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University of West Bohemia in Pilsen
Department of Computer Science and Engineering
Univerzitni 8
30614 Pilsen
Czech Republic

Scaling of Rendered Stereoscopic Scenes

Master Thesis Report

Ricardo José Teixeira dos Santos

Technical Report No. DCSE/TR-2005-09
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Rendered stereoscopic scenes suffer from a scaling problem, which causes major restrictions on their portability to other stereoscopic display mediums. A main solution for this problem is presented, as well as other complementary solutions. Also, the basics of depth perception are presented, and some insight on the current three-dimensional displays used.

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University of West Bohemia in Pilsen
Department of Computer Science and Engineering
Univerzitni 8
30614 Pilsen
Czech Republic

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Ricardo J.T. Santos (Ricardo.Santos@centrum.cz)
Faculty of Sciences of the University of Lisbon, Portugal
University of West Bohemia in Pilsen, Czech Republic

Abstract

Rendered stereoscopic scenes suffer from a scaling problem, which causes major restrictions on their portability to other stereoscopic display mediums. A main solution for this problem is presented, as well as other complementary solutions. Also, the basics of depth perception are presented, and some insight on the current three-dimensional displays used.

1. Introduction

Sir Charles Wheatstone, a British physicist and inventor, was the impulsionador in 1833 of a science called stereoscopy, making stereograms with drawings and using stereoscopes to view them. Although there was a time in which a stereoscope and viewing cards could be found in every American home, nowadays stereoscopy is not present on our everyday life.

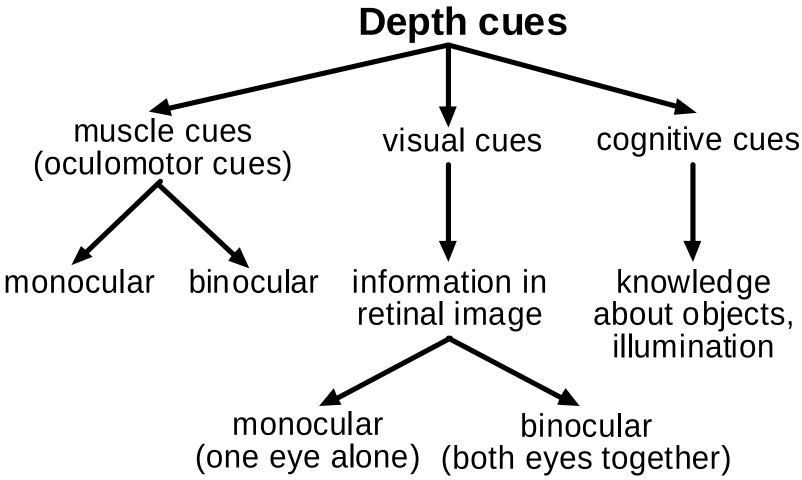
With the goal of making 3D displays present on our everyday life, a consortium of 19 entities led by Bilkent University, in Turkey, has been working on planning and conducting a 48-month project on 3DTV (https://www.3dtv-research.org), which started on September 1 of 2004. The University of West Bohemia in Pilsen, Czech Republic, is one of the entities involved in this project, having Prof. Ing. Vaclav Skala, CSc. as a scientific responsible in this university (http://3dtv.zcu.cz/).

The project of this report is part of a Post-Graduation on Informatics Engineering that I am attending on the Faculty of Sciences of the University of Lisbon, in Portugal. The project was fully made on the Computer Graphics Department of the University of West Bohemia in Pilsen, Czech Republic, under the supervision of Prof. Ing. Vaclav Skala, CSc., and it is a part of the 3DTV project. Prof. Carlos Lourenço is the supervisor of my project on the side of the University of Lisbon.

One of the major parts of research on the 3DTV project is the display of the final three-dimensional rendered scenes, and one of the problems is the variety of types of display mediums used, in which the same scene will be viewed in different size displays. This report has as goals to identify problems that may occur when scaling rendered stereoscopic scenes, and to present eventual solutions for those problems.

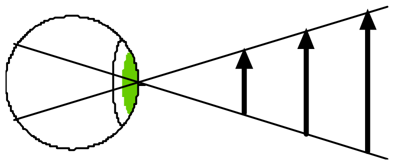
2. Perception of depth [1, 2, 3, 4]

The world we live in is three dimensional. We see this world through images projected in our retinas, and although the world is three dimensional, the images themselves are flat. The way we create depth perception from flat images is through depth cues, which are divided into several categories, as we can see below:

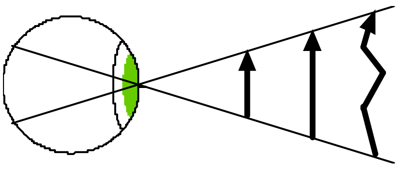


- Figure 2.I - Depth cues diagram -

The problem with perceiving depth from images is that the world is three dimensional, but the images in our retinas are simply flat projections of the world. So, as we can see on the next figures, objects with different size, shape and distance can produce the same image:



- Figure 2.II - Objects at different distances can have the same retinal image -



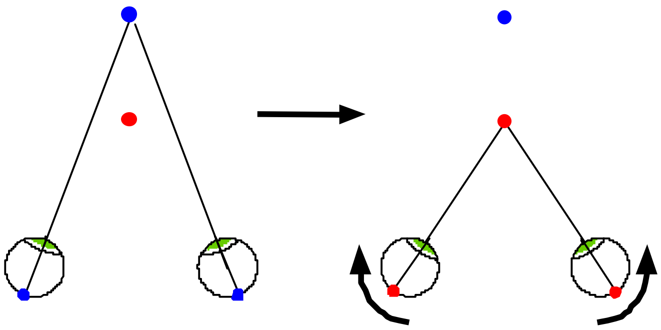
- Figure 2.III - Objects with different 3D shapes can have the same retinal image -

So, to overcome this problem, the visual system provides us with more depth information.

