DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DESIGN AND ANALYSIS OF A SCARA ROBOT

by
Alper Erdem DEMİRCİ

December, 2012
İZMİR

DESIGN AND ANALYSIS OF A SCARA ROBOT

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in Mechanical Engineering, Mechanics Program

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"DESIGN AND ANALYSIS OF A SCARA ROBOT"** completed by **ALPER ERDEM DEMİRCİ** under supervision of **PROF. DR. HİRA KARAGÜLLE** 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.

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Alper Erdem DEMİRCİ

DESIGN AND ANALYSIS OF A SCARA ROBOT

ABSTRACT

In this study, the design of a Scara type manipulator is done and the solid model of it is obtained by Solidworks and its static and frequency analyses was done by Simulation software which is add-on of Solidworks. Afterward, motion analysis of Scara robot is done by Motion software that is also Solidworks' add-on. The parts of the Scara robot which are designed and analyzed were manufactured and assembled if they are working properly.

Classification of industrial robots, selection requirements and programing methods are also discussed in this thesis.

Keywords: Scara, solidworks, static analysis, natural frequency

BİR SCARA ROBOTUN TASARIM VE ANALİZİ

ÖZ

Bu çalışmada, endüstride yaygın olarak kullanılan Scara tarzı bir manipülatörün Solidworks programı ile tasarımı yapılmış ve aynı programın analiz eklentisi olan Simulation programı ile statik ve doğal frekans analizleri gerçekleştirilmiştir. Daha sonra yine Solidworks programının eklentisi olan Motion programı ile de hareket analizleri tamamlanmıştır. Analizleri tamamlanan manipülatörün parçaları üretilerek montajı gerçekleştirilmiştir..

Bu kapsamda, endüstriyel robotların kullanım alanları, robotların sınıflandırılması, seçim kriterleri ve genel özellikleri konularında literatür arastırması yapılmıştır.

Anahtar sözcükler: Scara, solidworks, statik analiz, doğal frekans

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CHAPTER ONE

INTRODUCTION

The scope of this study is to perform design and analysis of a Selectively Compliant Articulated Robot Arm (SCARA) with 3D CAD Design Software Solidworks.

Selectively Compliant Articulated Robot Arm (SCARA) is an industrial robot, which is firstly designed at Japan’s Yamamachi University for filling the gap between simple pneumatic pick-and-place and servo controlled robot modeled upon the human arm like Unimation PUMA. It is engineered in this fashion in order to provide compliance in the horizontal directions; a characteristic is also essential for vertical insertion operations. This makes SCARA a good choice for limited assembly tasks where work piece access is from above like packaging applications or electronic applications. The motion possibilities of the robot arms are revolute motions confined to the horizontal plane, together with translation of this plane. Gripper axis works on vertically. Such a robot is also known as “articulated robot arm” or “an assembly robot arm”. SCARA is basically an anthropomorphic or jointed-arm (RRR) structure. The simple picture of Scara is given in Figure 1.1.

Dynamic behaviors of the laminated composite structures have been investigated by many researchers with analytical, numerical, and experimental methods according to the type of the problem. Most of the publications of dynamic behaviors of laminated composite structures are based on the classical laminated plate theory. In this theory, the transverse shear deformation effect is ignored. Qatu (1991) published results for the natural frequencies of laminated composite plates having rectangular shapes under different boundary conditions. Qatu (1994) published also results for the natural frequencies of laminated plates having triangular and trapezoidal shape.

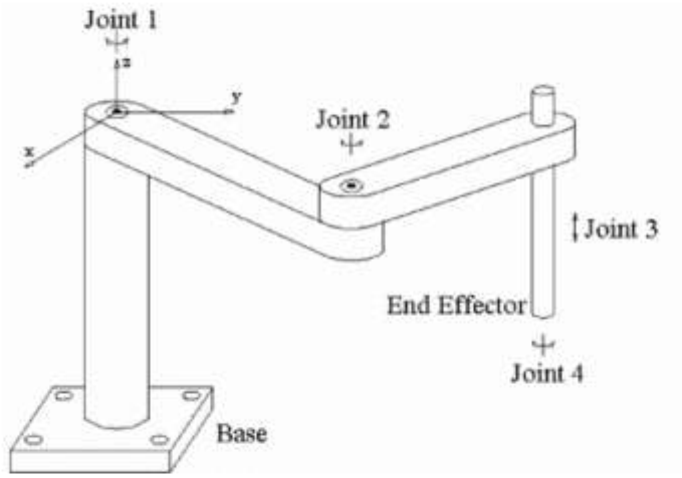


Figure 1.1 Simple picture of SCARA

SCARA has four degree's of freedom (DOF); three rotational axes which operate on X-Y plane, and the vertical axis performs up and down movement on Z plane.

Three rotational motions are provided by Joint1 is the main arm, the forearm is Joint2, third rotary axis roll is the gripper, Joint3. The gripper is usually belt driven from a motor at the fixed end of the arm. The importance of this configuration is that it keeps the gripper, and hence the work piece at a constant angle with respect to the bench independent from the arm movement. The vertical axis is also important for positioning of SCARA.

Burisch & Slatter (2005) designed and developed Parallel hybrid micro-scara robot and described the basic design process and design decisions of the parallel hybrid micro SCARA robot. Bhatia, Thirunarayanan & Dave developed an expert system to take up the job of the a designer in the iterative design of robots. This system carries out the static and dynamic analysis, and arrives at the dimensions of the individual parts of the robot. Das & Dülger developed a complete mathematical model of SCARA robot including servo actuators dynamics and presented together with dynamic simulation. Carbone & Ceccarelli published the the concept of a serial-parallel macro-milli manipulator is presented for medical applications by investigating the feasibility of combining two different robotic structures into one system. Liyanage, krouglicof & Gosine designed and developed high performance

SCARA type robotic arm with rotary hydraulic actuators and showed that it’s difficult to obtain high speeds and torques with electrical actuators. A comprehensive literature review releated to dynamic analyses of flexible robotic manipulators is presented by Dwivedy & Eberhard (2006). The review of the published papers is classified as modeling, control and experimental studies. In case of modeling, they are subdivided depending on the method of analysis and number of links involved in the analysis. In this work both link and joint flexibilities are considered. Total of 433 papers presented between the years 1974–2005 have been reviewed in this work. Akdağ (2008) presented integrated cae procedures to design and analysis of robot manipulators. He designed three different robots which are following this process and also investigated new concept named as “Rigidity Workspace” according to the end point static deflections and modal behavior of the robot. Das (2003) worked on SCARA robot motion control with a PLC unit. He developed PLC codes of Siemens S7-200 and controlled the SCARA for three different sized objects to pick and place from one point to the target. Sayğılı (2006) designed a SCARA type manipulator and manufactured it’s parts with CNC machine. He also obtained kinematic equations of SCARA type manupilator. Due to rapid point-to-point movements, SCARA robot arms exhibit large vibrations after reaching the destinations position. So, their residual vibration analysis must be done before manufacturing (Tao, Zhang, Ma & Yun, 2006).

CHAPTER TWO

ROBOTIC SYSTEM

2.1 Introduction to Robotic

The word "robot" is of Slavic origin; for instance, in Russian, the word pa6oTa (rabota) means labor or work. Its present meaning was introduced by the Czechoslovakian dramatist Karel Capek (1890-1938) in the early twentieth century. In a play entitled R. U.R. (Rosum's Universal Robots), Capek created automated substitutes for human workers, having a human outlook and capable of "human" feelings. Historically, in fact, the concept "robot" appeared much later than the actual systems that are entitled to answer to that name.

International standard ISO 8373 defines a “robot” as “An automatically controlled, reprogrammable, multipurpose, manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications.” Although this definition is capable to define robots, there are many other definitions of them also (ISO, 1994). You can see basic concept of the industrial robot.

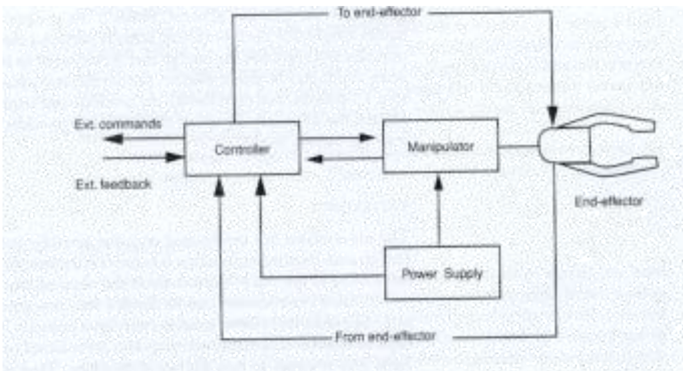


Figure 2.1 Basic concept of the industrial robot

The following conditions may be used as guidelines for using robots:

- Hazardous (risky) or uncomfortable working conditions: In situations where there are potential dangerous or health hazards (like heat, radiation, toxicity, etc.). robots may be used like hot forging, die casting, spray painting.
- Difficult handling: If the work piece or tool involved in the operation is awl ward in shape or of heavy type it is possible for the robot to do this type of work more easily.
- Repetitive task: If the work cycle consists of a sequence of elements which do not vary from cycle to cycle it is possible that the robot can be programmed to do the job. It reduces workers' boredom of monotonous work.

Continuous working: If machine is working for more hour or days or month then it is require that making it automatic.

2.2 Classification of Robots

Robots can be classified according to their degrees of freedom, workspace of geometry, motion characteristics, drive technology and kinematic structure (Tsai, 1999).

2.2.1 Degrees of Freedom

Degrees of freedom, in a mechanics context, are specific, defined modes in which a mechanical device or system can move. The number of degrees of freedom is equal to the total number of independent displacements or aspects of motion. A machine may operate in two or three dimensions but have more than three degrees of freedom. The term is widely used to define the motion capabilities of robots. Consider a robot arm built to work like a human arm. Shoulder motion can take place as pitch (up and down) or yaw (left and right). Elbow motion can occur only as pitch. Wrist motion can occur as pitch or yaw. Rotation (roll) may also be possible for wrist and shoulder.

2.2.2 Workspace Geometry

Robot workspace is the ability of a robot to reach a collection of points (workspace) which depends on the configuration and size of their links and wrist joint. The workspace may be found mathematically by writing equations that define the robot's links and joints including their limitations, such as ranges of motions for each joint. Alternatively can be found by subtracting all the space it can reach with what it cannot reach.

The robot which has the simplest kinematic structure is called as "cartesian robot" and it is made up of three mutually perpendicular "prismatic joints". Cartesian robot has a rectangular box regional workspace. "Gantry robot" is a type of cartesian robot which mounted on rails above its workspace.

If a cartesian robot has revolute joint, it is called as "cylindrical robot". "Spherical robot" has two intersecting revolute joints and one prismatic joint. On the other hand, if all three joints of the robot are revolute, it is called as "articulated robot". 6 axes industrial robot is a good example of an articulated robot. Scara robots have two revolute joints which are followed by a prismatic joint. While all the three axis of scara revolute, the 4th axis translates.

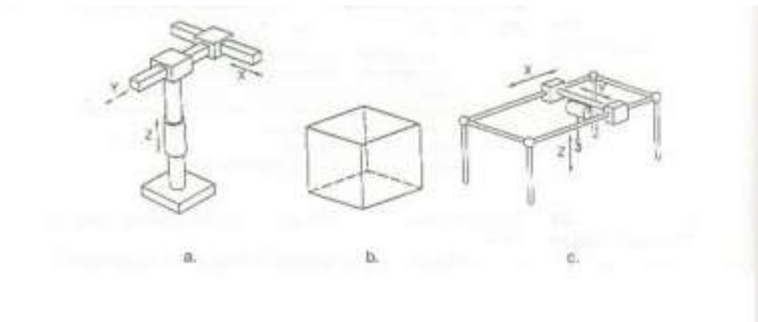


Figure 3.2 (a) A Cartesian or rectangular coordinate arm. (b) The box shaped work envelope within which a Cartesian coordinate manipulator operates (c) An overhead Crane

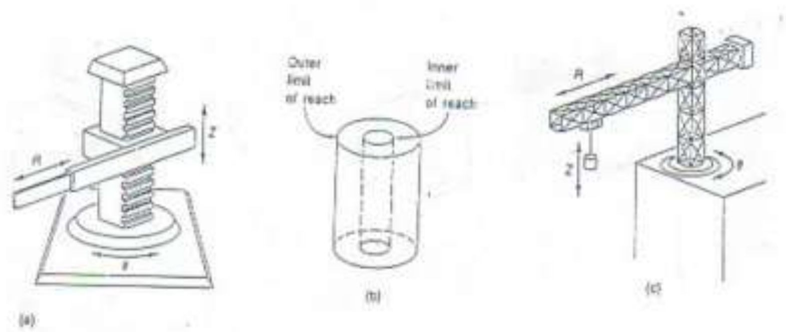


Figure 2.3 (a) A cylinder coordinate arm (b) The space between the two cylinders shown is the work envelop occupied by a cylin drical coordinates manipulator (c) A construction crane on top of a tall building.

