Kingdom and Australia as the Rag Trade) is a term used for industries primarily concerned with the design or manufacture of clothing as well as the distribution and use of textiles (Wikipedia,2009) .

A.26 Utilities

The term utilities generally refers to the set of services consumed by the public namely electricity, natural gas, water, sewage,etc. Utilities industry includes the activities for the production/service of the utilities(Wikipedia,2009) .

A.27 Entertainment

The entertainment industry(much of which is informally known as show business or show biz) consists of a large number of sub-industries devoted to entertainment. However, the term is often used in the mass media to describe the mass media companies that control the distribution and manufacture of mass media entertainment. In the popular parlance, the term *show biz* in particular connotes the commercially popular performing arts, especially musical theatre, vaudeville, comedy, film, and music(Wikipedia,2009) .

A.28 Financial services

Financial services refer to services provided by the finance industry. The finance industry encompasses a broad range of organizations that deal with the management of money. Among these organizations are *banks*, *credit card companies*, *insurance companies*, *consumer finance companies*, *stock brokerages*, *investment funds* and *some government sponsored enterprises*. As of 2004, the financial services industry represented 20% of the market capitalization of the S&P 500 in the United States (Wikipedia,2009) .

A.29 Health care

Health care, or healthcare, refers to the treatment and management of illness, and the preservation of health through services offered by the medical, dental, pharmaceutical, clinical laboratory sciences(*in vitro* diagnostics), nursing, and allied health professions. Health care embraces all the goods and services designed to promote health, including “preventive, curative and palliative interventions, whether directed to individuals or to populations”.Before the term *health care* became popular, English-speakers referred to *medicine* or to the *health sector* and spoke of the treatment and prevention of illness and disease(Wikipedia,2009).

A.30 Hospitality

Hospitality frequently refers to the hospitality industry jobs for *hotels*, *restaurants*, *casinos*, *catering*, *resorts*, *clubs* and any other service positions (Wikipedia,2009) .

A.31 Real estate

The terms *real estate* and *real property* are used primarily in common law, while civil law jurisdictions refer instead to immovable property. With the development of private property ownership, real estate has become a major area of business. Purchasing real estate requires a significant investment, and each parcel of land has unique characteristics, so the real estate industry has evolved into several distinct fields(Wikipedia,2009).

A.32 Telecommunication(also called Telecom)

Telecommunication is the assisted transmission of signals over a distance for the purpose of communication. In earlier times, this may have involved the use of smoke signals, drums, semaphore, flags or heliograph. In modern times, telecommunication typically involves the use of electronic devices such as the *telephone*, *television*, *radio* or *computer*. Early inventors in the field of telecommunication include Alexander Graham Bell, Guglielmo Marconi and John Logie Baird. Telecom is an important part of the world economy and the telecommunication industry's revenue was estimated to be $1.2 trillion in 2006(Wikipedia,2009) .

A.33 Tourism

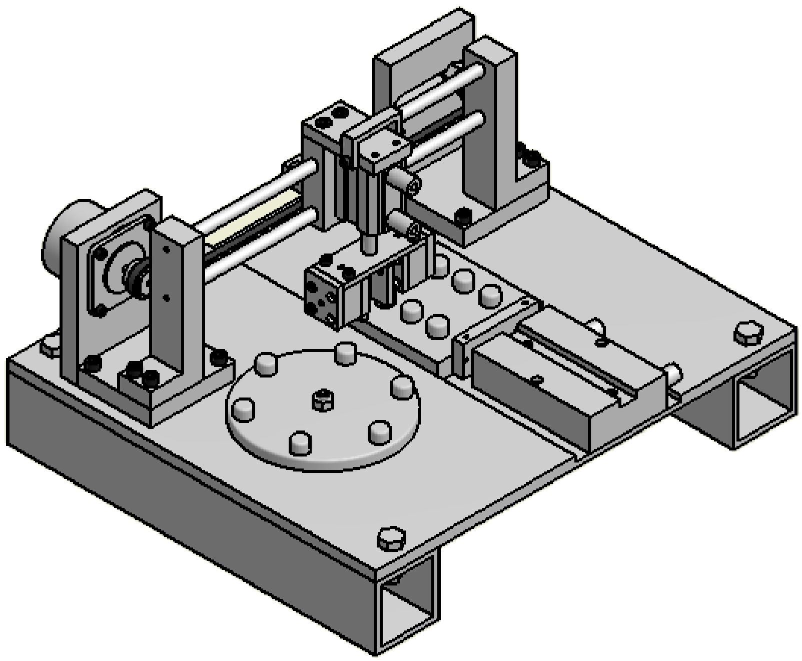
Tourism is travel for recreational, leisure or business purposes. The World Tourism Organization defines tourists as people who "travel to and stay in places outside their usual environment for more than twenty-four(24) hours and not more than one consecutive year for leisure, business and other purposes not related to the exercise of an activity remunerated from within the place visited". Tourism has become a popular global leisure activity. In 2007, there were over 903 million international tourist arrivals, with a growth of 6.6% as compared to 2006. International tourist receipts were USD 856 billion in 2007(Wikipedia,2009) .

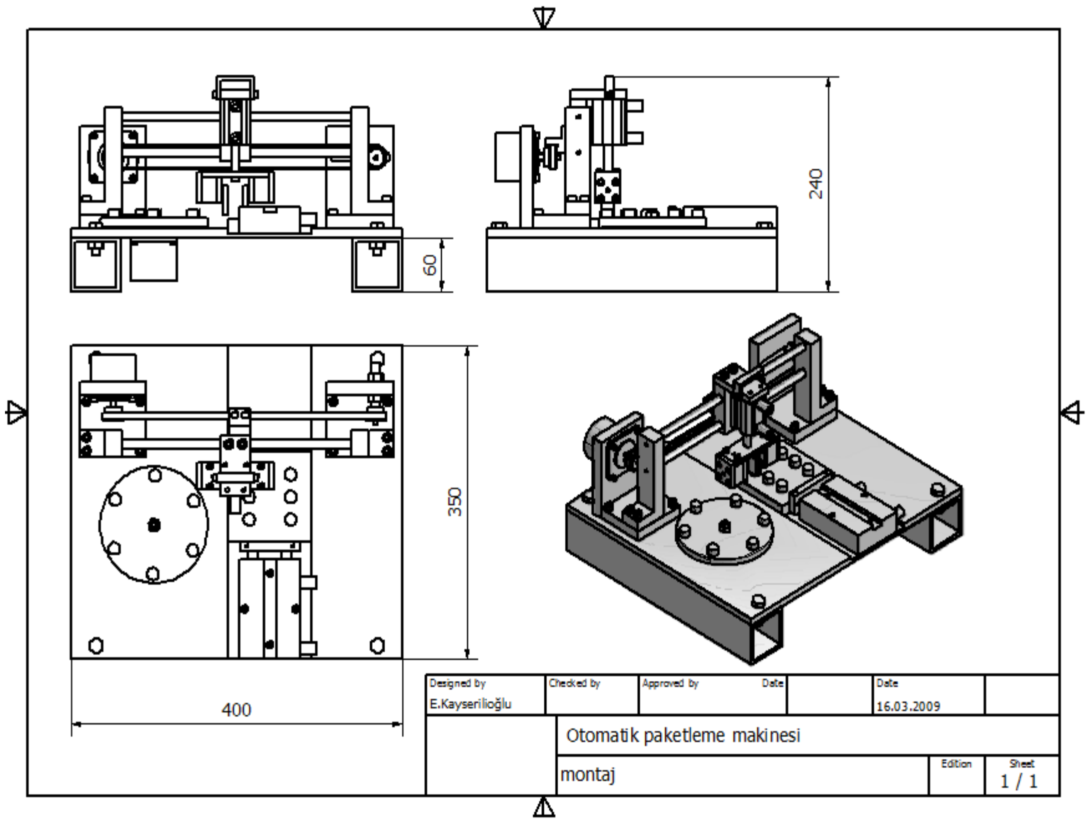
A.34 Transportation

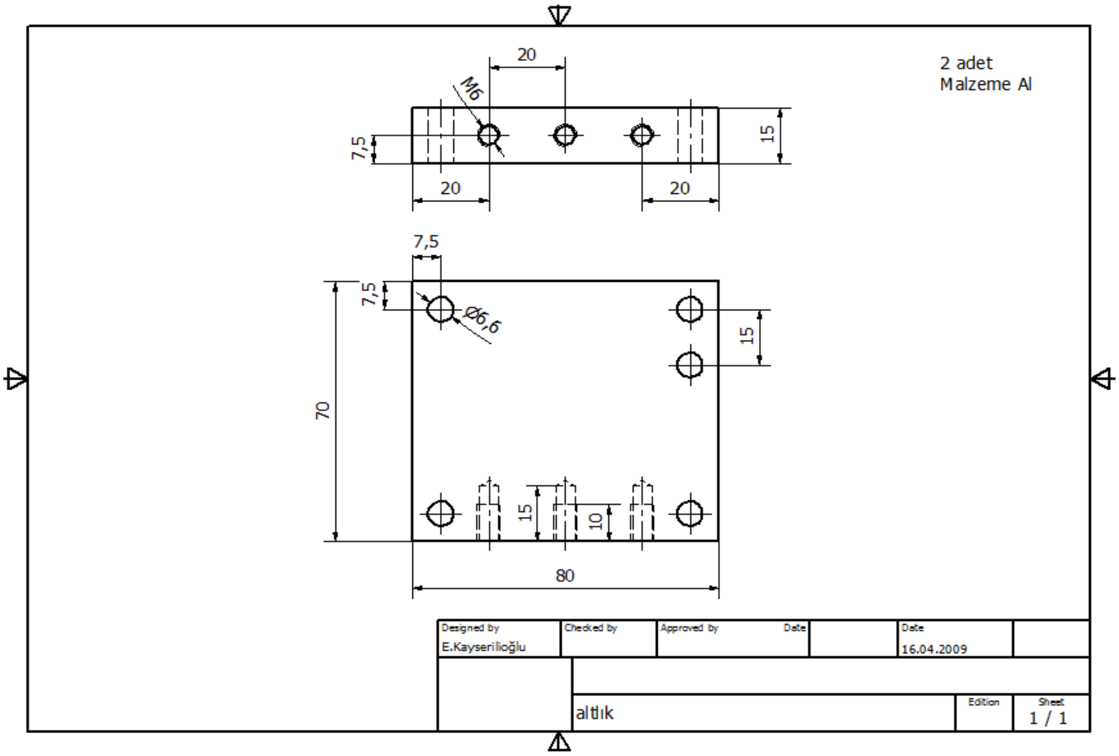
Transport or transportation is the movement of people and goods from one location to another. Transport is performed by various modes, such as air, rail, road, water, cable, pipeline and space. The field can be divided into infrastructure, vehicles, and operations(Wikipedia,2009).

