DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND
APPLIED SCIENCES

IMPROVEMENT OF VIDEO AND OPTIC PERFORMANCES OF 3D TELEVISIONS

by
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November, 2012
İZMİR

IMPROVEMENT OF VIDEO AND OPTIC PERFORMANCES OF 3D TELEVISIONS

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"IMPROVEMENT OF VIDEO AND OPTIC PERFORMANCES OF 3D TELEVISIONS"** completed by **KEREM DİRİK** under supervision of **ASST. PROF. DR. HALDUN SARNEL** 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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IMPROVEMENT OF VIDEO AND OPTIC PERFORMANCES OF 3D TELEVISIONS

ABSTRACT

Liquid crystal display (LCD) television technology is advancing very fast. In this area of consumer electronics, we can confront new applications every day. Nowadays, the newest trend for LCD technology is definitely three dimensional televisions (3D TV). Although there are significant number of 3D TV models in the market, integration of 3D visualization to television is in its early period and still under development. Critical video and optical related performance problems have already been introduced to litterateur. Authorities agreed on the idea that this new trend definitely needed to be improved to make viewers feel the third dimension better. The most significant problems of 3D TV's in the market are interference of right and left images (3D crosstalk), color shift due to the liquid crystal structure of the eye glasses, panel luminance decrease in 3D mode, and perceived depth problem and eye fatigue. This thesis aims to analyze and find solutions to these optical and video based problems in order to make 3D TV more comfortable and desirable to customers. In this thesis, a new shutter type 3D TV system is developed by implementing solutions to these problems. As first step, a hardware study which fine tunes the infrared synchronization signal between TV panel and glasses is performed to reduce crosstalk. The second part of the crosstalk reduction study, a software algorithm is designed and tested by computer simulation. This crosstalk reduction algorithm is based on adjusting every pixel's luminance before panel side by taking into account of the panel's crosstalk behavior. The algorithm is also realized on the designed 3D TV in real time by using FPGA and satisfactory results are obtained. A final study is for improving color accuracy and 3D luminance performance that is carried out by gamma color correction.

Keywords: 3D TV, stereoscopic displays, shutter glass, active glasses, passive glasses, 3D crosstalk, color shift, frame packing, side by side, top bottom

3 BOYUTLU TELEVİZYONLARIN VİDEO VE OPTİK PERFORMANSLARININ İYİLEŞTİRİLMESİ

ÖZ

LCD TV teknolojisi çok hızlı gelişmekte, her geçen gün yeni uygulamalar ile karşımıza çıkmaktadır. Günümüzde LCD TV teknolojisinin geldiği son nokta, kuşkusuz 3D TV'lerdir. Şuan piyasada birçok 3D TV bulunmasına rağmen, üç boyutlu görüntülemenin televizyona entegrasyonu henüz gelişme aşamasındadır. Önemli video ve optik problemler literatüre geçmiştir. Otoriteler bu yeni trendin, izleyiciye derinlik hissini daha iyi verebilmesi için mutlaka geliştirilmeye ihtiyacı olduğu konusunda birleşmiş durumdadırlar. Şu an piyasada yer alan tüm üç boyutlu televizyonların ortak problemleri, sağ ve sol göz için ayrılmış ayrı iki resmin birbirine karışması (çapraz karışma), gözlüklerin sıvı kristal yapısı nedeniyle oluşan renklerin tonlarının değişmesi (renk kayması), 3D modda panel parlaklığının azalması, algılanan derinliğin bozulması ve göz yorgunluğudur. Bu tez, yukarıda bahsedilen optik ve video kaynaklı bu hataları analiz ederek çözüme kavuşturmayı ve 3D TV performansını daha konforlu ve cazip bir konuma getirmeyi hedeflemektedir. Bu tezde, yukarıda sıralanan problemlerin çözümlerinin gerçeklendiği, aktif gözlükle çalışan yeni bir 3D sistemi geliştirilmiştir. İlk olarak, donanımsal bir çalışma yapılmış, çapraz karışmayı azaltmak için gözlük ile panel arasındaki senkronizasyonu sağlayan kızılötesi sinyali üzerine ayar yapılmıştır. Çapraz karışmayı iyileştirme çalışmasının ikinci kısmı olarak yazılımsal bir algoritma tasarlandı ve bilgisayar simülasyonuyla test edildi. Bu algoritma panelin çapraz karışma davranışına göre panel öncesi her pikselin parlaklık değerini yeniden ayarlamaya dayanmaktadır. Algoritma, aynı zamanda, FPGA kullanılarak TV üzerinde donanımsal ve gerçek zamanlı olarak çalıştırılmış ve olumlu sonuçlar alınmıştır. Son çalışma ise, renk doğruluğu ve parlaklık performansını arttırma adına TV'nin gamma eğrilerinin değiştirilmesi ile yapılmıştır.

Anahtar sözcükler: Üç boyutlu televizyon, stereoskopik görüntüleme, aktif gözlük, 3D çapraz karışma, renk kayması, 3D yan yana video, 3D üst üste video

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CHAPTER ONE
INTRODUCTION

1.1 Introduction

3D visualization is a highly popular concept nowadays with the rise of lots of 3D materials like films, games, TV shows etc. After its debut on theaters, 3D entertainment has caused a very high demand for consumer electronics application of this new technology. So, this demand has forced TV manufacturing industry to research and develop 3D visualization methods since the beginning of 90s.

3D term used in this thesis is the abbreviation of 3 dimensional images which are descriptive of a region of space that has length, width and depth. Human brain can detect environment in 3D with the help of his two eyes. Two images of a slightly different perspective are presented to each eye and human brain constitutes the depth sense automatically. So the two images accepted by the two eyes lead us to stereoscopic term; which is the main idea of generating artificial 3D visual on a 2D surface.

There are several ways to create 3D effect on a TV; some require glasses and some are glasses free. This thesis will be focusing on only "with glasses" methods since the current technology allows only them to be applicable on consumer electronics.

As 3D TV is a highly new concept, several important bugs are introduced to literature. These are:

- ❖ Interference of right and left images (3D crosstalk)
- ❖ Change in the colors' hues (color shift) due to the liquid crystal structure of the eye glasses (both passive and active),
- ❖ Panel luminance decrease in 3D mode,
- ❖ Perceived depth problem and eye fatigue.

All these problems are examined with their reasons and quantitative evaluation techniques in this thesis. Aim here is to develop proper and applicable improvements to all these problems, so contribute to the usability of 3D TVs by enhancing their overall 3D performance.

Crosstalk is the most important one among all these, as this artifact dramatically disrupt 3D quality, and become one of the main reasons of eye fatigue. So the most comprehensive study taken place in this project is to lower 3D crosstalk.

Two methods are considered to lower crosstalk, one is a hardware method to fine tune infrared sync signal between panel and glasses. The second method is a software study which aims to estimate 3D crosstalk effect on the screen and tolerating it by setting luminance values of the pixels. An algorithm known in literature for reducing crosstalk is first investigated. Then its software implementation work customized to a specific panel and glasses pair is carried out. This algorithm is finally implemented on FPGA for real-time operation on TV.

As to the color accuracy, gamma curves of the input video signal are altered to compensate for color shift caused by the 3D glasses.

So this thesis mainly deals with two problems, 3D crosstalk and color accuracy; which are the main reasons for the 4 performance problems mentioned above.

1.2 Outline

This thesis contains six chapters. Chapter 1 presents general information about 3D and its problems, and briefly mentions about the solutions to the highlighted problems.

In Chapter 2, the basis for 3D TV is given. Firstly stereoscopy term is introduced, than 3D visualization methods and 3D video signals are explained.

Chapter 3 includes the 3D TV quality parameters which are introduced to literature. These parameters are explained in detail, with their reasons and possible effects.

In Chapter 4, the method of measuring quality parameters which are introduced in Chapter 3 is given. Some benchmark measurement results are shared and according to these results, specification goal of a high performance 3D TV is determined.

Chapter 5 is the chapter that all the improvement works are explained. Two methods are introduced here to reduce crosstalk; one is hardware study and the other one is software study. Also to be able to increase 3D luminance, a software based color temperature defining work takes place.

And, finally, Chapter 6 presents a conclusion for all the work performed in this thesis.

CHAPTER TWO
3D BASIS

2.1 Introduction to 3D

At the present time, there are several ways to form 3D vision, but highly used and most efficient one is stereoscopic visualization. Stereoscopic visualization methods will be explained in next section, but firstly it's vital to understand how a human being perceives the environment.

2.1.1 Human Vision

To be able to understand the methods of creating artificial 3D visualization, the best starting point is to understand how we perceive in 3D. The main clues used by brain to manage this are listed and studied in this section.

2.1.1.1 Stereoscopic data

This is the main and the most valuable data for constructing depth for human brain. The distance between the eyes is 6.3 cm in average. So, both eyes see the same view in distinct perspectives and two pictures for the same view are transmitted to brain. Brain detects the objects locations by using these pictures.

2.1.1.2 Accommodation and converge

Accommodation is the process by which the vertebrate eye changes optical power to maintain a clear image (focus) on an object as its distance varies (Bhola, 2006). Accommodation acts like a reflex, but can also be consciously controlled.

When we try to focus on far away objects, the ciliary muscles stretch the eye lens, making it thinner, and hence changing the focal length. When we try to look an object from short distance, the muscles controlling the eye-lenses shrink. So this biological reaction on the muscles and eye-lenses provides clue for brain about how far is the object.

Convergence is the simultaneous inward movement of both eyes toward each other, usually in an effort to maintain single binocular vision when viewing an object (Cassin & Solomon, 1990). Projections of the picture on the both eyes' retinas are different. This term is about eyes' moving synchronously. In Figure 2.1, we can see retina projections for both left and right eyes.

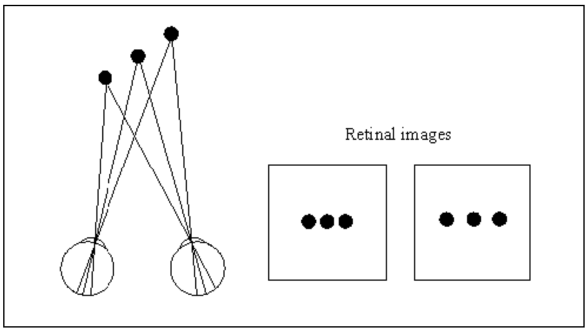

Figure 2.1 Retinal images

These two reflexes are interpreted by brain to sense the depth.

2.1.1.3 Motion Parallax

When an observer moves, the apparent relative motion of several stationary objects against a background gives hints about their relative distance. If information about the direction and velocity of movement is known, motion parallax can provide absolute depth information (Ferris, 1972).

2.1.1.4 Aerial Perspective

Due to light scattering by the atmosphere, objects that are a great distance away have lower luminance contrast and lower color saturation. In computer graphics, this is often called "distance fog". The foreground has high contrast; the background has low contrast, just like the mountains in Figure 2.2 are fader than the front hut.

Objects differing only in their contrast with a background appear to be at different depths (O'Shea., Blackburn & Ono, 1994).

Figure 2.2 Aerial perspective

2.1.1.5 Occlusion

Occlusion (blocking the sight) of objects by others is also a clue which provides information about relative distance. However, this information only allows the observer to create a "ranking" of relative nearness. In Figure 2.3b, viewer can detect automatically that the bigger tree is nearer than the small tree.

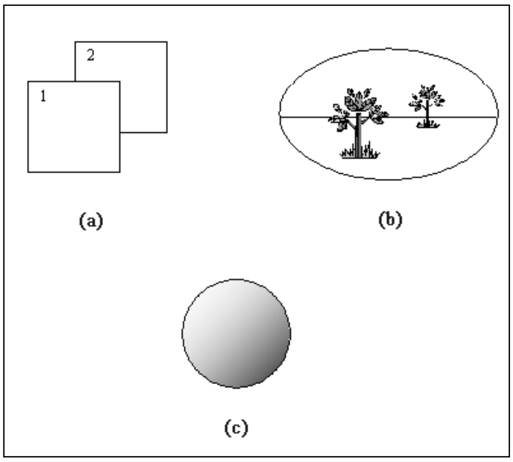

Figure 2.3 Occlusion

2.1.2 Stereoscopic 3D

Stereoscopy refers to a technique for creating or enhancing the illusion of depth in an image by presenting two offset images separately to the left and right eye of the viewer. These two-dimensional images are then combined in the brain to give the perception of 3-D depth.

Three strategies have been used so far to mechanically present different images to each eye:

- ❖ The viewer wears eyeglasses to combine separate images from two offset sources,
- ❖ The viewer wears eyeglasses to filter offset images from a single source separated to each eye,
- ❖ The light source split the images directionally into the viewer's eyes (Dodgson,2005)

Now in 3D TV technology, the second method is used. The technologies based on the second method require corresponding glasses to separate out the left and right eye images while any content is being presented by the display. 3D glasses can be **passive** (just lenses mounted in the frame), or **active** (electrically active, and therefore battery powered), with costs ranging from pennies to over a hundred dollars.

There are two passive, and one active method which are widely used. Each one has advantages and disadvantages according to their mechanical mechanism; which are the matter of interest directly for this thesis.

2.1.2.1 Anaglyph 3D - Passive Red-Cyan Glasses

Anaglyph is a spatial 3D display technique which creates a stereoscopic 3D effect by superimposing the two images using different colors that have offset. The two colors are usually chromatically opposite, typically red (for the left eye) and cyan (blue/green for the right eye). When viewed by using glasses with corresponding colored eyepieces, the eye merges the image into an integrated stereoscopic image.

Anaglyph is used for mass market consumer applications, since it requires only inexpensive cardboard glasses (Figure 2.4), and works with existing imaging equipment and displays as well as printed material.

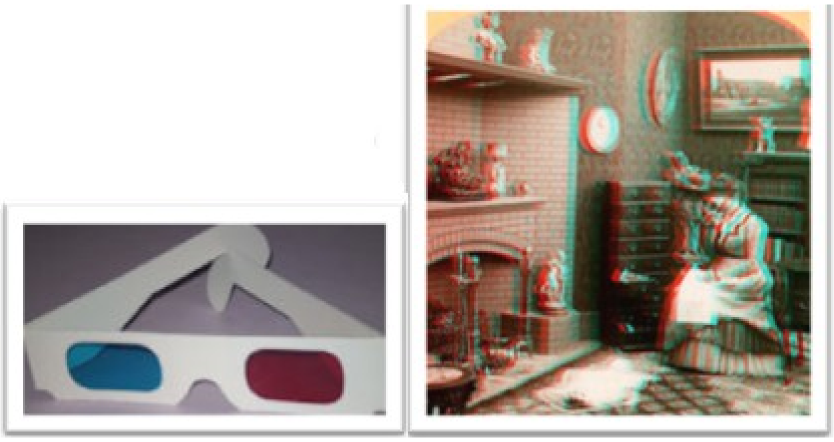

Figure 2.4 Anaglyph glasses and anaglyph picture

Anaglyph 3D method is the oldest one among others; the first method to produce anaglyph images was developed in 1852 by Wilhelm Rollmann in Leipzig, Germany (Rollmann, 1853).

- Pros

+ Used for mass market consumer applications
+ Works with existing delivery formats and media (physical DVD, PCs, online)
+ Works with existing imaging equipment displays
+ Also used for printed material
+ Consumer friendly - Very inexpensive glasses

- Cons

- Very poor color range
- Color shifts

2.1.2.2 Alternate Frame Sequential 3D

In this method, 3D Glasses containing liquid crystal block or pass light through in synchronization with the images on the panel, using the concept of alternate-frame sequencing.

It works by openly presenting the image intended for the left eye while blocking the right eye's view, then presenting the right-eye image while blocking the left eye, and repeating this so rapidly that the interruptions do not interfere with the perceived fusion of the two images into a single 3D image.

Since the left and right pictures are showed on the screen consecutively, panel’s refresh rate should be 120 Hz minimum to prevent motion judder. So 60 left and 60 right pictures will be delivered to each eyes in a second.

LCD pixel response time rises as a vital point here; response of the pixels should be fast enough to show each picture correctly.

To understand this subject, it’s better to check LCD’s behavior with the electrical input. As illustrated in Figure 2.5, pixels’ luminance cannot change right away, there is a transition time. So it takes time for liquid crystals to change position – so setting luminance - and all these transition times causes motion blur in LCD technology as shown in Figure 2.6.

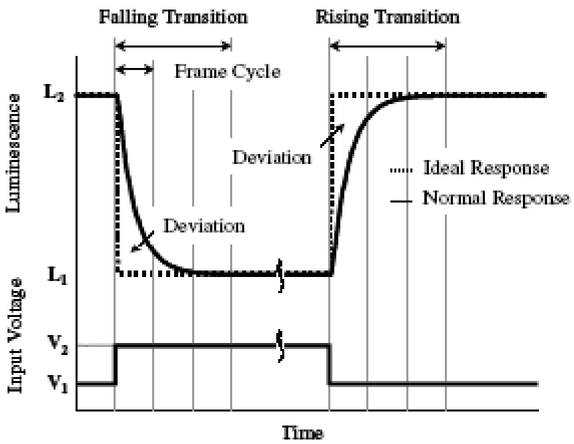

Figure 2.5 LCD Response time waveform

Figure 2.6 Motion blur

In regular 2D TVs, it is named as motion blur because the current picture of the video will always have residues coming from the previous picture. Since there is a slight difference between two adjacent frames, generally the biggest luminance changes occur on the edges of the objects and these edges look unsharp, or blurred.