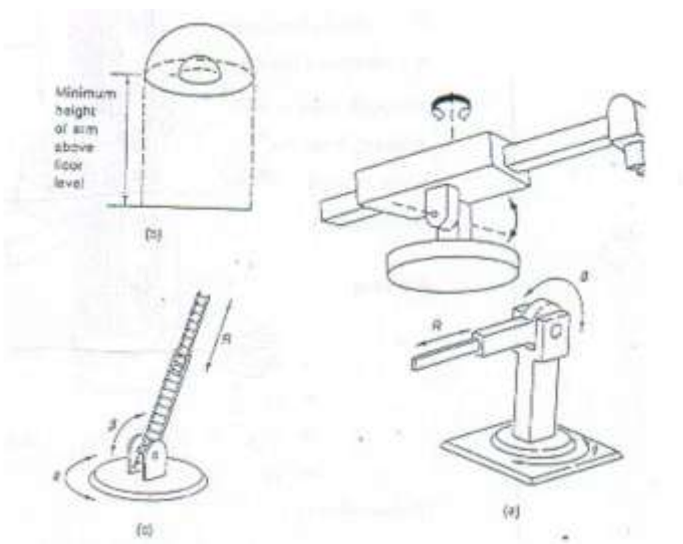


Figure 2.4 (a) A polar or spherical coordinate manipulator. (b) The work envelop for a polar-coordinates manipulator is the space between the two hemispheres (c) A ladder on a hook and ladder truck has movement similar to those of a polar coordinates manipulator

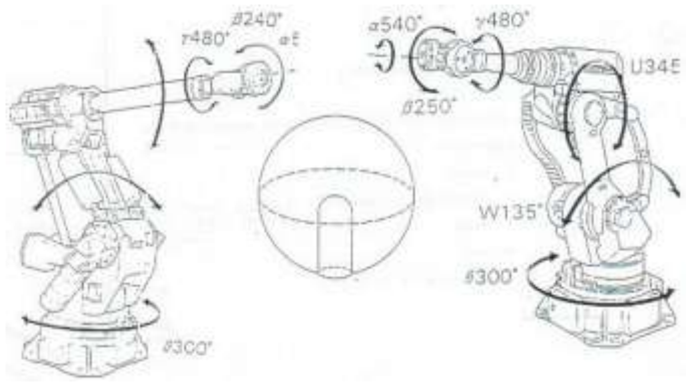


Figure 2.5 Articulated robot

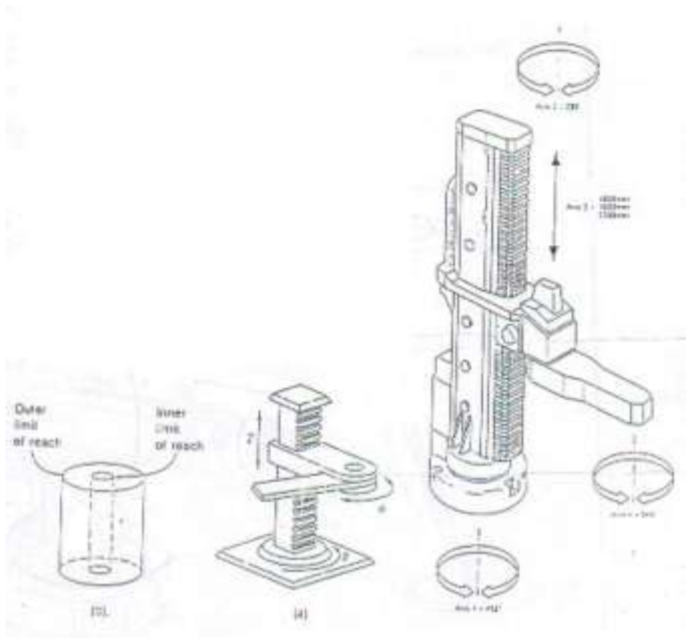


Figure 2.6 (a) A SCARA manipulator. (b) The work envelope for The SCARA manipulator is the space between the two cylinders. The SCARA manipulator can reach around obstacles. (c) A folding lamp has movements similar to those of a SCARA manipulator

2.2.3 Motion Characteristics

If a manipulator has “planar mechanism” it is defined as “planar manipulator”. To manipulate an object on a plane, planar manipulators are useful. Secondly, if a manipulator has “spherical mechanism” it is defined as “spherical manipulator”. As a pointing device, spherical manipulators are very useful. Furthermore, if motion of a rigid body cannot be defined as planar or spherical motion, the motion possibly defined as “spatial motion”. If at least one of the moving links of a mechanism makes general spatial motion, the manipulator defined as “spatial manipulator”.

The cladding of one metal with another is done to obtain the best properties of both. For example, high-strength aluminum alloys do not resist corrosion; however, some aluminum alloys are very corrosion resistant. Thus, a high-strength aluminum alloy covered with a corrosion-resistant aluminum alloy is a composite material with both high strength and the corrosion resistant.

2.2.4 Drive Technology

Although there are three main drive technologies such as electric, hydraulic and pneumatic, most of the manipulators use electric servo motors or stepper motors due to the fact that the advantages of electric motors are more obvious. From the other point of view, hydraulic and pneumatic drive has some advantages such as high-load-carrying capabilities.

2.2.5 Kinematic Structure

The robots are also classified by their kinematic structures. If a robot has open loop chain kinematic structure, it is defined as “serial robot” or “open loop manipulator”. If it has closed loop-chain kinematic structure, it is defined as “parallel manipulator”. Moreover, if a robot system consists of both structure types it is called as “hybrid manipulator”.

2.3 Types of Robot Joints

The purpose of the joint is to provide controlled relative movement between the input link and the output link. Nearly all industrial robots have mechanical joints that can be classified into one of five types. They include two types that provide linear motion and three types that provide rotary motion. Each of the joints have a range over which it can be moved. The five joint types illustrated in the figures below.

2.3.1 Linear joint

The relative movement between the input link and the output link is a linear sliding motion, with the axes of the two links being parallel (Figure 2.7).

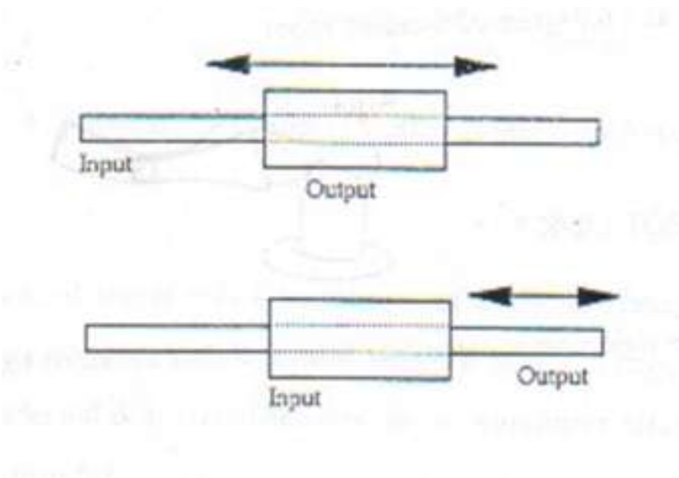


Figure 2.7 Linear joint

2.3.2 Orthogonal joint

This is also a linear sliding motion, but the input and output links are perpendicular to each other during the move (Figure 2.8).

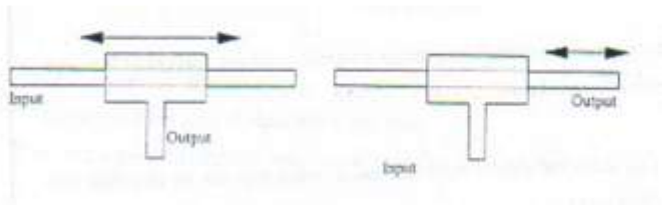


Figure 2.8 Orthogonal joint

2.3.3 Rotational joint

This type provides a rotational relative motion of the joints, with the axis of rotation perpendicular to the axes of the input and output links (Figure 2.9).

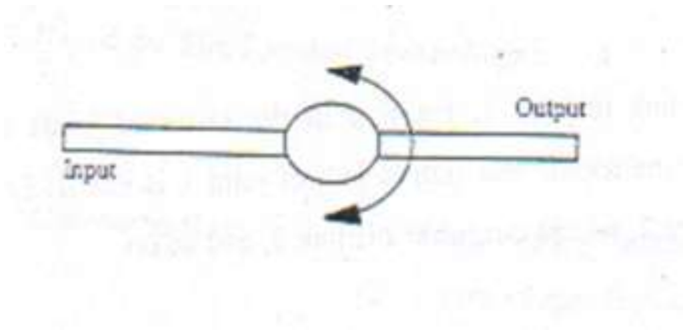


Figure 2.9 Rotational joint

2.3.4 Twisting joint

This joint also involves a rotary motion, but the axis of rotation is parallel to the axes of the two links(Figure 2.10).

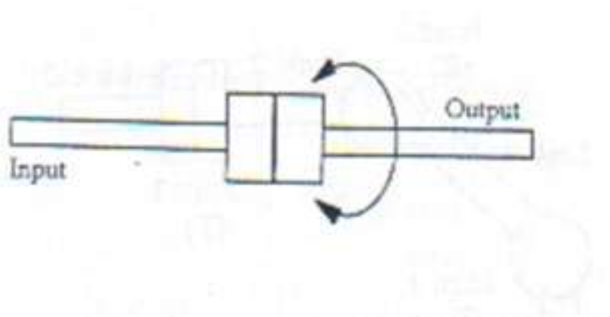


Figure 2.10 Twisting joint

2.3.5 Revolving joint

In this type, the axis of the input link is parallel to the axis of rotation of the joint, and the axis of the output link is perpendicular to the axis of rotation(Figure 2.11).

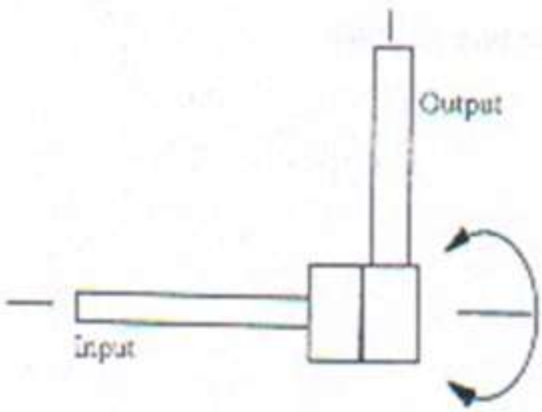


Figure 2.11 Revolving joint

2.4 Robot Manipulators

According to B.Z. Sandler a robot manipulator is "a mechanism, usually consisting of a series of segments, jointed or sliding relative to one another, for the purpose of grasping and moving objects usually in several degrees of freedom.” It may be remotely controlled by a computer or by a human. There are three main types of robot manipulators. Those are serial, parallel and hybrid manipulators.

2.4.1 Serial Manipulators

Serial manipulators which consist of a serial chain of rigid links connected by joints are most common industrial robots. Their joints are generally revolute joint. Most serial manipulators have a anthropomorphic arm structure. This means that they have “shoulder” (first two joints), an “elbow” (third joint) and a “wrist” (last three joints). According to rigid body motion, to place a manipulated object in an arbitrary position and orientation in the workspace of the robot a robot must have at least six degrees of freedom. Therefore most of the serial robots have six joints. On the other hand, Scara robot which is one of the most common serial robot applications has only four degrees of freedom. It is a special assembly robot and used in generally pick and place applications. Figure 2.12 shows a serial robot example (Scara).

Advantages of serial manipulators:

- Larger dexterous workspace,
- Simplicity of the forward and inverse position and velocity kinematics,
- Able to achieve high velocities and accelerations,
- Have revolute joints which are cheaper rather than prismatic joints.

Disadvantages of serial manipulators:

- They are very heavy because the links must be stiff,
- Errors are accumulated and amplified from link to link,
- Not energy efficient.

2.4.2 Parallel Manipulators

Parallel manipulator which consists of a fixed (base) and a movable (end effector) platform is a closed chain mechanism. Base platform is connected to the end effector platform by a number of “legs”. These legs are connected to the platforms by spherical or universal joints. Each leg is controlled by an actuator. The degree of freedom depends on number of actuated legs. Most important advantages of the parallel manipulators are accurate position capabilities and light constructions because the links feel only traction or compression, not bending. In addition that, actuators can be placed in the base platform, hence weight of movable construction decreases (Bruyninckx et al, 2001).

Advantages of parallel manipulators:

- High structural stiffness and load capacity.
- High bandwidth motion capability

Disadvantages of parallel manipulators:

• Limited workspace
• Loosing stiffness in singular position completely

Figure 2.12 Serial robot (Mitsubishi) & Delta robot

2.4.3 Hybrid Manipulators

If features such as accuracy, high speed, stiffness are required for a robotic application, parallel manipulators become as first choice for this application. However industrial robots generally have serial manipulators with open kinematic chain because work space of the parallel manipulators is very limited and this work space is not enough for many applications (Tanev, 2000).

Since parallel and serial manipulators have different advantages, hybrid type manipulation system combines these two manipulators and has features of both serial and parallel manipulators. In addition, hybrid manipulators overcome the limited workspace of the parallel manipulators. Hybrid manipulators generally consist of one serial and one parallel manipulator or two parallel manipulators. Kinematic chain of a hybrid manipulator which consists of two different parallel manipulators is shown in Figure 2.13. Hybrid manipulators can also be used to increase the Degree of freedom of the system. For instance, combination of a serial manipulator which has 7 DOF and a parallel manipulator which has 3 DOF forms a hybrid manipulator with 10 DOF.