APPENDIX A.2

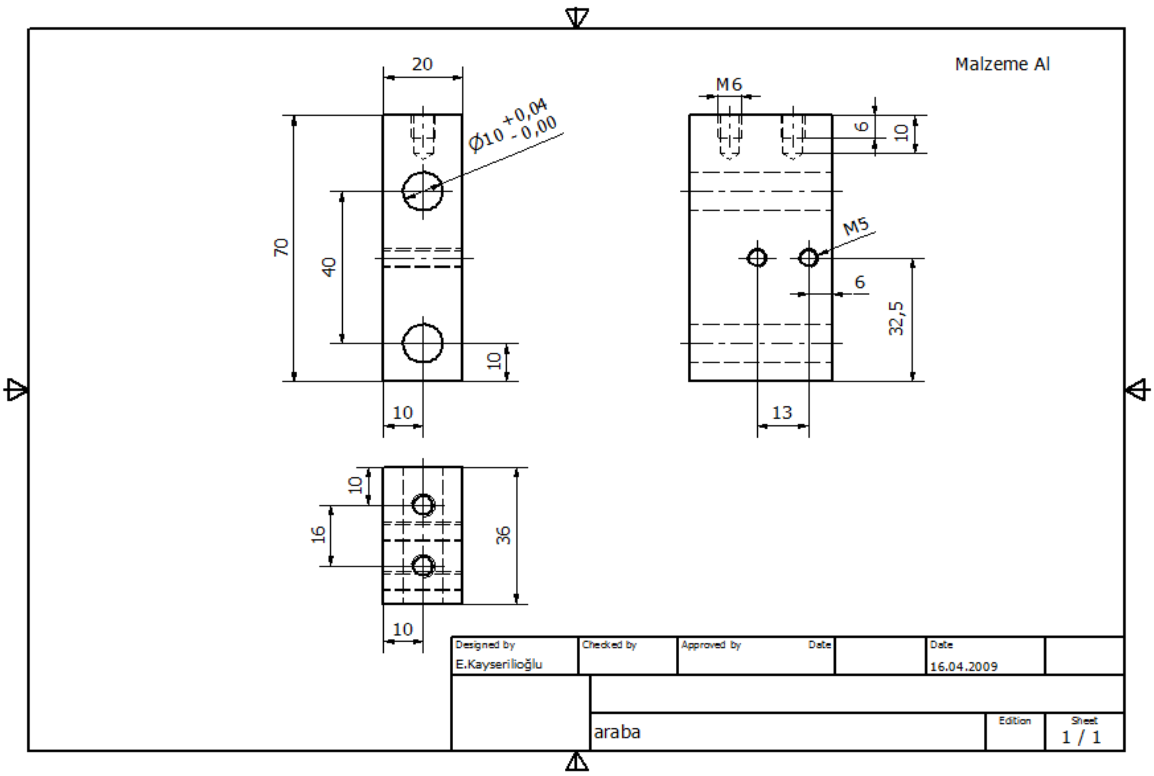
TECHNICAL DRAWINGS FOR THE PACKAGING MACHINE



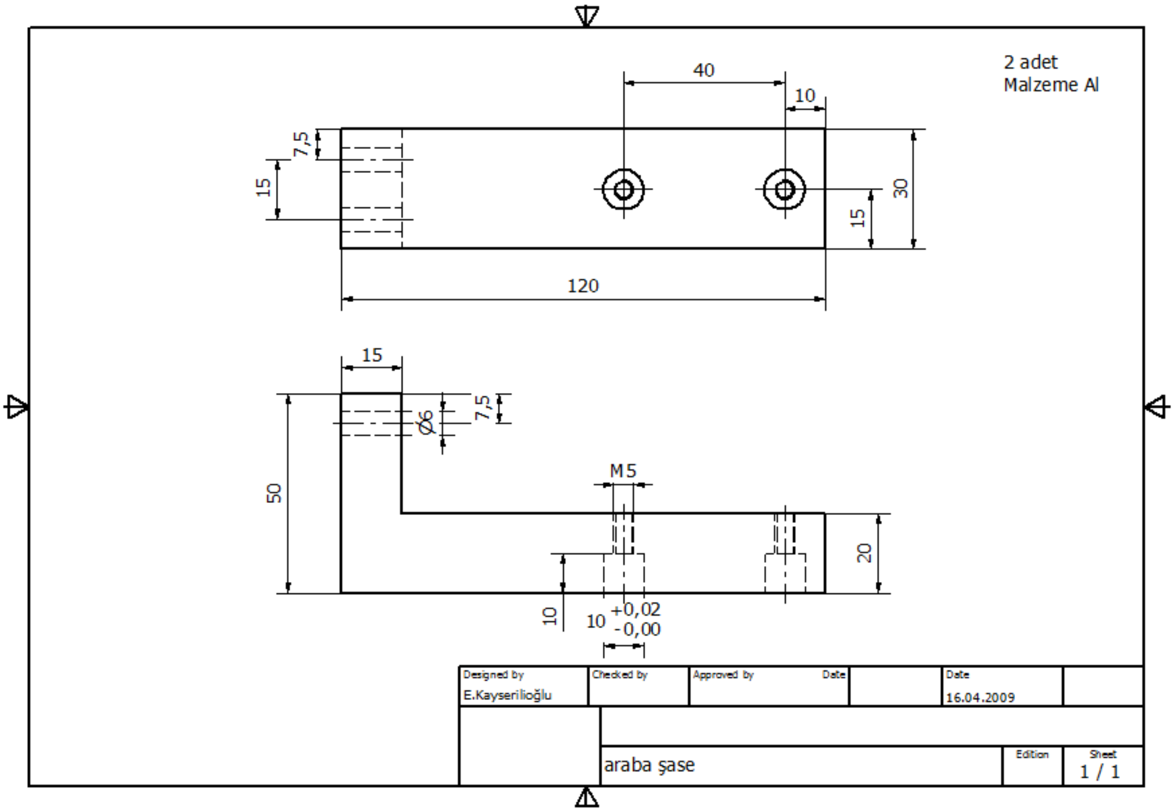


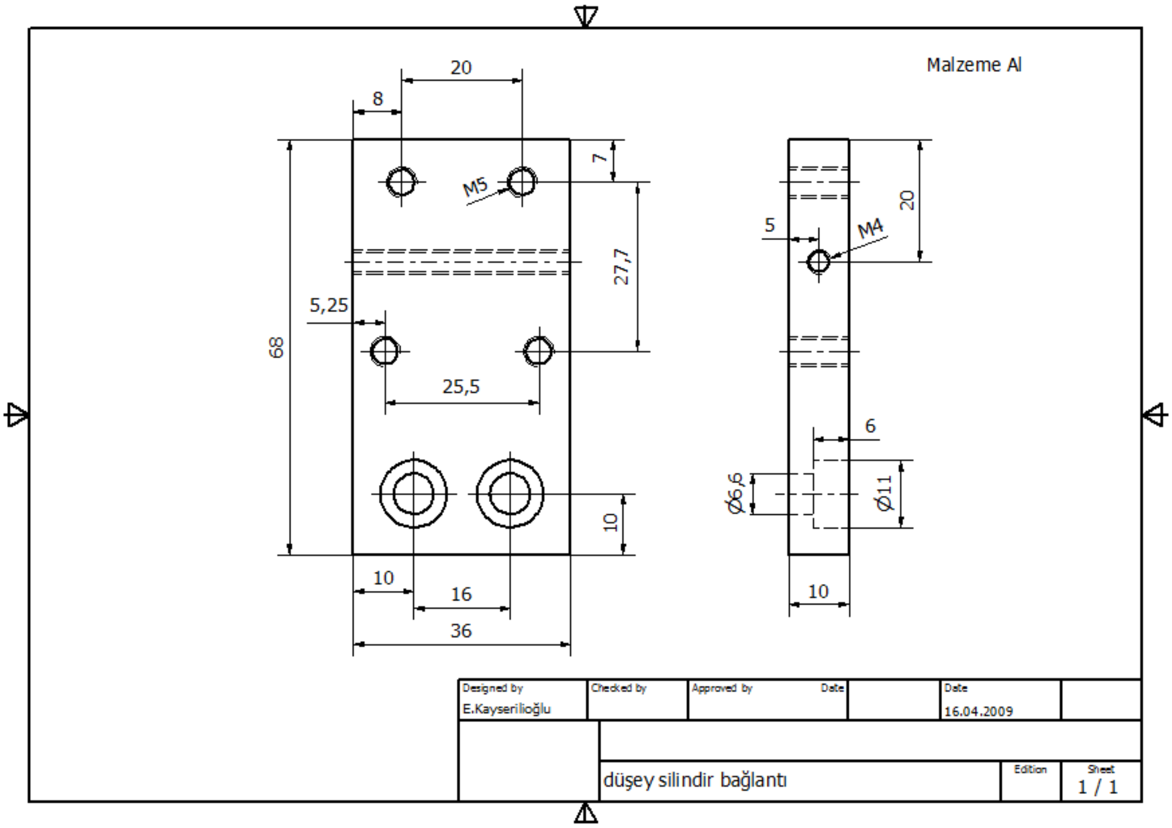


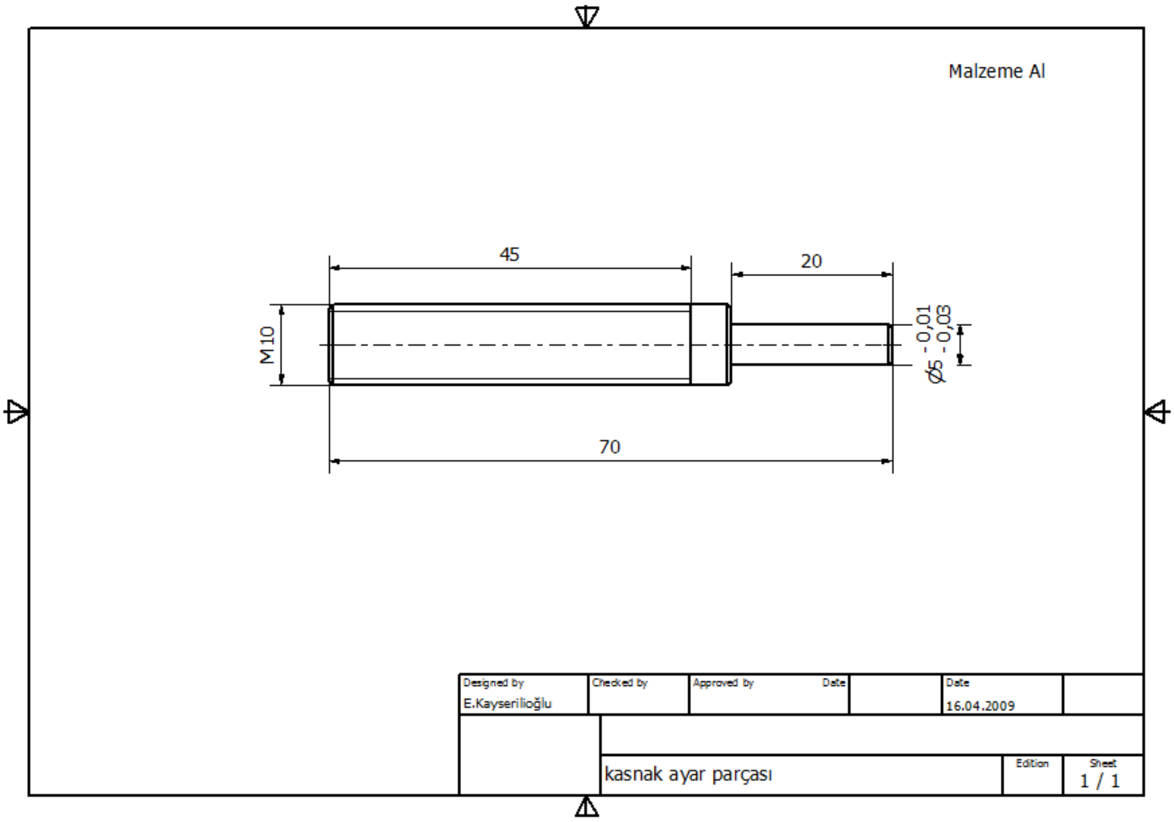
2 adet
Malzeme Al
20
M6
7,5
15
20
20
7,5
7,5
Ø6,6
15
70
15
10
80
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
altlık
Edition
Sheet
1 / 1

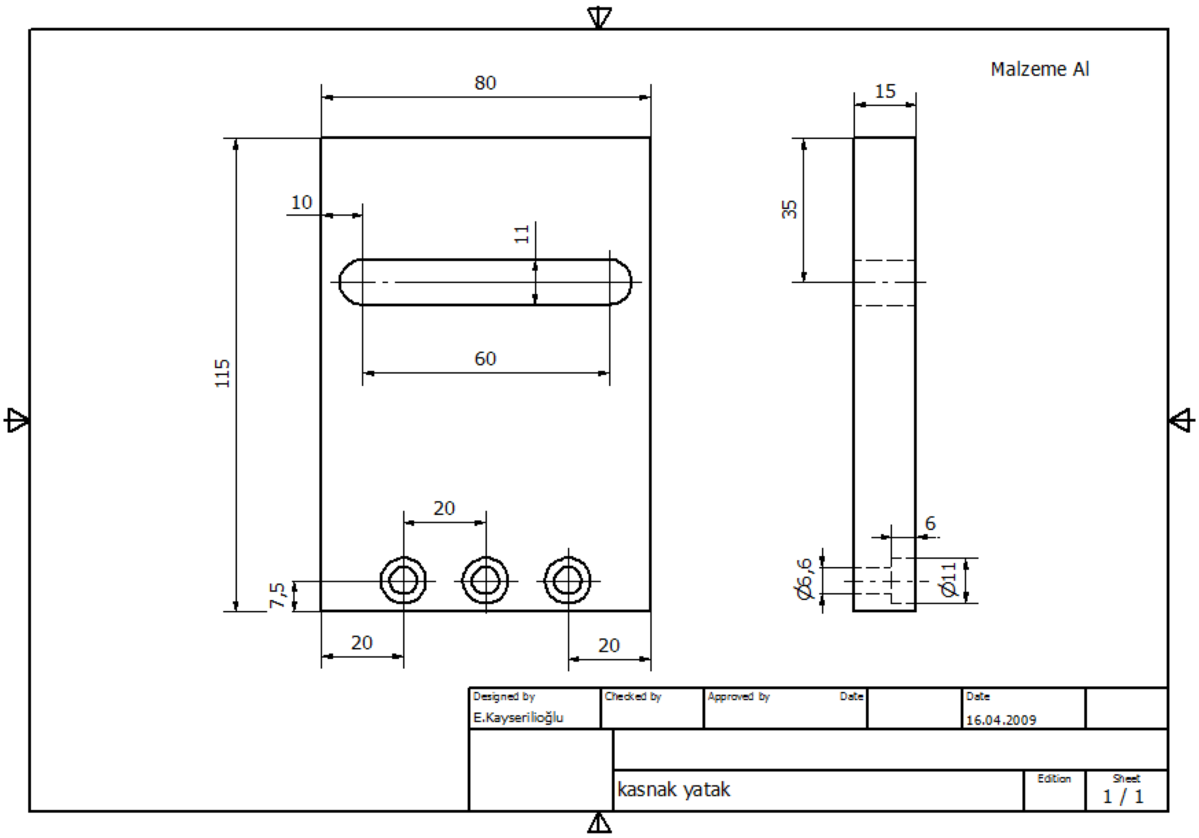


Malzeme Al
20
Ø10 +0,04 -0,00
70
40
10
10
M6
6
10
M5
6
32,5
13
10
16
36
10
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
araba
Edition
Sheet
1 / 1


2 adet
Malzeme Al
40
10
7,5
15
30
15
120
15
Ø6
7,5
50
M5
20
10
10 +0,02 -0,00
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
Edition
Sheet
araba şase
1 / 1


Malzeme Al
20
8
7
M5
27,7
68
5,25
25,5
10
10
16
36
20
5
M4
6
Ø6,6
Ø11
10
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
Edition
Sheet
düşey silindir bağlantı
1 / 1


Malzeme Al
45
20
M10
Ø5 -0,01 -0,03
70
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
kasnak ayar parçası
Edition
Sheet
1 / 1