2.1 Physiological information, the oculomotor cues

2.1.1 Convergence

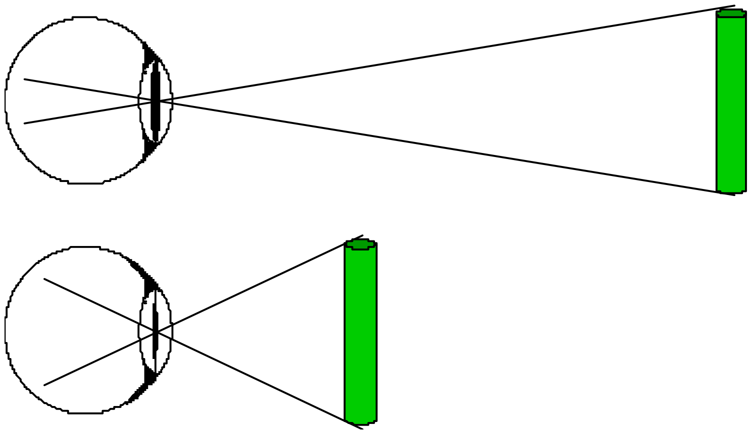
The human eyes are connected to muscles that allow them to rotate in their sockets. When we look at an object, the muscles contract and force the eyes to converge and look directly at the object. The closer the object is to the eyes, the more these have to converge, thus forcing the muscles more.



- Figure 2.1.1 - Eyes converging from the blue point to the red point -

2.1.2 Accommodation

Besides the muscles that move the eyes, there is a set of muscles attached to the lens that make it change shape to focus on objects at different distances. When the object is far away the muscles relax, and the lens become more spherical. When the object is nearby the muscles pull on the edges of the lens, making it flatten out. Just like in conversion, there is also a relationship between the object's distance and the degree of contraction of the muscles, and this relationship is also a depth cue.



- Figure 2.1.2 - Eye accommodating from a far object to a near object -

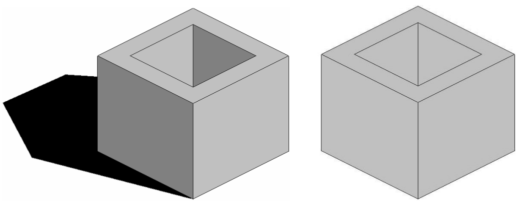
Accommodation and convergence work together. The eyes accommodate for the distance to where they are converged.

2.2 Monocular visual cues

Binocular disparity and stereopsis are very powerful sources of information for depth, but their usefulness depends on having two eyes. As reported on [5], the human eye cannot distinguish depth for objects farther than 5 meters using only the depth cues provided by accommodation and convergence.

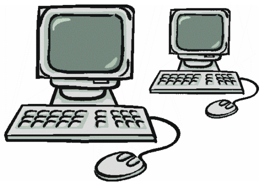
If we close one eye and see the world with the other, the world does not appear to be flat like a picture, and we still have a perception of depth, although it is more difficult to judge distances. This means that there are other sources of depth information that exist on a single image. These sources of information are called *monocular visual cues*.

Light and shade. Bright objects appear to be closer than dim ones, and objects with bright colors appear to be closer than dark ones. By drawing shades on an object, the illusion that the object is solid or rounded is given. By casting shadows from an object, the illusion that it's resting on a surface is given.



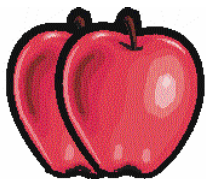
- Figure 2.2.I - Light and shade -

Relative size. When seeing a familiar object, their distance from us is judged by their size, being farther from us when it's smaller and closer when it's bigger.



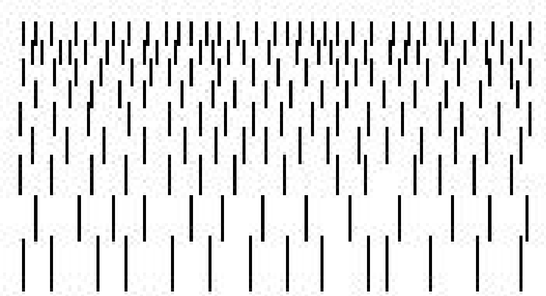
- Figure 2.2.II - Relative size -

Interposition. If we are looking at two objects from an angle in which one is in front of the other, we know that the one in front is closer to us than the one on the back.



- Figure 2.2.III - Interposition -

Textural gradient. This cue is the only one that was created by a psychologist in modern times, all the others were used by painters by the time of the Renaissance. The simplest example to explain this depth cue is a grassy lawn in which the texture is more apparent as the object is closer to the viewer.

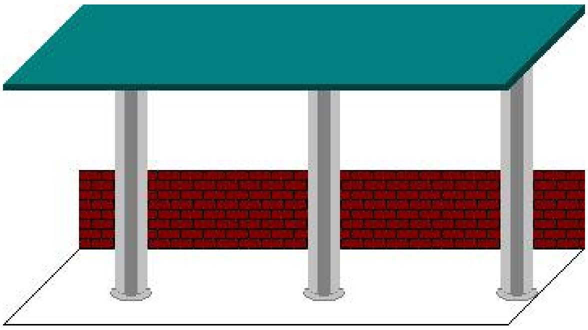


- Figure 2.2.IV - Textural gradient -
(Image taken from [2])

Aerial perspective is the diminution in visibility of distant objects caused by intervening haze. Often, distant objects are seen with a blue haze because of the scattering of the red light by the intervening atmosphere. When a thick fog of haze is present, objects sometimes appear to be farther than they actually are.

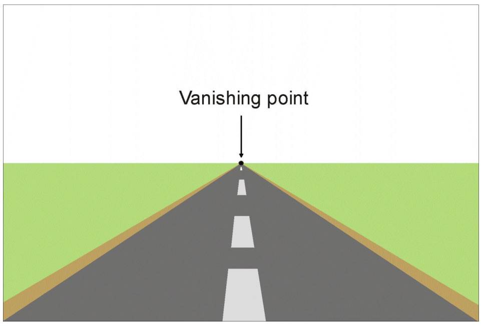
- Figure 2.2.V - Aerial perspective -

Motion parallax. A simple example to describe this depth cue is what we see when we are inside a train. The wall on the back of our view seems to be farther away than the columns because the columns move much faster than the wall.