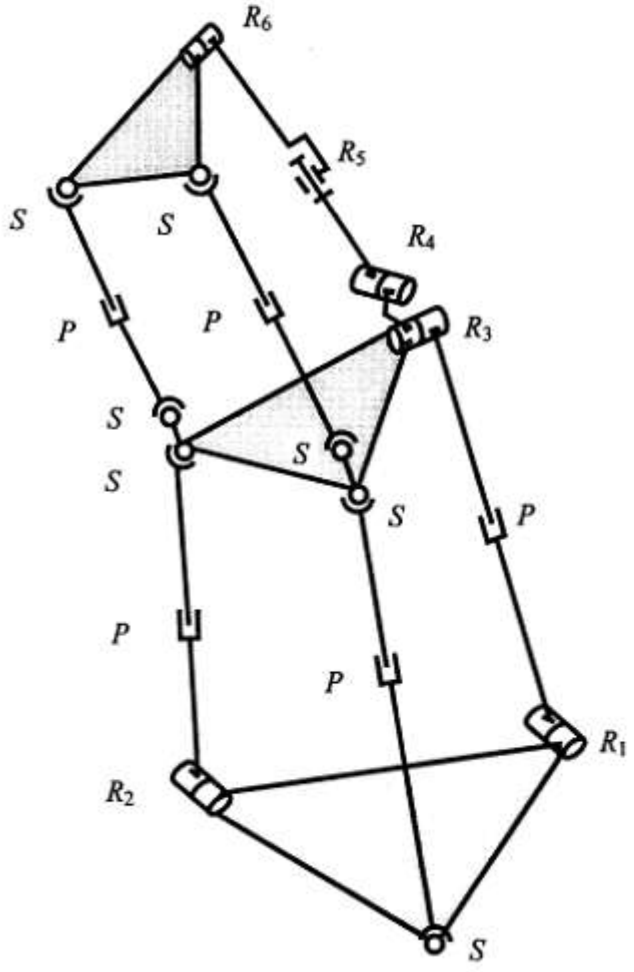


Figure 2.13 Hybrid manipulator

2.5 Motors and Actuators

Each joint of the manipulator is actuated by an actuator. Actuators are devices that make robot move.

Robot drive systems determine :

- the capacity to move its body
- the speed of operation

- the strength
- dynamic performance
- and the kinds of applications that the robot can be used

For most industrial robots, the actuators are coupled to the respective robot link through a, gear train. The effect of the gear reduction is largely to decoupled the system by reducing the coupling among the joints. However, the present of gears introduces friction, backlash and drive train compliance. For direct drive robots, the problems of backlash, friction, and compliance due to gears are eliminated since no gears are used in such a robot. However, the nonlinear coupling among the links is significant, and the dynamics of the actuators themselves may be much more complex.

The commonly used actuators are :

1. Stepper motors
2. DC servomotors
3. AC servomotors
4. Hydraulic pistons
5. Pneumatic pistons

By far, hydraulic and electric drives are the most commonly used on more sophisticated robots.

Some comparisons on the drive systems are below.

2.5.1 Electric Drive

Small and medium size robots are usually powered by electric drives via gear trains using servomotors and stepper motors. Most commonly used are dc motors, although for larger robots, ac motors may be utilised.

Advantages

- Better accuracy & repeatability
- Require less floor space
- More towards precise work such as assembly applications

Disadvantages

- Generally not as speedy and powerful as hydraulic robots
- Expensive for large and powerful robots, can become fire hazard

2.5.2 Hydraulic Drive

Larger robots make use of hydraulic drives. Hydraulic drive system can provide rotational motion (rotary vane actuators) and linear motion (hydraulic pistons).

Advantages

- more strength to weight ratio
- can also actuate at a higher speed

Disadvantages

- Requires more floor space
- Tendency to oil leakage.

2.5.3 Pneumatic Drive

For smaller robots that possess fewer degrees of freedom (two-to four joint motions).They are limited to pick and place tasks with fast cycles. Pneumatic drive system can be applied to the actuation of piston devices to provide linear motions. Rotational motions can be achieved by rotary actuators.

2.5.4 Direct Drive Robots

In 1981 a "direct drive robot" was developed at Carnegle Mellon University, USA. Is used electric motors located at the manipulator joints without the usual mechanical transmission linkages used on most robots. The drive motor is located contiguous to the joint.

Benefits

- Eliminate backlash and mechanical defiencies
- Eliminate the need of a power transmission (thus more efficient)
- Joint backdrivable (allowing for joint space force sensing)

CHAPTER THREE

DESIGN OF SCARA ROBOT

3.1 Introduction to Design

In this chapter, designed steps of ths SCARA robot explained. This SCARA robot's first and second axes were designed and manufactured before by Erturun (2007). Brief description of that steps showed firstly. So, it means that my project is a kind of continuation of his project. Also some of industrial manufacturers and their products are tried to describe in following sections.

3.1.1 Scara Robots in Industry

The SCARA acronym stands for Selective Compliant Assembly Robot Arm or Selective Compliant Articulated Robot Arm (Wikipedia, 2012). SCARA robots have been using in industry since their invention, especially in assembly of electronic units, packaging and pick-and-place jobs. So, they are very popular in industry. For this reasons SCARA robot is one of the main product for manufacturers. Table 3.1 shows the main manufacturers of SCARA robot and some specifications of that robots (Roboter – info, 2012).

3.1.2 Design of First and Second Axes of Scara Robot

As I mentioned in introduction, first and second axes of Scara robot were designed by Erturun (2007). These axes designed for carry out 45 kg payload. So design parameters were chose to obtain highly rigid structure. At all design steps, he considered the flow chart of the integrated analysis as I did in this project which is shown in Figure 3.1.

For determining the basic parameters of the robot simple design created firstly. So, with this model simulations and inverse kinematic analyses are made in

CosmosMotion software to find required actuator torque. According to results of the simulations and analyses, CHA-32A-100 type hollow shaft AC servo actuator is chosen for first axis and CHA-20A-100 type is chosen for second axis of the robot. Detailed informations of servo motors can be find in that thesis.

Table 3.1 Manufacturers of scara robot

Manufacturer / representation	Robot kinematics		Maximum payload [kg]		Special robot edition for	Suppliers main application focus
	Articulated	Scara	Smallest	Biggest		
Fanuc GmbH	x	x	3	1200	Palletizing, Coating (explosion-proof), Console version, Food, Clean room	Welding, Packing, Palletizing, Handling, Pick & Place, Loading / Unloading, Coating
Yaskawa GmbH	x	x	2	800	7-and 15 axis robots, Dispensing (EX), Console versions	All applications
Comau GmbH	x		6	800	Console version, Foundry, Interpress	All applications, except coating in EX-sector
Epson GmbH	x	x	3	20	Clean room, Antistatic, Pharmac., Microassembly	Assembly, Handling, also camera assisted
Kawasaki Robotics	x		2	500	Palletizing, Coating	All applications
Nachi Robotic Systems GmbH	x		5	700	Low working position	Welding, Palletizing, Handling, Sealing
Denso GmbH	x	x	2	20	Clean Room, Dust, Splash	
LacTec GmbH	x		10	20	Coating (explosion-proof)	Coating, Grouting
Stäubli Tec-Systems GmbH	x	x	0.5	220	Clean room, Painting, Plastics	Assembly, Handling, Testing, Measuring, Machine tending
Panasonic Industrial GmbH	x		4	32		Welding
Nachi GmbH	x		5	700	7 axis robot, 20-50kg Payload	Handling
Hirata Robotics GmbH		x	5	12	Clean room, Wall mounting	Assembly, Handling
TM Robotics		x	3	70		Handling, Pick & Place, Assembly
Innovative Robotic Solutions, Inc.		x	5	5	Clean room, Vaporous Hydrogen Peroxide atmosphere (VHP)	Wafer handling, Handling in semiconductors, Pharmaceuticals, Biotech applications
Sony-Wega Produktions GmbH		x	2	5		Assembly
ABB Automation GmbH	x		5	500	Coating (explosion-proof)	All applications
Manutec VaWe Robotersystem GmbH	x	x	2	30	Clean room, Coating (explosion-proof)	Deburring, Welding
Reis GmbH & Co	x	x	6	300		All applications, except coating in EX-sector

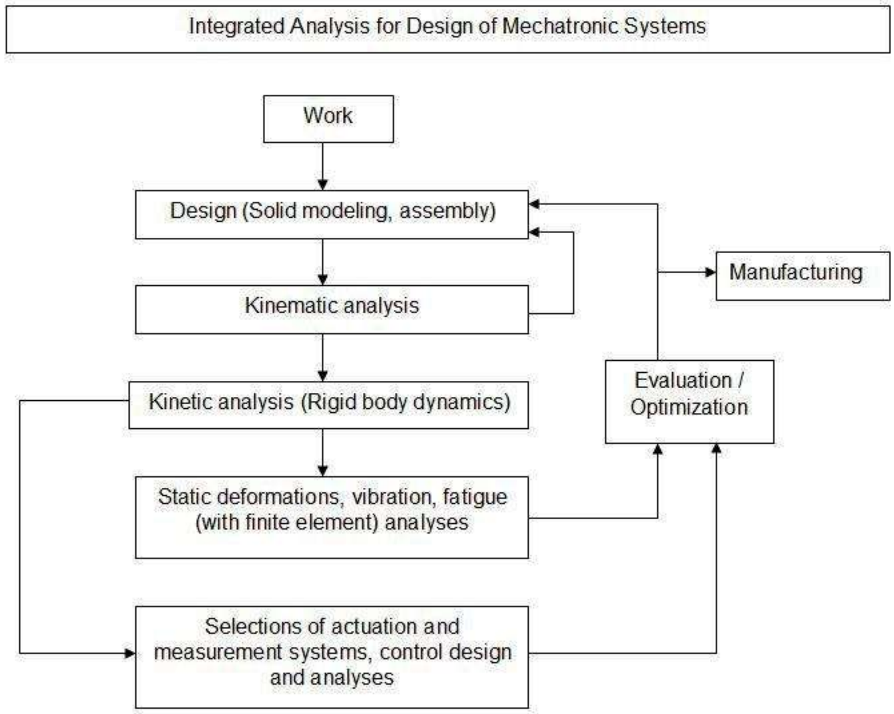


Figure 3.1 Flow chart of the integrated analysis

After the selection of servo motors, first model of scara robot is designed. To see how this design can fulfill the requirements, static and frequency analyses are done for maximum distance from reference point. Results (Table 3.2) showed that minimum natural frequency is 30.629 Hz which is enough for a robot system. But the maximum displacement of the model is quite high (2.950mm) which cannot be acceptable for a robot system (Figure 3.2).

Table 3.2 Results of Analyses for the first model

Static Analyzes	
Displacement (max.)	2.950 mm
Stress (vonMises, max.)	71.984 MPa
Strain (Equivalent, max.)	0.00096 ESTRN
Natural Frequency Analyzes	
1st mode (min.)	30.629 Hz
2nd mode	38.269 Hz
3rd mode	111.49 Hz

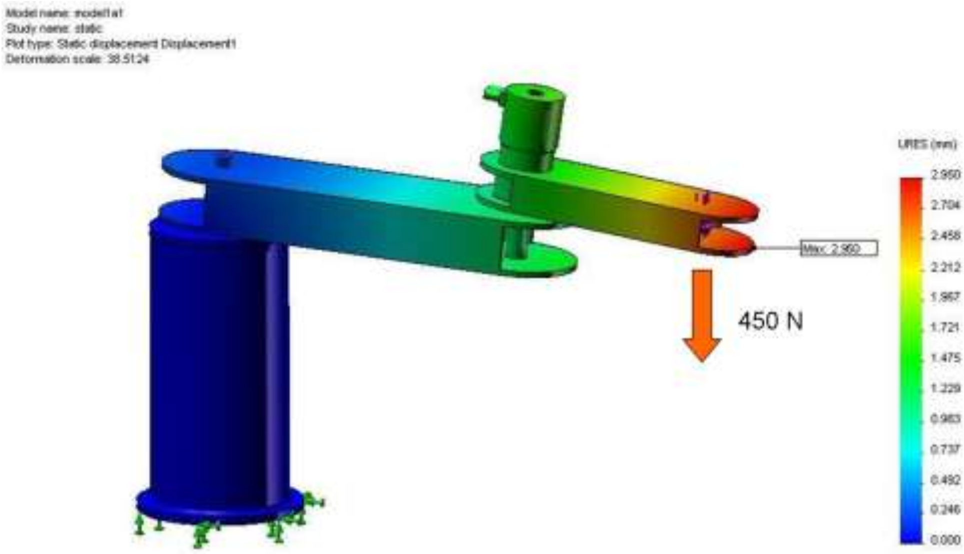


Figure 3.2 Maximum displacement of the first model

According to integrated analysis flow chart, the first model is evaluated and final model is designed. Same analyses are done for the final designed and results obtained. The lowest natural frequency is obtained 31.084 Hz and maximum displacement is measured 0.312 mm which is under 0.4mm so it can be suitable for a robotic system.