In 3D alternate frame sequential 3D TVs, the adjacent frames are left and right pictures, so the same idea works here but this effect is not like blur any more, it has a new name: 3D crosstalk.

To prevent 3D crosstalk, a black frame insertion method is used in nearly every shutter type panel. As shown in Figure 2.7, this method rises from a very simple idea; inserting a dummy fully black picture between each frame dramatically reduces the interference between adjacent frames.

So, increasing panel refresh rate to 240 Hz and inserting black frame between each left and right frame has become highly popular in this 3D method recently.

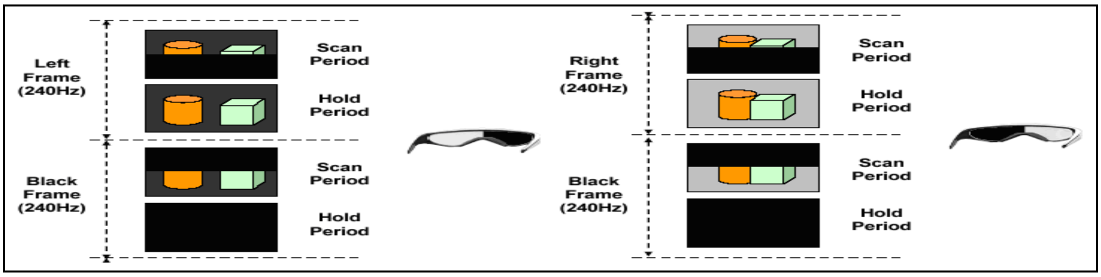

Figure 2.7 Alternate Frame Sequential type 3D

- Pros

+ Natural upgrade for existing displays, still support 2D
+ Display alternating frames with opposite polarization
+ Liquid crystal shutter glasses turn transparent / dark, to open / block each eye
+ Wireless emitter to sync display rate and glasses - 240 Hz (120 per eye)
+ Full resolution image

- Cons

- Used for small groups: 3D TV, 3D on PCs
- More expensive glasses - Liquid crystal, battery powered, more rugged construction
- Panel flickers because of the nature of this 3D technology; human brain detects flicker and this can cause eye fatigue and headache.
- Each eye sees full dark in half of the time, so this directly causes 3D luminance to be halved.

2.1.2.3 Frame Pattern Retarder Type 3D

FPR type 3D is also known as polarized 3D or passive 3D. Polarization is a spatial 3D display technique that creates a stereoscopic 3D effect by projecting the two images superimposed with different polarizing filters from slightly different perspectives as shown in Figure 2.8. When viewed using glasses with corresponding polarizing filters, the eye merges the images into an integrated stereoscopic image. To manage this, left and right images are first interlaced line by line to produce a merged image. Then odd lined pixels and even lined pixels are polarized distinctly on a FPR screen. This causes the left image to be monitored only through the left eye glass and the right image only through the right eye glass. The filters for the left and right eyes are oriented differently to pass the light polarized for the corresponding eye and block the light for the other eye. The polarization is typically circular (clockwise/counterclockwise) or at 90 degree angles (45 and 135 degrees) (Kaiser, 1955), so the effect continues to work even if the head is tilted.

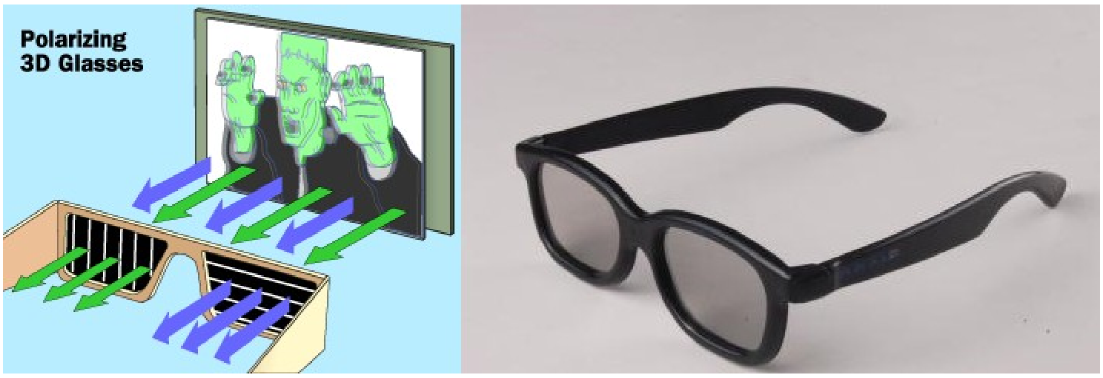

Figure 2.8 Polarized glasses

- Pros

+ Used for large audiences - 3D cinema (RealD)
+ Display with polarized screen
+ Relatively inexpensive glasses
+ Avoid color artifact issues

- Cons

- Lose half the horizontal resolution
- Panel is more expensive

2.1.3 Highly Used Terminologies for stereoscopic Visualization

2.1.3.1 3D Crosstalk

In Stereoscopic 3D Displays, "crosstalk" refers to the incomplete isolation of the left and right image channels so that one leaks or bleeds into the other. In this area, crosstalk and ghosting are often used interchangeably; however crosstalk is a physical entity and can be objectively measured, whereas ghosting is a subjective term and refers to the perception of crosstalk.

In Figure 2.9, the visual experience of crosstalk is illustrated. The unintended image can barely be seen by the intended eye, so it looks like a ghosting replicate of the intended image.

Figure 2.9 3D Crosstalk (or ghosting effect)

2.1.3.2 Eye Fatigue

A recent academic study into the effects of stereoscopic 3D at the University of California, Berkeley goes some way to explaining the cause of headaches and eye fatigue caused by three dimensional viewing, with professor of optometry and vision science, Banks (2011), explaining:

"When watching stereo 3D displays, the eyes must focus - that is, accommodate - to the distance of the screen because that's where the light comes from. At the same time, the eyes must converge to the distance of the stereo content, which may be in front of or behind the screen."

Symptoms indicating a potential problem viewing images in 3D can vary, but some common symptoms include headaches, blurred vision, nausea and dizziness.

Beside these facts, there is another parameter directly related to eye fatigue which is named stereoscopic comfort zone as illustrated in Figure 2.10. This parameter depends on the content itself.

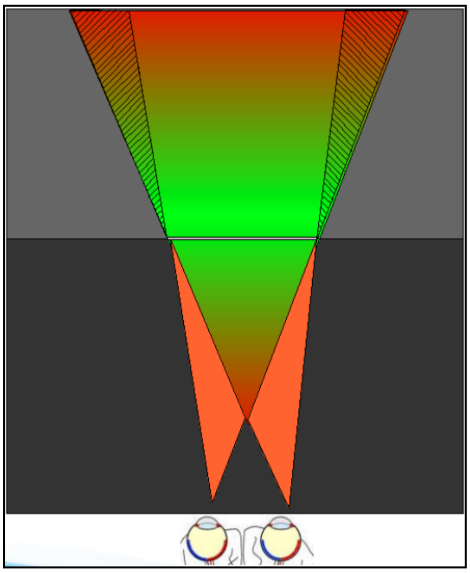

Figure 2.10 Stereoscopic comfort zone

Gray: viewer cannot see this area

Red: This area is stressful for eyes to see. It is not recommended to watch scenes long time in this area.

Orange: This area is dangerous for eyes. Objects in the content shouldn't stay in this area, only show up for a brief period.

Green: This area is comfortable for eyes. In most of the time, a 3D content should stay in this area.

2.1.3.3 Stereoscopic Parallax

The displacement of an object caused by a change in the point of observation is called parallax. Stereoscopic parallax is caused by taking photographs of the same object but from different points of observation (Lathrop, 1999). Parallax can be classified as positive and negate as shown in Figure 2.11. Parallax is positive when image is shifted to the left for the left eye and to the right for the right eye in which case an object appears behind the screen. In contrast, when the image is shifted to the right for the left eye and to the left for the right eye, parallax is negative and the object is perceived in front of the screen in this case.

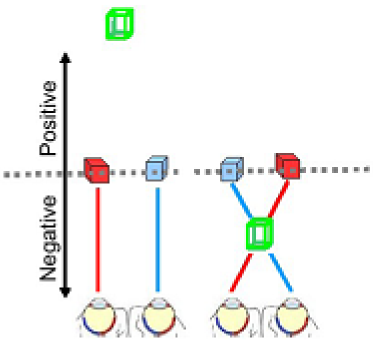

Figure 2.11 Positive and negative parallax (Mendiburu,2009)

2.1.3.4 Maximum Positive Parallax (MPP)

MPP is equal to average distance between our eyes (approximately 6 cm) as the parallax is positive. Objects are perceived at Stereoscopic infinity in this point as shown in Figure 2.12. Beyond MPP, objects are seen even further away and this causes eyes to diverge, which is painful (Mendiburu, 2009).

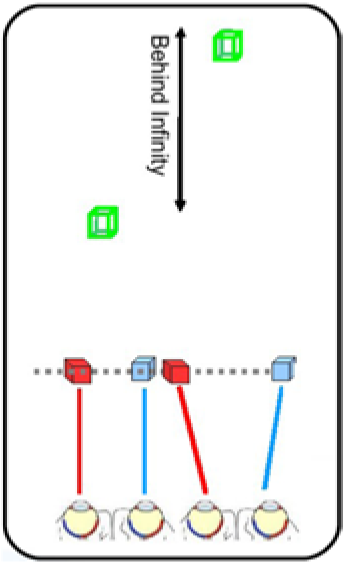

Figure 2.12 Maximum positive parallax (Mendiburu, 2009)

2.1.3.5 Medium Negative Parallax (MNP)

MNP is equal to the MPP in magnitude as the parallax is negative. Objects will be seen half way to screen as illustrated in Figure 2.13 (Mendiburu, 2009).

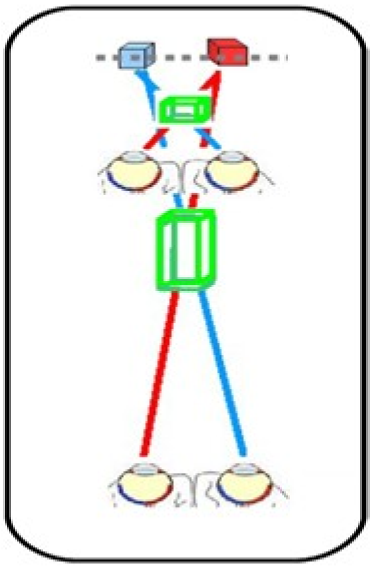

Figure 2.13 Medium negative parallax (Mendiburu, 2009)

2.1.3.6 Depth Budget

This refers to the overall 3D of a movie. Depth budget is not necessarily limited MPP and MNP. To increase the 3D creativity in movies, positive parallaxes behind the screen can be expanded up to double MPP and negative parallaxes in front of the screen up to three to four times MNP depending on the type of the movie and audience. In practice, these extreme parallaxes are measured in pixel for an intended screen size and production resolution, such as -50 and +150 (Mendiburu, 2009).

2.2 TV Video Signal Formats

2.2.1 Frame Packing 3D

Format Frame Packing refers to the left and right image packed into one video frame with twice the normal bandwidth. All three resolutions (720p50, 720p60, and 1080p24) have to be supported by display devices, and at least one of those by playback devices. Other resolutions and formats are optional (HDMI, 2010). To be able to transmit 3D pictures in full 1080p, devices should support HDMI 1.4. HDMI 1.3 does not include such support. Figure 2.14 depicts the Frame Packing Full HD 3D format. This format consists of two 1080p sub-frames, one for each eye, that are stacked vertically with a 45 pixel active blanking space.

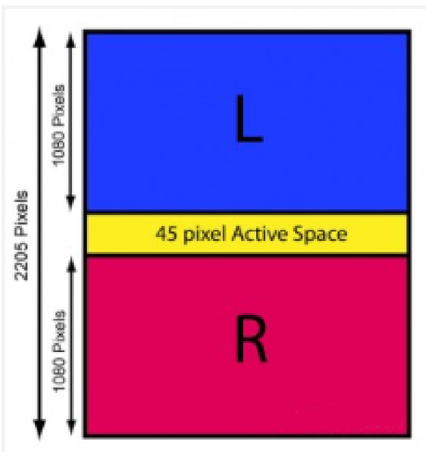

Figure 2.14 Frame Packing Structure (Best 3DTVS, 2010)

The same structure above is also applicable for 1280x720p @50, @60.

2.2.2 Frame Compatible 3D

Both Frame Compatible 3D and Frame Packing 3D formats involve forming a single frame that contains "sub-frames" for the left and right eye. In both cases, the Sub-frames can be packaged together into a single frame via the Side-by-Side 3D format or the Top-and-Bottom 3D format.

The key difference of a Frame Compatible signal is that each sub-frame for each eye is down sampled along one axis to lower the resolution of each sub-frame along one axis. As a result, the total dimension of a Frame Compatible Frame is the same as a regular 2D HD frame.

2.2.2.1 Side by Side 3D

In Side-by-Side 3D, each frame has the same dimension as a regular 2D HD frame but each sub-frame is down sampled to reduce the horizontal resolution by half as shown in Figure 2.15. (Best 3DTVS, 2010)

As a result, in the case of 720p side-by-side 3D, each sub-frame is downscaled from 1280×720 to 640×720 resolution. For 1080p, down sampling occurs from 1920×1080 to 960×1080. Then the left and right eye sub-frames are combined to produce a single Frame Compatible Side-by-Side 3D frame.

Figure 2.15 Structure of Side by Side 3D

2.2.2.2 Top and Bottom 3D

Top-and-Bottom (or Over-Under) Frame Compatible 3D works in exactly the same way, except that the halving of resolution of each sub-frame is in the vertical dimension as illustrated in Figure 2.16. So a 1080p video feed (1920×1080) formatted using Top-and-Bottom Frame Compatible 3D will consist of two vertically stacked sub-frames, each having a resolution of 1920×540 pixels. (Best 3DTVS, 2010)

For 1280x720 signal, the same vertical resolution halving is applied. Each sub-frame becomes 1280x360.

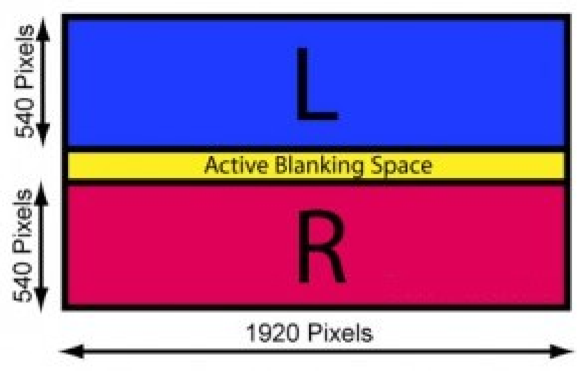

Figure 2.16 Structure of a 1080p top-bottom 3D

CHAPTER THREE
3D TV QUALITY PARAMETERS

3.1 Color Accuracy

Color accuracy is one the most important performance criteria for not only for 3D TV's, but for all LCD TVs. To be able to examine the black and white details and chromaticity, gamma correction idea and usage should be well understood first.

3.1.1 Gamma Correction

Gamma is an important but seldom understood characteristic of virtually all digital imaging systems. It defines the relationship between a pixel's numerical value and its actual luminance. Without gamma, shades captured by digital cameras wouldn't appear as they did to our eyes. It's also referred to as gamma correction, gamma encoding or gamma compression, but these all refer to a similar concept. (Cambridgeincolour, 2012)

Our eyes do not perceive light the way cameras do. With a digital camera, when twice the number of photons hit the sensor, it receives twice the signal (a "linear" relationship). That's not how our eyes work. Instead, we perceive twice the light as being only a fraction brighter — and increasingly so for higher light intensities as shown in Figure 3.1 (a "nonlinear" relationship). (Cambridgeincolour, 2012)

Compared to a camera, we are much more sensitive to changes in dark tones than we are to similar changes in bright tones. There's a biological reason for this peculiarity: it enables our vision to operate over a broader range of luminance. Otherwise the typical range in brightness we encounter outdoors would be too overwhelming.

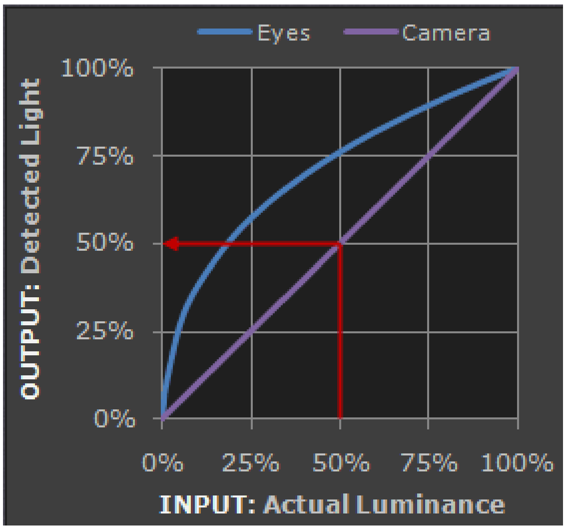

Figure 3.1 Actual luminance vs. detected light

(Cambridgeincolour, 2012)

In this case, gamma is what translates between our eye's light sensitivity and that of the camera. When a digital image is saved, it's therefore "gamma encoded" — so that twice the value in a file more closely corresponds to what we would perceive as being twice as bright.