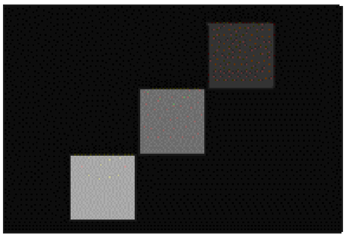
- Figure 2.2.VI - Motion parallax -

Perspective is the relation between background and foreground objects. Images with a strong perspective cue have a better depth effect. If it is exaggerated, or if there are perspective cues such as lines receding to a vanishing point, the image's depth will be enhanced.



- Figure 2.2.VII - Perspective -

Depth cuing is the name of a technique used in computer graphics. Depth cuing reduces the intensity of the object in proportion to the distance from the viewer.



- Figure 2.2.VIII - Depth cuing -

Depth perception through color is also possible, because of an anomaly that the visual eye system has. The more a color approaches red the more it will seem to approach us, and the more it approaches blue, the more it will seem to move away from us. This particular subject will be discussed in more detail on the chapter 2.4.

- Figure 2.2.IX - Depth perception through color -
(Image taken from [6])

2.3 Binocular visual cues

We have two eyes, which provide us different images of the world. These images are flat projections on our retinas of the three dimensional visual world. Even though the images are flat, we can perceive depth from them. This is possible because the images that our retinas capture are slightly different, due to the physical distance between them. This physical distance is called *retinal disparity*.

After the two slightly different images are captured by our retinas, the brain *fuses* them into a single image, achieving with that process a sense of depth.

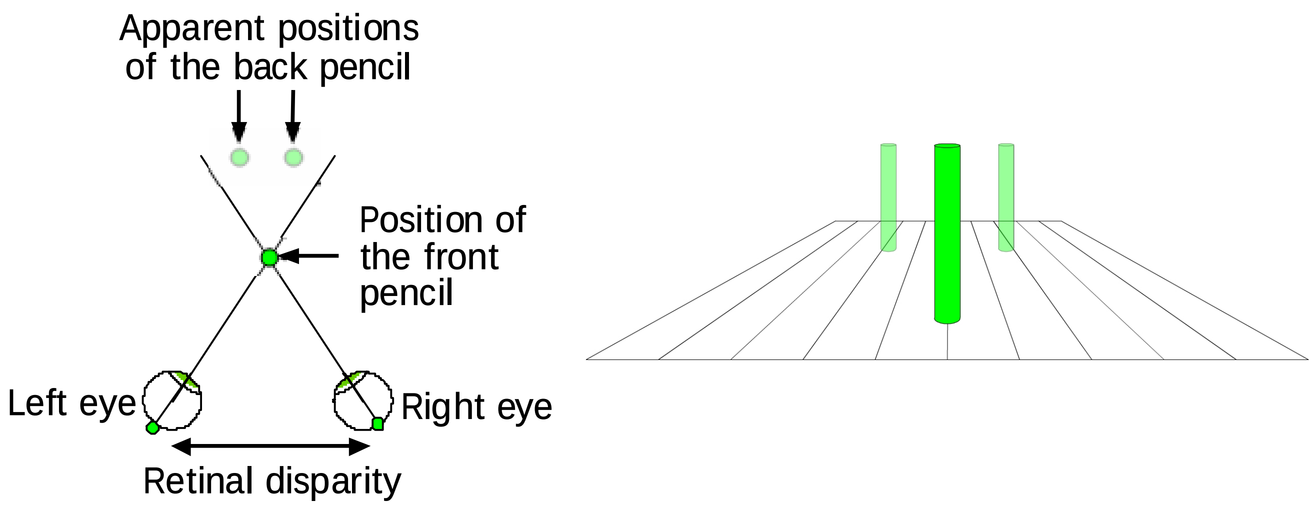
2.3.1 Retinal disparity

The retinal disparity effect can be seen by doing a simple experiment.

Hold a pencil with your left hand, and stretch your left arm in front of your eyes. On your right hand, hold another pencil, on the same direction as the previous, so that both of the pencils are in a straight line with your eyes. But put this pencil closer to your eyes, let's say at 20 cms.

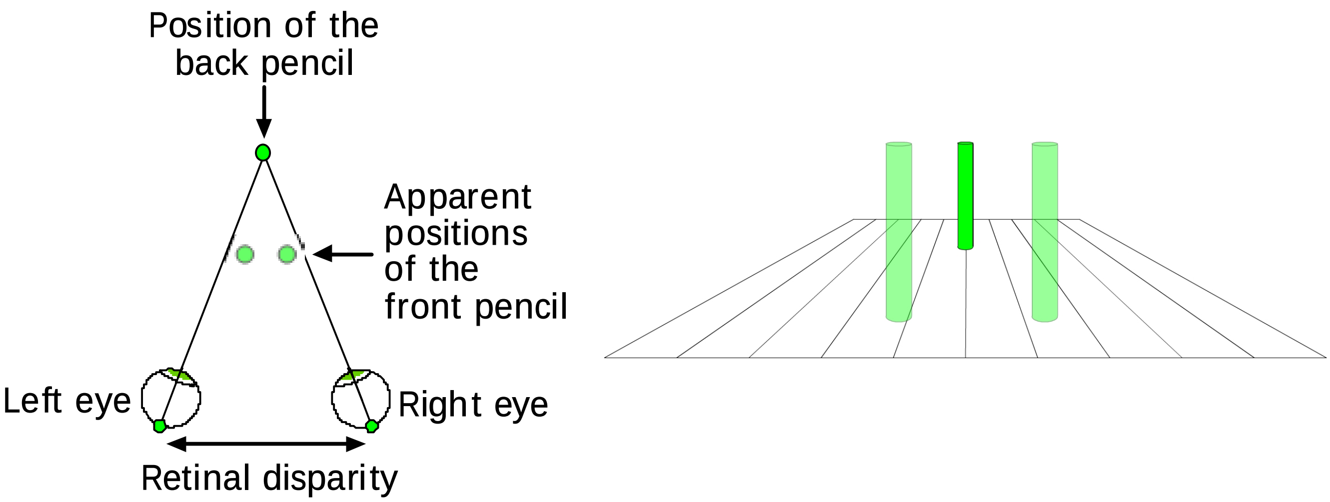
Look on the front pencil.