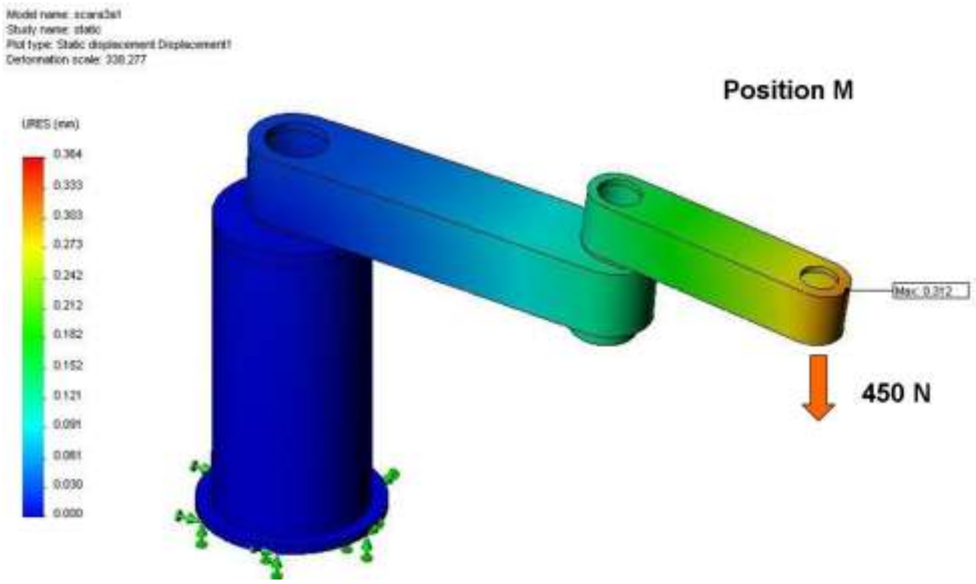


Figure 3.3 Final design analyses result

Table 3.3 Results of the final design

	Position M
Static Analyses	
Displacement (max.)	0.312 mm
Stress (vonMises, max.)	37.238 MPa
Strain (Equivalent, max.)	0.000090 ESTRN
Natural Frequency Analyses	
1^{st} mode (min.)	31.084 Hz
2^{nd} mode	41.643 Hz
3^{rd} mode	88.558 Hz

This macro positioning was planned to use with hexapod which is micro-positioning use for medical operations. So, macro positioning needs a special table for this kind of operations which has approximately 750 mm height. This console should have high rigidity and natural frequencies for micro-positioning operations to reduce possible vibrations. After same steps of scara robot design are done for this console, final design was obtained. It is made by square section steel profiles which have 100x100 mm section dimensions and 5 mm thicknesses.

3.2 Design & Analyses

In first sections of this chapter, short brief about Scara robots and short history of the my Scara robot can be found. I think that to develop something, beginning and history should be known. That is why I give informations.

The Scara which has first and second axes needed third and fourth axes. With one of my advisor is Research Assistant Dr. Murat Akdağ, we made large research about the Scara robots and examine the applications. After this study, we decided the concept of third and fourth axes but we had some design restricts. One of these restricts which was also the biggest one is second arm of the Scara. First and second axes were not designed to have third and fourth axes like this. Main aim of this Scara robot was to carry Hexapod precisely. So, we tried to do our best and made a working sample (Figure 3.4).

Figure 3.4 Prototype of the third and fourth axes

All parts of the third and fourth axes are designed by ourselves. They are not copy of anything. All parts 2D technical drawings can be found in Appendix A.

3.2.1 Design Steps

The flow chart of the integrated analysis which described at the beginning of this chapter also applied to the design of the third and fourth axes. Different types of structures are tried, kinematic and kinetic analyses are performed in Motion. According to results, design is evaluated and changed and reached the end design.

3.2.2 Calculation of Center line Distance

It is important the calculate center line distance. Because, the length of the belt, position of the stretcher is determined according to this calculation. Belt length formulation is below.

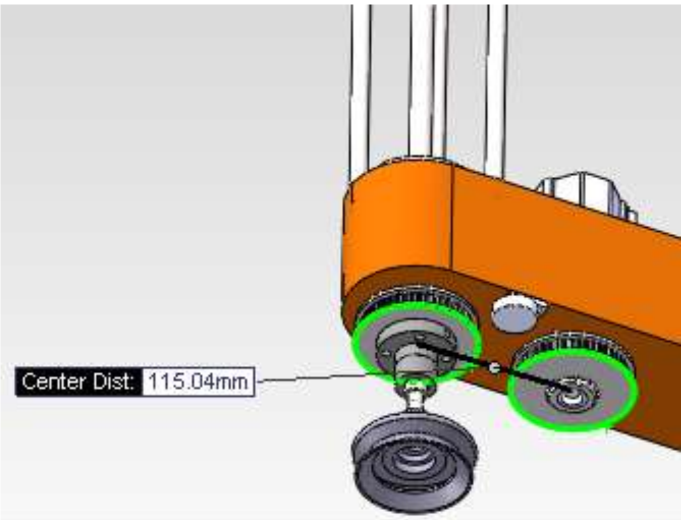


Figure 3.5 Center line distance between servo motors

$$L_w = 2a + \frac{\pi}{2}(d_{01} + d_{02}) - \frac{(d_{02} - d_{01})^2}{4\pi}$$

- L_w = Length of the belt,
- a = Center line distance,
- d_{01} = First pulley diameter,
- d_{02} = Second pulley diameter.

Because of the design restrict, center line distance determined as 115 mm and the pulleies are used 48 tooth / module :5 type.

$$L_w = 2.115 + \frac{\pi}{2}(76.4 + 76.4) - \frac{(76.4 - 76.4)^2}{4\pi}$$

L_w = 469.869 mm

According to belt length table, closest value is 475 mm. So, equation is calculated again with this value and,

$$475 = 2.a + \frac{\pi}{2}(76.4 + 76.4) - \frac{(76.4 - 76.4)^2}{4\pi}$$

a = 117.552 mm

Instead of new center line distance, the first value (115 mm) is used to easy assembly. To make the belt stretch, stretcher is added to the design (Figure 3.6).

Figure 3.6 Stretcher mechanism

3.2.3 Vacuum type gripper

Vacuum type grippers make connection between vacuum pump and workpiece which will be carry. This type of grippers are low cost and safety solutions to carry small pieces and packages. Suction pads can be polyurethane, viton, silicon etc.

To select vacuum gripper, to decide the quality of the material of the gripper, below conditions are important.

- Resistance to abrasion
- Needed suction force per square
- Working conditions
- Quality of the work piece (surface, weight, precision)
- Type of usage

Thanks to vacuum technology, lots of product with lots of surface can be carry easily, cheaply and safely.

Main criteria's of selection of a system's gripper are below.

- Total volume of the vacuum system

- Cycle time of the operation
- Efficiency of the vacuum pump
- Others

Hooded type of vacuum pad is most common gripper type in industry. Because of it's shape, at the vertical movement a short stroke can be useful. This short stroke gains the system flexibility at the vertical movement. Working of the hooded type vacuum pad can be seen in Figure 3.7.

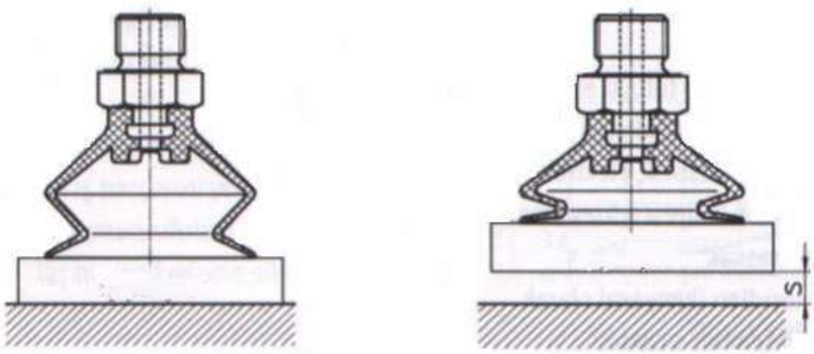


Figure 3.7 Working of the vacuum pad

Three main criteria should be considered at the calculation of gripper.

- Weight of the work piece
- Suction force
- Material and surface quality of the work piece

Friction coefficient (μ), is between work piece and vacuum pad. Some friction coefficients of the some surfaces are below.

Oil	$\mu = 0.1$
Wet	$\mu = 0.2\text{-}0.3$
Rough	$\mu = 0.6$
Wood, metal, glass, stone, etc.	$\mu = 0.5$

Safety factor (S), generally is chosen 1.5 to prevent accidents. This minimum value should be used in calculation. This factor can be increased to 2 when the surface of the work piece is rough, not plane, etc. Also, when the suction works vertically the safety factor should be increased.

3.2.4 Analyses

For testing different positions of the robot and finding characteristics of actuators, a basic model is created. Same weights of the real parts are entered to the basic model. Figure 3.8 shows 3D view of this basic solid model.

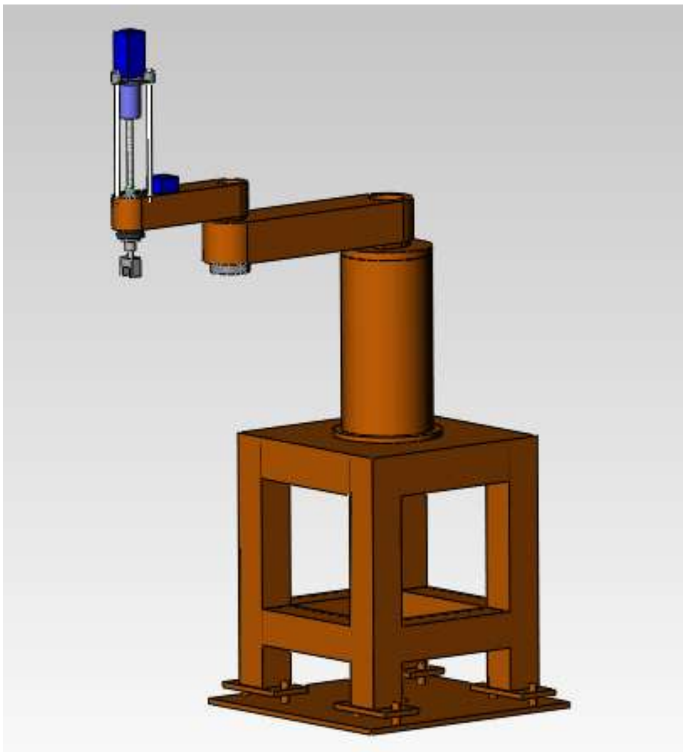


Figure 3.8 Simple model is designed for analyses

For all analyses, the payload of the gripper is chosen 2 kg. Analyses are done for the different stroke of the gripper. First analysis is done for 500 mm stroke and lowest natural frequency is 16.475 Hz which is not acceptable for a robotic system, Mesh properties for these FEM analyses are given as followings; mesh type: solid mesh, element size: 17.230 mm, total nodes: 65223, total elements: 35.260. With same mesh properties, analyses are done for 400 mm, 300 mm and 200 mm strokes. At last analyses, lowest natural frequency is 23.868 Hz which is acceptable and maximum deformation is 0.24 mm which is also quite enough. Figure 3.9 and 3.10 shows the results of the analyses. With these results, stroke of the gripper is determined 200 mm. The system is designed according to 500 mm but results of analyses show that 500 mm can not be realistic.

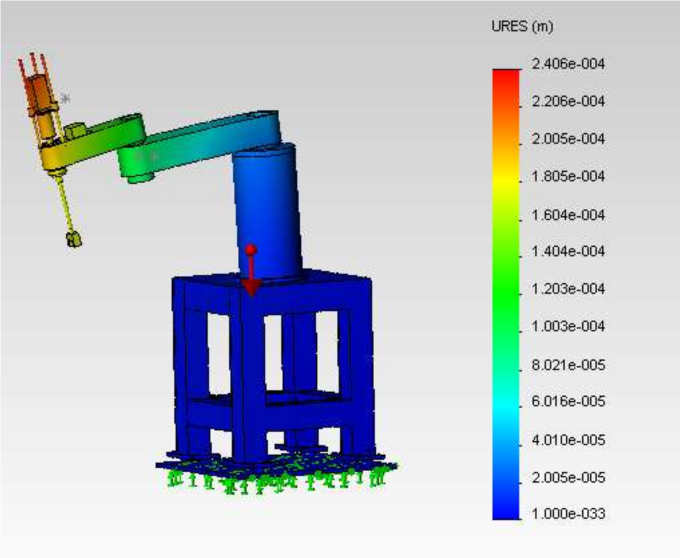


Figure 3.9 Maximum deflection of the system

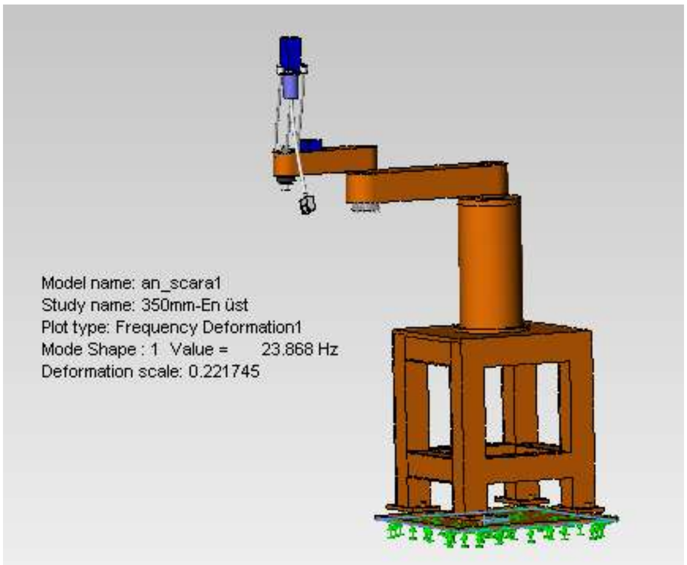


Figure 3.10 Frequency analyses result

In addition to frequency and static analysis, motion analyses are done to check motors' capability and reactions. For motion analyses, sub-assemblies are created. A sub-assembly consist of the parts which are moving together. According to this rule, in my design five sub-assemblies are created. It is important to create sub-assemblies. Because, when creating an assembly in solidworks; mates are defined between sub-assemblies not parts.

In this study, a demo path is determined and motors' torques are examined. In figure 3.12, you can see the initial position of the robot. I accept this position as the start position. In this position, all θ values are accepted 0.