Gamma correction is defined by the following power-law expression:

$$V_{out} = A . V_{in}^{\gamma} \quad 3.1$$

In the Figure 3.2, CRT gamma correction is illustrated with ɣ = 1 / 2.2 for encoding and ɣ = 2.2 for decoding.

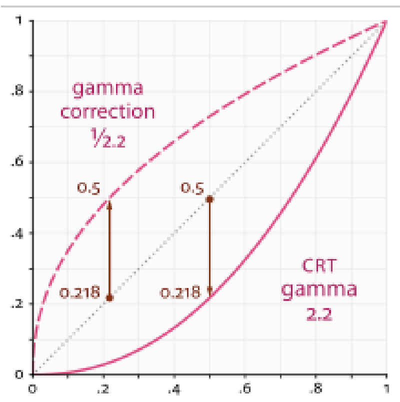

Figure 3.2 CRT gamma correction example

Gamma encoding redistributes tonal levels closer to how our eyes perceive them; fewer bits are needed to describe a given tonal range. Otherwise, as shown in Figure 3.3, an excess of bits would be devoted to describe the brighter tones (where the camera is relatively more sensitive), and a shortage of bits would be left to describe the darker tones (where the camera is relatively less sensitive).

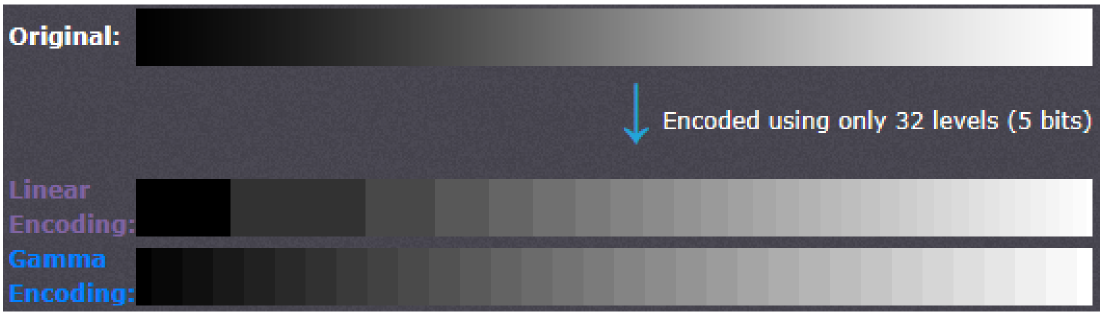

Figure 3.3 Linear encoding vs. gamma encoding (Cambridgeincolour, 2012)

A gamma encoded image has to have "gamma correction" applied when it is viewed which effectively converts it back into light from the original scene. In other words, the purpose of gamma encoding is for recording the image, not for displaying the image (Cambridgeincolour, 2012).

Fortunately this second step (the "display gamma") is automatically performed by your monitor and video card. Figure 3.4 illustrates how all of this fits together.

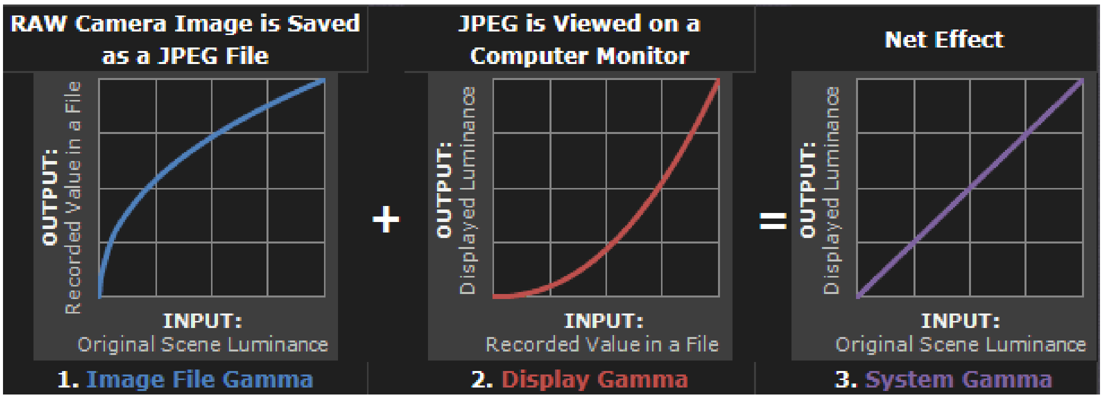

Figure 3.4 Gamma workflow (Cambridgeincolour, 2012)

A common misconception is that gamma encoding was developed to compensate for the input–output characteristic of cathode ray tube (CRT) displays (Poynton, 2003). In CRT displays the electron-gun current, and thus light intensity, varies nonlinearly with the applied anode voltage. Altering the input signal by gamma compression can cancel this nonlinearity, such that the output picture has the intended luminance. But in fact, the gamma characteristics of the display device do not play a factor in the gamma encoding of images and video—they need gamma encoding to maximize the visual quality of the signal, regardless of the gamma characteristics of the display device (Poynton, 2010). The similarity of CRT physics to the inverse of gamma encoding needed for video transmission was a combination of luck and engineering which simplified the electronics in early television sets.

In most computer systems, images are encoded with a gamma of about 0.45 and decoded with a gamma of 2.2.

For a CRT, the gamma that relates brightness to voltage is usually in the range 2.35 to 2.55 (Poynton, 2003).

Other display devices have different values of gamma: for example, a Game Boy Advance display has a gamma between 3 and 4 depending on lighting conditions. In LCDs relation between the signal voltage VS and the intensity I is very nonlinear and cannot be described with gamma value. However, such displays apply a correction onto the signal voltage in order to approximately get a standard $\gamma = 2.5$ behavior.

3.1.2 Gamma Color Correction

Adjusting the overall brightness of an image via gamma correction is first step, but it does not address the issue of color balance.

Anyone who has visited a typical consumer electronics store has probably noticed that not every model on the wall of televisions displays the same way. Some may have a reddish tinge, some green; some usually display very bright, saturated colors, while others may operate for slightly paler but more realistic hues.

With the variety of such kind of physical variables for panel side made TV manufacturing companies to find innovative solutions in software side to achieve desired color specifications.

So gamma color correction put into use here means the gamma correction is applied for each red, green and blue component separately.

The most widely used and one of the first defined color space is the CIE 1931 XYZ color space, created by the International Commission on Illumination. (CIE, 1932)

In Figure 3.5, color space chromaticity diagram is illustrated. The blob represents the complete range of hues and saturation levels that the human eye can discern; a true spectrum would wrap around the numbered edge. The numbers on the border give the wavelength of visible light in nanometers.

The brighter triangle in the middle represents the colors that can be displayed by a particular monitor (not including any brightness information) and is known as the *color gamut* of the display. The corners of the triangle give the maximum-intensity red, green, and blue hues; these directly correspond to the physical characteristics of the phosphors used in the display. The monitor's gamut in figure 2.5 covers less than half of the complete color range. In other words, there are many colors that the human eye can perceive but that cannot be correctly represented on a monitor.

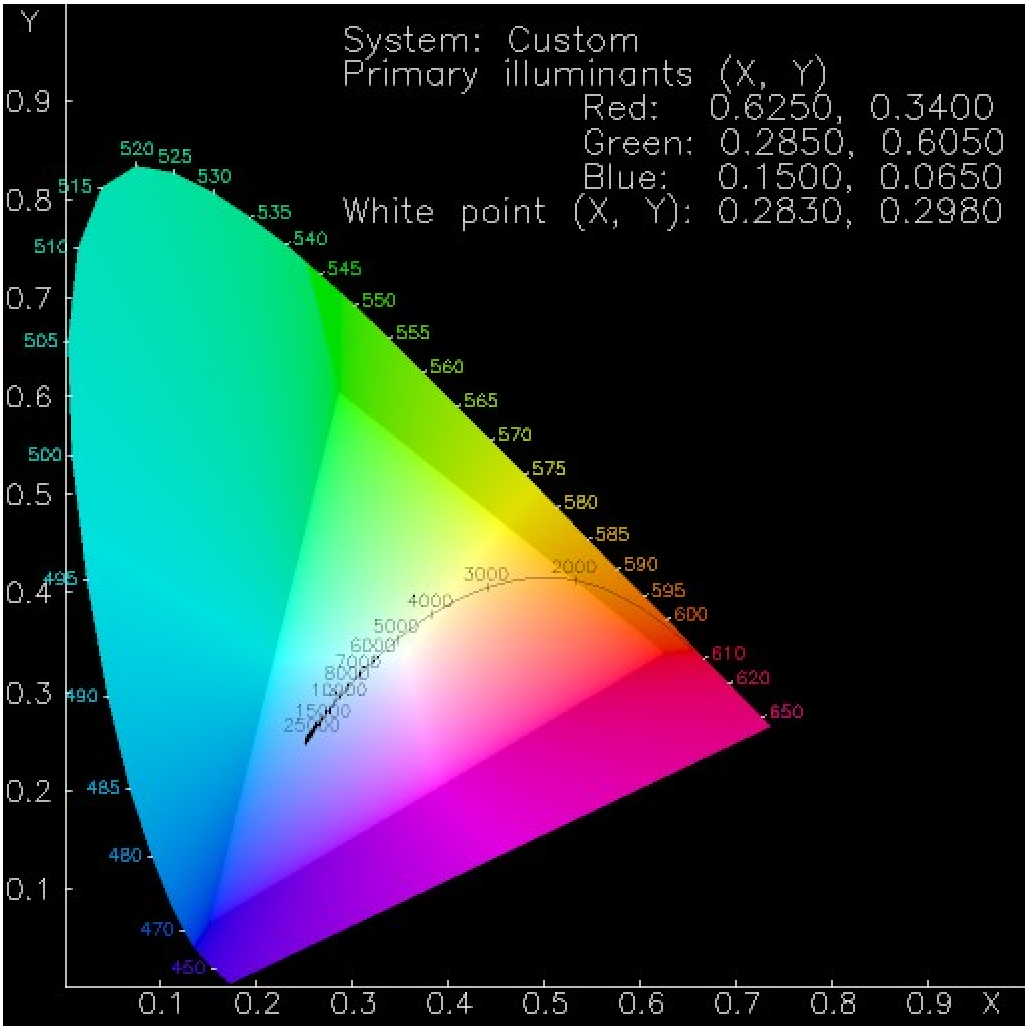

Figure 3.5 The CIE 1931 color space chromaticity diagram and an example of a particular device (Libpng, 2012)

The curved line in the middle represents all possible values of ``white" for a given monitor, only one of which will be displayed as such. The associated numbers along the curve refer to the ``blackbody temperature" or color temperature of any given white value.

So, if the encoding software knows the locations of the three corners of the triangle and of white point, it is possible to change the R, G, B’s input characteristics to catch the desired color temperature, so the desired color hues.

It is possible to detect the locations of these three corners by applying full red (digitally 255 red, 0 green, 0 blue), full green and full blue to panel and measure the displayed colors' color coordinates by any color analyzing device.

3.1.3 Color shift Reason

The main contribution to such color variations comes from the manufacturers' choices of light-emitting chemicals (phosphors) in monitors and of filters used in liquid crystal displays. For 3D systems, beside the panel side, also the glasses causes an important color shift and brightness change.

3.2 Brightness

Brightness is one of the first rising problems of 3D technology with glasses. Especially for shutter type 3D, the natural mechanism of the frame sequencing system causes the big luminance decrease; the black frame insertion halves the cumulative luminance. Also the liquid crystal structure of shutter glasses causes a serious color shift and this indirectly affects the luminance. To be able to correct the color shift, gamma color correction method should be used and every modification on R, G, B curves causes a luminance decrease.

For FPR, the polarized film on the glasses causes a lower direct and indirect luminance decrease compared to shutter glass type.

3.3 Eye Fatigue

Flicker can be easily seen at shutter glass due to the glasses' on/off action and interference with other light sources. Excessive flicker has been the source of complaints over eye fatigue and poor picture quality, as well as serious health concerns like photosensitive epilepsy.

The second reason of the visual discomfort comes from the fact that the viewers' eyes are simultaneously trying to focus on the screen, and on objects that appear to be located either in front of or behind that screen. The eyes must focus - that is, accommodate - to the distance of the screen because that's where the light comes from. At the same time, the eyes must converge to the distance of the stereo content, which may be in front of or behind the screen.

3.4 3D Crosstalk

One of the more obvious downsides to the current generation of 3D home theater is an artifact known as crosstalk (or “ghosting”), in which picture information meant for one eye intrudes into the other eye’s view. This results in a ghostly double-image around objects in the frame as indicated in Figure 3.6. It can be incredibly distracting when it happens.

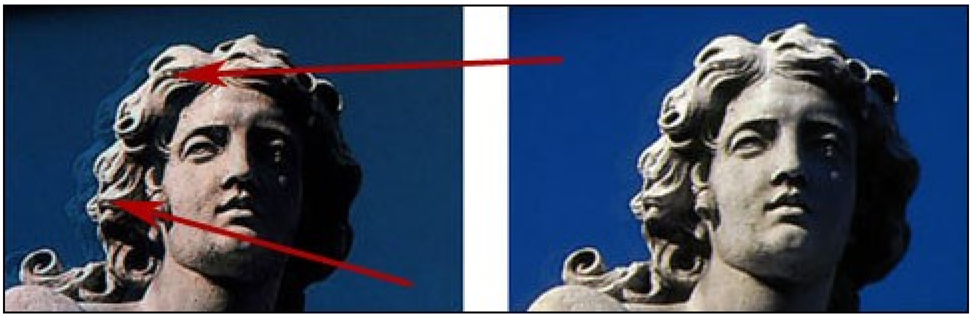

Figure 3.6 3D Crosstalk effect

There are various reasons of crosstalk for different display technologies. Since this phenomenon constitutes a large area of focus for this thesis and will be examined deeply to be able to design lowering techniques, I need to explain its reasons here in detail.

3.4.1 Reason of Crosstalk

The mechanism behind the leakage image is a combined effect of the whole image capture and display process. This section merely deals with the effects caused by the display characteristics. The individual mechanism causing crosstalk varies depending on the type display. The major 3D display types and the mechanism causing crosstalk on the display side are explained in this section.

3.4.1.1 Time Sequential 3D on PDP's (Plasma Display Panels)

- The performance of the liquid crystal cells in the shutter glasses
- The amount of phosphor persistence
- The timing of the shuttering of the glasses
- Crosstalk does not vary with screen position on PDPs.

3.4.1.2 Time Sequential 3D on DLP's (Digital Light Processing)

Digital Light Processing (DLP) is a brand of projector technology that uses a digital micromirror device (DMD). DLP technology can be found in DLP front projectors as well as DLP rear projection television sets.

- The performance of the liquid crystal cells in the shutter glasses
- The timing of the shuttering of the glasses with respect to the images on the screen.

There is no crosstalk introduced by the actual DLP display itself. There is no phosphor decay (the DMD mirrors can switch completely from one state to another in ~2μs) and the entire image changes from one frame to the next at effectively the same time (hence crosstalk does not vary with screen position on DLPs except where the viewing angle through the LCS glasses might be different for viewing different parts of the screen).

3.4.1.3 Time Sequential 3D on LCS (LC Shutter) 3D Glasses

- The optical performance of the liquid crystal cells (the rise time, the fall time)

- The specific timing of the image update method on the screen (the effects of backlight, increased frame rate, and/or modulated backlight)
- The pixel response rate of the LCD (black-to-white, white-to-black, and grey-to-grey),
- The relative timing (synchronization) of the glasses
- The angle of view through the liquid crystal cells
- The temporal performance of the particular display
- The x-y position on the screen (depending upon shutter timing, the top and bottom of the screen may exhibit more crosstalk than the middle of the screen)

3.4.1.4 Polarized 3D Projection

- The optical quality of the polarizer
- The optical quality of the particular projection screen
- Incorrect orientation of the coding or decoding polarizer

3.4.1.5 Micro-Polarized 3D LCD's

As shown in Figure 3.7, a special optical filter is applied to the front of a conventional LCD panel in order to polarize odd numbered rows of pixels with one polarization state and the even numbered rows with the opposite polarization state.