Malzeme Al
80
15
10
11
35
60
115
20
6
7,5
Ø6,6
Ø11
20
20
Designed by
E.Kayserilioğlu
Checked by
Approved by
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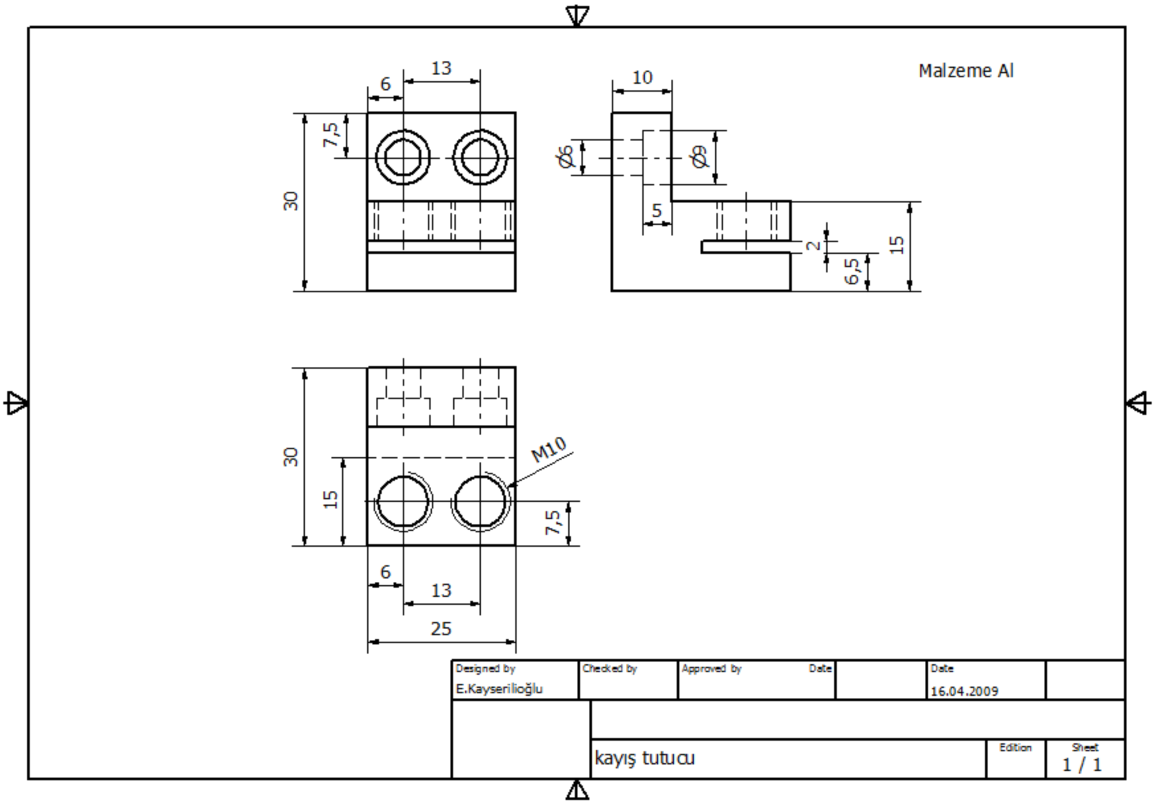
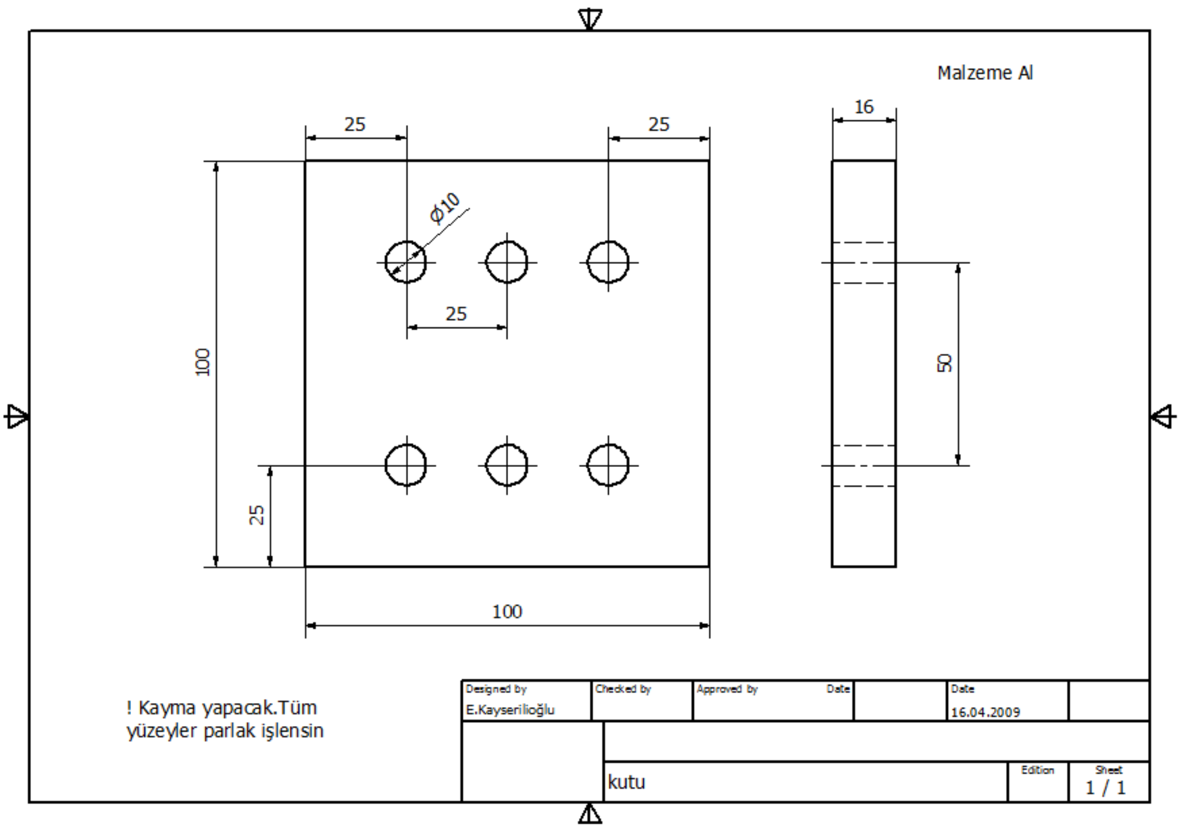
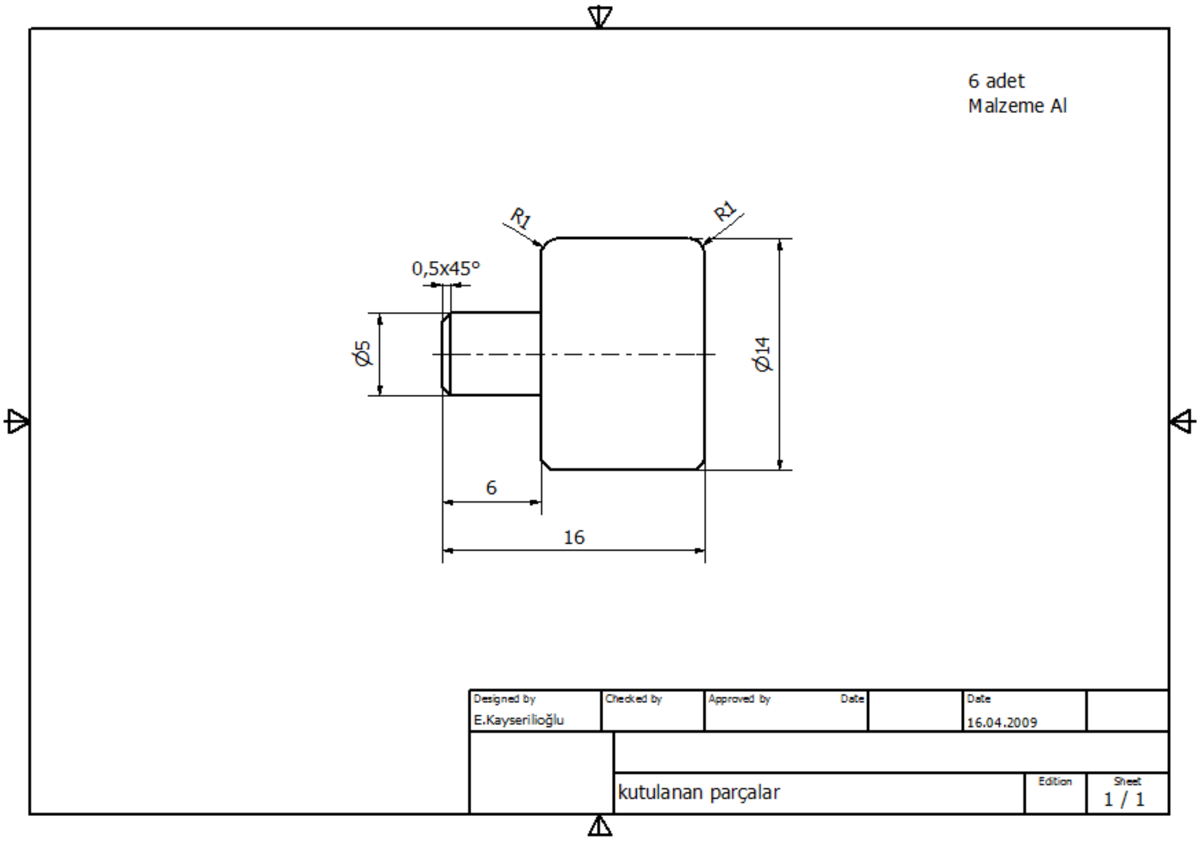
Date
16.04.2009
kasnak yatak
Edition
Sheet
1 / 1