When you look at that pencil, your eyes are converging on the pencil, that is, the optical axes of both eyes cross on the pencil. There are sets of muscles which move your eyes to accomplish this by placing the images of the pencil on each *fovea*, or central portion of each retina.



- Figure 2.3.1.I - Converging on the front pencil -

When you have the front pencil focused, you'll notice that the back pencil appears to be double. On the other hand, when you look at the back pencil your eyes are converging on it, and the front pencil will now appear to be double.



- Figure 2.3.1.II - Converging on the back pencil -

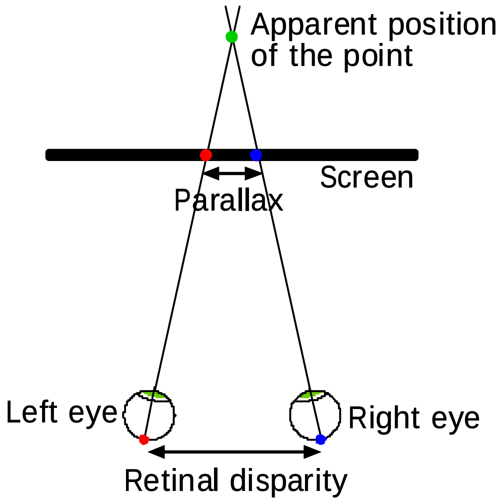
The points on which the eyes are converged will have *zero disparity*.

Retinal disparity is caused by the fact that each of our eyes sees the world from a different point of view. The eyes are, on average for adults, 64 millimeters apart. The disparity is processed by the brain into a single image of the visual world. The mind's ability to combine two different, although similar, images into one image is called *fusion*, and the resultant sense of depth is called *stereopsis*.

2.3.2 Parallax

The only difference between a planar display and a stereoscopic display is that this last one is able to display *parallax values* of the image points. Parallax produces disparity on the eyes, providing the stereoscopic cue.

The distance between left and right corresponding image points is called parallax, and when measured, the parallax value is discovered.



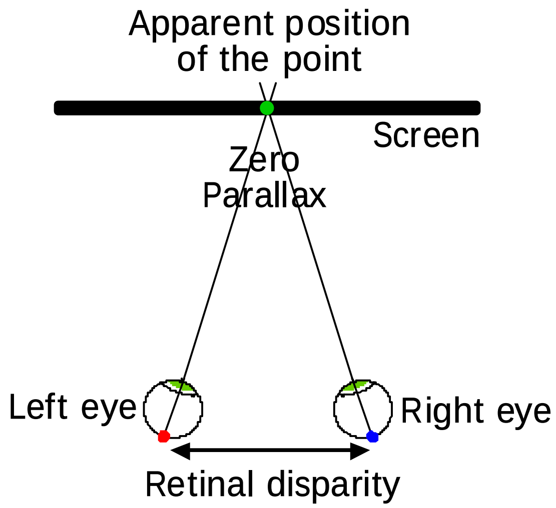
- Figure 2.3.2 - Parallax -

Parallax and disparity are similar entities. Parallax is measured on the display screen, and disparity is measured at the retina. It is parallax that produces retinal disparity, and disparity in turn produces stereopsis.

Parallax may also be given in terms of angular measure, which relates it to disparity by taking into account the viewer's distance from the display screen.

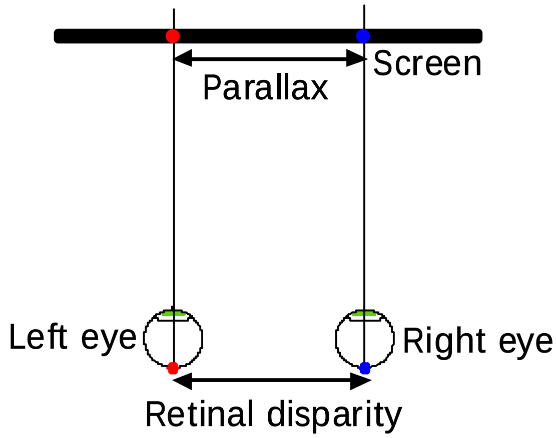
2.3.2.1 Parallax classifications

There are four basic types of parallax. On the first case, when the homologous image points of the two images exactly correspond or lay on top of each other, we have *zero parallax*. When looking at the display screen and observing objects with zero parallax, the eyes are converged at the plane of the screen, which means that the optical axes of the eyes cross at the plane of the screen. When image points have zero parallax, they are said to have *zero parallax setting (ZPS)*.



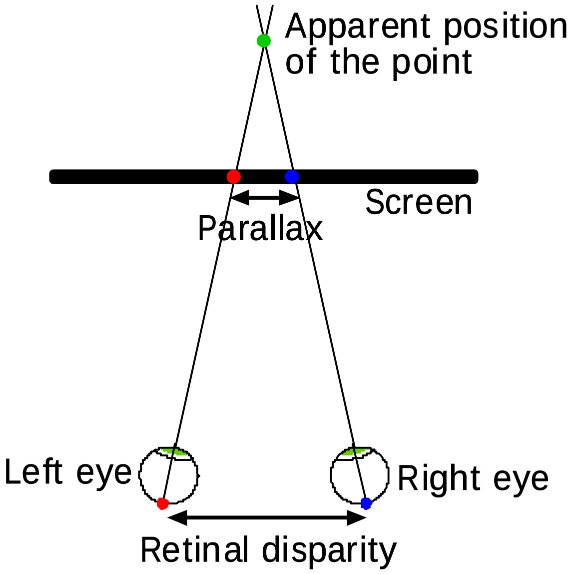
- Figure 2.3.2.1.I - Zero parallax -

The second case of parallax is *positive parallax*, which occurs in two situations. The first is when the axes of the left and right eyes are parallel. This happens on the visual world when looking at objects that are at a great distance. The same happens in a stereoscopic display, when the parallax value is equal to the distance between the eyes. It is known that this situation produces discomfort when used on small display screens.