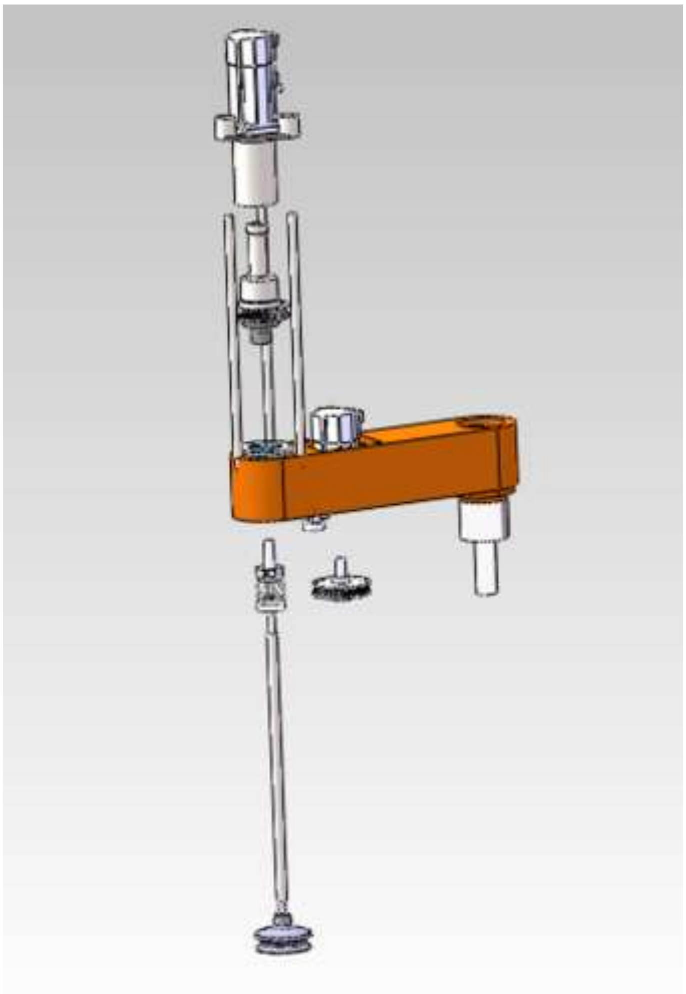


Figure 3.11 Exploded view of the sub-assemblies

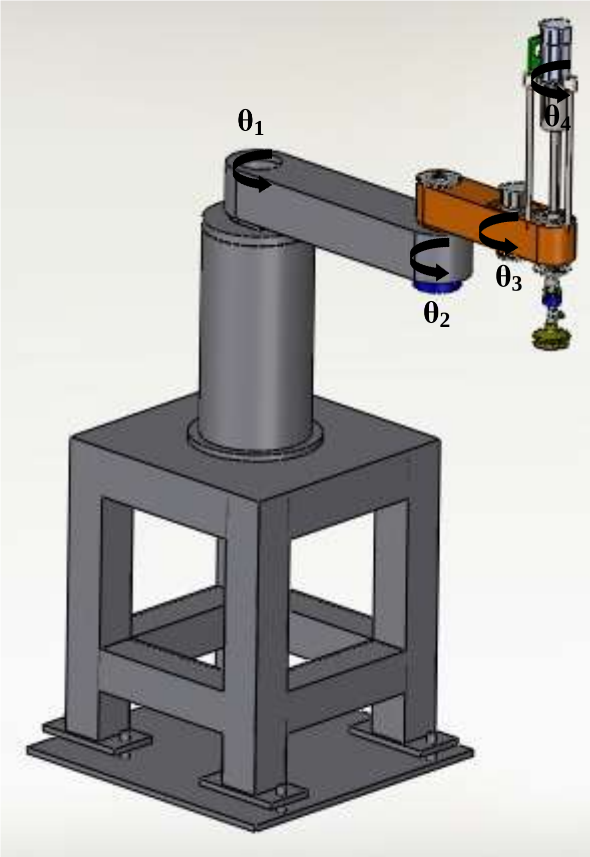


Figure 3.12 Initial position of the robot

In demo path, values which are below were given to the motors :

- **θ_1** : 30°
- **θ_2 :** 45°
- **θ_3 :** 0 °
- **θ_4 :** 13957.2 ° (which is equal to ~200mm translation on vertical direction, because pitch of the ball-spline is 5mm.)

In figure 3.13, you can see the motors' movement when the simulation program is running.

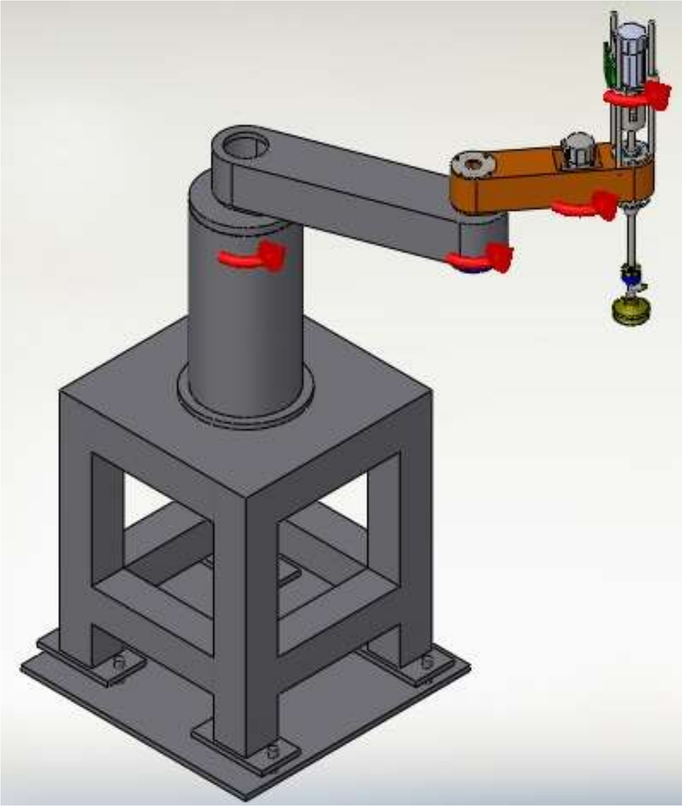


Figure 3.13 View from simulation program.

Now, I want to explain why I gave 0 ° to the motor 3. There is a belt-pulley connection between 3rd and 4th axes, you can see in figure 3.14 and 3.15. So, there is a mathematical relation between them:

Case 1;

- $\theta_3 \neq 0$ and $\theta_4=0$ => $S=h.(\theta_3/2\pi)$

Case 2;

- $\theta_4 \neq 0$ and $\theta_3=0$ => $S=h.\ \theta_4$
- $\theta_p= \theta_4$

So,

- $S=h/2\pi(\theta_3+ \theta_4)$

Here, S is the translation value of the gripper and h is the pitch of the ball-spline.

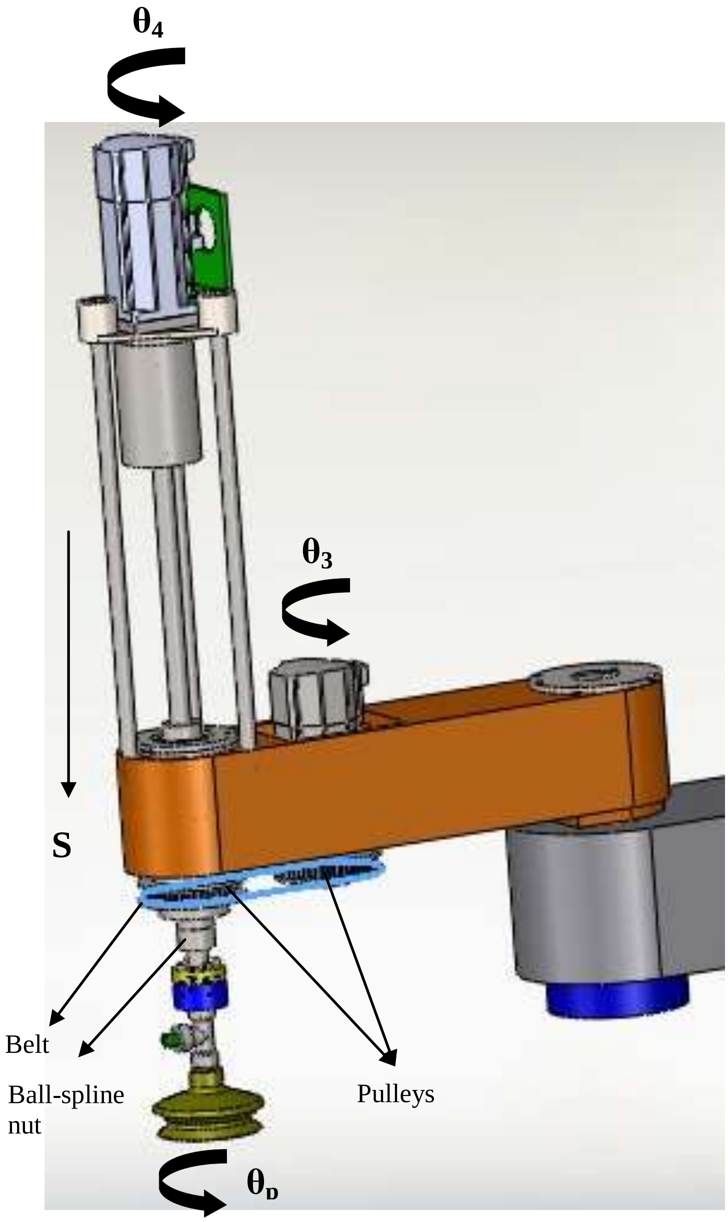


Figure 3.14 Belt- pulley and definitions

Thanks to simulation program motor torques' can be seen easily. To see and compare with the real values, an experimental motion is created and details are given below.

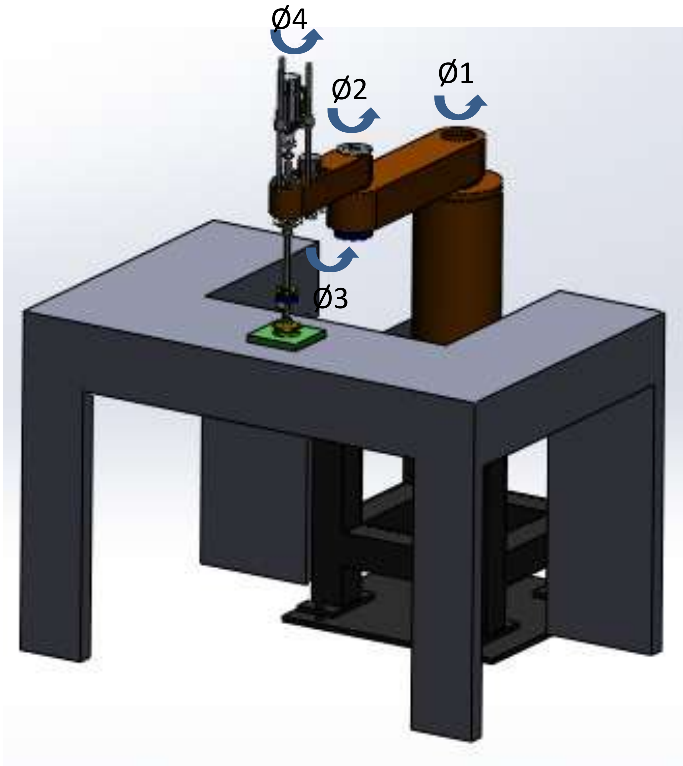


Figure 3.15 An experimental motion design

2 kg weight and table are modeled for motion analysis in Figure 3.15

Table 3.4 Experimental motion values.

t(sn)	Ø1	Ø2	Ø3	Ø4
0sn – 1sn	0 deg	0 deg	10800 deg	0 deg
1sn – 2sn	0 deg	0 deg	0 deg	0 deg
2sn – 10sn	90 deg	90 deg	10800 deg	0 deg
10sn – 15sn	-90 deg	-90 deg	0 deg	0 deg
15sn – 20sn	0 deg	0 deg	10800 deg	0 deg

According to these values, on this path maximum velocity is seen 20000 deg/s (Figure 3.16) which is equal to 3333.3 rpm. This value is between 3000 rpm and

4500 rpm, which are minimum and maximum values of the motor. So we can say that our these motors are good enough for this job.

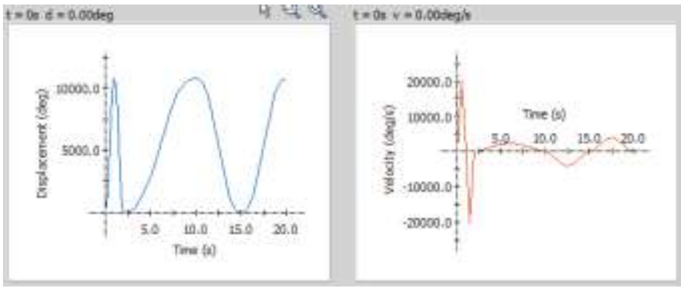


Figure 3.16 Motor velocity graph

And also motor torques are compared with catalogue values (Figure 3.17). Simulation values are seen inside the continues running range. So these motors can be used for this kind of jobs.