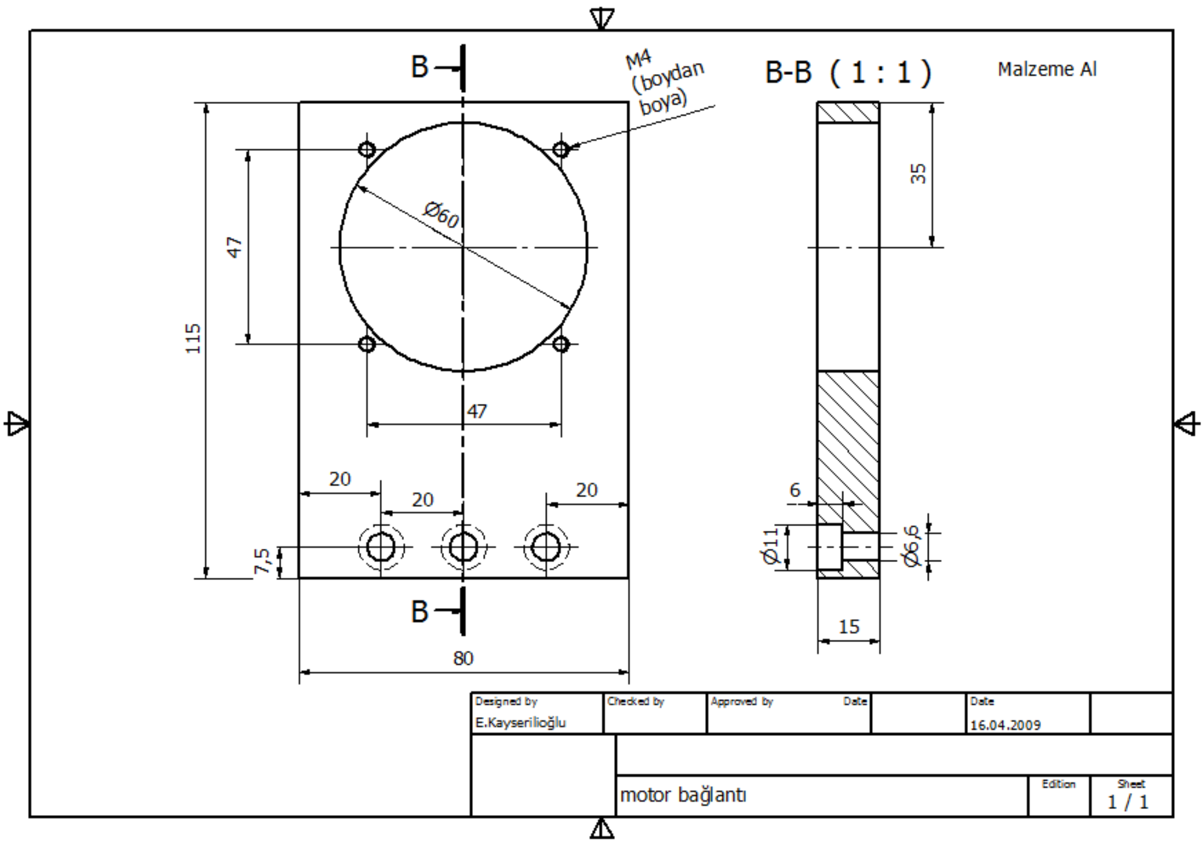


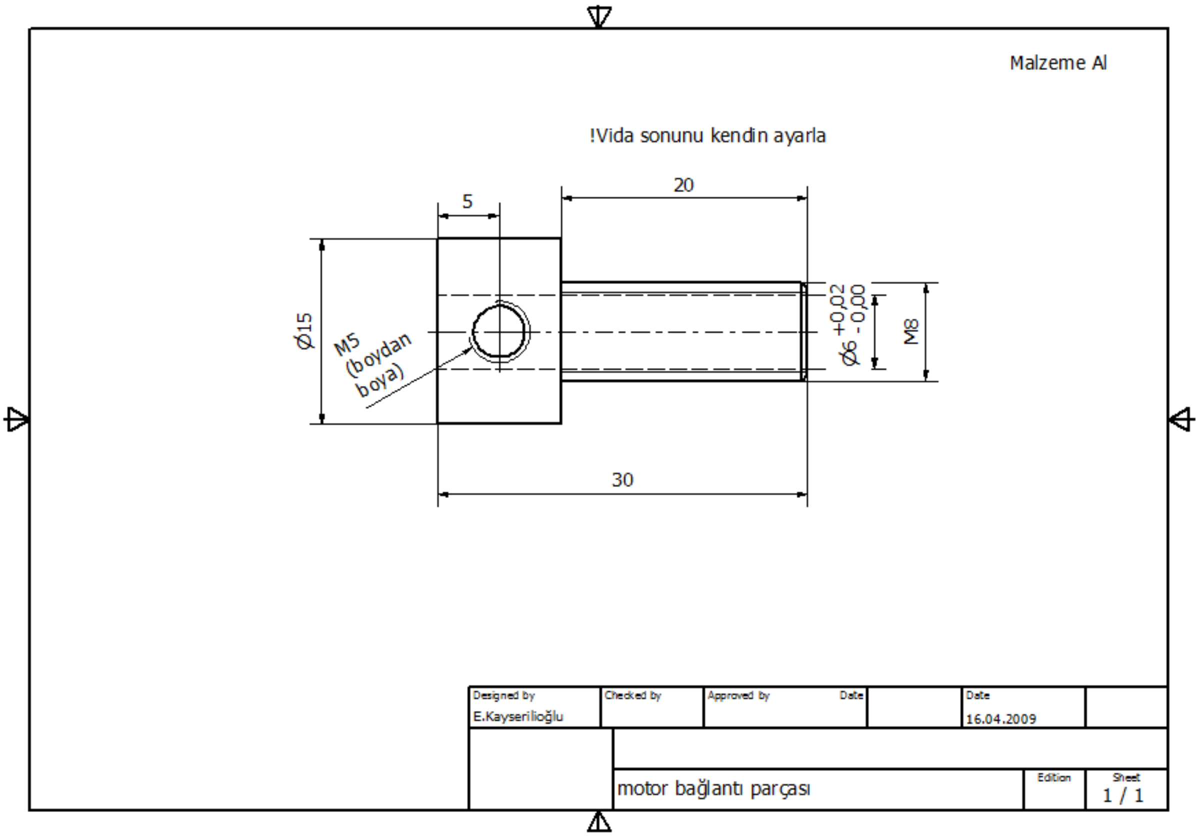
Malzeme Al
6
13
10
7,5
30
Ø6
Ø9
5
2
15
6,5
M10
15
7,5
25
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
kayış tutucu
Edition
Sheet
1 / 1

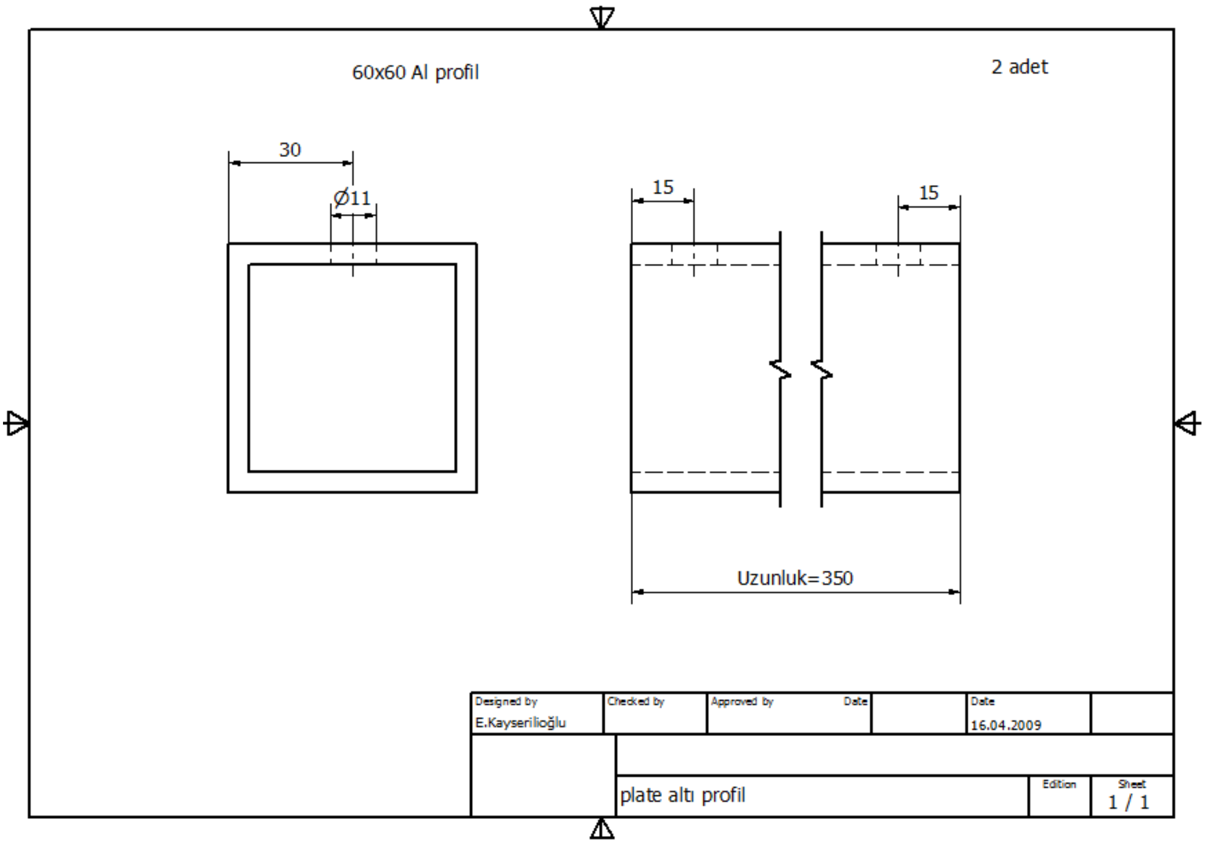


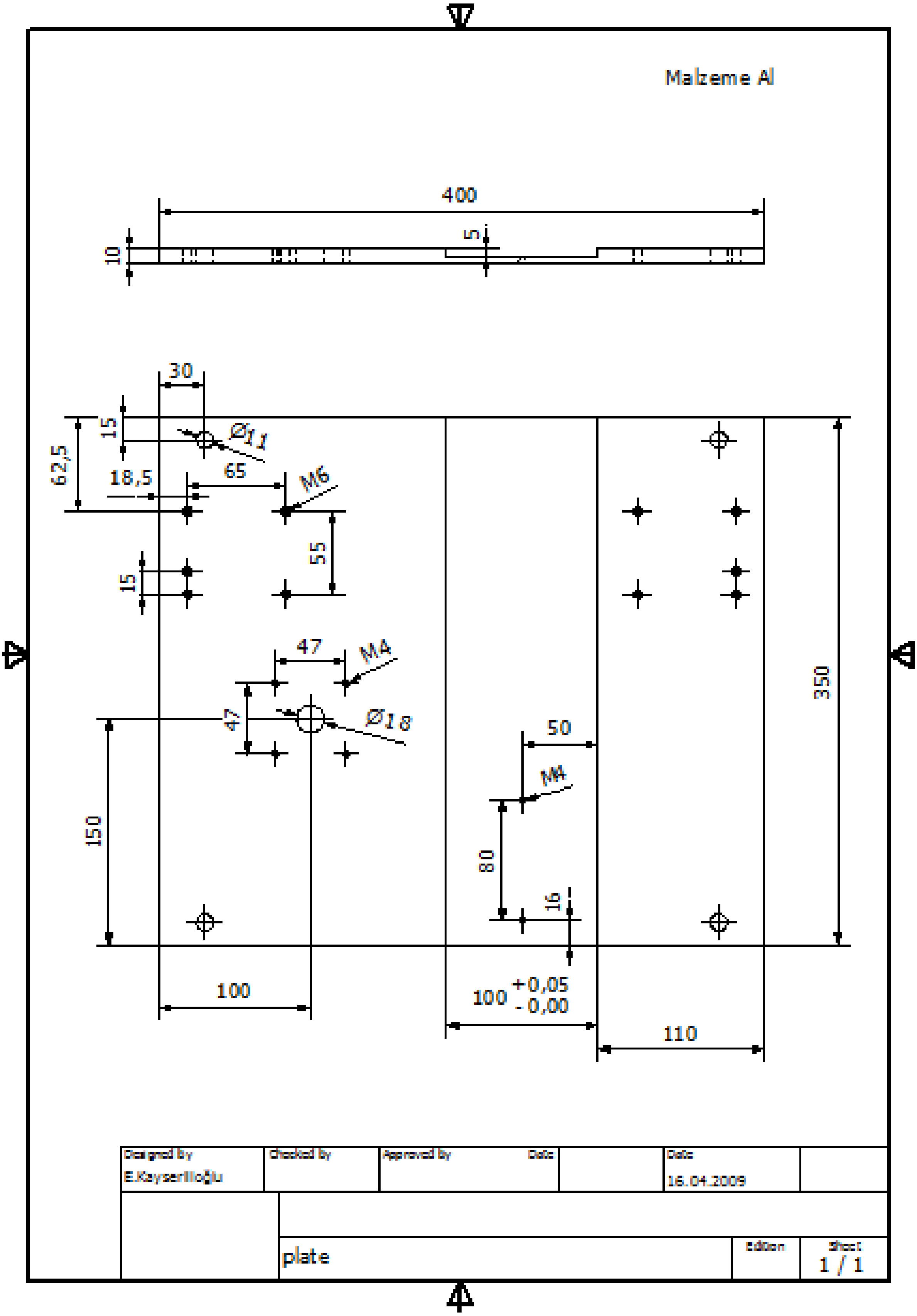
Malzeme Al
25
25
16
Ø10
25
100
50
25
100
! Kayma yapacak.Tüm
yüzeyler parlak işlensin
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
kutu
Edition
Sheet
1 / 1

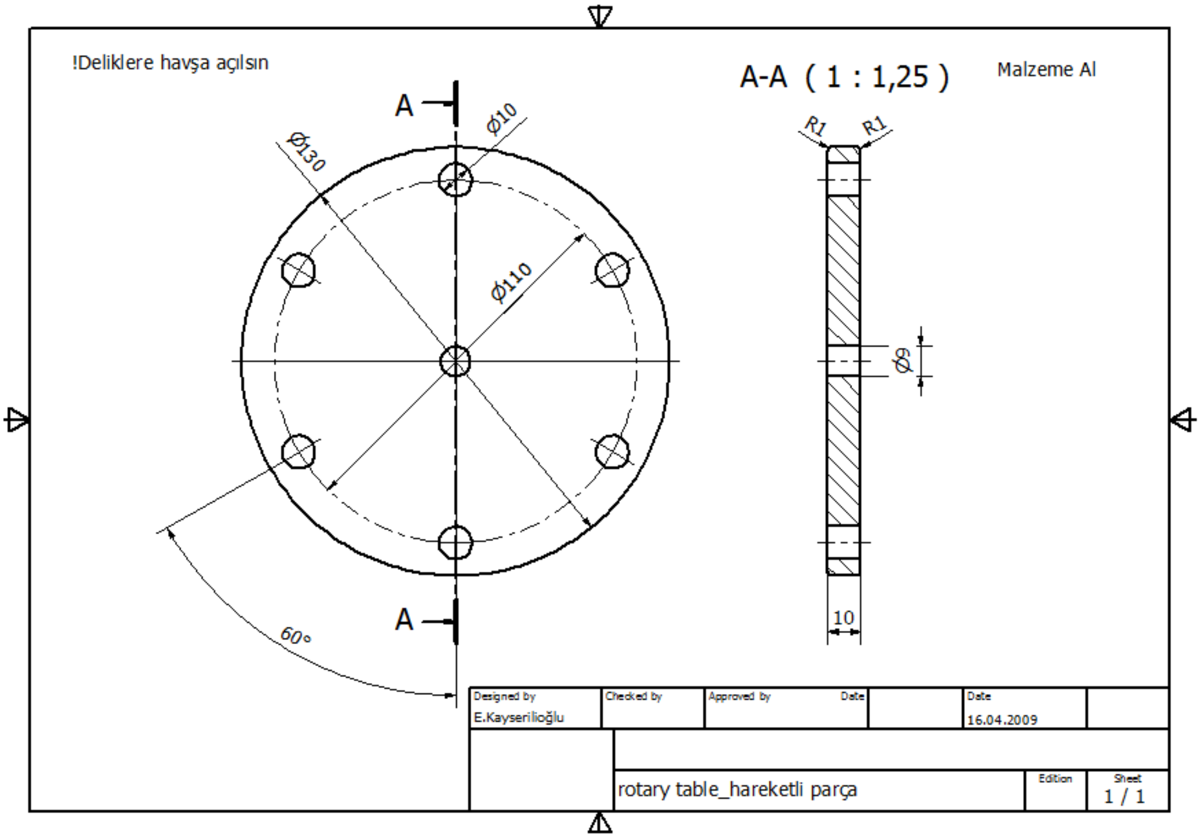

6 adet
Malzeme Al
R1
R1
0,5x45°
Ø5
Ø14
6
16
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
kutulanan parçalar
Edition
Sheet
1 / 1