➢ Display related:

- The optical quality of the micro-polarizer film
- Alignment accuracy of micro-polarizer 'strips' to the rows of pixels on display
- Pitch of micro-polarizer 'strips relative to the pitch of rows of pixels on display
- The presence of a black mask between micro-polarizer 'strips' - presence of black mask improves size of the viewing zones but sacrifice screen brightness.
- The x-y position on the screen
- Viewing position of the observer (most current micro-pol monitors are highly sensitive to vertical viewing position, also sensitive to viewing distance.
- The thickness of the front glass layer

➢ Glass related:

- The orientation, optical quality, and optical match of the polarized 3D glasses

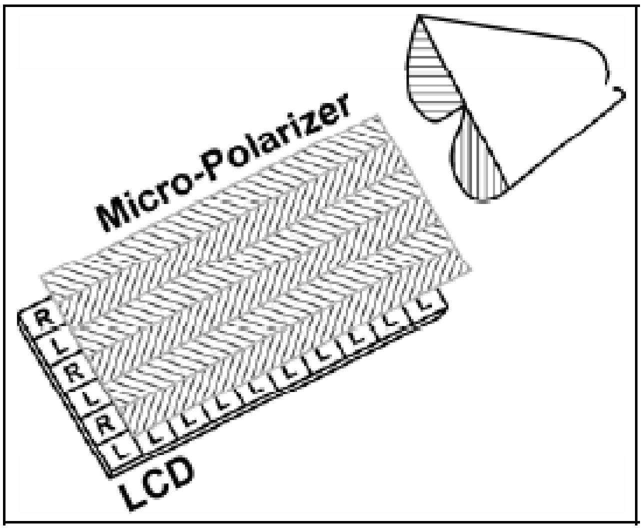

Figure 3.7 Optical Layout of micro polarized 3D LCD

3.4.1.6 Auto stereoscopic Displays

- The optical quality and type of the lenticular lens / parallax barrier
- The accuracy of alignment of the lenticular/barrier to the layout of pixels on the display
- The pitch of the individual lenticules/barrier strips relative to the pitch of pixels on the display
- The width of the barrier strips
- The R,G,B sub-pixel layout of the display,
- The viewing position (in x, y, and z directions)
- The x-y position on the screen (different areas of the screen may exhibit different levels of crosstalk)

CHAPTER FOUR
MEASUREMENT TECHNIQUES

This section is based on IEC TC110 standards. IEC TC110 determines the following measuring methods for characterizing the performance of stereoscopic display devices using either active or passive glasses.

4.1 Measurement Setup

The standard measuring distance is 3 times the height of active area. The standard observing point is at the standard measuring distance from the screen on the centre line which is perpendicular to the screen and through the screen centre as shown in Figure 4.1.

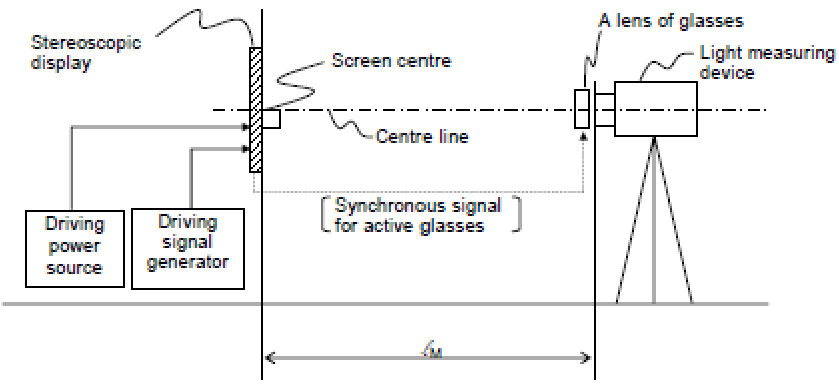

Figure 4.1 Measurement setup (IEC TC 110, 2009)

The light measuring shall be aligned perpendicularly to the area to be measured on the screen of the display. The SI unit of luminance is candela / m^2 (cd/ m^2). Nit can also be used for luminance unit which is equal to cd/ m^2, but cd/ m^2 will be preferred throughout this chapter.

Konica Minolta CA-210 is used for all kind of luminance and color measurements.

The left or right lens of glasses shall be set at the front of light measuring device and parallel to the object lens of the light measuring device. The eye-side surface of the lens shall be faced to the object lens as shown in Figure 4.2. The horizontal axis of the glasses shall be set parallel to the horizontal axis of the screen. The distance of the glass from the light measuring device shall be the designed distance when the distance is defined in the relevant specification, or the minimum distance keeping over 10 mm from the object lens and avoiding any touch of the glasses to the light measuring device.

The measurement should be carried out in dark room conditions to avoid stray light.

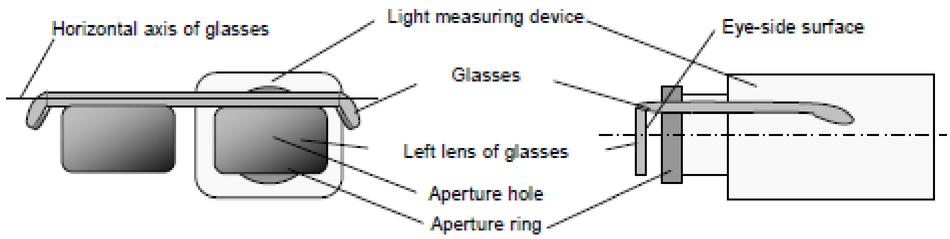

Figure 4.2 Position of glasses (IEC TC 110, 2009)

4.2 Input Patterns

Four kinds of input patterns are used while measuring 3D panel & glass performances. Input pattern signal type can be side by side or top bottom, both can be used. Throughout this thesis, 1080p side by side video signal is used. Input patterns are created on PC as .JPEG file and applied to TV in HDMI source from Astro pattern generator VG-870B device.

Required input patterns are these:

- Full screen white signal; full screen input signal with the level 100%
- Full screen black signal; full screen input signal with the level 0%

- 4% white window signal at level 100% is set at the screen centre and surrounded by black ground at level 0% as shown in figure 3.3.
- Offset 4% white window; 4% white window at level 100% is shifted by V/5 and H/5 from the screen centre surrounded by black back ground at level 0% as shown in Figure 4.3.

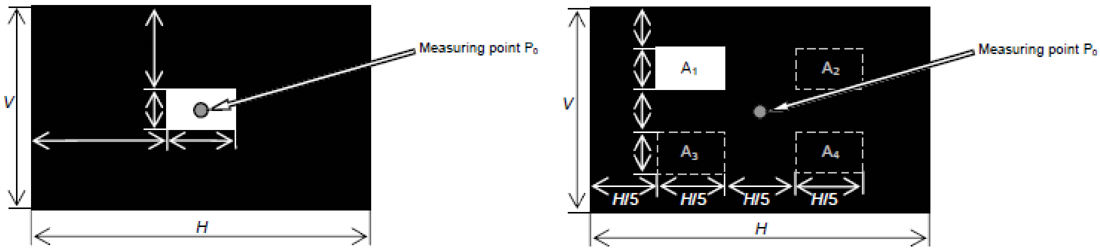

Figure 4.3 4% White window signal and shifted 4% white window signal

4.3 Measuring Points

9 measuring points are defined by IEC TC110 standard. The measuring points are shown in Figure 4.4.

In this thesis, only P_0 point will be used. The other points generally used to check homogeneity of the panels in luminance and chrominance manner which is not related to this thesis's scope.

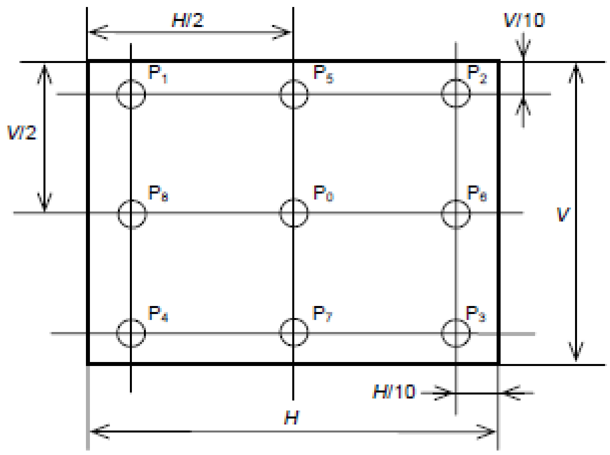

Figure 4.4 Measuring Points (IEC TC 110, 2009)

4.4 3D Crosstalk Calculation Formula

To measure the crosstalk, the below steps are performed one by one.

- 4% white window signal is applied to left image and an offset 4% white window signal is applied to right image. The left lens of 3D glasses is set on the light measuring device, luminance value is measured from P0 and recorded as the left eye luminance with the input signals of 4% window white for observed image and full black for the other image $L_{L0,4\%B}$.

- Now right lens of the glasses is used and luminance at P0 is measured and recorded as the right eye luminance with the input signals of full black for observed image and 4% window for the other $L_{R0,B4\%}$.

- Input signals is changed as an offset 4% white window signal to left image and a 4% white window signal to right image.

- Luminance is measured from P0 and recorded as the right eye luminance with the input signals of 4% window and full black $L_{R0,4\%B}$.

- Lens is changed to left one, luminance is measured from P0 and recorded as the left eye luminance with the input signals of black and 4% window $L_{L0,B4\%}$.

Change the input signals as an offset 4% white window signal to both left and right image. Measure the luminance at P0 and record the left eye luminance with the input signals of black and black LL0,BB. Change the lens to the right one, measure the luminance at P0 and record the right eye luminance with the input signals of black and black LR0,BB.

The crosstalk ratio formulas for left eye and right eye are:

$$X_{RtoL} = \frac{L_{L0,B4\%} - L_{L0,BB}}{L_{L0,4\%B} - L_{L0,BB}} \times 100$$

$$X_{LtoR} = \frac{L_{R0,B4\%} - L_{R0,BB}}{L_{R0,4\%B} - L_{R0,BB}} \times 100$$

4.5 Evaluation of various 3D TV's in the market

In this section, several benchmark televisions are evaluated to form an opinion about performances of 3D TV's in the market. So, specification goals will be determined and the later studies will be based on all these data.

4.5.1 40"Samsung Shutter Type 3D LED TV

4.5.1.1 Luminance

As first study, the luminance of the panel is measured without glasses from P_0. 2D luminance is 475 cd/m^2, 3D luminance is 162 cd/m^2 as indicated in Table 4.1. 3D luminance is relatively low compared to 2D although the measurements are performed without glasses.

The reason for the measured luminance decrease is black frame insertion feature of the panel. Panel is 240 Hz panel, so ¼ of the time left picture is displayed, ¼ of the time right picture is displayed and ½ of the time, black frame is applied. This contributes to reduction of 3D crosstalk as mentioned before.

Table 4.1 Luminance in 2D and 3D (without glasses)

Full White	2D	3D
Luminance	474.80	162.01
Ratio	100.00%	34.12%

4.5.1.2 Glass Transmittance and Color Shift

Glass transmittance performance is directly related to glasses itself. But color shift is affected by both glasses and panel.

As depicted in Tables 4.2 and 4.3, the transmittance is 30.19% in average and the luminance deviation between left and right eyes is 4.46%. It means that the left lens and the right lens of the glasses are not exactly the same.

Table 4.2 3D Luminance from left and right glasses

Full White	3D	Left	Right
Luminance	162.01	49.99	47.81
Ratio	100.00%	30.86%	29.51%

Table 4.3 Deviation between left and right glasses

Difference / Deviation			
Left	Right	Difference	Deviation
49.99	47.81	2.18	4.46%

Table 4.4 shows the color shift between 2D and 3D modes. 3D column values are measured without glasses when TV is forced to 3D mode. Purpose here is to understand the change in panel side in luminance manner when the panel is driven in 3D.

Also with left lens and right lens of the glasses, two separate measurements are taken.

Taking measurements both with glasses and without glasses in 3D mode provides the pure effect of the glasses itself.

CIE Color shift between 2D and 3D modes is an important criteria as it shows us how different do these two modes seem. So in full white pattern, for 2D mode and 3D mode (for left and right lens) colour coordinate measurements are taken as shown in Table 4.4. For ideal performance here, 2D and 3D should have the same coordinates. According to Table 4.4, between 2D and 3D, CIE color shift average is: $\Delta x = 0.011$ and $\Delta y = 0.020$. And the color difference between left and right eye is $|\Delta x| = 0.005$ and $|\Delta y| = 0.005$.

Table 4.4 Color shift values

CIE	2D	3D	Left	Right
CIE x	0.264	0.283	0.276	0.272
CIE y	0.272	0.278	0.294	0.289
CIE x Shift from 3D	-0.020	0.000	-0.007	-0.012
CIE y Shift from 3D	-0.006	0.000	0.017	0.011
CIE x Shift from 2D	0.000	0.020	**0.013**	**0.008**
CIE y Shift from 2D	0.000	0.006	**0.023**	**0.017**

This means that 2D and 3D color temperatures are quite different. We understand that there is no concern here to equate these two although it is quite possible by modifying gamma color curves in IC domain.

4.5.1.3 Crosstalk

Table 4.5 shows that, from the measuring point, left glass measurements are 51.83 cd/m^2 for left picture white and right picture black, 1.34 cd/m^2 for left picture black and right picture white. According to the 3D crosstalk calculation formula, crosstalk is 2.59% for left lens of the glasses.

For right lens, measurements are 51.43 cd/m^2 for right picture white and left picture black, 1.12 cd/m^2 for right picture black and left picture white. Crosstalk for right lens of the glasses is 2.17%.

The average crosstalk is 2.38%.

Table 4.5 Crosstalk Measurement of 40” Samsung 3D TV

	Left glass measurement	Right glass Measurement
Left White Right Black	51.83	1.12
Left Black Right White	1.34	51.43
Left Black Right Black	0.00	0.00
crosstalk right to left %	2.59%	Crosstalk Average
crosstalk left to right %	2.17%	2.38%

4.5.2 55” Samsung Shutter Type 3D LED TV

4.5.2.1 Luminance

The luminance of the panel is 456 cd/m^2 in 2D mode and 185 cd/m^2 in 3D mode. The reason of this huge difference is again the black frame insertion.

Panel’s 3D luminance over 2D luminance is 40% as indicated in Table 4.6.

Table 4.6 Luminance in 2D and 3D modes (without glasses)

Full White	2D	3D
Luminance	456.30	184.98
Ratio	100.00%	40.54%

4.5.2.2 Glass Transmittance and Color Shift

The transmittance is 31.57% in average and the luminance deviation between left and right eyes is 1.34% as shown in Tables 4.7 and 4.8.

Table 4.7 Luminance from left and right glasses

Full White	3D	Left	Right
Luminance	184.98	58.01	58.8
Ratio	100.00%	31.36%	31.78%

Table 4.8 Deviation between left and right glasses

Difference / Deviation			
Left	Right	Difference	Deviation
58.01	58.8	0.783	1.34%

As shown in Table 4.9, CIE Color shift between 2D mode and 3D mode with glasses in average is: $\Delta x = 0.001$ and $\Delta y = 0.004$. And the color difference between left and right eye is $|\Delta x| = 0.001$ and $|\Delta y| = 0$.

Table 4.9 Color Shift Values

CIE	2D	3D	Left	Right
CIE x	0.271	0.278	0.270	0.269
CIE y	0.279	0.270	0.283	0.283
CIE x shift from 3D	-0.007	0	-0.007	-0.008
CIE y shift from 3D	0.009	0	0.013	0.013
CIE x shift from 2D	0	0.007	-0.001	-0.002
CIE y shift from 2D	0	-0.009	0.004	0.004

4.5.2.3 Crosstalk

Table 4.10 shows that, from the measuring point, left glass measurements are 59.1 cd/m^2 for left picture white and right picture black, 1.11 cd/m^2 for left picture black and right picture white. According to the 3D crosstalk calculation formula, crosstalk is 1.78% for left lens of the glasses.

For right lens, measurements are 59.6 cd/m^2 for right picture white and left picture black, 1.28 cd/m^2 for right picture black and left picture white. Crosstalk for right lens of the glasses is 2.05%.

The average crosstalk is 1.92%. This value is better than the previous 40” TV.

Table 4.10 Crosstalk Measurement of 55" Samsung 3D TV

	Left glass measurement	Right glass Measurement
Left 4 % white window signal Right offset 4 % white window signal	59.1	1.28
Left offset 4 % white window signal Right 4 % white window signal	1.11	59.60
Left offset 4 % white window signal Right offset 4 % white window signal	0.06	0.06
crosstalk right to left %	1.78%	Crosstalk Average
crosstalk left to right %	2.05%	1.92%

4.5.3 40"Sony Shutter Type 3D LED TV

4.5.3.1 Luminance

The luminance of the panel is around 410 cd/m^2 in 2D mode and 159 cd/m^2 in 3D mode as depicted in Table 4.11.

Table 4.11 Luminance in 2D and 3D (without glasses)

Full White	2D	3D
Luminance	410,58	159,02
Ratio	100,00%	38,73%

4.5.3.2 Glass Transmittance and Color Shift

The transmittance is 31.32% in average and the luminance deviation between left and right eyes is 0.59% as shown in Tables 4.12 and 4.13.

Table 4.12 Luminance from left and right glasses

Full White	3D	Left	Right
Luminance	159,02	49,65	49,94
Ratio	100,00%	31,22%	31,41%

Table 4.13 Deviation between left and right glasses

Difference / Deviation			
Left	Right	Difference	Deviation
49,65	49,94	0,296	0,59%

The CIE Color shift between 2D mode and 3D mode with glasses in average is: $\Delta x = 0.010$ and $\Delta y = 0.042$ as shown in Table 4.14. And the color difference between left and right eye is $|\Delta x| = 0.016$ and $|\Delta y| = 0.014$.