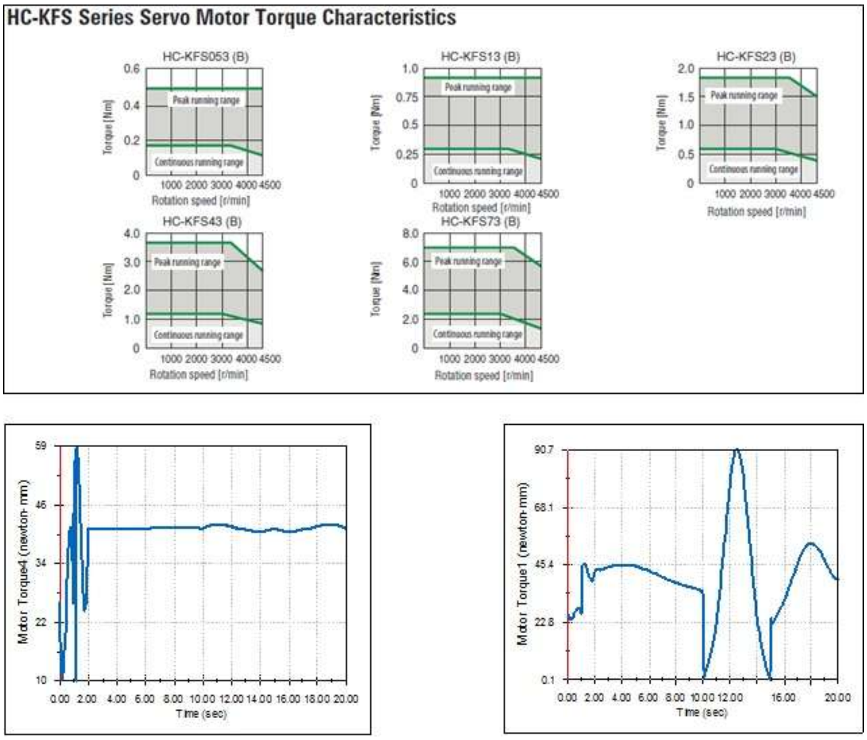


Figure 3.17 Comparison between simulation and catalogue values

3.2.5 Final Design

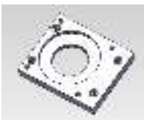
Analysis showed that system can be designed and produced. So final model of the parts are designed and assembled in Solidworks. All parts' technical drawings are prepared and they are produced. You can find the technical drawings in Appendix A.

All manufactured parts' 3D models are shown in Table 3.5. These parts are designed according to existing design. Because of this existing design, parts' design is made with some restrictions. For example, positions of the shafts had limits and also it is same for the diameters. Taking diameter thinner made the system weaker so natural frequencies were lower. As I mentioned before, I determined the stroke of the system 200mm, not 500mm. That is why I choosed this stroke is above.

Anyway, design and prototype of this scara robot is the best with these failures and restrictions. The flow chart of the integrated analysis which described at the beginning of this chapter also applied to the design of the third and fourth axes. Different types of structures are tried, kinematic and kinetic analyses are performed in Motion. According to results, design is evaluated and changed and reached the end design.

This robot design is not suitable to carry 40 kg, first and second axes' were designed to carry 40 kg. But because of the restrictions in design and limits in budgets made design like this. But with some improvements these design can be improved. So another master thesis or project can consider this robot to make it better. But this should take consider; this design is not a copy of any existing system. Everything designed by ourselves and all parts manufactured with ourselves capabilities.

Table 3.5 manufactured parts

Part number	Part name	3D views of solid models
1	Arm	
2	Bearing house	
3	Cover	
4	Shaft	
5	Servo guide	
6	Caplin cover	
7	Support	
8	Connector	

The prototype of the Scara robot is manufactured with datas' which are collected with this study. It was good to see working robot instead of computer. The prototype of the robot can be seen in figure 3.18.

Figure 3.18 Prototype of the Scara robot

After this prototype production, new parts designed and manufactured for pneumatic gripper assembly and cable construction. With these new parts, scara robot will have the part transfer capability. So experimental jobs will be done in real life.

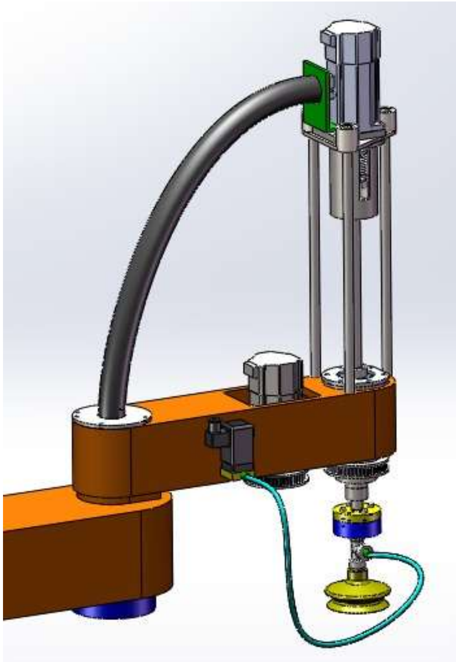


Figure 3.19 New parts of scara robot

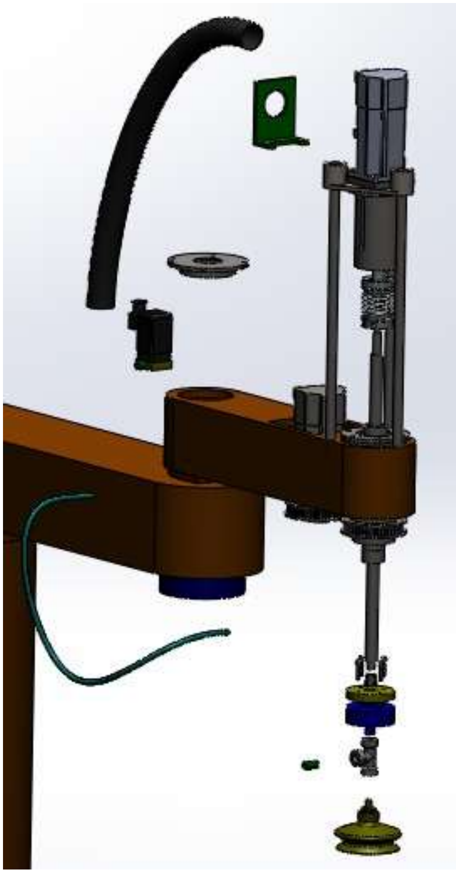


Figure 3.20 Exploded view of new parts

All these studies are done with existing’s parts. Because of the lack of the budget, design also is done to use these parts. So this robot can be more efficient and flexible with new design and new parts. So I just made a small change in the design and made new analyses with this new design. I only changed the thickness of the second arm, third and fourth axes. Only to increase the thickness effects the results in a good way to carry 40kg with this scara robot. Results are shown in Figure 3.21. Improvement in the results can be seen easily. So, with new project this robot can be modified with new design.

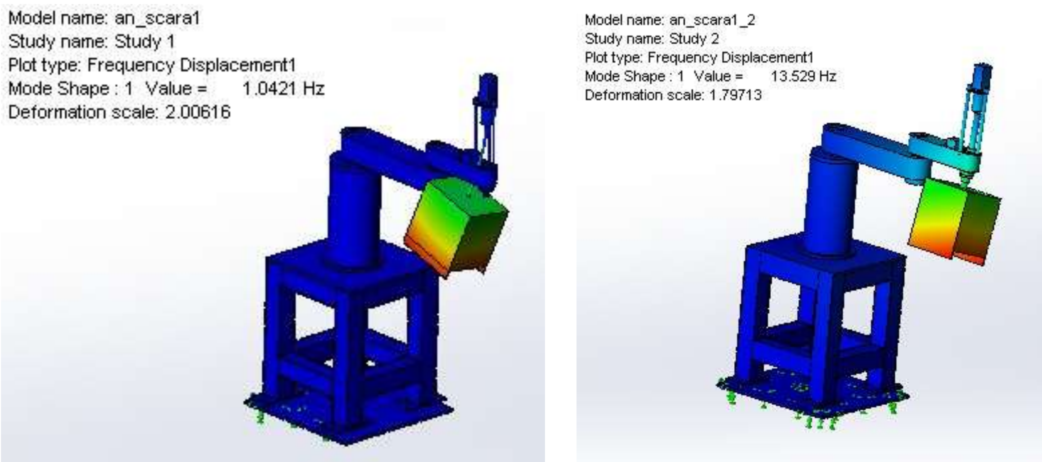


Figure 3.21 Comparison between results

CHAPTER FOUR

KINEMATIC OF ROBOT

4.1 Forward kinematic analyses

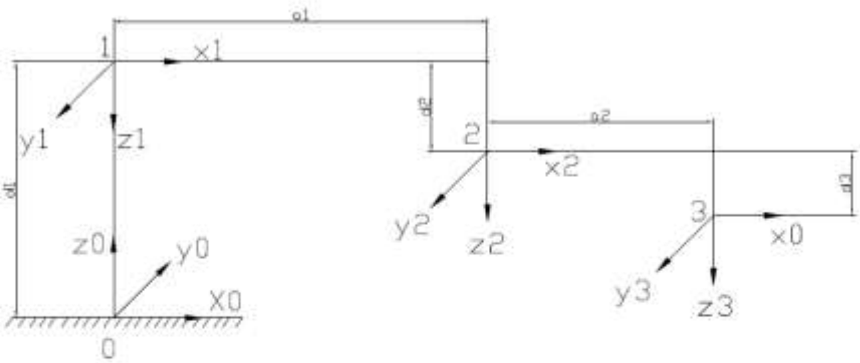


Figure 4.1 Coordinate system of the Scara

$$T_{01} = \begin{bmatrix} \cos\theta_1 & \sin\theta_1 & 0 & 0 \\ \sin\theta_1 & -\cos\theta_{10} & 0 & 0 \\ 0 & 0 & -1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.1)$$

$$T_{12} = \begin{bmatrix} 1 & 0 & 0 & a_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.2)$$

$$T_{23} = \begin{bmatrix} \cos\theta_2 & -\sin\theta_1 & 0 & a_2\cos\theta_2 \\ \sin\theta_2 & \cos\theta_{10} & 0 & a_2\sin\theta_2 \\ 0 & 0 & 1 & d_3 + d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.3)$$

$$T_{03} = T_{01} x T_{13} \quad (4.4)$$

$$T_{03} = \begin{bmatrix} c_1.c_2 + s_1.s_2 & -c_1.s_2 + s_1.c_2 & 0 & c_1.(a_2.c_2 + a_1) + s_1.(a_2.s_2) \\ s_1.c_2 - c_1.s_2 & -s_1.s_2 - c_1.c_2 & 0 & s_1.(a_2.c_2 + a_1) - c_1.(a_2.s_2) \\ 0 & 0 & -1 & d_1 - (d_3 + d_2) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.5)$$

4.2 Inverse Kinematic

$$T_{04} = \begin{bmatrix} nx & sx & tx & kx \\ ny & sy & ty & ky \\ nz & sz & tz & kz \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.6)$$

Equate equation (4.5) and (4.6)

$$nx = (c_1.c_2) + (s_1.s_2) \quad (4.7)$$

$$ny = (-s_1.c_1) + (c_2.s_1) \quad (4.8)$$

$$nz = 0 \quad (4.9)$$

$$sx = (c_s.s_1) - (s_2.c_1) \quad (4.10)$$

$$sy = (-s_s.s_2) - (c_1.c_2) \quad (4.11)$$

$$sz = 0 \quad (4.12)$$

$$tx = 0 \quad (4.13)$$

$$ty = 0 \quad (4.14)$$

$$tz = 1 \quad (4.15)$$

$$kx = c_1.(c_2.a_2 + a_1) + s_1.(s_{2.}.a_2) \quad (4.16)$$

$$ky = s_1.(a_2.c_2 + a_1) - c_1.(a_{2.}.s_2) \quad (4.17)$$

$$kz = d_1 - (d_{3.} + d_2) \quad (4.18)$$

$$\cos a.\cos b = 1/2.[\cos(a+b) + \cos(a-b)] \quad (4.19)$$

$$\sin a.\sin b = 1/2.[\cos(a+b) - \cos(a-b)] \quad (4.20)$$

Equation (4.7) is arranged with (4.19) and (4.20)

$$nx = \cos(\theta_1 + \theta_2) \quad (4.21)$$

Equation (4.16) and (4.17) are arranged

$$kx = a_2.nx + a_1.\cos\theta_2 \quad (4.22)$$

$$ky = a_2.ny + a_1.\sin\theta_1 \quad (4.23)$$

Equation (4.22) and (4.23) are divided to theirselves, so θ_1 is obtained

$$\tan\theta_1 = \frac{ky - a_2.ny}{kx - a_2.nx}; \qquad \theta_1 = \arctan(\frac{ky - a_2.ny}{kx - a_2.nx}) \quad (4.24)$$

From equation (4.21) θ_2 is obtained

$$\theta_2 = \arccos nx - \arctan(\frac{ky - a_2.ny}{kx - a_2.nx}) \quad (4.25)$$

Arrange of the equation (4.18)

$$nx = \cos(\theta_1 + \theta_2) \tag{4.26}$$

CHAPTER FIVE

CONCLUSION

In this thesis, design of the Scara robot is obtained and this design is analyzed with FEM techniques. In the design period, the flow chart of the integrated analyses is followed. Prototype of the robot is manufactured and working of the robot is observed. Some unexpected vibrations are observed at the gripper side when prototype is working. This problem is researched and it seems that backlash of the ballspline nut is the reason. So in the second version of the robot, it is decided that pre-load nut will be used.

This project is done with very small budget. But it seems that it is similar with the industrial one's. With a large budget project, this robot can be easily upgrade by using better raw materials, qualified manufacturing techniques.