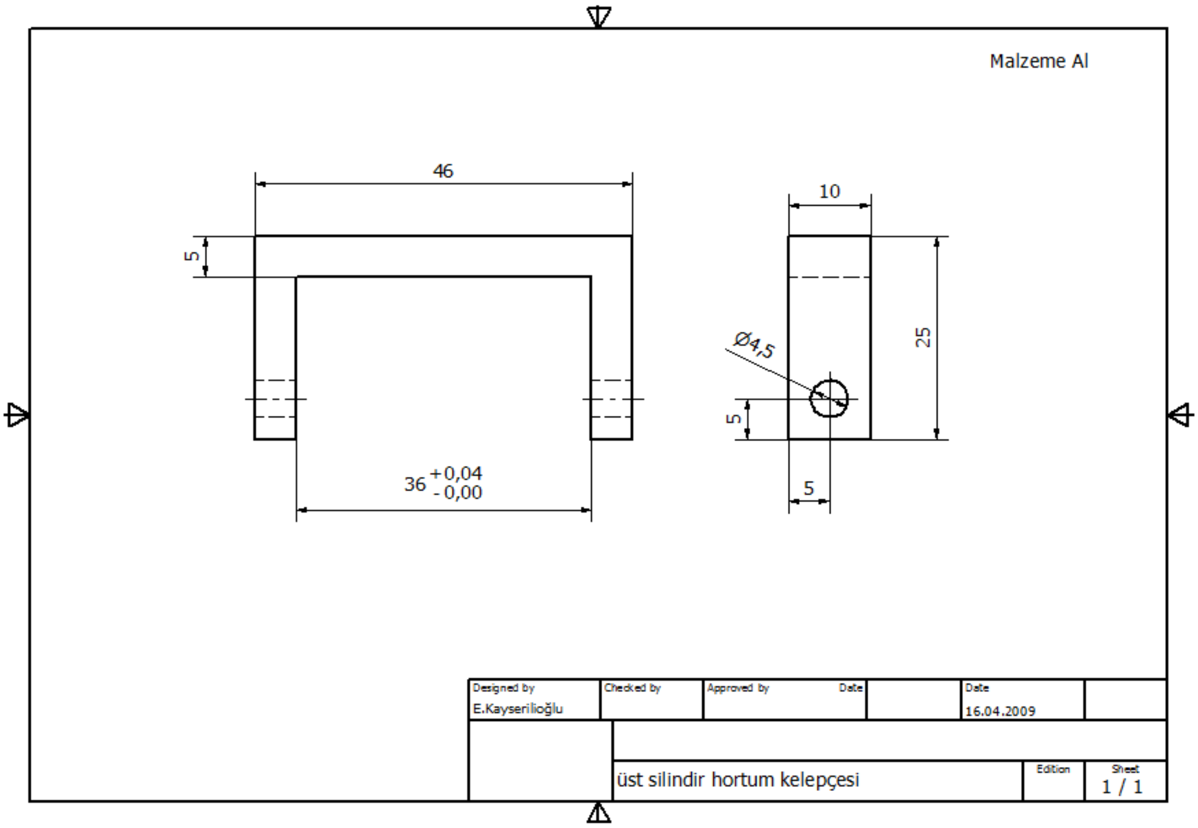

B
M4
(boydan
boya)
B-B (1 : 1)
Malzeme Al
35
Ø60
47
115
47
20
20
20
7,5
B
80
6
Ø11
Ø6,6
15
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
motor bağlantı
Edition
Sheet
1 / 1


Malzeme Al
!Vida sonunu kendin ayarla
20
5
Ø15
M5 (boydan boya)
Ø6 +0,02 -0,00
M8
30
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
motor bağlantı parçası
Edition
Sheet
1 / 1

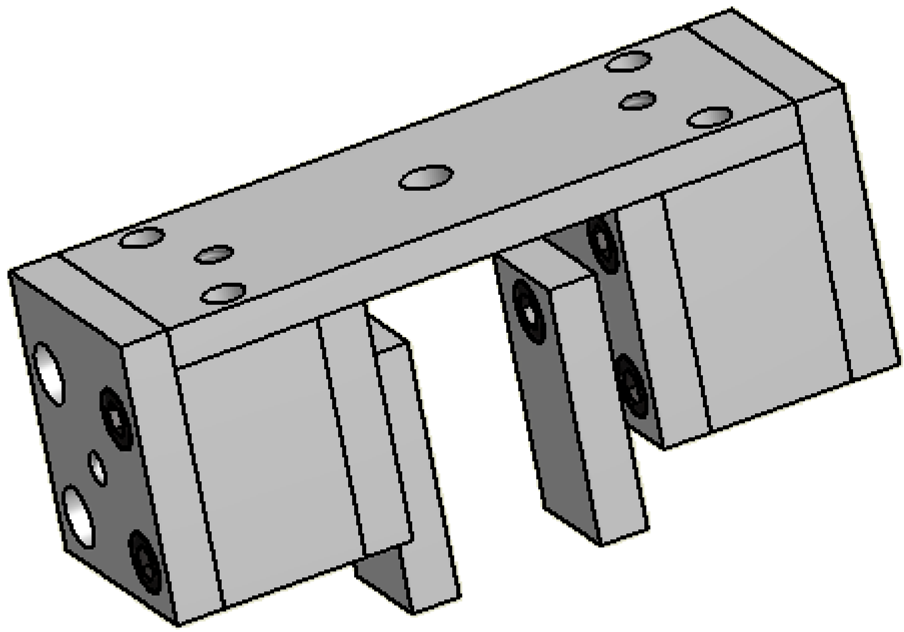

60x60 Al profil
2 adet
30
Ø11
15
15
Uzunluk=350
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
plate altı profil
Edition
Sheet
1 / 1

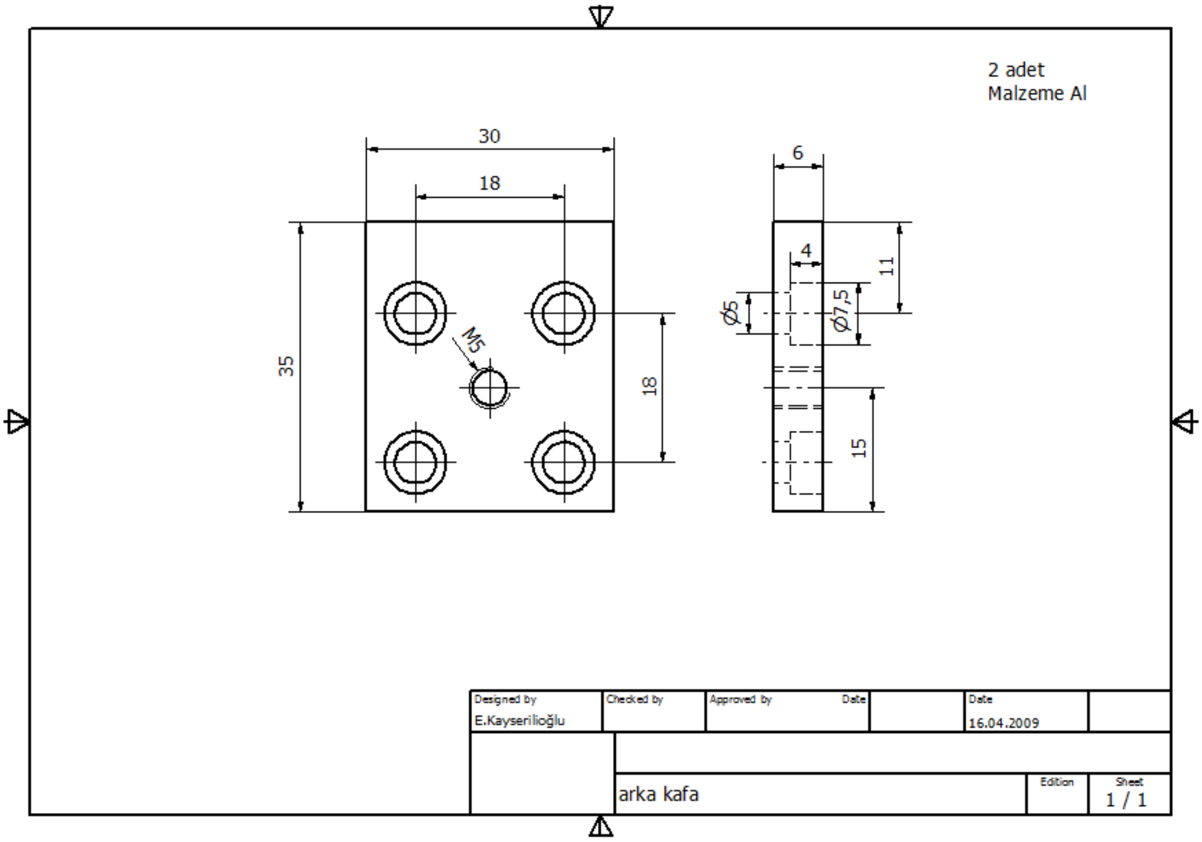

Malzeme Al
400
10
5
30
15
Ø11
62,5
18,5
65
M6
55
15
47
M4
47
Ø18
150
50
M4
80
16
350
100
100 +0,05 - 0,00
110
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
plate
Edition
Sheet
1 / 1

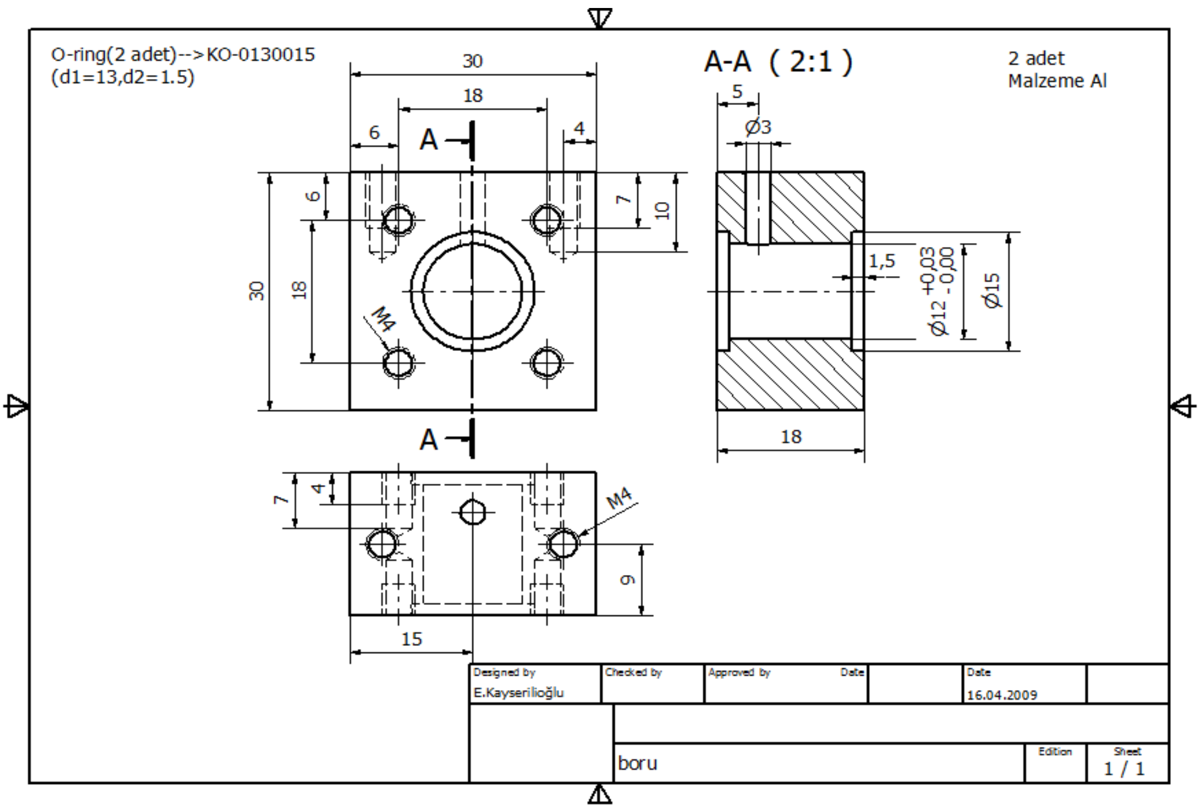

!Deliklere havşa açılsın
A-A (1 : 1,25)
Malzeme Al
A
Ø10
Ø130
Ø110
R1
R1
Ø9
10
A
60°
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
rotary table_hareketli parça
Edition
Sheet
1 / 1

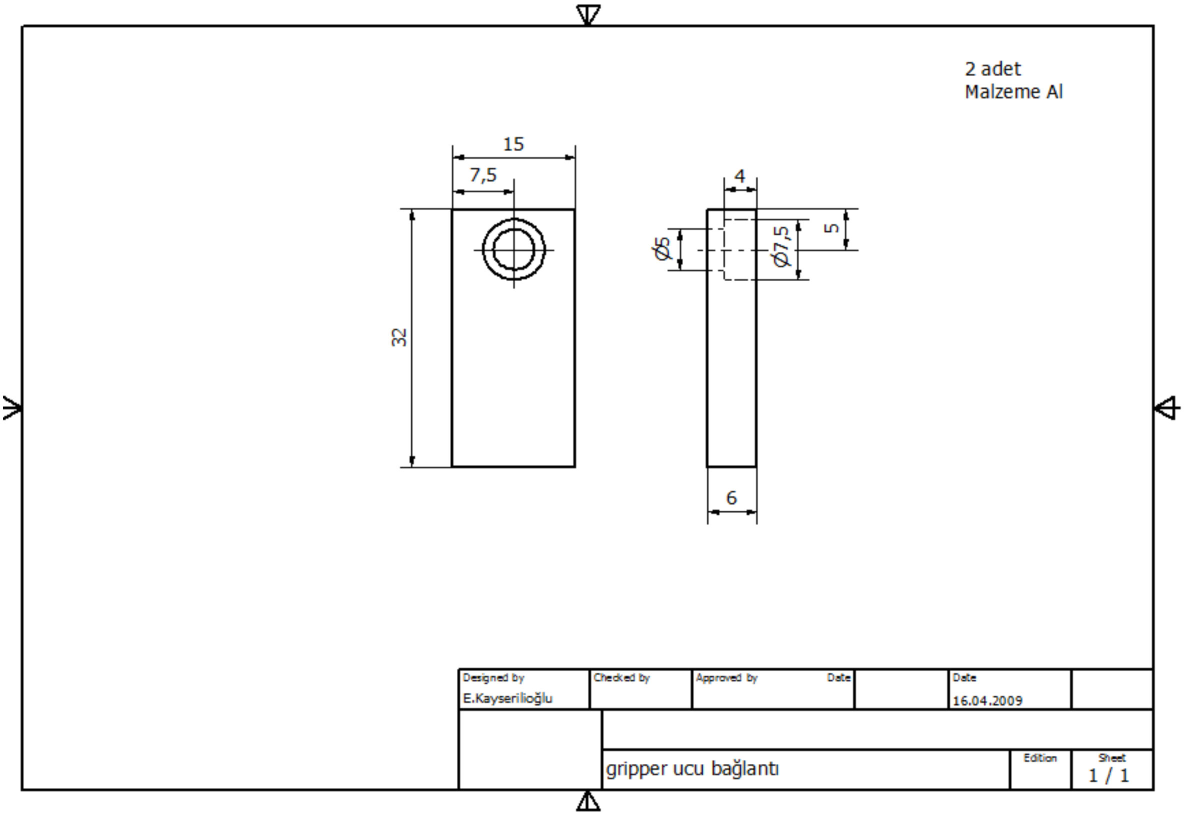

Malzeme Al
46
10
5
Ø4,5
25
5
36 +0,04 - 0,00
5
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
üst silindir hortum kelepçesi
Edition
Sheet
1 / 1