Table 4.14 Color Shift Values

CIE	2D	3D	Left	Right
CIE x	0,280	0,284	0,298	0,283
CIE y	0,275	0,285	0,329	0,305
CIE x Shift from 3D	-0,003	0,000	0,015	-0,001
CIE y Shift from 3D	-0,010	0,000	0,044	0,020
CIE x Shift from 2D	0,000	0,003	0,018	0,002
CIE y Shift from 2D	0,000	0,010	0,054	0,030

4.5.3.3 Crosstalk

Table 4.15 shows that, from the measuring point, left glass measurements are 51.92 cd/m^2 for left picture white and right picture black, 0.83 cd/m^2 for left picture black and right picture white. Crosstalk ratio is 1.48% for left lens of the glasses.

For right lens, measurements are 52.65 cd/m^2 for right picture white and left picture black, 1 cd/m^2 for right picture black and left picture white. Crosstalk ratio for right lens of the glasses is 1.75%.

The average crosstalk is 1.61%. This value is the best one among the examined 3 shutter type 3D TVs.

Table 4.15 Crosstalk Measurement of 40” Sony 3D TV

INTEROCULAR CROSSTALK WINDOW		
	Left glass measurement	Right glass Measurement
Left 4 % white window signal Right offset 4 % white window signal	51,92	1,00
Left offset 4 % white window signal Right 4 % white window signal	0,83	52,65
Left offset 4 % white window signal Right offset 4 % white window signal	0,06	0,08
crosstalk right to left %	1,48%	Crosstalk Average
crosstalk left to right %	1,75%	1,61%

4.6 Evaluation of the panel and 3D Glasses used in the Thesis

In this thesis, Samsung 47” 240 Hz led panel was selected to work with. As the 3D technology is too new and there are only a couple of 3D shutter type panels available in the market, we did not have many options to select from.

Also a pair of Accupix brand 3D glasses were purchased and synchronized with panel. In hardware side, Vestel Research and Development Hardware Design Group worked on the main board design and an immature 3D TV was constituted.

After bringing up the first board, the below optical measurements were obtained and compared to the previous measurements taken from the benchmark TVs.

4.6.1 Luminance

The luminance of the panel is 446 cd/m^2 in 2D mode and 116 cd/m^2 in 3D mode (without glasses) as shown in Table 4.16.

Table 4.16 Luminance

Full White	2D	3D
Luminance	446.04	116.97
Ratio	100.00%	26.22%

4.6.2 Glass Transmittance and Color Shift

The transmittance is 30.8% in average and the luminance deviation between left and right eyes is 15.10% as shown in Tables 4.17 and 4.18.

Table 4.17 Luminance from left and right glasses

Full White	3D	Left	Right
Luminance	116.97	33.30	38.74
Ratio	100.00%	**28.47%**	**33.12%**

Table 4.18 Deviation between left and right glasses

Difference / Deviation			
Left	Right	Difference	Deviation
33.30	38.74	5.439	**15.10%**

CIE Color shift between 2D mode and 3D mode with glasses in average is: $\Delta x = 0.003$ and $\Delta y = 0.024$ as can be computed from Table 4.19. And the color difference between left and right eye in 3D mode is $|\Delta x| = 0.005$ and $|\Delta y| = 0.006$.

There is a big "y" coordinate difference ($\Delta y = 0.024$) between 2D and 3D modes. This indicates that the glasses used cause a nontrivial color shift.

Table 4.19 Color Shift Values

CIE	2D	3D	Left	Right
CIE x	0.286	0.286	0.286	0.281
CIE y	0.290	0.291	0.317	0.311
CIE x Shift from 3D	0.000	0.000	0.000	-0.005
CIE y Shift from 3D	-0.001	0.000	0.025	0.020
CIE x Shift from 2D	0.000	0.000	**0.001**	**-0.004**
CIE y Shift from 2D	0.000	0.001	**0.026**	**0.021**

4.6.3 Crosstalk

Table 4.20 indicates that the average crosstalk is 2.83%.

One important point here is that luminance behind the glasses is low compared to the benchmark products.

Table 4.20 Crosstalk Ratio

	Left glass measurement	Right glass Measurement
Left 4 % white window signal Right offset 4 % white window signal	34.91	1.16
Left offset 4 % white window signal Right 4 % white window signal	0.91	35.88
Left offset 4 % white window signal Right offset 4 % white window signal	0.04	0.03
crosstalk right to left %	2.52%	Crosstalk Average
crosstalk left to right %	3.15%	2.83%

4.6.4 Color Gamut

In Table 4.21, Red, green and blue is measured in 2D and 3D without glasses and with glasses. Color gamut is calculated and drawn for all of them in Figure 4.5.

Color gamut here illustrates the colors that can be seen by human eyes. From 460 nm to 620 nm, human eye can detect electromagnetic waves as colors.

To determine the color performance of a panel (or panel and glasses pair), pure red, green and blue color patterns are given as input and color coordinates of these tree main colors are measured with a color analyzer device. According to these three CIE coordinates for red, green and blue, a triangle is formed and the area surrounded by this triangle is called color gamut of the panel.

NTSC standardized color gamut is illustrated as black triangle, 2D and 3D color gamuts are illustrated as grey and red in Figure 4.5.

Table 4.21 Color Gamut

	LEFT		RIGHT		2D		3D W/O Glasses		NTSC	
	x	y	x	y	x	y	x	y	x	y
R	0.611	0.329	0.609	0.329	0.627	0.332	0.611	0.329	0.670	0.330
G	0.304	0.628	0.303	0.629	0.320	0.621	0.304	0.628	0.210	0.710
B	0.154	0.048	0.154	0.047	0.155	0.044	0.154	0.048	0.140	0.080
COLOR GAMUT		70.57%		70.46%		71.05%		70.57%		100.00%

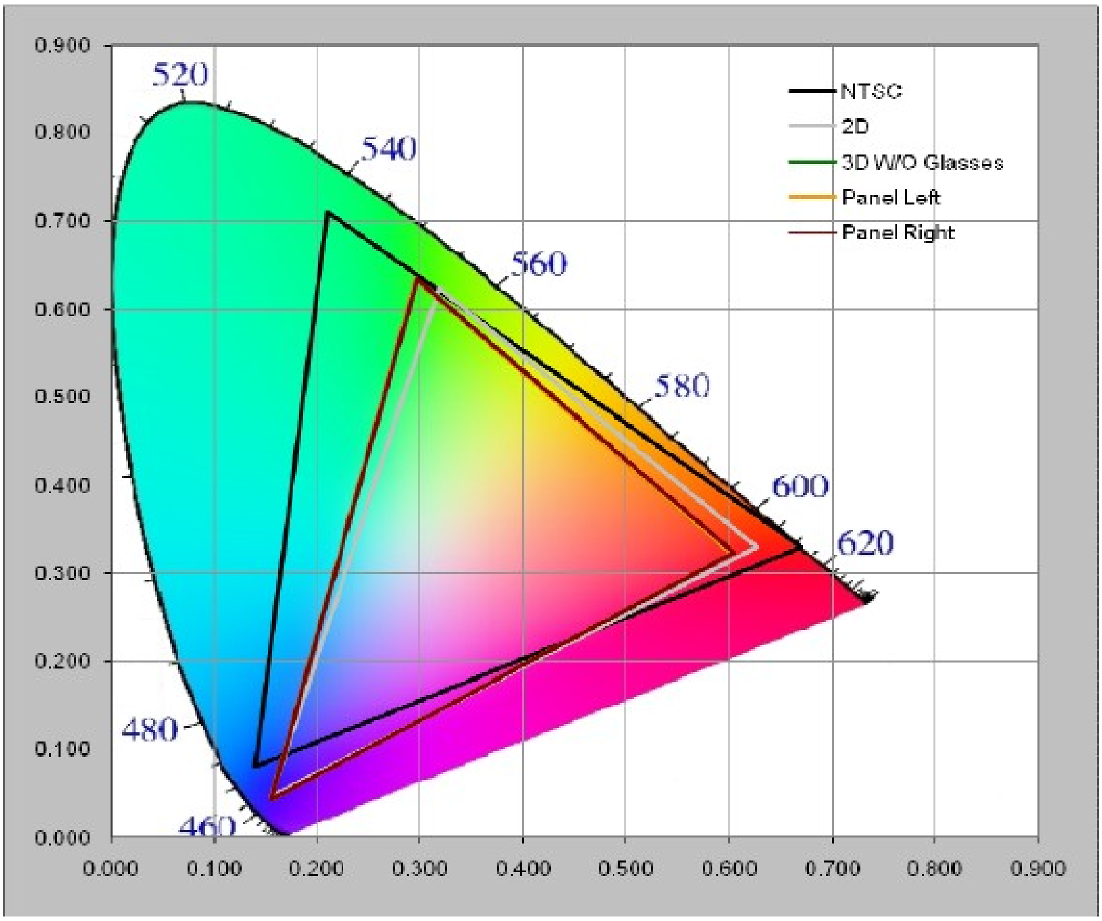

Figure 4.5 Graphical Illustration of Color Gamut

4.7 Specification Goal of a High Performance 3D TV and Improvement Study Plan

After the detailed measurements and estimations for 3D performance parameters, it is found out that 3D crosstalk is nearly 2% for all these 3D benchmark TVs, and luminance after the glasses is higher than 50 cd/m^2.

First specification goal of this project is to decrease 3D crosstalk from 2.83% to 2% or below. To achieve this goal, firstly a hardware study will be considered to fine tune infrared synchronous signal between panel and glasses. Slightly shifting opening and closing timings of the glasses will absolutely affect the density of the residues coming from the unintended picture.

After the hardware study, a software solution will be implemented to reduce the crosstalk more. This algorithm is based on the work presented by Konrad (Konrad J., Lacotte B. & Dubois, E, 2000).

After the crosstalk improvement studies have been finalized, new concentration point will be 3D luminance.

Luminance behind the glasses is 35 cd/m^2 which is very low compared to other TVs in the market. The second important performance goal is to increase 3D luminance to 50 Nits. The previous timing modification will absolutely affect 3D luminance too. That's why, after setting crosstalk to best performance, the plan here is to set new gamma color curves for 3D mode.

In Figure 4.5, 2D and 3D gamut triangles can be seen. Since the glasses themselves have a liquid crystal structure, there is a notable color shift. This means the viewer will see the entire picture more greenish. So another specification goal arises here as the 3D gamma color correction applied to increase luminance also should contribute to achieve true colors.

CHAPTER FIVE
IMPROVEMENT STUDIES

5.1 Crosstalk Reduction by Hardware Study

The first idea for reducing the crosstalk is modification of sync signal between glasses and panel.

The ideal operation of sync signal is illustrated in Figure 5.1.

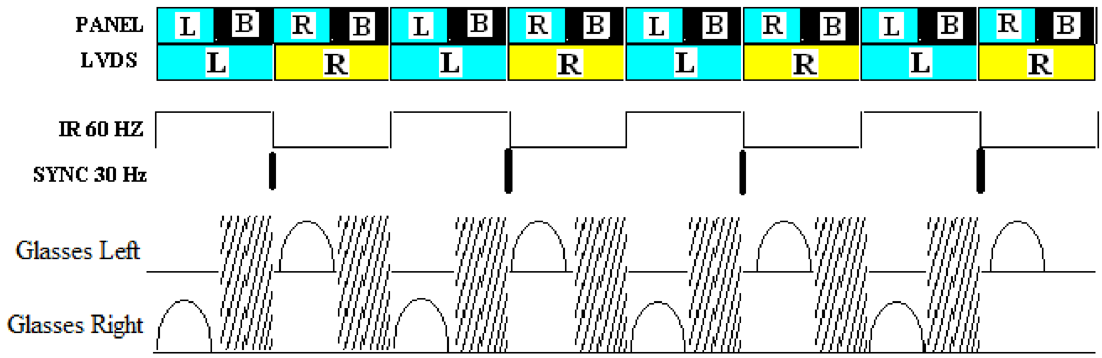

Figure 5.1 Sync Signal

The 60 Hz picture is transmitted to the panel as side by side, and panel converts this rate to 240 Hz by generating left and right pictures and inserting black frame between each of them. Between glasses and panel, there is a 60 Hz infrared signal and for every falling edge of the left picture, a pulse is transmitted to glasses.

This illustration on Figure 5.1 is the ideal version of the sync signal diagram. In reality, glasses spec requires a 1.2 ms delay after left (and right) picture is shown on the screen as the vendor of the glasses specifies. The idea here is to increase this delay and let panel have more time to be cleared from the leakage images left from the previous image.

Firstly, decreasing the delay below 1.2 ms was tried although glass's spec states that this is the minimum delay. With this new setting, the crosstalk become higher but more critically, there arises a very high flicker. So by trial and error method, several delays were applied over 1.2 ms step by step and the best performance was gained with additional 1 ms delay.

So, totally 2.2 ms delay makes the 3D crosstalk performance better.

So the new sync diagram becomes as shown in Figure 5.2.

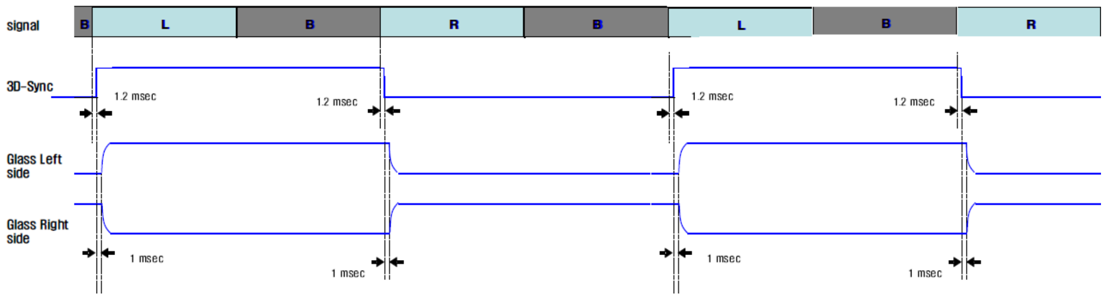

Figure 5.2 Sync signal with delay

With this modification, crosstalk ratio was decreased to 2.48%.

5.2 Crosstalk Reduction by Software Study

5.2.1 Software Crosstalk Cancellation Idea

The reduction of crosstalk refers to optimizing the reasons causing crosstalk so that less crosstalk is produced; whereas cancellation of crosstalk involves pre-distortion (image processing) of the image before display. This section will mainly deal with the shutter glasses type micro polarized 3D displays. Similar methods can be applied for any kind of display with ghosting in correlation with the unintended image intensity. The reason is that this algorithm offers a panel independent solution.

Intended view and unintended view phrases will be widely used in this section. Intended view means the view user supposed to see from the left or right lens of the glasses. Unintended view is the view for the other eye. For example for left eye, intended view is left picture and unintended view is right picture.

Basic idea of crosstalk cancellation is to evaluate the amount of leakage expected to occur from the unintended view to the intended view, and to subtract this amount from the intended view. Ideally, (if the display characteristics could be very well identified) the addition of the modified intended view plus the leakage from the unintended view results in the equivalent of the original intended image. However it has to be noted that if the intended view is very dark or unintended view is very bright; cancellation might go off the limits. For example there is no possible cancellation for the case that the intended and unintended view has 0 and 255 intensities correspondingly.

To explain this phenomenon with an example:

Let's assume that for left eye, we have an intended intensity of 50 cd/m^2 for a specific pixel on the display, and for right eye, the same pixel has an unintended 100 cd/m^2 luminance. So with the interference of unintended luminance to intended luminance, left eye sees that pixel's luminance as 55 cd/m^2. If we can predict this +5 luminance increase for left eye, it is possible to lower the luminance of intended pixel in the image for left eye to 45 cd/m^2 before displaying on the panel; so with the luminance interference from pixel in the image for right eye, the intended pixel will be seen as 50 cd/m^2 for left eye.

The cross talk model is obtained as follows (Konrad, Lacotte and Dubois, 2000):

$$f'(x) = f(x) + \emptyset(g(x), f(x))$$

Where f(x) is the intended image, g(x) is the unintended image and f'(x) is the total image observed after the additional crosstalk from the unintended image. Similarly the observed images on the left and right eyes (f_l' and f_r') are modeled as (Konrad, Lacotte and Dubois, 2000):

$$f_l' = f_l + \emptyset(f_r, f_l)$$

$$f_r' = f_r + \emptyset(f_l, f_r)$$

Where f_l and f_r are original left and right images, and $\emptyset$ is a crosstalk function that quantifies the amount of crosstalk seen by an eye as a function of unintended and intended stimuli.

5.2.2 Algorithm Details

The intensity based idea is utilized for the crosstalk parameterization. The general algorithm is considered in three independent steps for obtaining final crosstalk cancelation as show in Figure 5.3.