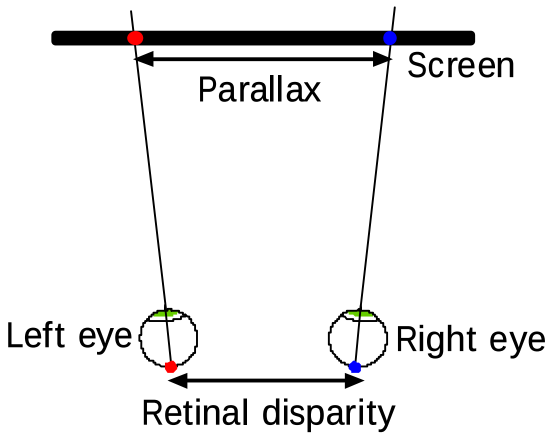
- Figure 2.3.2.1.II - Positive parallel parallax -

The second is when the axes of the eyes cross after the screen, which means that the value of parallax is positive, and inferior to the distance between the eyes. Any value of parallax between the eye distance and zero will produce objects that appear to be within the cathode ray tube (CRT), or behind the screen. These objects are said to be ***within CRT space***.



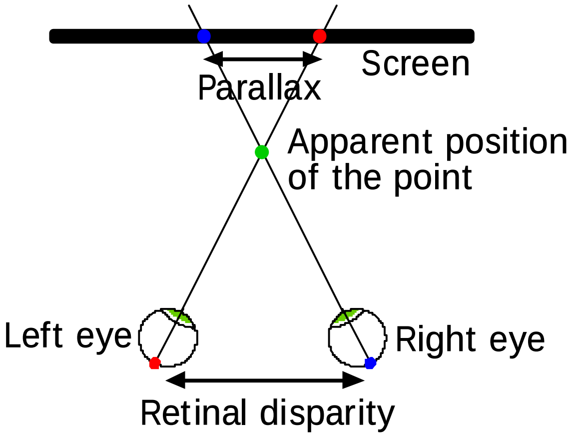
- Figure 2.3.2.1.III - Positive parallax -

Another kind of positive parallax is ***divergent parallax***, when images are separated by a distance greater than the eye distance. In this case, the axes of the eyes are ***diverging***. This divergence does not occur when looking at objects on the visual world, and the unusual muscular effort needed to fuse such images may cause discomfort. This kind of parallax is usually not used in computer-generated stereoscopic images.



- Figure 2.3.2.1.IV - Divergent parallax -

The last case of parallax is *negative parallax*, when the axes of the eyes are crossed and parallax points are said to be crossed, or negative. Objects with this kind of parallax will appear to be closer than the plane of the screen, which means, between the screen and the viewer. These objects are said to be *within viewer space.*

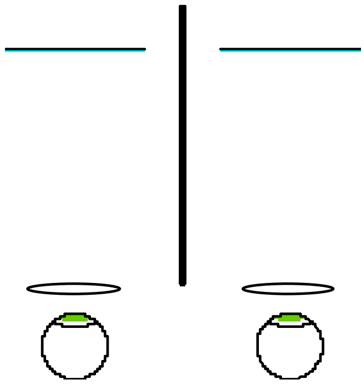


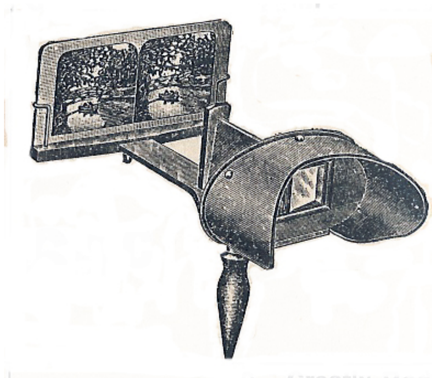
- Figure 2.3.2.1.V - Negative parallax -

2.3.3 Stereograms

As said before, Sir Charles Wheatstone discovered that by taking photographs from slightly different positions and having people fuse them visually through a mirror or lens system, he could produce pictures that were compelling representations of space and depth. These double pictures are called stereograms.

Stereograms were made with either two cameras or two lenses on the same camera, side by side on both cases, with the same distance between them as the human eyes. After the pictures were made, they were seen through a *stereoscope*.



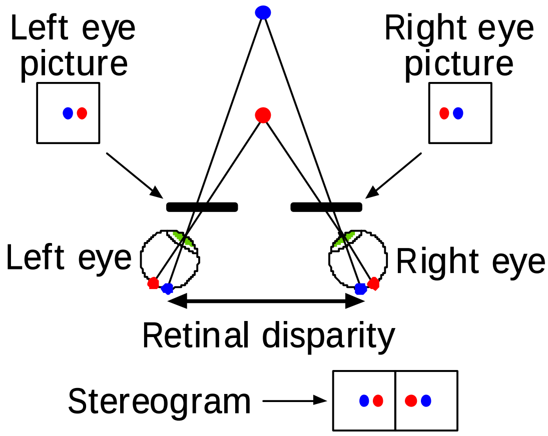


- Figure 2.3.3.I - Wheatstone's first stereoscope -

(Right image taken from [7])

On the previous figure, we have a model of the first stereoscope, invented by Sir Charles Wheatstone. This stereoscope contains a divider, which forces the left and the right eyes to see their respective pictures, a pair of convex lenses, which allow the eyes to see pictures close-up, but with accommodation relaxed, so that the eyes can be diverged (looking straight ahead, or nearly so), as they are normally when viewing distant objects.

On the image below we can see how stereograms are made.



- Figure 2.3.3.II - Stereogram -

2.4 Perception of depth from color with ChromaDepth Glasses [6, 8]

A technique for creating the illusion of depth through the use of different colours is known for more than 100 years. This technique is used in scientific areas, commercial areas, and it makes use of an aberration that the human visual system has. Chromatek developed, patented, and commercialized the ChromaDepth glasses, a special kind of glasses that enhance this depth illusion with the use of special gratings. When viewed through these glasses, a normal flat colored image can gain a depth sense, but as we shall see, it is not applicable to all images.