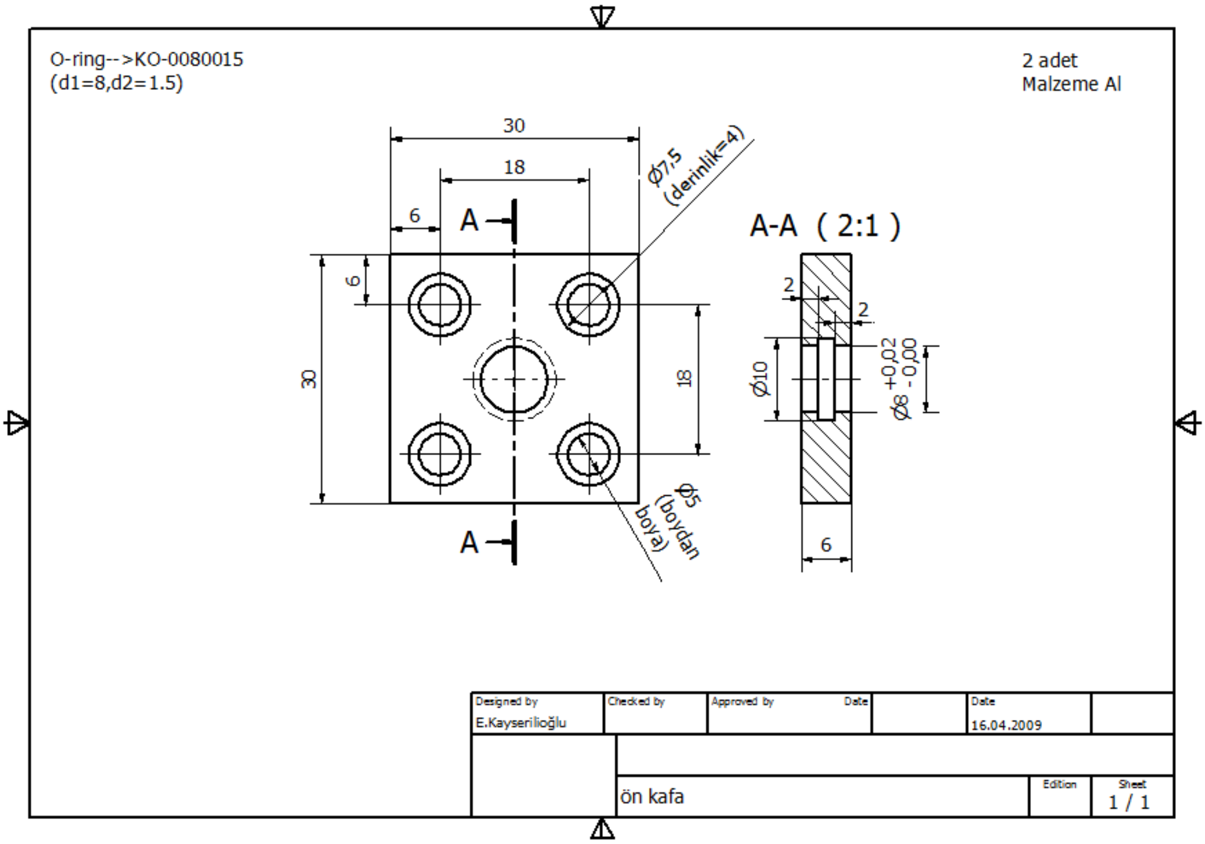
Gripper:

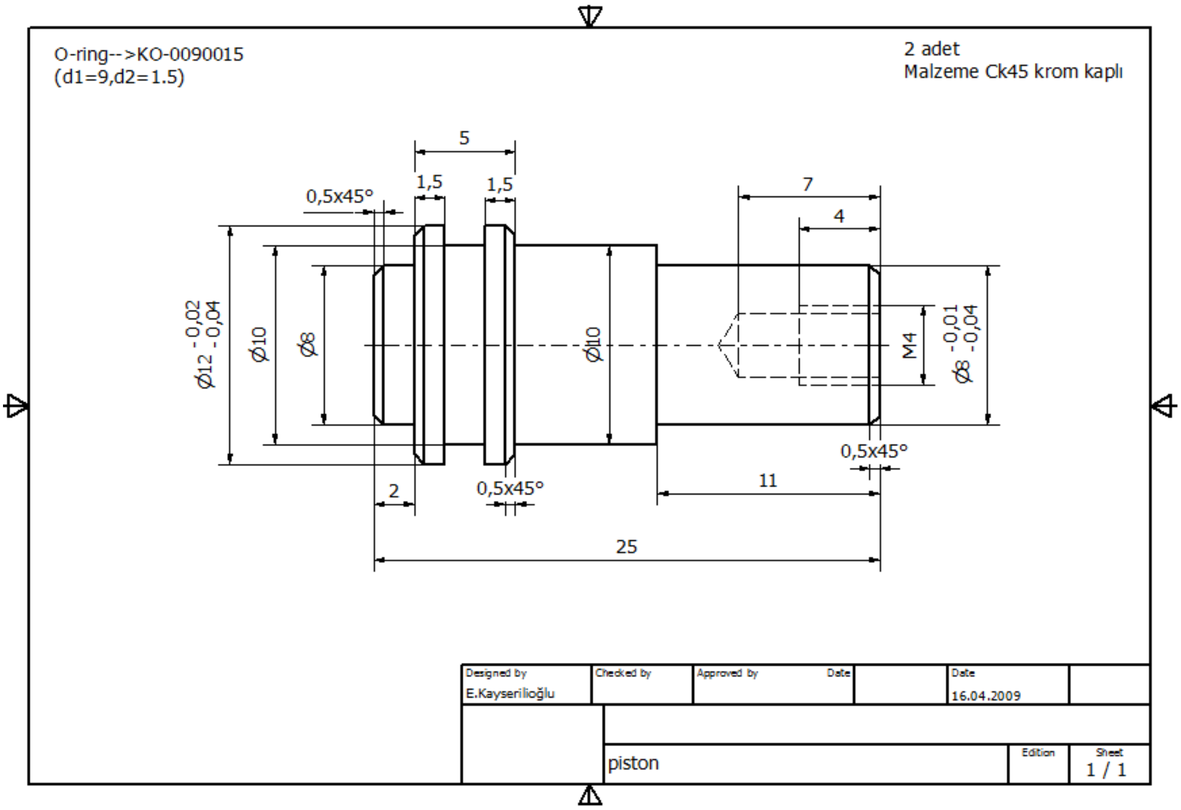


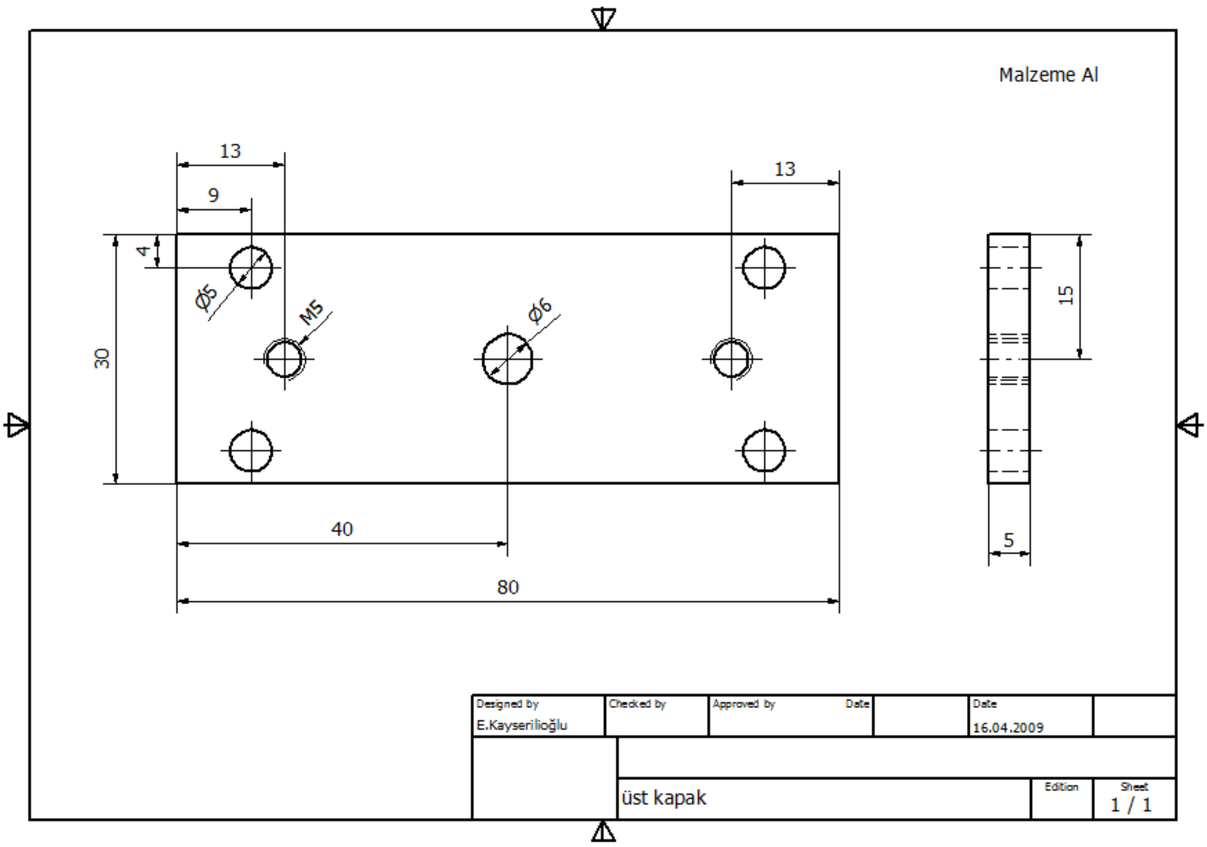

2 adet
Malzeme Al
30
18
6
4
11
35
M5
18
Ø5
Ø7,5
15
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
arka kafa
Edition
Sheet
1 / 1


O-ring(2 adet)-->KO-0130015
(d1=13,d2=1.5)
A-A (2:1)
2 adet
Malzeme Al
30
18
6
4
A
5
Ø3
7
10
6
30
18
M4
1,5
Ø12 +0,03 -0,00
Ø15
18
A
7
4
M4
9
15
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
boru
Edition
Sheet
1 / 1


2 adet
Malzeme Al
15
7,5
32
4
Ø5
Ø7,5
5
6
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
gripper ucu bağlantı
Edition
Sheet
1 / 1