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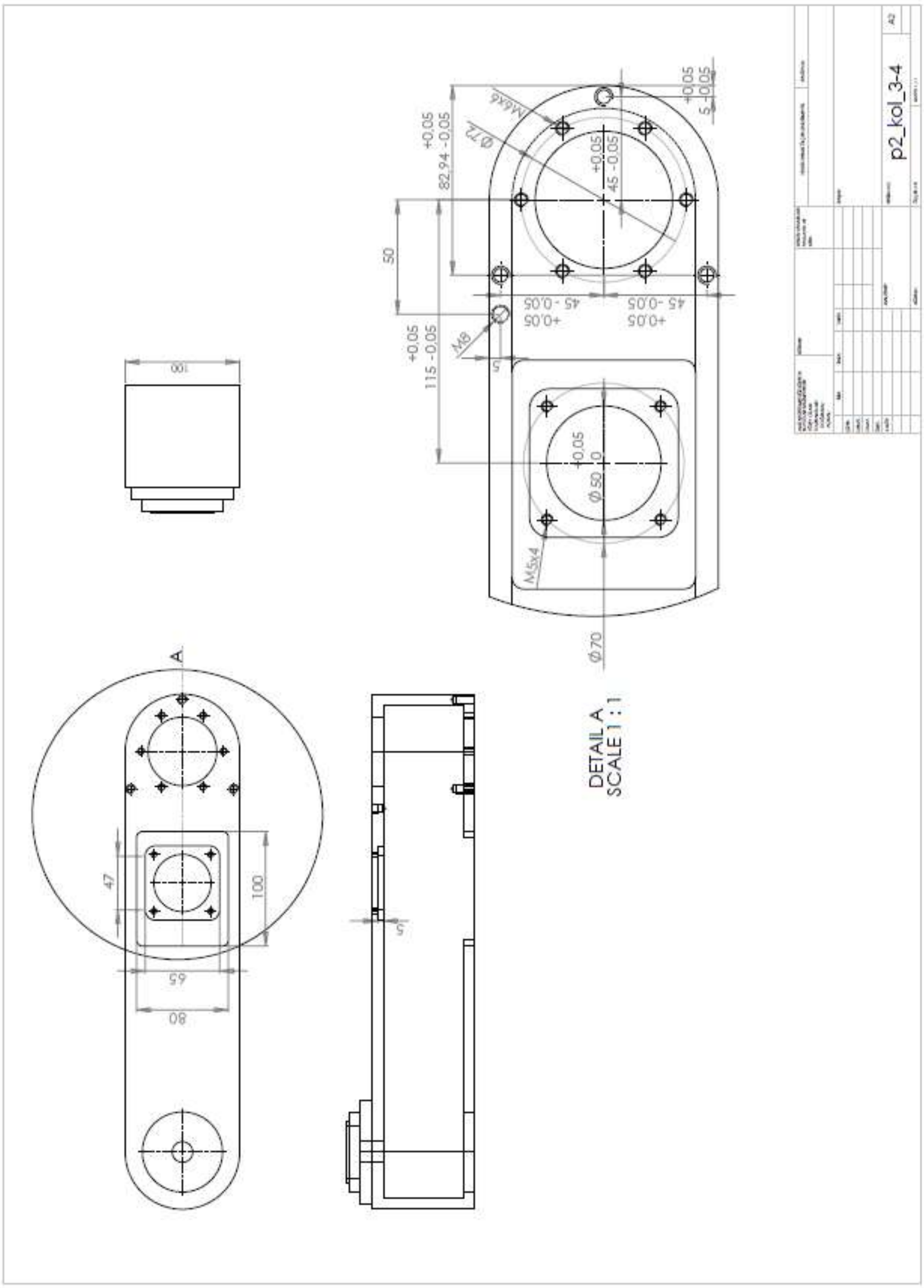
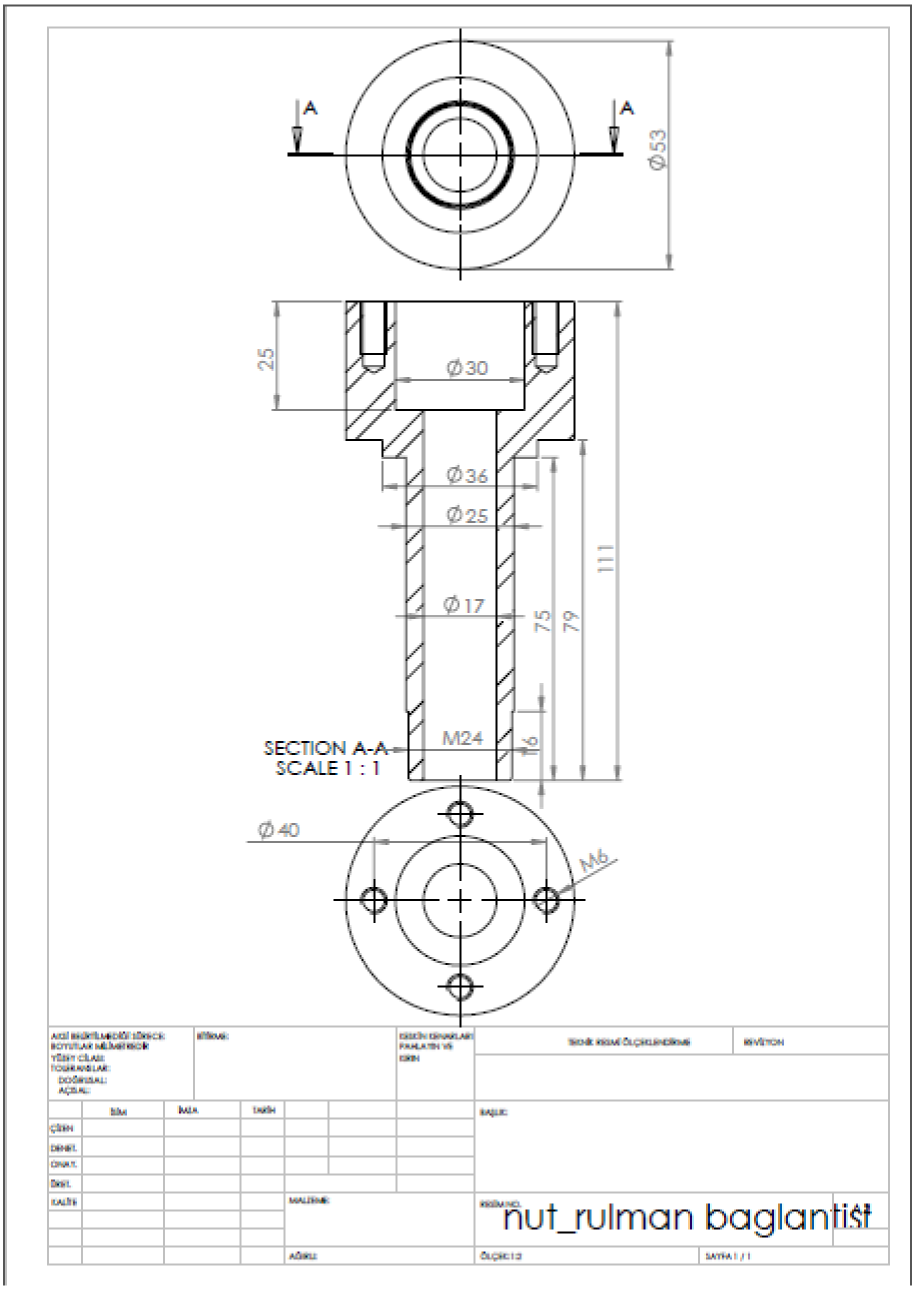
APPENDIX A