2.4.1 Depth perception from color

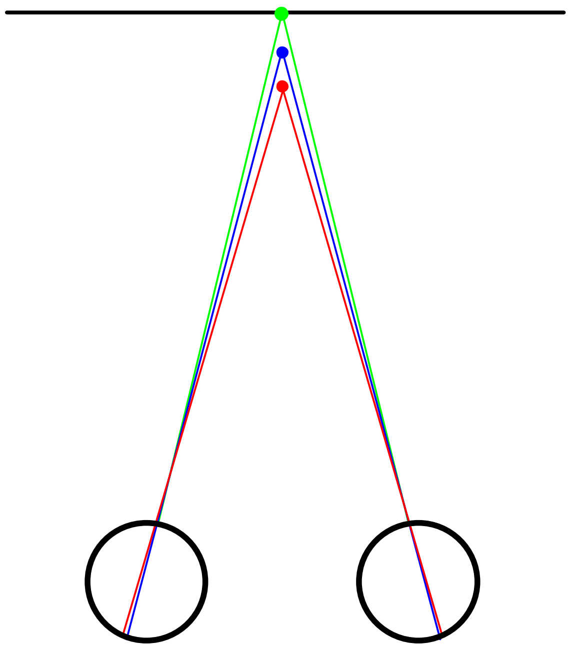
As explained before, when we look at an object, our eyes *converge* on it, which means that each eye rotates in order to point directly at the object. The amount that our eyes have to look inward to see the object is one of the cues that our brain uses to judge the distance of that object to us.

The fluids in the eye refract different wavelengths at different angles. Therefore, objects with the same shape, size, and distance from us, can appear to be at different distances merely because they have different colors. Besides this, bright-colored objects will appear to be closer to us than dark-colored objects.

Because different colors are refracted in different ways in the eye media, the human eye can make mistakes when judging the distance of objects of different colors. This is called *longitudinal chromatic aberration* of the eye media.

Besides this aberration, there is another one, which is that the line of sight does not coincide with the optical axis of the eye. This is called *transversal chromatic aberration* of the eye media.

This can be seen with a simple example, with a blue point and a red point, on the same position. When we look at the blue point, the image of the blue point is directly on the fovea. Because red light is not refracted so strongly, the red point will appear to be a little on the side of the blue point on the temporal side. The brain interprets this as if there were two points at different distances. The red point will appear to be closer to us than the blue one.



- Figure 2.4.1 - Depth perception from color -

- The green point represents the original position of both red and blue points; the blue point represents the apparent position of the blue point; the red point represents the apparent position of the red point -

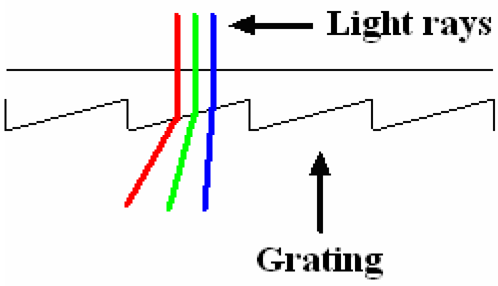
This effect is known as chromo-stereoscopy or color-stereo effect, and most people are unable to see it.

2.4.2 ChromaDepth glasses depth effect

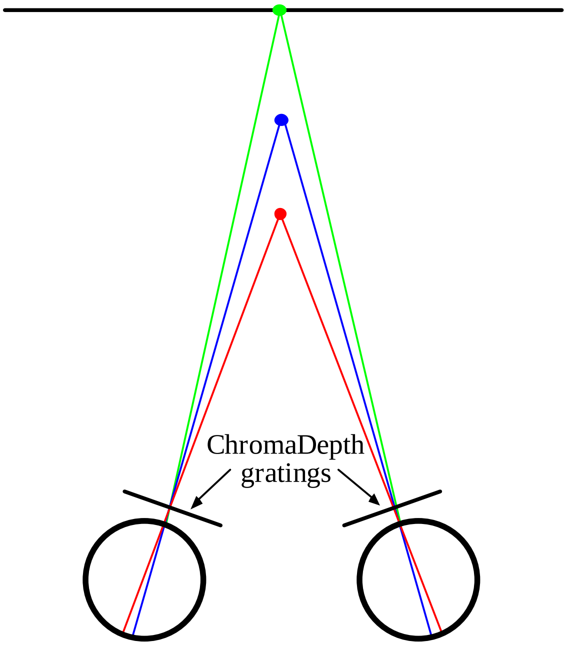
The ChromaDepth glasses enhance these abnormalities of the human eye system. They are essentially flat prisms that bend light, bending different colors of light a different amount. The more they bend light of a certain color, the more our eyes have to look inward too see that color light, giving the illusion that objects of that color are more near.

The more the color of the light approaches red, the more it will be bent, and the more it approaches blue, the less it will be bent. This means that red objects will appear to be closer to us than green objects, and green objects will appear to be closer to us than blue objects.

On the image on our right side, we can see an enhanced part of the left lens of the ChromaDepth glasses. The grating has a saw-tooth profile, with a regular spacing and regular angle between each tooth. Because of this angle, all light rays that hit the grating are refracted to the outer side of the retina, some more than the others, depending on their color, making the eyes converge inward to look at it, giving the impression that the object that emitted that light ray is closer to us than it actually is.



- Figure 2.4.2.I - Part of ChromaDepth Glasses' left lens -



- Figure 2.4.2.II - Depth perception with ChromaDepth Glasses -

- The green point represents the original position of both red and blue points; the blue point represents the apparent position of the blue point; the red point represents the apparent position of the red point -

The ChromaDepth glasses have these gratings on both sides, giving a stronger depth sense, but making the vertical edges appear not as sharp as the rest. Because of this problem, there are glasses with only one grating, on the left eye, the ChromaDepth 3-D High Definition Glasses. On the right eye, there is only a transparent film, and with this eye, we can see the image sharp. The negative part on these glasses is that the depth effect is reduced to half.

The advantage of ChromaDepth is that only one image is used for both eyes. One image alone contains X, Y and Z information by virtue of the image contrast and the image colors. All the other methods for creating stereoscopic depth need two images, one for each eye.