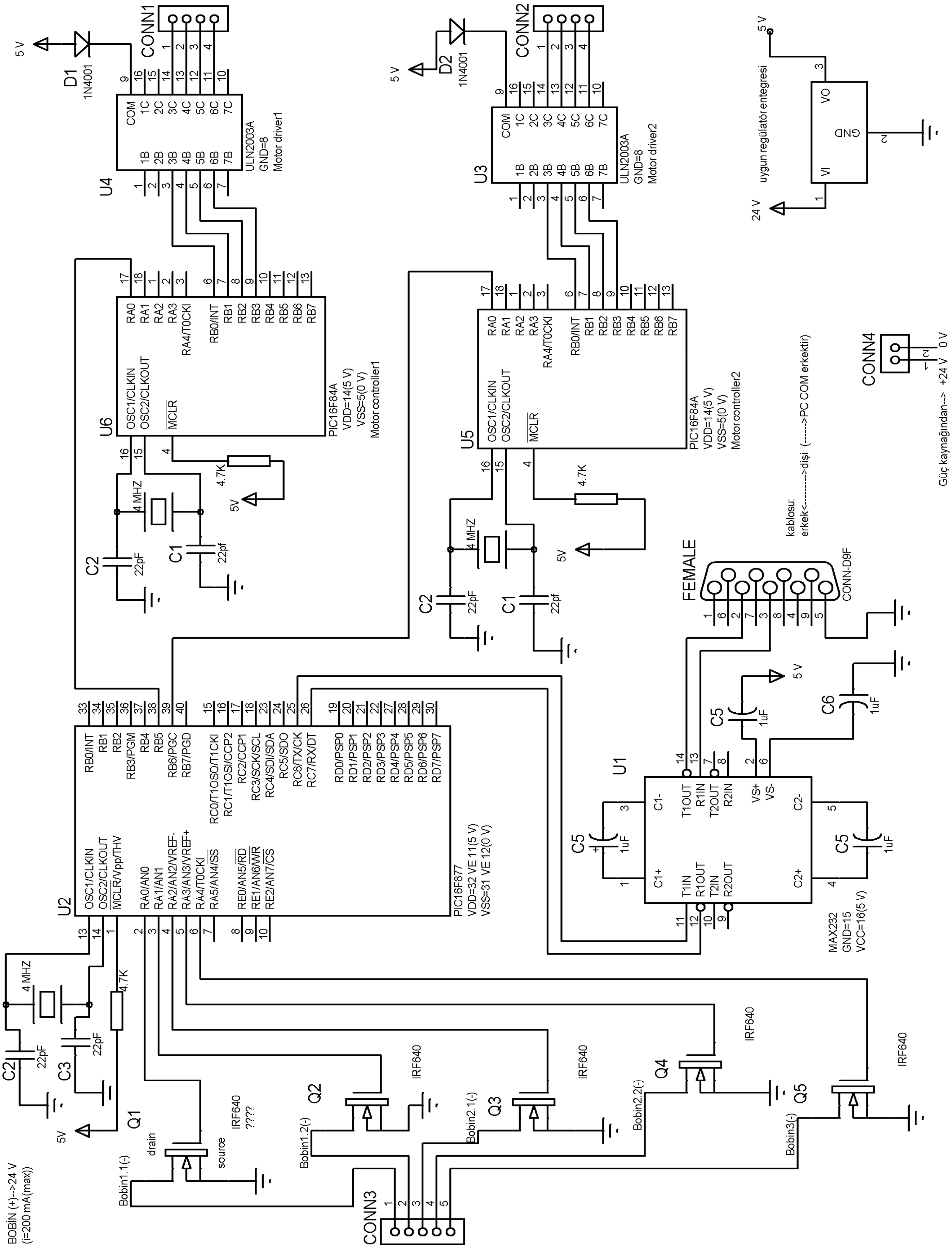

O-ring-->KO-0080015
(d1=8,d2=1.5)
2 adet
Malzeme Al
30
18
6
Ø7,5
(derinlik=4)
A
A-A (2:1)
6
30
18
2
2
Ø10
Ø8 +0,02 -0,00
Ø5
(boydan
boya)
A
6
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
ön kafa
Edition
Sheet
1 / 1


O-ring-->KO-0090015
(d1=9,d2=1.5)
2 adet
Malzeme Ck45 krom kaplı
5
1,5
1,5
0,5x45°
7
4
Ø12 -0,02 -0,04
Ø10
Ø8
Ø10
M4
Ø8 -0,01 -0,04
0,5x45°
11
2
0,5x45°
25
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
piston
Edition
Sheet
1 / 1


Malzeme Al
13
9
13
4
Ø5
M5
Ø6
15
30
40
80
5
Designed by
E.Kayserilioğlu
Checked by
Approved by
Date
Date
16.04.2009
üst kapak
Edition
Sheet
1 / 1

APPENDIX A.3

CIRCUIT DIAGRAMS FOR MASTER AND MOTOR CONTROLLERS



APPENDIX A.4

MATLAB CODES(M files) FOR CONTROLLER SIMULATIONS

```
%LQG_V2
%A-State-space plant model

k=25;R=20;Jm=54;bm=13.3e-3;b=0;m=2.5;
A=[0 1 0 0;-k*R^2/Jm -bm/Jm k*R/Jm 0;0 0 0 1;k*R/m 0 -k/m -b/m];
B=[0 0;1/Jm 0;0 0;0 0];
C=[1 0 0 0;0 0 1 0];
D=[0 0;0 0];
plant=ss(A,B,C,D);

%Controller and estimator coefficients(K ve L)
%First with arbitray poles

p=[-1 -2 -3 -4];
q=3*p;

K=place(A,B,p);
L=place(A',C',q)';

%B-Now,trying the optimal controller and estimator(Kalman filter)

%First,"weighting" matrices for controller

W1=100*diag([1 1 1 1]);
W2=0.01*diag([1 1]);

K_opt=lqr(plant,W1,W2);
K=K_opt;

%C-Now,determining the optimal estimator(Kalman filter)

%First  "covariances"(QN for disturbance and RN for noise)

QN=diag([0.1^2 0.1^2 0.1^2 0.1^2]);
RN=diag([0.2^2 0.2^2]);

G=B;
H=D;

est_plant=ss(plant.a,[plant.b G],plant.c,[plant.d H]);
[kest,L_opt]=kalman(est_plant,QN,RN);
L=L_opt;
```

APPENDIX A.5

C CODES FOR MASTER CONTROLLER(PIC 16F877)

```
/*Program for Master controller*/

#include<16f877.h>

#fuses
XT,NOWDT,NOPROTECT,NOBROWNOUT,NOLVP,NOPUT,NOWRT,NODEB
UG,NOCPD

#use delay(clock=4000000)
#use rs232(baud=9600,xmit=pin_C6,rcv=pin_C7,parity=N,stop=1)

char command[15];

#define motor_kafa pin_b5
#define motor_tabla pin_b6
#define kafa_silindiri_asagi pin_a0
#define kafa_silindiri_yukari pin_a1
#define gripper_kapat pin_a2
#define gripper_ac pin_a3
#define tabla_silindiri_ileri pin_a4

/*Delay in seconds function*/

void Delay_Sn(unsigned int s)
{
   unsigned int i,j;

   for(i=1;i<=s;i++)
   {
              for(j=1;j<=4;j++)
              Delay_Ms(250);
              }
              }


/*Interrupt for RS232*/

#int_rda

void PC_interrupt(void)

{
   for(;;)
   {
```

```
     gets(command);
     if(command=="start")
{
            /***part no 1***/

            output_high(motor_kafa);  /*motor_kafa ON*/
            set_tris_b(0b00010000);   /*pin B5'i girişe çevirdik*/
            for(;;)
            {
             if(pin_b5==0) break; /*operasyonun bitmesini bekle*/
             else;
                 }
            set_tris_b(0b00000000);  /*pin B5 tekrardan çıkış*/

            output_high(kafa_silindiri_asagi);
            Delay_sn(5);

            output_high(gripper_kapat);
            Delay_Sn(5);

            output_high(kafa_silindiri_yukari);
            Delay_Sn(5);

            output_high(motor_kafa);
            set_tris_b(0b00010000);   /*pin B5'i girişe çevirdik*/
            for(;;)
            {
             if(pin_b5==0) break; /*operasyonun bitmesini bekle*/
             else;
                 }
            set_tris_b(0b00000000);  /*pin B5 tekrardan çıkış*/

            output_high(kafa_silindiri_asagi);
            Delay_Sn(5);

            output_high(gripper_ac);
            Delay_Sn(5);

            output_high(kafa_silindiri_yukari);
            Delay_Sn(5);

            output_high(motor_tabla);
            set_tris_b(0b00100000);   /*pin B6'i girişe çevirdik*/
            for(;;)
            {
             if(pin_b6==0) break; /*operasyonun bitmesini bekle*/
             else;
                 }
```

```
set_tris_b(0b00000000);  /*pin B6 tekrardan çıkış*/
/***part no 2***/

output_high(motor_kafa);  /*motor_kafa ON*/
set_tris_b(0b00010000);   /*pin B5'i girişe çevirdik*/
for(;;)
{
 if(pin_b5==0) break; /*operasyonun bitmesini bekle*/
 else;
      }
set_tris_b(0b00000000);  /*pin B5 tekrardan çıkış*/

output_high(kafa_silindiri_asagi);
Delay_sn(5);

output_high(gripper_kapat);
Delay_Sn(5);

output_high(kafa_silindiri_yukari);
Delay_Sn(5);

output_high(motor_kafa);
set_tris_b(0b00010000);   /*pin B5'i girişe çevirdik*/
for(;;)
{
 if(pin_b5==0) break; /*operasyonun bitmesini bekle*/
 else;
      }
set_tris_b(0b00000000);  /*pin B5 tekrardan çıkış*/

output_high(kafa_silindiri_asagi);
Delay_Sn(5);

output_high(gripper_ac);
Delay_Sn(5);

output_high(kafa_silindiri_yukari);
Delay_Sn(5);

output_high(tabla_silindiri_ileri);
Delay_Sn(5);

output_high(motor_tabla);
set_tris_b(0b00100000);   /*pin B6'i girişe çevirdik*/
for(;;)
{
 if(pin_b6==0) break; /*operasyonun bitmesini bekle*/
 else;
```

```
      }
set_tris_b(0b00000000);  /*pin B6 tekrardan çıkış*/

/***part no 3***/

output_high(motor_kafa);  /*motor_kafa ON*/
set_tris_b(0b00010000);   /*pin B5'i girişe çevirdik*/
for(;;)
{
 if(pin_b5==0) break; /*operasyonun bitmesini bekle*/
 else;
      }
set_tris_b(0b00000000);  /*pin B5 tekrardan çıkış*/

output_high(kafa_silindiri_asagi);
Delay_sn(5);
output_high(gripper_kapat);
Delay_Sn(5);

output_high(kafa_silindiri_yukari);
Delay_Sn(5);

output_high(motor_kafa);
set_tris_b(0b00010000);   /*pin B5'i girişe çevirdik*/
for(;;)
{
 if(pin_b5==0) break; /*operasyonun bitmesini bekle*/
 else;
      }
set_tris_b(0b00000000);  /*pin B5 tekrardan çıkış*/

output_high(kafa_silindiri_asagi);
Delay_Sn(5);

output_high(gripper_ac);
Delay_Sn(5);

output_high(kafa_silindiri_yukari);
Delay_Sn(5);

output_high(motor_tabla);
set_tris_b(0b00100000);   /*pin B6'i girişe çevirdik*/
for(;;)
{
 if(pin_b6==0) break; /*operasyonun bitmesini bekle*/
 else;
      }
set_tris_b(0b00000000);  /*pin B6 tekrardan çıkış*/
```

```
/*part no 4***/
output_high(motor_kafa);  /*motor_kafa ON*/
set_tris_b(0b00010000);   /*pin B5'i girişe çevirdik*/
for(;;)
{
 if(pin_b5==0) break; /*operasyonun bitmesini bekle*/
 else;
      }
set_tris_b(0b00000000);  /*pin B5 tekrardan çıkış*/

output_high(kafa_silindiri_asagi);
Delay_sn(5);

output_high(gripper_kapat);
Delay_Sn(5);

output_high(kafa_silindiri_yukari);
Delay_Sn(5);

output_high(motor_kafa);
set_tris_b(0b00010000);   /*pin B5'i girişe çevirdik*/
for(;;)
{
 if(pin_b5==0) break; /*operasyonun bitmesini bekle*/
 else;
      }
set_tris_b(0b00000000);  /*pin B5 tekrardan çıkış*/

output_high(kafa_silindiri_asagi);
Delay_Sn(5);

output_high(gripper_ac);
Delay_Sn(5);
output_high(kafa_silindiri_yukari);
Delay_Sn(5);

output_high(tabla_silindiri_ileri);
Delay_Sn(5);

output_high(motor_tabla);
set_tris_b(0b00100000);   /*pin B6'i girişe çevirdik*/
for(;;)
{
 if(pin_b6==0) break; /*operasyonun bitmesini bekle*/
 else;
      }
set_tris_b(0b00000000);  /*pin B6 tekrardan çıkış*/
```

```
/***part no 5***/

output_high(motor_kafa);  /*motor_kafa ON*/
set_tris_b(0b00010000);   /*pin B5'i girişe çevirdik*/
for(;;)
{
  if(pin_b5==0) break; /*operasyonun bitmesini bekle*/
  else;
      }
set_tris_b(0b00000000);  /*pin B5 tekrardan çıkış*/

output_high(kafa_silindiri_asagi);
Delay_sn(5);

output_high(gripper_kapat);
Delay_Sn(5);

output_high(kafa_silindiri_yukari);
Delay_Sn(5);

output_high(motor_kafa);
set_tris_b(0b00010000);   /*pin B5'i girişe çevirdik*/
for(;;)
{
  if(pin_b5==0) break; /*operasyonun bitmesini bekle*/
  else;
      }
set_tris_b(0b00000000);  /*pin B5 tekrardan çıkış*/

output_high(kafa_silindiri_asagi);
Delay_Sn(5);

output_high(gripper_ac);
Delay_Sn(5);

output_high(kafa_silindiri_yukari);
Delay_Sn(5);

output_high(motor_tabla);
set_tris_b(0b00100000);   /*pin B6'i girişe çevirdik*/
for(;;)
{
  if(pin_b6==0) break; /*operasyonun bitmesini bekle*/
  else;
      }
set_tris_b(0b00000000);  /*pin B6 tekrardan çıkış*/
/***part no 6***/
```

```
output_high(motor_kafa);  /*motor_kafa ON*/
set_tris_b(0b00010000);   /*pin B5'i girişe çevirdik*/
 for(;;)
 {
  if(pin_b5==0) break; /*operasyonun bitmesini bekle*/
  else;
      }
 set_tris_b(0b00000000);  /*pin B5 tekrardan çıkış*/

 output_high(kafa_silindiri_asagi);
 Delay_sn(5);

 output_high(gripper_kapat);
 Delay_Sn(5);

 output_high(kafa_silindiri_yukari);
 Delay_Sn(5);

 output_high(motor_kafa);
 set_tris_b(0b00010000);   /*pin B5'i girişe çevirdik*/
 for(;;)
 {
  if(pin_b5==0) break; /*operasyonun bitmesini bekle*/
  else;
      }
 set_tris_b(0b00000000);  /*pin B5 tekrardan çıkış*/

 output_high(kafa_silindiri_asagi);
 Delay_Sn(5);

 output_high(gripper_ac);
 Delay_Sn(5);

 output_high(kafa_silindiri_yukari);
 Delay_Sn(5);

 output_high(motor_tabla);
 set_tris_b(0b00100000);   /*pin B6'i girişe çevirdik*/
 for(;;)
 {
  if(pin_b6==0) break; /*operasyonun bitmesini bekle*/
  else;
      }
 set_tris_b(0b00000000);  /*pin B6 tekrardan çıkış*/

 /***Go to zero reference and wait***/

 output_high(motor_kafa);
```

```
                    }

   else if(command=="stop")
   for(;;);


    }
}

/*Main program*/


main(void)
{
        setup_psp(PSP_disabled);
        setup_spi(SPI_SS_disabled);
        setup_timer_1(T1_disabled);
        setup_timer_2(T2_disabled,0,1);
        setup_adc_ports(NO_analogs);
        setup_adc(ADC_off);
        setup_ccp1(CCP_off);
        setup_ccp2(CCP_off);

        set_tris_a(0b000000);
        set_tris_b(0b00000000);

        for(;;)
        {
        enable_interrupts(int_rda);
        enable_interrupts(global);
        }

}
```