TECHNICAL DRAWINGS OF THE MAUFACTURED PARTS OF ROBOT

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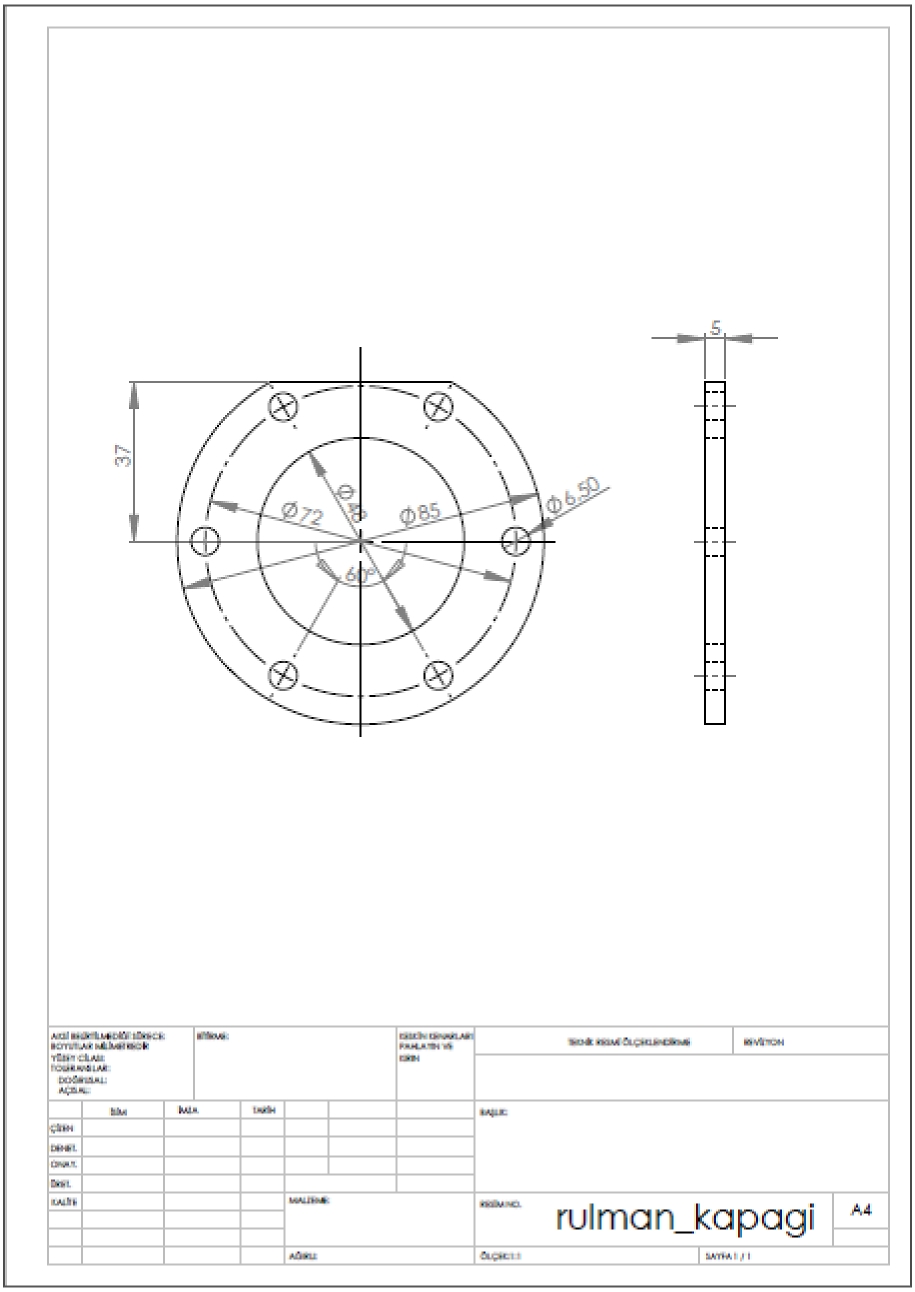
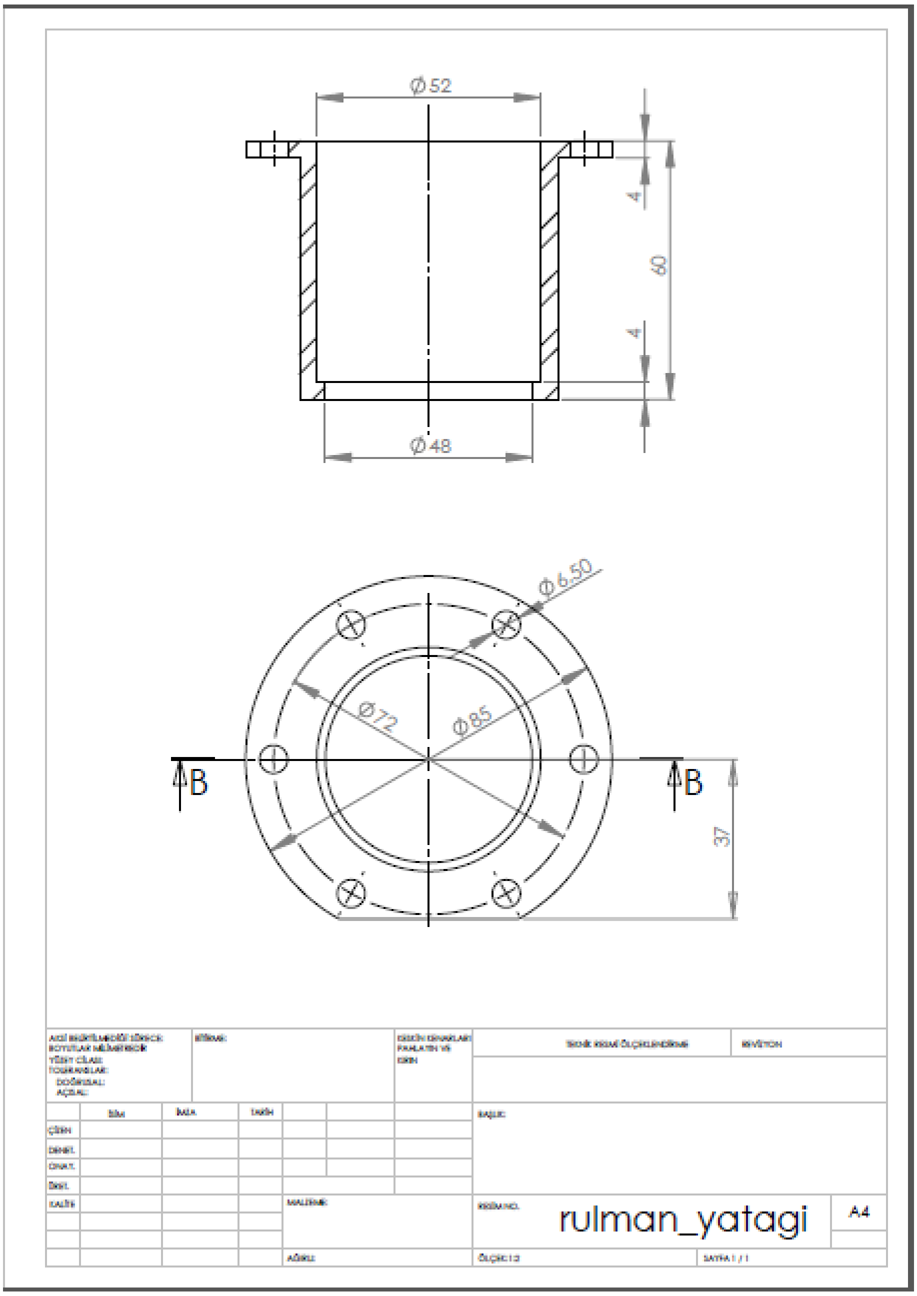
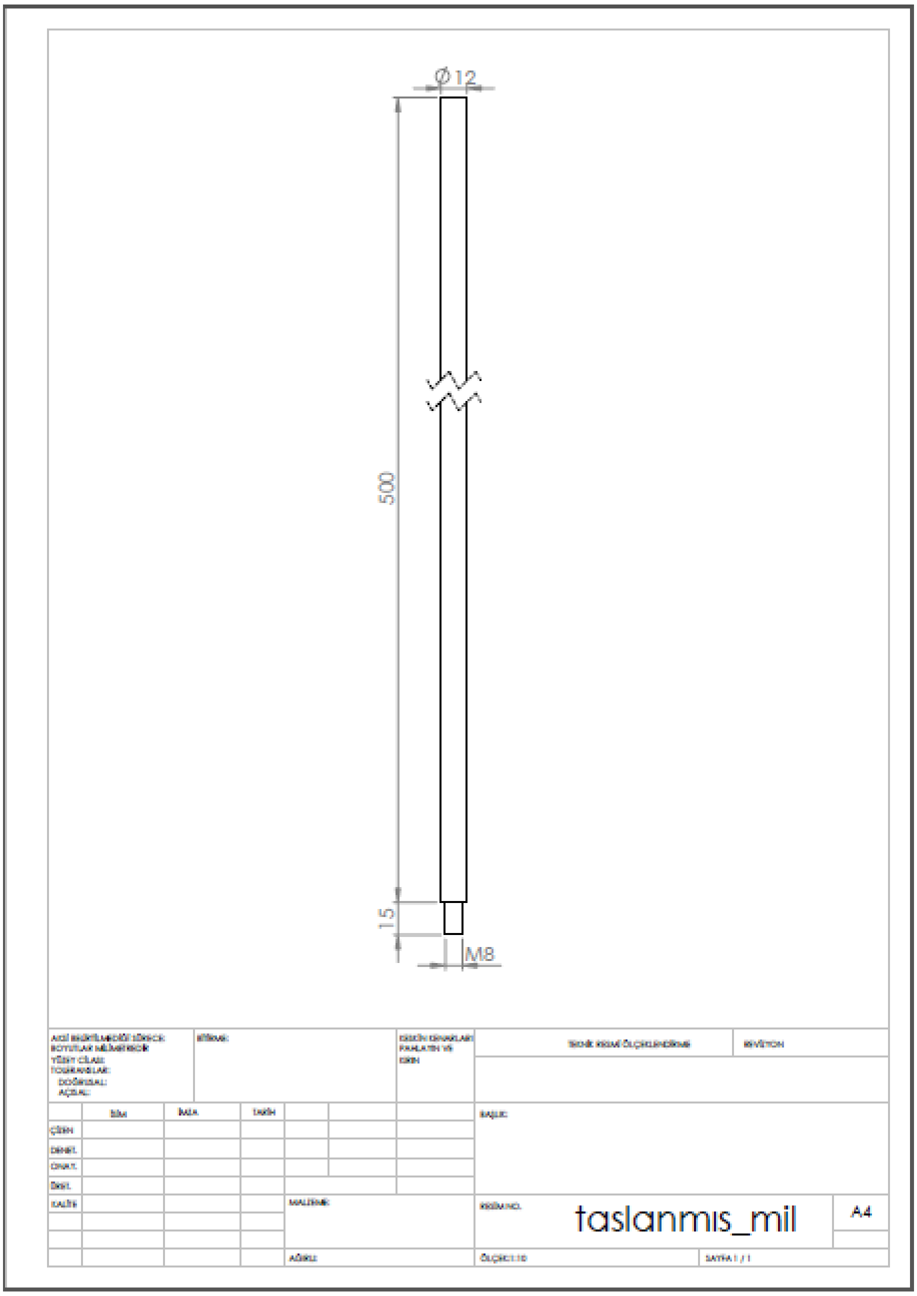
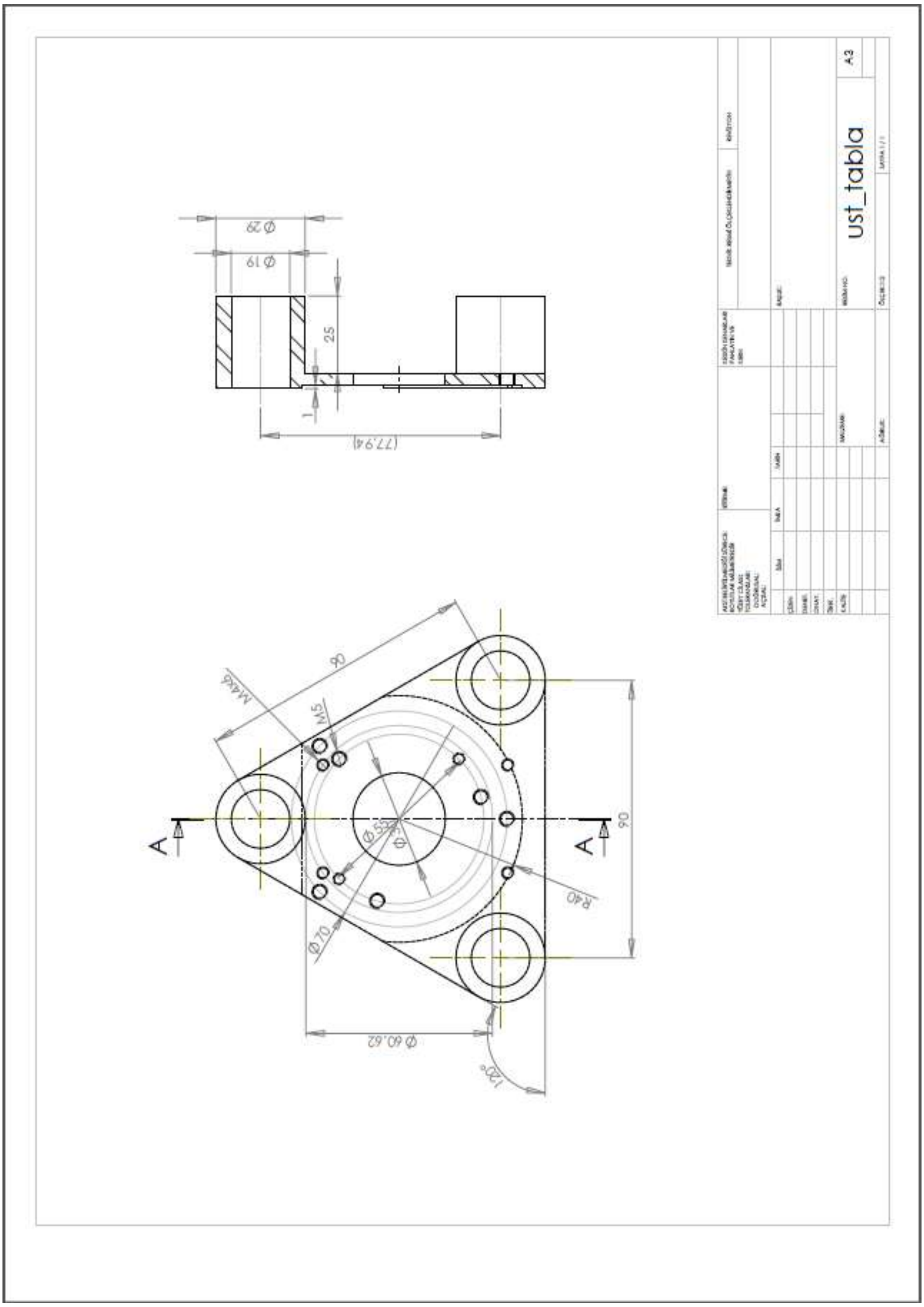
M6
nut_rulman baglantisi

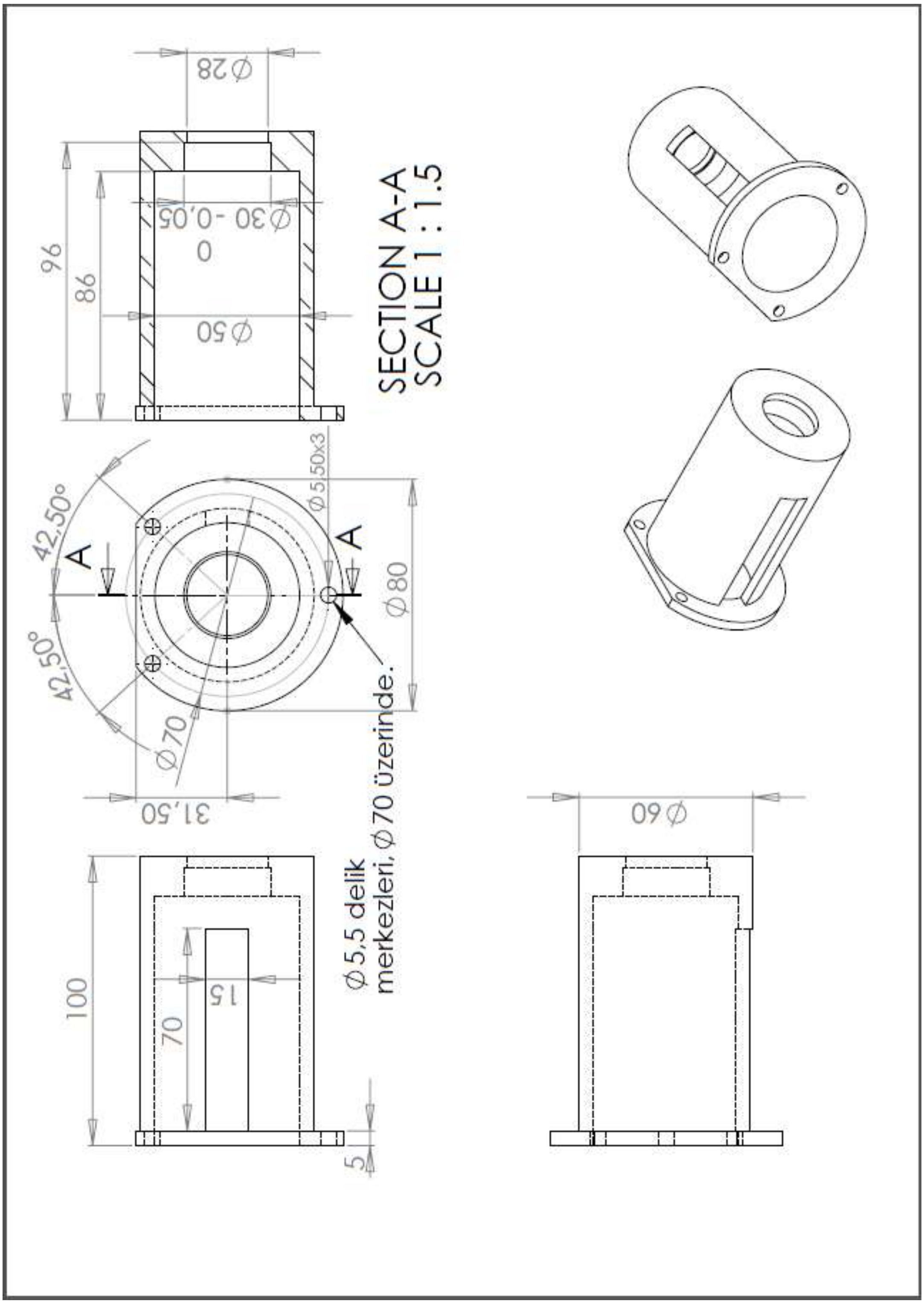

5
37
Ø72
Ø85
Ø6.50
60°
rulman_kapagi
A4



Ø52
4
60
4
Ø48
Ø6.50
Ø72
Ø85
B
B
37
rulman_yatagi
A4


Ø12
500
15
M8
taslanmıs_mil
A4


ust_tabla
A3
A
A
Ø 29
Ø 19
25
1
(77,94)
90
90
M4x6
M5
Ø 55
R40
Ø 70
Ø 60,62
120°


Ø28
96
86
Ø30 -0,05
0
Ø50
SECTION A-A
SCALE 1 : 1.5
42,50°
42,50°
A
A
Ø5,50x3
Ø80
Ø70
31,50
Ø5,5 delik
merkezleri, Ø70 üzerinde.
100
70
15
5
Ø60