However, there are also disadvantages. The colors of the image cannot be arbitrary, because they are supposed to carry the Z coordinate, so the method will not work on arbitrary images. To create an image with a strong depth sense, there are several rules to follow with the use of colors. Because the color limitation is rather big, images with a big depth sense do not appear to be real, and the more real they are, the less depth sense they will have. From the tests made for this report with the C3D™ glasses, especially with the images on ChromaTek's website, the conclusion is that, if the images don't have strong monocular depth cues, and are not made essentially from red and blue solid colors, they will appear to be almost flat, without a strong depth sense, with the extra of not being sharp.

Another disadvantage is that sometimes CRT images appear to be blurred on some regions. The light emitted from a CRT consists on different intensities of red, green and blue, and when the image has, for example, small regions of yellow, the ChromaDepth glasses can cause the color to separate into its primary elements and blur the region. Nevertheless, this problem is reduced with the ChromaDepth 3-D High Definition Glasses, which put most of the optical power on one eye, leaving the other eye to see the image clearly.

3. State of the art

In this chapter, several three-dimensional technologies are presented, with and without viewing aids. The study problem of this report is present in any stereoscopic display that works with stereopairs, with the depth information encoded as screen disparity.

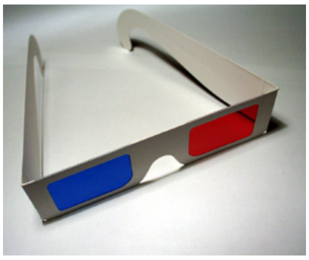
Because one of the goals of 3D-TV is to provide the same freedom to the viewers that a normal television has, autostereoscopic displays are more recommended for a 3D television implementation, since they don't make use of any viewing aids, and they support several viewers at the same time.

3.1 Stereoscopic displays [1, 9, 10]

Stereoscopic displays present two images to the viewer, one for each eye, achieving with that a sense of depth with the depth information encoded in the disparity between the two provided images. To prevent the eye from seeing the wrong image, glasses or goggles are used.

3.1.1 Anaglyph

This method blocks the unwanted image from the eye by encoding the images in color. To separate the images, the viewer uses glasses with filters of complementary colors, like red-blue and red-green, for example, in which a filter of a certain color will block the image with the same color encoding, and so on. Because it's a very cheap system, it's widely used in magazine publications, personal computer monitors and cinema. As a downside, it has the problem of color changes caused by the type of encoding used, also a certain luminosity lost, and a visual tiredness with prolonged use.



- Figure 3.1.1 - Red-blue anaglyph glasses -

(Image taken from [11])

There are two very similar systems using glasses with amber-blue lenses, the SpaceSpex [12] and the ColorCode 3-D [13], used on some IMAX films and also commercialized on some DVDs in 3D.

3.1.2 Polarization

To separate the left eye image from the right eye image, polarized light is used on both images, allowing them to be displayed on the same screen. Using glasses with polarized filters, the correct image is viewed on the desired eye. This is the system used on the stereo-wall presented on the chapter 5.2.3 of this report. The polarization system doesn't change the colors, but it has some luminosity loss, although this can be improved by adjusting the light intensity of the screen or projectors, depending on the display system used. This technology is widely use in 3D cinemas as well as in computer monitors with alternative polarization screens. This is one of the most economical systems with an acceptable image quality these days.

- Figure 3.1.2 - Polarized glasses -

(Image taken from [14])

3.1.3 Shutter-glasses

With this system, the left and right images are presented alternatively on the screen, synchronized with a pair of glasses with liquid-crystals that block the unwanted image. These glasses are known as *liquid crystal shutter* glasses (LCS) or *liquid crystal display* glasses (LCD). Because they work at a high frequency rate, the images can be alternated without the user noticing any image flickering. Computer monitors, television and 3D cinemas can use these glasses, provided that they have a frequency rate high enough to avoid perceptible image flickering.

- Figure 3.1.3 - Shutter-glasses -
(Image taken from [15])

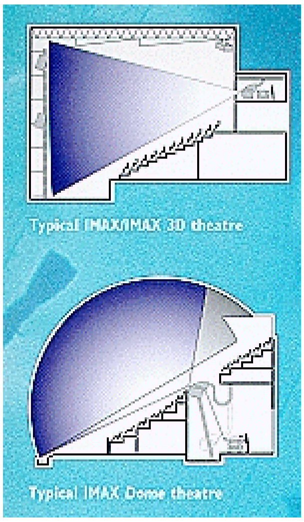
3.1.4 Head mounted displays (HMD)

A head mounted display supports the screens and optical systems for both eyes, in a way that the image is generated on the HMD screens. Because of the its high prices until some time ago, the use of these devices was mainly in Virtual Reality systems, but with the prices becoming more and more accessible, they is starting to be used in home entertainment systems, like video games.

- Figure 3.1.4 - Head mounted displays -
(Image taken from [15])

3.1.5 IMAX 3D

The history of IMAX goes back to 1967 during the EXPO 67 in Montreal, Canada. A group of Canadian film makers created a powerful projector for a giant screen using a 70mm film. These days, IMAX has two types of screens, the IMAX Classic, and the IMAX Dome (previously known as IMAX Solido). The IMAX Classic has a flat screen, where the seats are placed on a floor with 25º of inclination and the projector is located on the top of the room. The IMAX Dome has a semi-spherical screen type planetarium, and the projector uses special high angle lenses (fish-eye lenses) to cover the entire screen. Here, the seats are placed on a floor with 30º of inclination, but the projector is located on a central zone of the circular room, slightly above the geometrical centre.



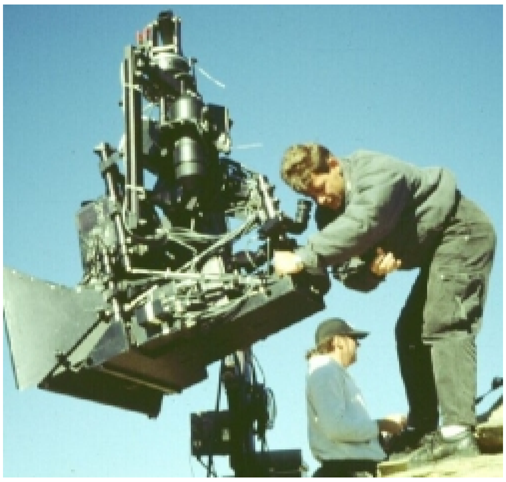
- Figure 3.1.5.I - IMAX Classic and IMAX Dome theatres -
(Image taken from [9])

On the EXPO 86 in Vancouver, a stereoscopic version of IMAX was presented, IMAX 3D, which works with two simultaneous 65mm films, one for each eye. The first versions worked with polarized glasses on IMAX Classic screens, with two synchronized projectors.