APPENDIX A.6

C CODES FOR MOTOR CONTROLLERS(PIC 16F84)

```
/*LİNEER KAFA STEP MOTOR KONTROL/SÜRÜŞ PROĞRAMI
*******************************************************/
/*Yazan:Emin Kayserilioğlu(Tarih:19.05.2009)
*********************************************
Kullanılan donanım:
-------------------------------
PIC 16F84
ULN2003A step motor driver(16 pinli)
Mitsui 5V,1.8 deg/pulse step motor
********************************************/

#include<pic.h>
#include<delay.c>

/*Gecikme(sn cinsinden) fonksiyonu*/

void DelaySn(unsigned int s)
{
    unsigned char k,j;
    for(k=0;k<s;k++)
    {
                for(j=0;j<4;j++)
                {
                            DelayMs(250);
                            }
                            }
}

/**********Main program******************************************/

main(void)
{
        int i;
        TRISB=0;
        TRISA=1;

/*Dönüş hızını Delay zamanından(T) ayarlarız.T(msn) küçüldükçe dönüş hızı
artar*/

for(;;)
{
```

```
for(;;)        /*master controller'dan ilk emri bekliyoruz*/
{
      while(RA0==1);
      else break;
      }

/*part no1*/

/*1.hareket(sıfırlama)---->*/

/*CCW yönünde 120 pulse'lık(yani 120*1.8=216 derece) dönüş */
        for(i=0;i<=120;i++)
        {
             PORTB=9;
             DelayMs(5);   /*T=5 ms aldık*/
             PORTB=3;
             DelayMs(5);
             PORTB=6;
             DelayMs(5);
             PORTB=12;
             DelayMs(5);
             }
             TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
             RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/

             for(;;)    /*Master controller emrini beklemeye geç*/
             {
                  TRISA=1;
                  while(RA0==1);
                  else break;
                  }
                  TRISA=0;

/*2.hareket(paket üstüne git)----->*/

/*CW yönünde(yukarıdaki döngüdeki sırayı tersine çevirdik)*/


          for(i=0;i<=120;i++)
        {
             PORTB=12;
             DelayMs(5);
             PORTB=6;
             DelayMs(5);
             PORTB=3;
             DelayMs(5);
```

```
            PORTB=9;
            DelayMs(5);
            }
            TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
            RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/

            for(;;)    /*Master controller emrini beklemeye geç*/
            {
                TRISA=1;
                while(RA0==1);
                else break;
                }
                TRISA=0;
/*part no2*/

/*1.hareket(sıfırlama)<--------*/


        for(i=0;i<=120;i++)
        {
            PORTB=9;
            DelayMs(5);   /*T=5 ms aldık*/
            PORTB=3;
            DelayMs(5);
            PORTB=6;
            DelayMs(5);
            PORTB=12;
            DelayMs(5);
            }
            TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
            RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/

            for(;;)    /*Master controller emrini beklemeye geç*/
            {
                TRISA=1;
                while(RA0==1);
                else break;
                }
                TRISA=0;

/*2.hareket(paket üstüne git)--------->*/


         for(i=0;i<=120;i++)
        {
            PORTB=12;
```

```
            DelayMs(5);
            PORTB=6;
            DelayMs(5);
            PORTB=3;
            DelayMs(5);
            PORTB=9;
            DelayMs(5);
            }
            TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
            RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/

            for(;;)    /*Master controller emrini beklemeye geç*/
            {
                TRISA=1;
                while(RA0==1);
                else break;
                }
                TRISA=0;
/* part no3*/

/*1.hareket(sıfırlama)<---------*/


        for(i=0;i<=120;i++)
        {
            PORTB=9;
            DelayMs(5);   /*T=5 ms aldık*/
            PORTB=3;
            DelayMs(5);
            PORTB=6;
            DelayMs(5);
            PORTB=12;
            DelayMs(5);
            }
            TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
            RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/

            for(;;)    /*Master controller emrini beklemeye geç*/
            {
                TRISA=1;
                while(RA0==1);
                else break;
                }
                TRISA=0;

/*2.hareket(paket üstüne git)---------->*/
```

```
         for(i=0;i<=120;i++)
        {
            PORTB=12;
            DelayMs(5);
            PORTB=6;
            DelayMs(5);
            PORTB=3;
            DelayMs(5);
            PORTB=9;
            DelayMs(5);
            }
            TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
            RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/

            for(;;)    /*Master controller emrini beklemeye geç*/
            {
                TRISA=1;
                while(RA0==1);
                else break;
                }
                TRISA=0;

/* part no4*/

/*1.hareket(sıfırlama)<---------*/
        for(i=0;i<=120;i++)
        {
            PORTB=9;
            DelayMs(5);   /*T=5 ms aldık*/
            PORTB=3;
            DelayMs(5);
            PORTB=6;
            DelayMs(5);
            PORTB=12;
            DelayMs(5);
            }
            TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
            RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/

            for(;;)    /*Master controller emrini beklemeye geç*/
            {
                TRISA=1;
                while(RA0==1);
                else break;
                }
                TRISA=0;
```

```
/*2.hareket(paket üstüne git)----------->*/


  for(i=0;i<=120;i++)
 {
    PORTB=12;
    DelayMs(5);
    PORTB=6;
    DelayMs(5);
    PORTB=3;
    DelayMs(5);
    PORTB=9;
    DelayMs(5);
    }
    TRISA=0;  /*PORTA'yı çıkışa çevirdik*/
    RA0=1;    /*Master controller'a operasyonun bittiğini bildir*/
    for(;;)   /*Master controller emrini beklemeye geç*/
    {
        TRISA=1;
        while(RA0==1);
        else break;
        }
        TRISA=0;

/* part no5*/

/*1.hareket(sıfırlama)<-----------*/


 for(i=0;i<=120;i++)
 {
    PORTB=9;
    DelayMs(5);  /*T=5 ms aldık*/
    PORTB=3;
    DelayMs(5);
    PORTB=6;
    DelayMs(5);
    PORTB=12;
    DelayMs(5);
    }
    TRISA=0;  /*PORTA'yı çıkışa çevirdik*/
    RA0=1;    /*Master controller'a operasyonun bittiğini bildir*/
    for(;;)   /*Master controller emrini beklemeye geç*/
    {
        TRISA=1;
        while(RA0==1);
```

```
        else break;
        }
        TRISA=0;

/*2.hareket(paket üstüne git)--------->*/


    for(i=0;i<=120;i++)
    {
      PORTB=12;
      DelayMs(5);
      PORTB=6;
      DelayMs(5);
      PORTB=3;
      DelayMs(5);
      PORTB=9;
      DelayMs(5);
      }
      TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
      RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/

      for(;;)    /*Master controller emrini beklemeye geç*/
      {
        TRISA=1;
        while(RA0==1);
        else break;
        }
        TRISA=0;

/* part no6*/

/*1.hareket(sıfırlama)<---------*/

    for(i=0;i<=120;i++)
    {
      PORTB=9;
      DelayMs(5);   /*T=5 ms aldık*/
      PORTB=3;
      DelayMs(5);
      PORTB=6;
      DelayMs(5);
      PORTB=12;
      DelayMs(5);
      }
      TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
      RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/
```

```
        for(;;)   /*Master controller emrini beklemeye geç*/
        {
            TRISA=1;
            while(RA0==1);
            else break;
            }
            TRISA=0;

/*2.hareket(paket üstüne git)------------>*/

      for(i=0;i<=120;i++)
     {
        PORTB=12;
        DelayMs(5);
        PORTB=6;
        DelayMs(5);
        PORTB=3;
        DelayMs(5);
        PORTB=9;
        DelayMs(5);
        }
        TRISA=0;  /*PORTA'yı çıkışa çevirdik*/
        RA0=1;    /*Master controller'a operasyonun bittiğini bildir*/

        for(;;)   /*Master controller emrini beklemeye geç*/
        {
            TRISA=1;
            while(RA0==1);
            else break;
            }
            TRISA=0;

/*Son sıfırlama<-----------*/

      for(i=0;i<=120;i++)
       {
        PORTB=12;
        DelayMs(5);
        PORTB=6;
        DelayMs(5);
        PORTB=3;
        DelayMs(5);
        PORTB=9;
        DelayMs(5);
        }
        TRISA=0;  /*PORTA'yı çıkışa çevirdik*/
```

```
            RA0=1;    /*Master controller'a operasyonun bittiğini bildir*/

            for(;;)   /*Master controller emrini beklemeye geç*/
            {
                 TRISA=1;
                 while(RA0==1);
                 else break;
                 }
                 TRISA=0;

  }

}


/**Rotary Table sürüş proğramı**
*************************************
Yazan:Emin Kayserilioğlu
*********************************************
Kullanılan donanım:
------------------------------
PIC 16F84
ULN2003A step motor driver(16 pinli)
8V,~8 deg/pulse step motor
********************************************/

#include<pic.h>
#include<delay.c>

/*Gecikme fonksiyonu*/

void DelaySn(unsigned int s)
{
   unsigned char k,j;
   for(k=0;k<s;k++)
   {
            for(j=0;j<4;j++)
            {
                     DelayMs(250);
                     }
                     }
}

/***************Main Program*************************************/

main(void)
```

```
{
        int i;
        TRISB=0;
        TRISA=1;

for(;;)        /*Sonsuz döngü*/
  {
            for(;;)      /*Master controller'dan ilk emri bekliyoruz*/
            {
                 while(RA0==1);
                 else break;
                 }

/*part no 1*/

          for(i=0;i<=7;i++)
            {
             PORTB=9;
             DelayMs(150);   /*T=150 ms aldık*/
             PORTB=3;
             DelayMs(150);
             PORTB=6;
             DelayMs(150);
             PORTB=12;
             DelayMs(150);
             }

             TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
             RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/

             for(;;)    /*Master controller emrini beklemeye geç*/
             {
                  TRISA=1;
                  while(RA0==1);
                  else break;
                  }
                  TRISA=0;

/*part no 2*/

            for(i=0;i<=8;i++)
            {
             PORTB=9;
             DelayMs(150);   /*T=150 ms aldık*/
             PORTB=3;
             DelayMs(150);
```

```
            PORTB=6;
            DelayMs(150);
            PORTB=12;
            DelayMs(150);
            }

            TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
            RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/

            for(;;)    /*Master controller emrini beklemeye geç*/
            {
                 TRISA=1;
                 while(RA0==1);
                 else break;
                 }
                 TRISA=0;
/*part no 3*/

           for(i=0;i<=7;i++)
           {
            PORTB=9;
            DelayMs(150);   /*T=150 ms aldık*/
            PORTB=3;
            DelayMs(150);
            PORTB=6;
            DelayMs(150);
            PORTB=12;
            DelayMs(150);
            }

            TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
            RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/

            for(;;)    /*Master controller emrini beklemeye geç*/
            {
                 TRISA=1;
                 while(RA0==1);
                 else break;
                 }
                 TRISA=0;

/*part no 4*/

           for(i=0;i<=8;i++)
           {
            PORTB=9;
```

```
            DelayMs(150);   /*T=150 ms aldık*/
            PORTB=3;
            DelayMs(150);
            PORTB=6;
            DelayMs(150);
            PORTB=12;
            DelayMs(150);
            }

            TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
            RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/

            for(;;)    /*Master controller emrini beklemeye geç*/
            {
                TRISA=1;
                while(RA0==1);
                else break;
                }
                TRISA=0;

/*part no 5*/

           for(i=0;i<=7;i++)
           {
            PORTB=9;
            DelayMs(150);   /*T=150 ms aldık*/
            PORTB=3;
            DelayMs(150);
            PORTB=6;
            DelayMs(150);
            PORTB=12;
            DelayMs(150);
            }

            TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
            RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/

            for(;;)    /*Master controller emrini beklemeye geç*/
            {
                TRISA=1;
                while(RA0==1);
                else break;
                }
                TRISA=0;

/*part no 6*/
```

```
for(i=0;i<=7;i++)
{
PORTB=9;
DelayMs(150);   /*T=150 ms aldık*/
PORTB=3;
DelayMs(150);
PORTB=6;
DelayMs(150);
PORTB=12;
DelayMs(150);
}

TRISA=0;   /*PORTA'yı çıkışa çevirdik*/
RA0=1;     /*Master controller'a operasyonun bittiğini bildir*/

for(;;)    /*Master controller emrini beklemeye geç*/
{
     TRISA=1;
     while(RA0==1);
     else break;
     }
     TRISA=0;
     }
}
```