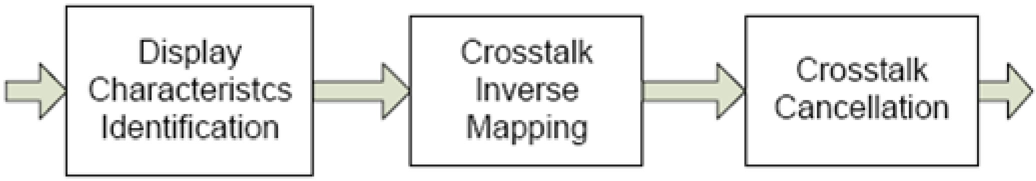

Figure 5.3 Algorithm Overview

In the first stage, the display characteristics are to be identified in order to transcribe the actual crosstalk effect on the predefined patterns. The method by Konrad (2000) proposes a measurement pattern for display identification.

Intended stimulus: 0, 25, 50, 75, 100, 150, 235

Unintended stimulus: 30, 60, 95, 135, 185, 235

The intended stimulus is supplied to one eye and the crosstalk effect is observed by changing the pair image. For an intended stimulus 0; the unintended stimulus is applied to observe the increase of crosstalk with the increase of unintended stimulus. Here a reference metric has to be defined for observations. The method by Konrad proposes the reference of 0 as unintended stimulus and the user decides level for the intended stimulus. The user is required to match the intensity level coming from the pattern on the display to the level set by user. This match is repeated for all patterns given above. This measurement provides some rough but valuable information about the general display crosstalk characteristics. These roughly scattered values are interpolated for the whole intensity scale of 0-255 as shown in Figure 5.4.

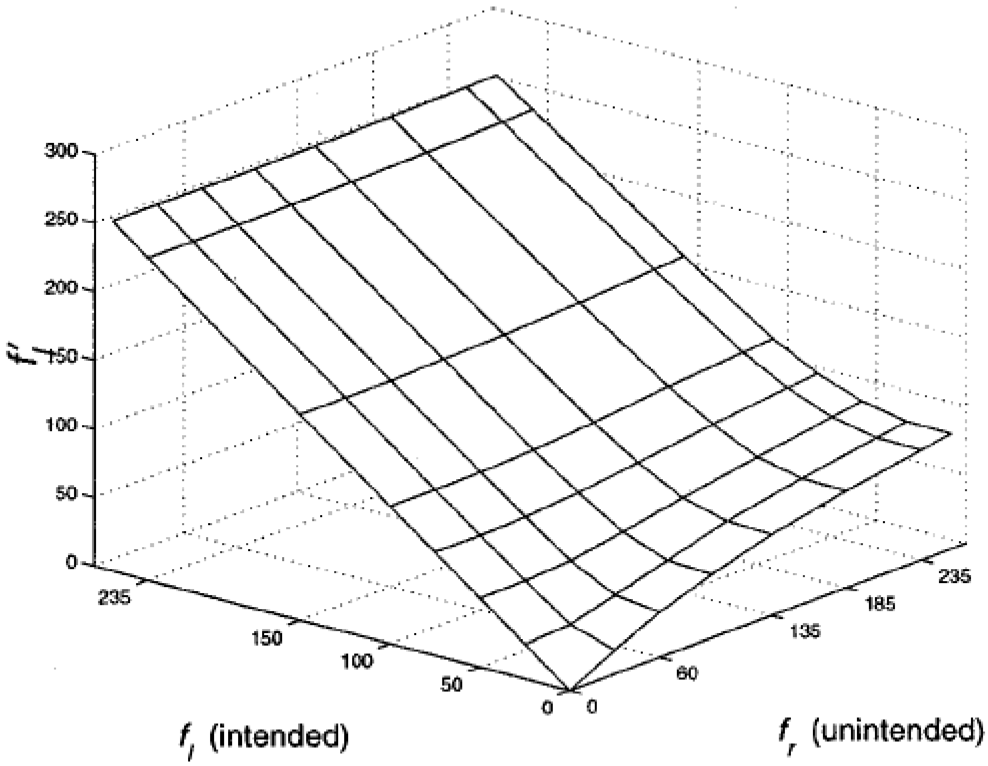

Figure 5.4 Effect of Intended vs Unintended Stimulus over Observed Stimulus of a ordinary stereoscopic display (Konrad, Lacotte and Dubois, 2000)

The general input output values of the algorithmic blocks are shown in Figure 5.5.

The estimated crosstalk model is used to obtain an inverse mapping function as a look up table for the input LCD values. The inverse mapping function is calculated iteratively with minimal updates in the error minimization direction where at each step the observed image is cross checked with the actual intended image. The iteration stops as soon as the two matching values are met; or the maximum iteration number is reached.

As it was previously mentioned for some very high contrast regions the cancellation in crosstalk is almost impossible, hence it is a worthless effort to run iteration and wait for convergence.

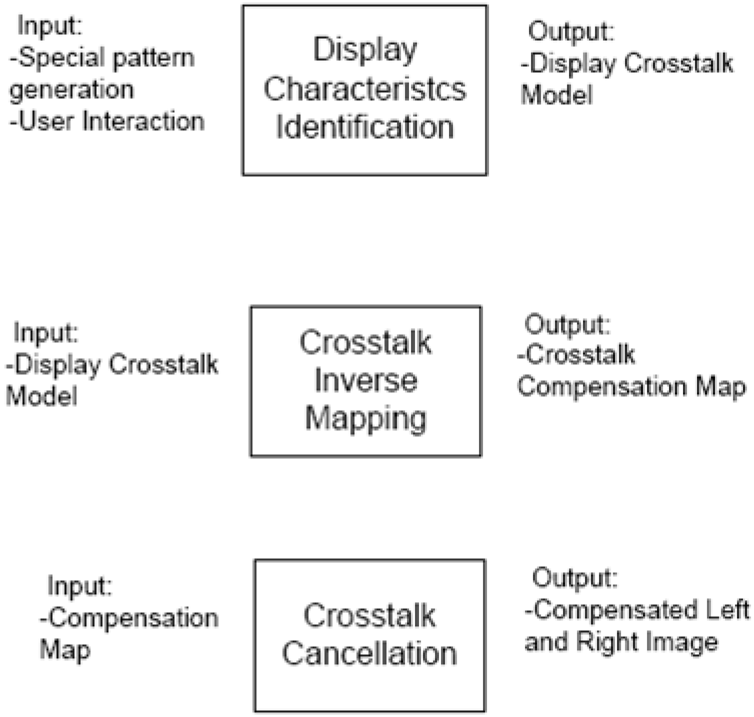

Figure 5.5 Individual algorithm Blocks

5.2.3 Implementation Studies

Implementation of crosstalk reduction algorithm to find LUT is performed using Matlab 2008a. All Matlab codes can be found in section 5.2.5.

In algorithmic design, the compensation domain is chosen as Y domain due to mainly two reasons. The enhancement in Y domain mostly protects the gamut of the image hence preventing color shift after compensation. Secondly, it suffices minimum complexity compared to 3 channel enhancement. The update mechanism is to change the luminance of a pixel by comparing it with its counterpart pixel in stereo image pair.

.

In order to develop an update algorithm to reduce the crosstalk, there has to be valid crosstalk characteristics of the used display system (shutter panel and glass together) for each pair of intensity levels that are expected from left and right images at any pixel location.

To obtain the crosstalk characteristics, a set of 8 constant values for each intended and unintended intensity levels are applied to the left and right images for displaying on the TV screen. These values are 0, 25, 50, 75, 100, 150, 235 and 255. Then luminance (intensity) from the intended glass is measured for all 64 configurations in Table 5.1. The values inside the cells are the sensed intensities from the intended eye. This phenomenon can be explained better with an example:

In Table 5.1, we can see that when the intended and unintended images have the intensity values of 50 and 150, respectively, the measured (sensed) luminance is equal to 55. This represents a crosstalk of 5 intensity levels for the given pair (50, 150).

Table 5.1 Intended and Unintended Stimulus of Shutter Type 3D

	Unintended Stimulus							
Intended	0	25	50	75	100	150	235	255
0	0	5	12	17,5	23	32	45	47
25	25	25,4	26	29	32	39	50	52
50	48	48,2	49	51	51,8	55	63	65
75	74	74,2	74,3	75,1	76	77	82,4	83
100	98	98,1	98,3	98,8	100,1	101,8	105	106
150	146	146,3	146,4	146,5	147,8	150	152,7	153
235	231,4	231,5	231,6	231,8	231,9	132,5	235,5	235,6
255	252,1	252,3	252,4	252,5	253.7	253,8	254,2	255

After linear interpolation of this table, a 256x256 matrix is acquired. The graphical illustration of this matrix can be seen in Figure 5.6.

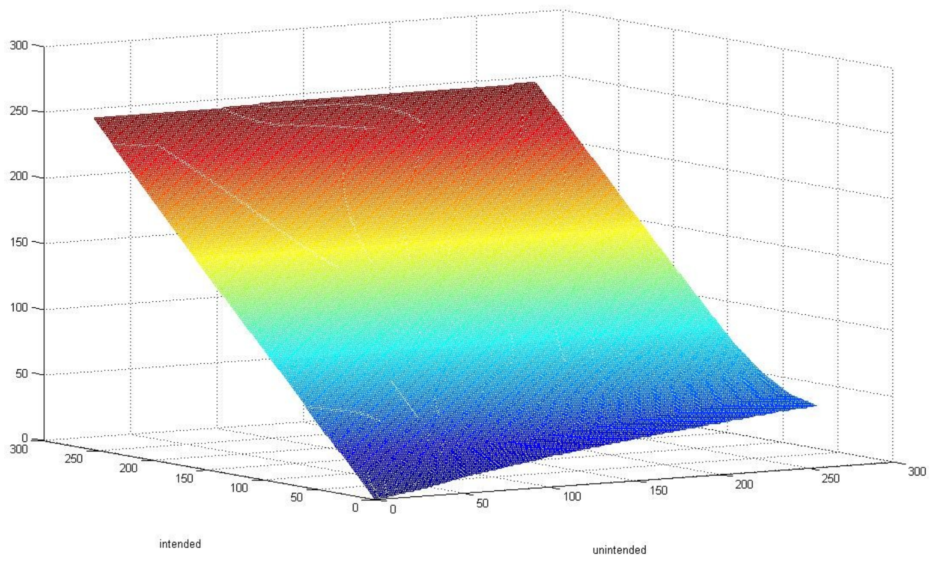

Figure 5.6 Graphical representation of linear interpolated intensity matrix

We can simply get the crosstalk characteristics by subtracting the intended values from each value in table 1. This is given in Table 5.2.

Table 5.2 Measured crosstalk characteristics of the display system

	Unintended Stimulus							
Intended	0	25	50	75	100	150	235	255
0	0	5	12	17,5	23	32	45	47
25	0	0,4	1	4	7	14	25	27
50	-2	-1,8	-1	1	1,8	5	13	15
75	-1	-0,8	-0,7	0,1	1	2	7,4	8
100	-2	-1,9	-1,7	-1,2	0,1	1,8	5	6
150	-4	-3,7	-3,6	-3,5	-2,2	0	2,7	3
235	-3,6	-3,5	-3,4	-3,2	-3,1	-2,5	0,5	0,6
255	-2,9	-2,7	-2,6	-2,5	-1,3	-1,2	-0,8	0

After linear interpolation of Table 5.2 to 256x256, Figure 5.7 is drawn where crosstalk characteristics of the panel is plotted.

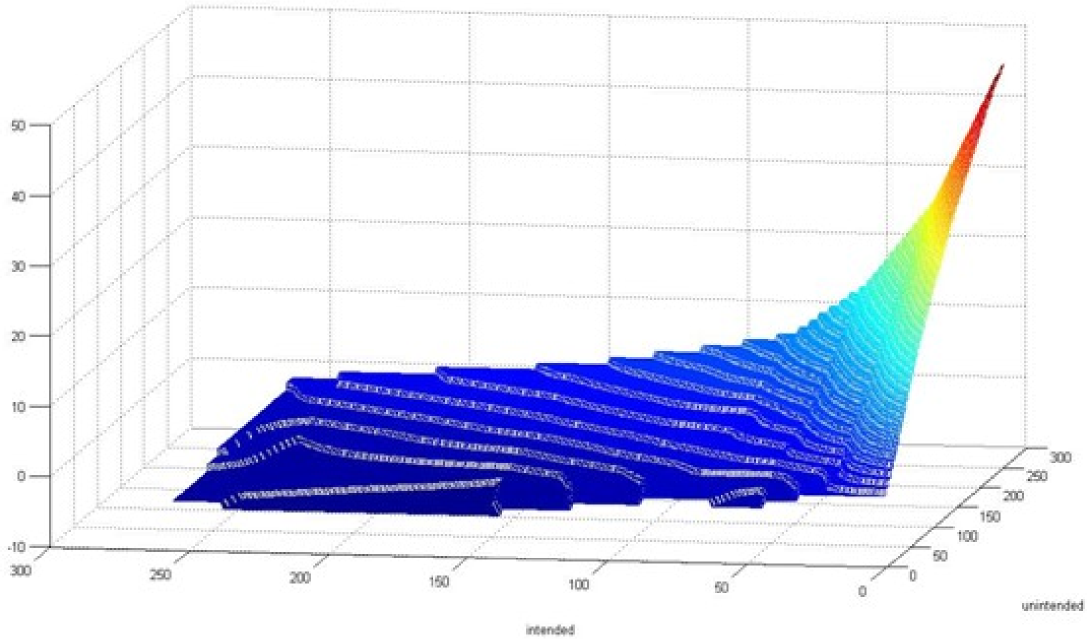

Figure 5.7 Graphical illustration of table 4.2: Crosstalk Characteristics

After getting characterization of panel & glass pair, an inverse mapping is calculated by an offline iterative algorithm and arranged in a LUT to update the left and right image intensity values to reduce the crosstalk.

The LUT design idea given by Konrad (2000) is also adopted in this thesis. Using the LUT, the new intended intensity values are updated for both left and right images in the form of

IntendedPixelUpdate8Bit = LUT (int8Bit,unint8Bit)

The first and second eight bit integer values in the parenthesis denote intensities of pixels in the intended and unintended images, respectively. For a side by side image, the same LUT is used to update left and right images as follows

leftUpd8Bit = LUT (left8Bit,right8Bit)

rightUpd8Bit = LUT(right8Bit, left8Bit)

Figure 5.8 shows the LUT computed to update left and right images. As seen from the computed LUT, it has some negative update values for some combinations of intended and unintended intensity combinations. This is noticeable in the region where intended intensity is zero and unintended intensity is relatively high. For example: (0, 250).

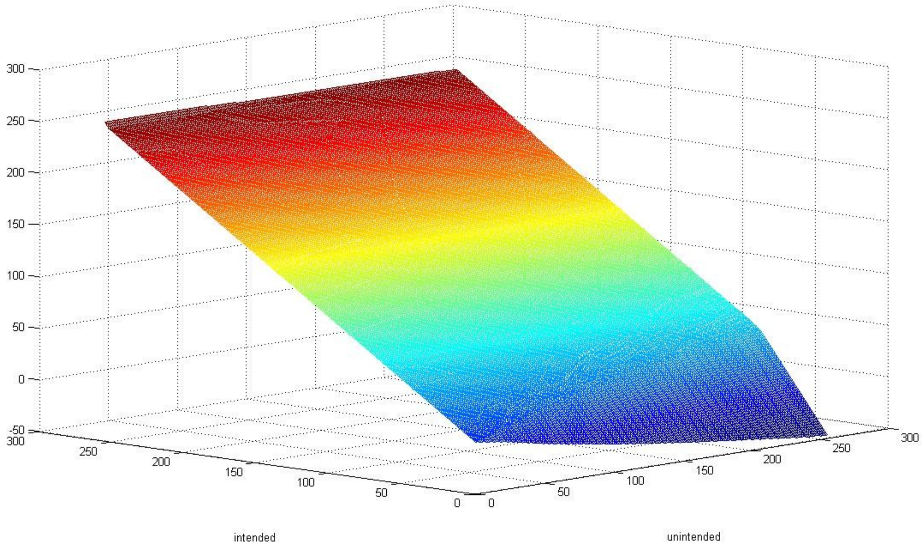

Figure 5.8 Graphical illustration of LUT

In TV applications, it is impossible to give negative intensity levels to intended pixels as mentioned before. So, the realistic LUT graph is obtained by replacing those negative values by zeroes as shown in Figure 5.9. This LUT is used to update left image pixel values. To update right image pixel values, the same LUT is used by reversing the roles of intended and unintended intensity levels.

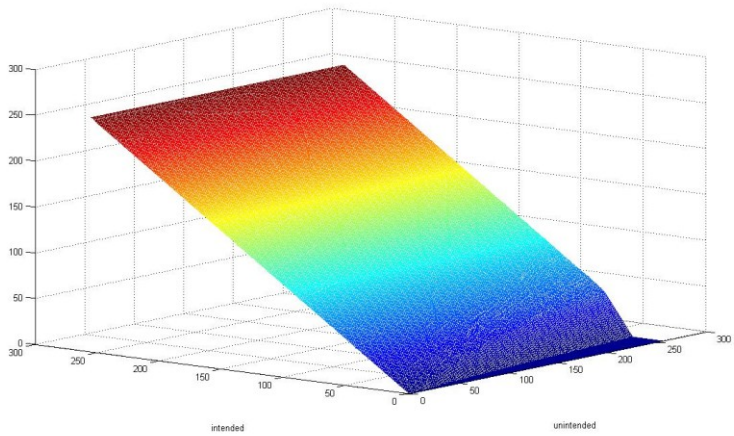

Figure 5.9 Graphical illustration of LUT in TV application

5.2.4 Hardware Implementation of Crosstalk Reduction Algorithm

After all the offline studies on panel and glass pair are completed, a 3D system specific LUT is obtained. On the TV implementation of this LUT, Spartan 6 FPGA is used between the main IC and panel.

After all the 3D formatting, scaling, color enhancements, and gamma corrections executed by main IC of the TV, all pixel data are transmitted to FPGA via LVDS lines.

FPGA firstly converts pixel data values from RGB to YCbCr color space. Then "Y" component of every pixel pair (for left and right eyes) are updated in real time by using the LUT.

Since the panel receives 10 bit pixel data, a full scale LUT would have a size of 1024x1024. To have a memory efficient hardware LUT, full scale LUT is subsampled at a factor of 16 both horizontally and vertically. This hardware LUT designed and used in FPGA has a size of 64x64 and contains 8 bit update values. This means that linear interpolations of the LUT values are required to find the 10 bit update values for 10 bit input intensity values. The linear interpolation idea is explained below.

Input intensity LUT(m,n) is an 8 bit and updated intensity IntUpd10(i, j) is a 10 bit number. The interpolation is done after converting input intensity to 10 bit by multiplying by 4. We introduce two new table indices h and w that are the highest integer multiples of 16 less than i and j, respectively. h and w are computed using integer division operator \ as h=(i\16)*16 and w=(j\16)*16. Using the offset (x, y), relation between (i, j) and (h, w) can be written as (i, j) = (h+y, w+x). Finally, IntUpd10(i, j) is computed from the LUT using linear interpolation as follows.

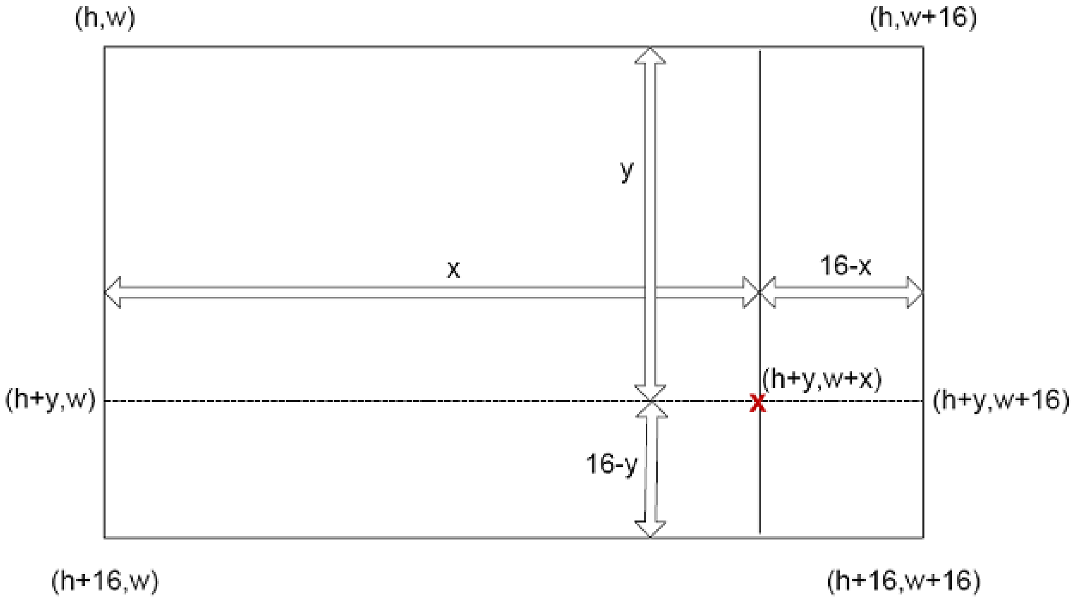

Figure 5.10 Bilinear Interpolation idea for memory efficient LUT design.

IntUpd10(h+y, w) = (4*LUT(h/16, w/16)*(16-y) + 4*LUT(h/16+1, w)*y)/16

IntUpd10(h+y, w+16) = (4*LUT(h/16, w/16+1)*(16-y) + 4*LUT(h/16+1, w/16+1)*y)/16

IntUpd10(i,j)=IntUpd10(h+y, w+x) = (IntUpd10(h+y, w)*(16-x) + IntUpd10(h+y, w+16)*x)/16

The total FPGA source used for the crosstalk reduction algorithm is 830 registers, 1354 LUTs, 3 BRAM-16 and 1 BRAM-8. The required clock frequency of 160 Mhz is achieved successfully.

After FPGA solution is verified, ASIC production phase is performed. Now in Vestel 3D TVs, the crosstalk reduction algorithm is available with an FPGA based IC named PIX 3D which is shown in a photograph of a 3D TV main board below (Figure 5.11). Detailed block diagram of the 3D main board project including PIX 3D IC is given in Figure 5.12.

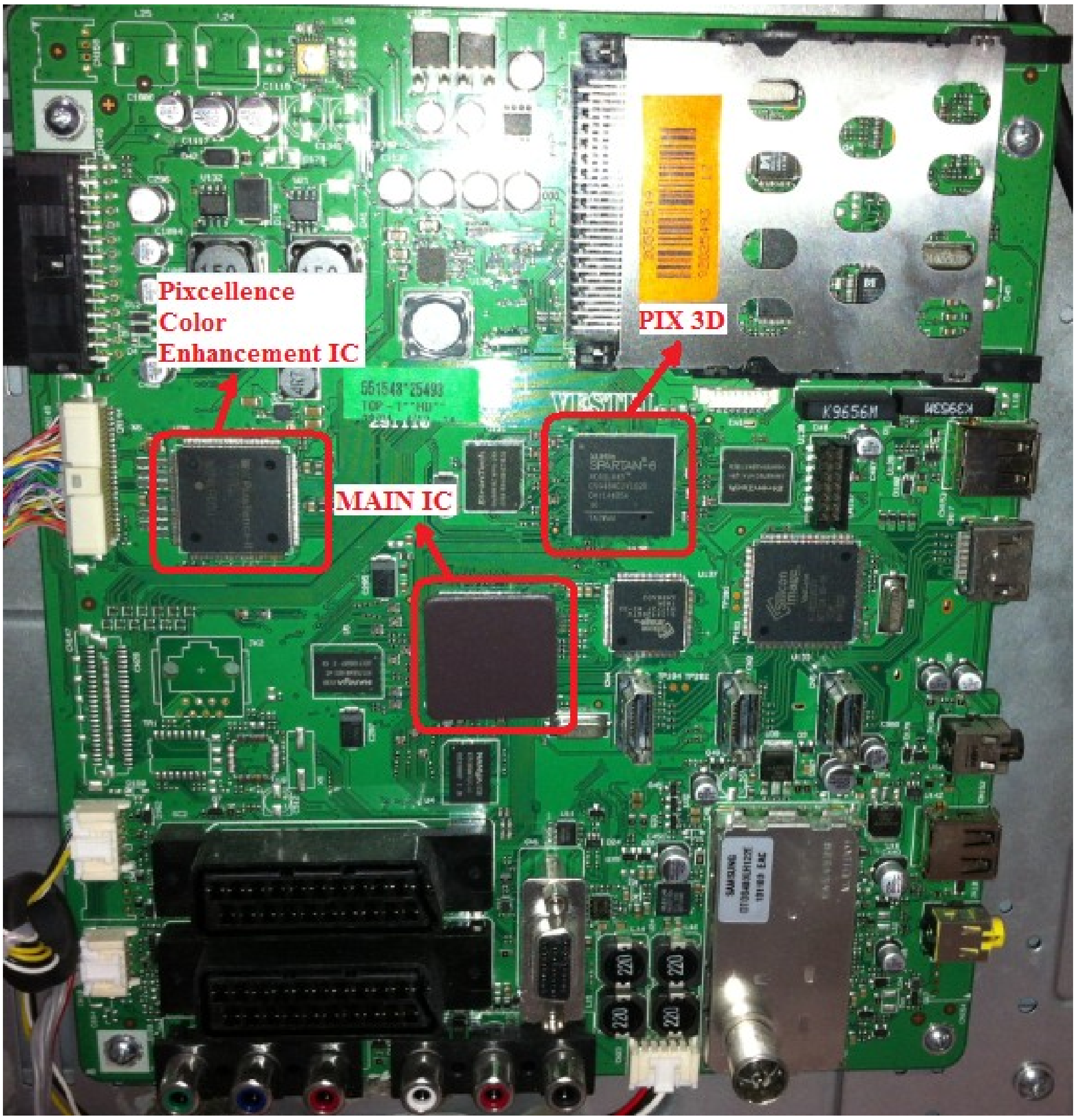

Figure 5.11 PIX 3D IC on 3D Main Board Design

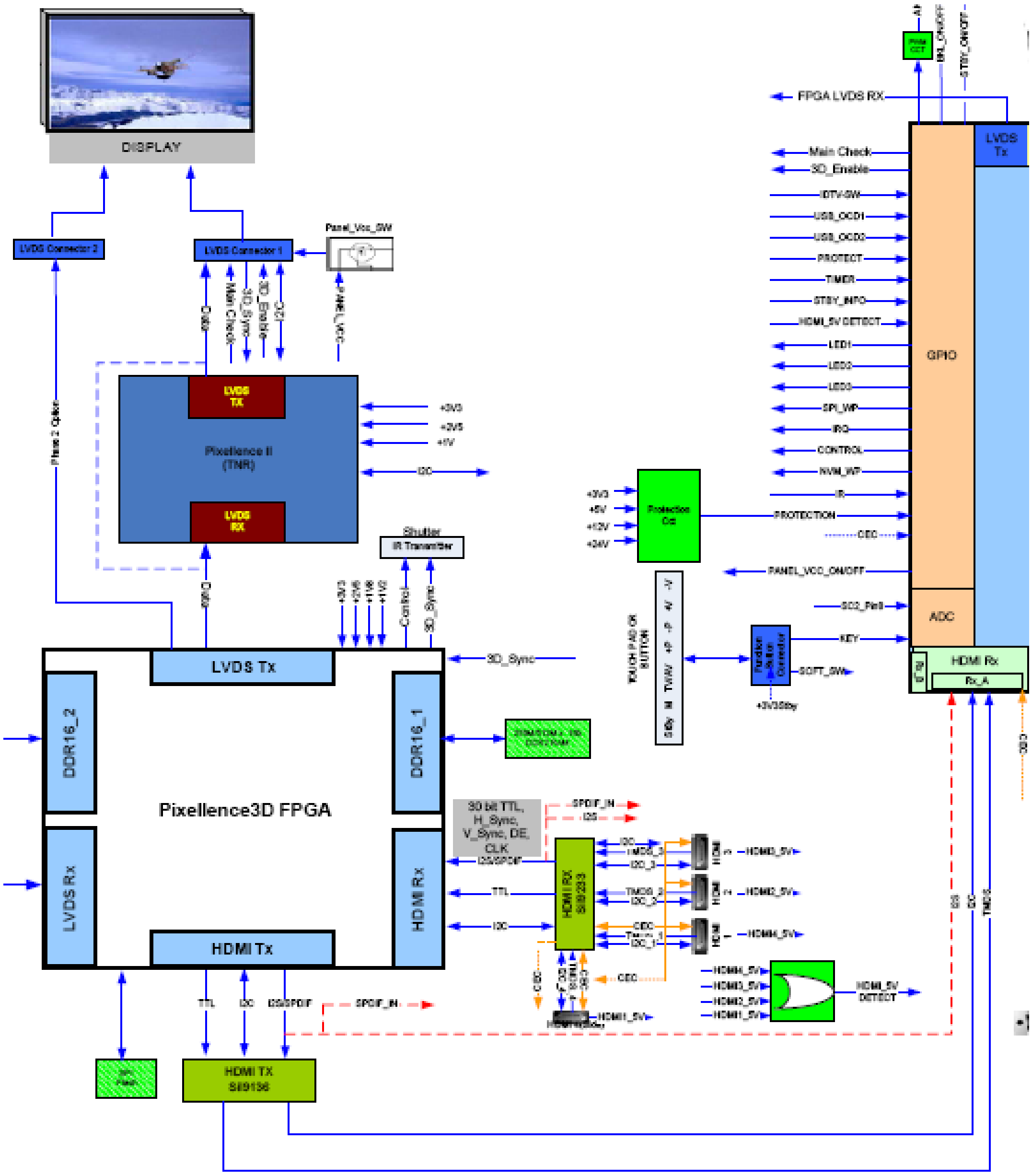

Figure 5.12 Detailed Block Diagram

As depicted in Figure 5.12, video signal is transmitted to Pixcellence3D IC through main IC, and all the 3D formatting process is carried out here. Then some color enhancements are performed in Pix II IC and finalized video signal is sent to the panel through LVDS signal.

5.2.5 Matlab Simulation of Crosstalk Reduction Algorithm

In this section, panel characterization data table 5.1 is used as input and according to this data, the LUT for all intensity pixels are calculated in Matlab environment. To see the effect of the algorithm, a side by side picture is processed with the obtained LUT and updated left and right eye images are produced.

In the first stage of the code below, the side by side picture is read by matlab, the left and right components are extracted, RGB to YCbCr conversion is processed and Y components of the pixels are found.

```
file='C:\Users\Pb\___TEZ___\3D Images\1_19.bmp';

img=imread(file); % Side by Side image is loaded
image(img)       % Side by Side image is displayed - Figure 5.13
[rows,columns,color_comp] = size(img); % getting row and column info

img_left = img(:,1:(columns/2),:);   % Left picture is cropped

figure
imshow(img_left) % Left picture is displayed - Figure 5.14
title('Left Picture')

img_right=img(:,((columns/2)+1):columns,:); % Right picture is cropped
figure
imshow(img_right) % Right picture is displayed - Figure 5.14
title('Right Picture')

img_left_ycbcr = rgb2ycbcr(img_left); % RGB to YCbCr conversion
img_left_y = img_left_ycbcr(:,:,1);   % Getting only Y component
figure
imshow(img_left_y) %Displaying Y component of left image -  Figure 5.15
```

```
title('Luminance component of the Left Picture')

img_right_ycbcr=rgb2ycbcr(img_right); % RGB to YCbCr conversion
img_right_y=img_right_ycbcr(:,:,1); % Getting only Y component
figure
imshow(img_right_y) %Displaying Y component of right image - Figure 5.16
title('Luminance component of the Right Picture')

left_minus_right = imsubtract(img_left_y,img_right_y);
figure
imshow(left_minus_right)
title('Right Picture's luminance is subtracted from Left Picture's luminance')

right_minus_left=imsubtract(img_right_y,img_left_y);
figure
imshow(right_minus_left)
title('Left Picture's luminance is subtracted from Right Picture's luminance')
```

Figure 5.13 Side by Side Image

Figure 5.14 Left and Right Pictures

Figure 5.15 Luminance component of left picture

Figure 5.16 Luminance component of right picture

Figure 5.17 Right Picture's luminance is subtracted from Left Picture's luminance

Figure 5.18 Left Picture's luminance is subtracted from Right Picture's luminance

Figures 5.17 and 5.18 illustrate luminance differences of left and right pictures and these data gives some idea about in which areas 3D crosstalk will appear.

In the below part, intended and unintended stimulus table of the panel (Table 5.1) is introduced to code, and linear interpolation is performed.

```
x=[0 5 12 17.5 23 32 45 47;
  25 25.4 26 29 32 39 50 52;
  48 48.2 49 51 51.8 55 63 65;
  74 74.2 74.3 75.1 76 77 82.4 83;
  98 98.1 98.3 98.8 100.1 101.8 105 106;
  146 146.3 146.4 146.5 147.8 150 152.7 153;
  231.4 231.5 231.6 231.8 231.9 232.5 235.5 235.6;
  252.1 252.3 252.4 252.5 253.7 253.8 254.2 255];
```

```
linear_interpolated_x=[];
row_counter=0;

for i=1:7
   column_counter=0;
   row_current=25;

   if i==5
      row_current=50;
   end
   if i==6
      row_current=85;
   end
   if i==7
      row_current=20;
   end

   for j=1:7

      column_current=25;

      if j==5
         column_current=50;
      end
      if j==6
         column_current=85;
      end
      if j==7
         column_current=20;
      end
```

```
linear_interpolated_x((1+row_counter):(row_current+row_counter+1),(1+column_c
ounter):(column_counter+column_current+1))=linearint(x(i,j),x(i,j+1),x(i+1,j),x(i+1,
j+1),row_current,column_current);

column_counter=column_counter+column_current;

    end
  row_counter=row_counter+row_current;
end

A=round(linear_interpolated_x);

intensity=A;
crosstalk=A;

%%%%%%%     Crosstalk Characteristics of the Panel      %%%%%%%%%%%%

for j=1:256
    for i=1:256
        crosstalk(i,j)=crosstalk(i,j)-(i-1);
    end
end

%%%%%%%%%%%%%%%%%      Default LUT    %%%%%%%%%%%%%%%%%%

LUT=[];
for i=1:256
    for j=1:256
        LUT(i,j)=i-1;
    end
end
```

Function ‘linearint’ is given below.

```
function [x] = linearint(a1,a2,b1,b2,number_satir,number_sutun)

B=[];
C=[];

if a2==a1
    for i=1:number_sutun+1
    B(i)=a1;
    end
else
B=a1:((a2-a1)/(number_sutun)):a2;
end



if b2==b1
    for i=1:number_sutun+1
    C(i)=b1;
    end
else
C=b1:((b2-b1)/(number_sutun)):b2;
end

for k=1:(number_sutun+1)

    A(:,k)= B(k):((C(k)-B(k))/number_satir):C(k);
end
x=A;
```

In the below part of the code, LUT is calculated in five iterations. The 256x256 matrix of intended and unintended stimulus over observed image is used here.

```
A_updated=A;

for n=1:5     % Five iterations are executed to achieve LUT
   A=A_updated;
   count=0;

for m=1:256
for k=1:256

intended = m-1;

e=intended-A(m,k);
me=m+e;

LUT(m,k)=me-1;  % Calculating LUT

 if m+e<1
    me=1;
 end
if m+e>256
   me=256;
end

LUT_real(m,k)=me-1; % Real LUT. Intended pixels cannot have nagitive values

A_updated(m,k)=A(me,k);

if A_updated(m,k)==intended
```

```
count=count+1;
end
end
end
end

intensity_updated=A_updated;
crosstalk_updated=A_updated;

% Crosstalk characteristics After the update on Intensity table

for j=1:256
    for i=1:256
        crosstalk_updated(i,j)=crosstalk_updated(i,j)-(i-1);
    end
end

figure
mesh(crosstalk)    %  illustrated in Figure 5.7
xlabel('unintended')
ylabel('intended')
title('Crosstalk Characteristics')

figure
mesh(crosstalk_updated)  % illustrated in Figure 5.23
xlabel('unintended')
ylabel('intended')
title('updated Crosstalk characteristics')

figure
mesh(LUT)   % illustrated in Figure 5.8
xlabel('unintended')
ylabel('intended')
```

```
title('Look up Table')

figure
mesh(LUT_real)  % illustrated in Figure 5.9
title('LUT REAL')
xlabel('unintended')
ylabel('intended')
```

For every intensity pixel of intended and unintended view, the intended pixels are updated in the code given below. Figures 5.19 and 5.20 are the updated versions of Figures 5.15 and 5.16.

```
for i=1:rows
   for j=1:columns/2
      p=img_left_y(i,j)+1;
      r=img_right_y(i,j)+1;
      img_left_y_updated(i,j)=LUT_real(p,r);  % Left image intensity levels are
updated.

      img_right_y_updated(i,j)=LUT_real(r,p); % Right image intensity levels are
updated.
   end
end
img_left_y_updated=uint8(img_left_y_updated);
img_right_y_updated=uint8(img_right_y_updated);

figure
imshow(img_left_y_updated)
title('Left Picture intensity updated')

figure
imshow(img_right_y_updated)
```

```
title('Right Picture intensity updated')
```

Figure 5.19 Left picture intensity updated

Figure 5.20 Right picture intensity updated

5.2.6 Results

For many combinations of intensity pairs from the left and right images, crosstalk reduction is possible with this algorithm. Unfortunately, due to the negative values (which are later replaced by zeroes as the nearest realizable intensity) in the originally computed LUT, crosstalk cannot be reduced for a small number of combinations of intensity pairs.

A stereoscopic image taken behind left shutter glass is given in Figure 5.21 when crosstalk reduction algorithm is OFF and Figure 5.22 shows the same image when the crosstalk reduction algorithm is ON. Crosstalk characteristics of the display are substantially improved after the algorithm is used especially in red circled areas indicated in Figure 5.21.

Figure 5.21 Picture sample when crosstalk reduction algorithm is OFF

Figure 5.22 Picture sample when crosstalk reduction algorithm is ON

Tables 5.3 and 5.4 give measured luminance in cd/m^2 (nits) when algorithm is OFF and ON, respectively. These measurements are taken without glasses. It is clearly seen that measured luminances are decreased when algorithm is ON, which states that effect of the unintended stimulus is lowered.

Table 5.3 Measured luminance (nits) when Crosstalk Reduction Algorithm is OFF

	Unintended Stimulus							
Intended	0	25	50	75	100	150	235	255
0	0.11	0.14	0.24	0.49	0.88	1.65	3.44	3.45
25	0.58	0.86	0.77	0.95	1.31	2.03	3.77	3.74
50	2.87	2.85	3	2.9	3.11	3.72	5.31	5.2
75	8.29	8.35	8.85	8.9	9	9.1	9.2	9.38
100	14.48	15.01	15.21	15.91	16.48	16.86	17.26	17.91
150	44.2	44.3	43.4	43.93	44.52	45.19	46.74	47.79
235	110.8	111.2	111.5	110.9	110	111.2	98.65	103.8
255	111.2	111.4	111.7	111.9	112	113.2	115.6	115.3

Table 5.4 Measured luminance (nits) when Crosstalk Reduction Algorithm is ON

	Unintended Stimulus							
Intended	0	25	50	75	100	150	235	255
0	0.11	0.14	0.24	0.49	0.89	1.68	3.48	3.15
25	0.59	0.86	0.71	0.8	1.06	1.79	3.61	3.61
50	2.91	2.85	3	2.94	2.95	3.34	4.18	4.13
75	9.49	9.23	8.92	8.83	8.25	8.3	8.34	8.4
100	15.77	15.34	15.03	15.22	16.48	16	16.2	16.49
150	45.9	44.87	43.98	44.01	44.12	45.04	45.5	46.01
235	113.6	113.1	112.9	112	111	112.1	98.05	102.8
255	113.6	113.1	112.9	112.7	113	114	115.7	115.3

Figure 5.23 shows the improved crosstalk characteristics of display system after using the crosstalk reduction algorithm. Improvement is clearly visible on the wide flat area where the crosstalk is reduced to almost zero from much higher values that outstand in the original crosstalk characteristics given in Figure 5.7.

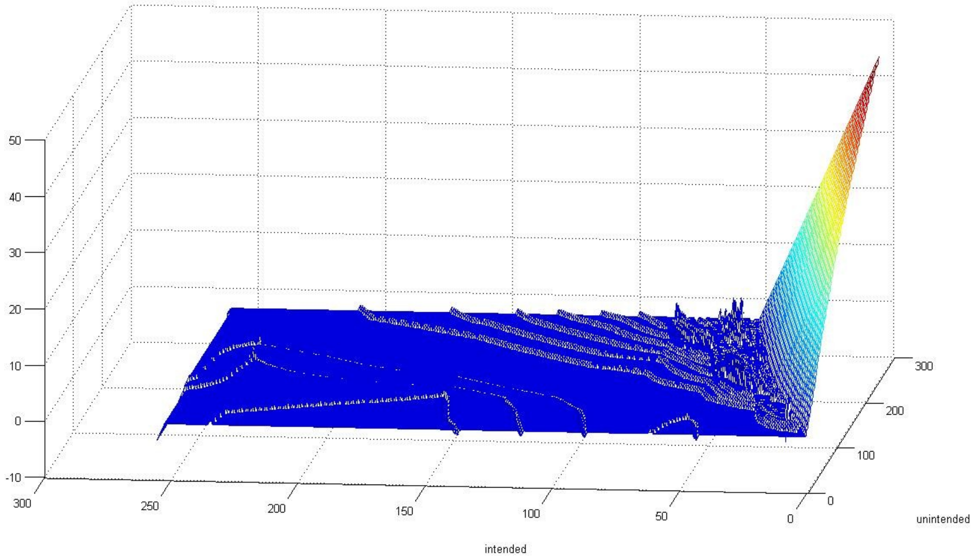

Figure 5.23 Improved crosstalk characteristics after using the algorithm

5.3 Defining Color Temperature Specification on 3D TV

Another vital performance problem for 3D TV technology was the color accuracy and major luminance decrease behind 3D glasses.

As stated before, since the glasses have liquid crystal structure, color shift becomes a matter of interest.

If the regular 2D gamma curves are applied to 3D, the whole picture looks quite greenish. When Table 4.19 is examined, it is seen that there is a huge difference in "y" chromaticity coordinate between 2D and 3D modes. Besides, 3D luminance becomes too low.

As a solution, a gamma color correction exclusive for panel and glasses pair is applied here. Panel and glasses pair should be considered as a single system.

In ordinary condition, the gamma curves shown in Figure 5.24 are used for 2D mode. With these curves, 2D color temperature is measured as x = 0.286 and y= 0.290.

If the same gamma curves were used for 3D mode too (when 3D glasses are also included in the system), 3D color temperature would shift to x = 0.286 and y = 0.316.

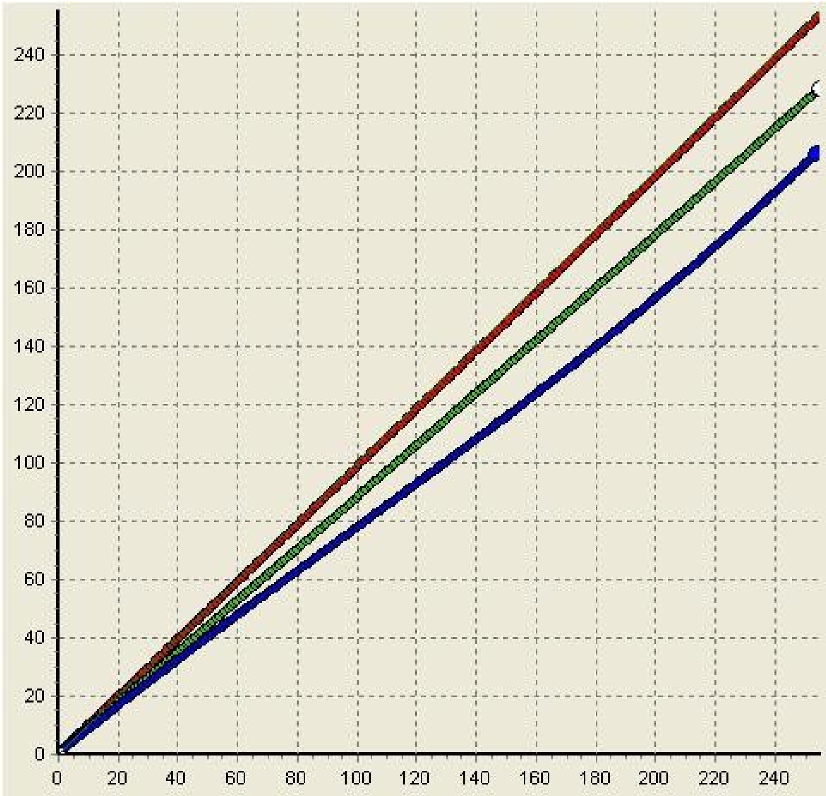

Figure 5.24 2D Gamma color curves for ordinary 3D TV

In the main IC, gamma color curves are applied after all color management blocks. Color management is done in YCbCr format, then all the color information is transformed to RGB and gamma curves can be altered in this stage. In Figure 5.25, a simplified video block diagram of the main IC is illustrated.

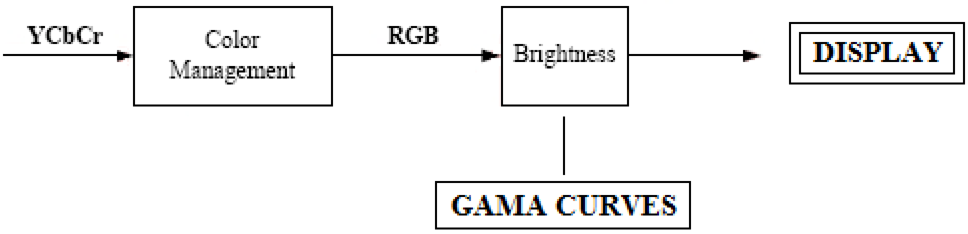

Figure 5.25 Simplified video block diagram

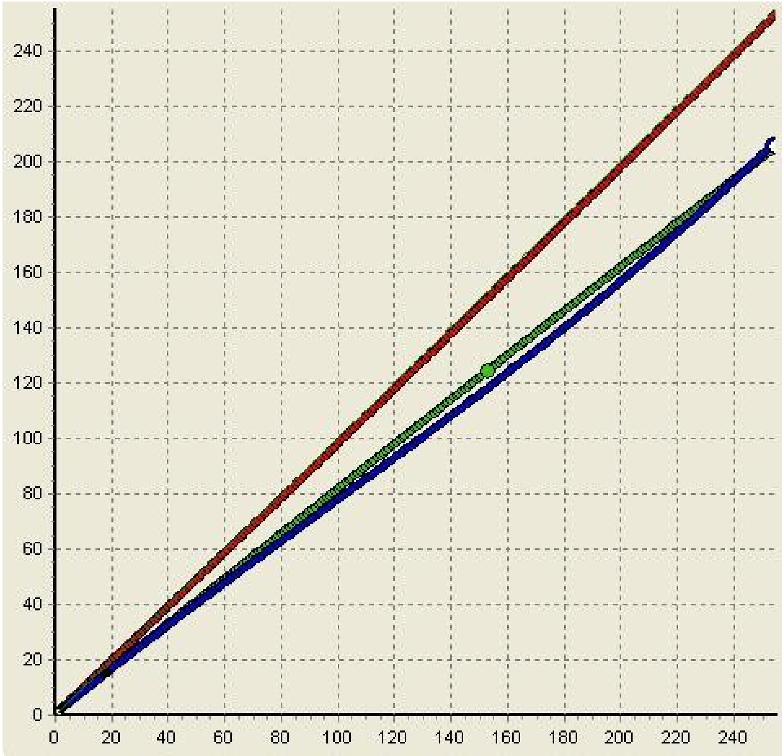

Figure 5.26 3D Gamma color curves

With the modification on green curve as shown in Figure 5.26, 3D color temperature measured behind the glasses is at x = 0.285 and y = 0.291. Besides, 3D luminance is increased to 45 cd/m^2 with these new gamma curves.

Comparing the two plots in Figure 5.24 and Figure 5.26, it can be seen that green curve is lowered nearly for every input values. Red and blue curves are kept unchanged.

LUT of gamma curves is kept in main IC's memory. An additional LUT exclusive for 3D mode is also introduced.

With this study, color shift is prevented and 2D & 3D modes of the TV look same in color. This study is vital to provide better 3D picture quality for home usage since the colors have to look natural to make people feel the depth better and perceive 3D effect more.

A 2D content can also be watched as 3D with special 2D to 3D conversion algorithms nowadays. So, a viewer should see the colors the same as the ones in 2D mode for the sake of preserving the fidelity of content with a 3D product.

Also 3D luminance is increased to 45 cd/m^2 behind the glasses and this provides a more vivid picture experience for viewers.

CHAPTER SIX
CONCLUSION

In the scope of this thesis, the most important performance problems of 3D televisions are covered. It is very clear that crosstalk is the most critical one and the main reason is hardware structures; panel and glass materials. Crosstalk is a physical issue, so it is quite easy to measure it and come to quantitative results.

While maximizing the crosstalk performance of a 3D TV in design process, the first study should be choosing panel and glasses very carefully; the base performance of crosstalk is directly related to these two elements. Refresh rate of the 3D panel should be 200 Hz for a proper 3D performance. Refresh rate directly affects flickering effect and surely headache issue. Besides, 200 Hz refresh rate is convenient for black frame insertion performed by panel itself; which greatly reduces crosstalk.

Liquid crystal response time of both panel and glasses are also vital for crosstalk performance as the leakage of light greatly increases with the increased response time. 2 ms is the best performance among the TV panels in the market.

As second step, hardware fine tune of communication system between panel and glasses should be performed carefully. Timing of sync signal should be modified in an effort to minimize crosstalk as implemented in this thesis. This is achieved by taking crosstalk measurements as sync signal is delayed by several time instants. There is no formulation for the best case here, so this workout is needed to be performed with trial and error method.

If crosstalk performance is not good enough, the crosstalk reduction algorithm studied in this thesis and implemented in hardware gives satisfactory results. Hardware implementation of the algorithm requires only a pre-computed LUT which updates left and right eye images in stereoscopic contents. It is a cheap solution but requires that display crosstalk characteristics of targeted panel-glasses system be obtained by measurements in order to compute an effective LUT. Both test measurements of luminance and subjective evaluations of 3D images show that the algorithm noticeably reduces crosstalk.

For preserving color accuracy and increasing luminance in 3D mode, it is found out that the only way is to set gamma curves exclusive to used panel and glasses pair. An implementation of modifying gamma curves accordingly in this thesis shows that it is possible to prevent the color shift and increase the luminance at the same time in 3D mode. Both panels and glasses of different brands may behave quite different in color and luminance manner, so a generalized solution to color shift and luminance decay looks impossible here.

I hope that this thesis including some implementations for improving vision quality of 3D TVs and some design experience will be a good reference for the upcoming 3D TV projects.

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APPENDIX

List of Figures

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