The system IMAX Dome is the first 3D projection system designed for semi-spherical screens type planetarium. This system was presented on the EXPO 90 in Osaka, Japan, and later on the EXPO 92, in Sevilla, Spain. Instead of using light polarization, it uses alternative projection, with shutter-glasses, with two synchronized projectors, working on 24 frames per second. The shutters on the glasses and on the projectors open and close 48 times per second, providing a flicker free image. The image synchronization between the projectors and the glasses is made with infra-red signals. There is only one IMAX Dome [16] in Europe, and it can be visited at the Futuroscope [17], in France.

IMAX 3D films are made with one of two methods, either with two standard simultaneous cameras or with one specially designed camera.

On the first method, because of the large size of the cameras, in order to situate them in a way that the separation between objects is not greater or similar to the human inter-ocular separation, the cameras are placed one above the other, with a 90º angle between them, with the camera placed above pointing at the floor, and the camera below pointing directly at the scene. In front of both cameras a mirror is placed with a 45º inclination, so that the camera above records the image reflected on the mirror, and the camera below records the image seen through the mirror. This setup allows the film maker to define the distance between objects, but it doesn't allow the use of wide-angle lenses or fish-eye lenses.



- Figure 3.1.5.II - The stereographer Noel Archembault filming "The last buffalo" in 3D with two IMAX cameras -

(Picture taken from [9])

On the second method, a special IMAX 3D camera was designed, with two objectives separated 70mm apart, and it allows the use of objectives with different focal lengths, including the fish-eye super angle objective, used to project the filming directly on the IMAX Dome 3D. To record the stereogram pairs, the IMAX 3D camera has internal high precision mirrors. The more compact version allows film makers to film on situations where the normal double IMAX cameras wouldn't work, like on underwater scenes, or scenes made in small spaces, for example.

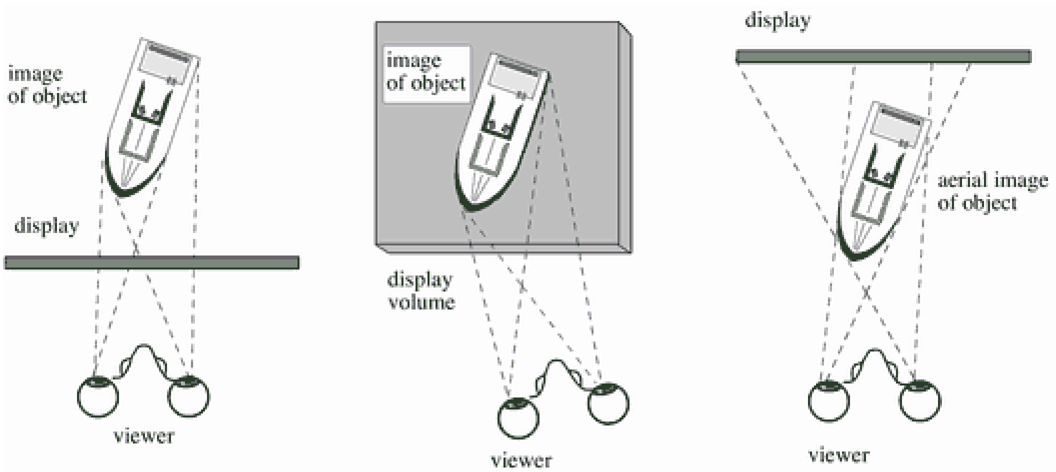
- Figure 3.1.5.III - Left side: Compact version of the IMAX 3D Camera; Right side, the astronauts Sheperd and Krikalev filming on the mission STS-98, in February of 2001 - (Pictures taken from [9])

3.2 Autostereoscopic displays [1, 18, 19]

Autostereoscopic displays provide the user with a three-dimensional image without the use of glasses, goggles or any other viewing aids. One of their biggest advantages is that they offer the best approximation to the optical characteristics of a real object.

Because the viewer doesn't have any optical medium to redirect the images provided by the autostereoscopic display, all display mediums or elements must always lie along a line of sight between the viewer and all parts of the spatial image. The photons of the image must originate in, or be redirected by some material, which can be behind, in front of, or within the space of the image.

On the next figure we can see the possible relationships between the images and the display medium:

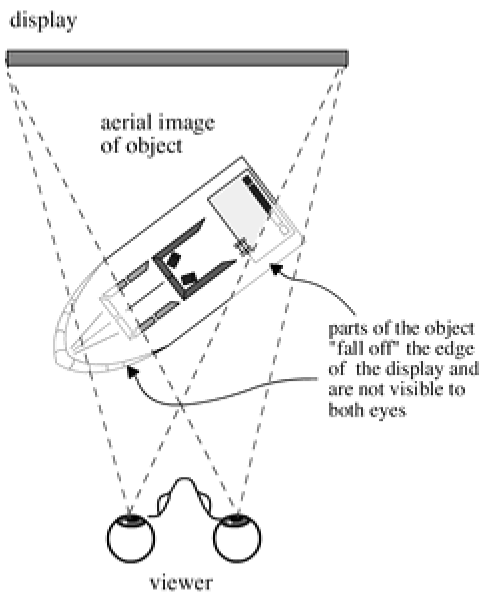


- Figure 3.2.I - Relationships between the images and the display system -
(Image taken from [18])

Several problems occur due to the natural constraints on this type of display systems, making from air, water and smoke very poor display media.

Another problem is when the viewer is on a bad position or when he moves, the sides of the image can be clipped. For example, if the image appears in front of the display, and the viewer moves to one side continuously, the image will be clipped partially or even totally on that side. This problem is known as window violation, and it's one of the more disturbing in aerial images.

On the next image we can see a window violation:



- Figure 3.2.II - Window violation example -

(Image taken from [18])

3.2.1 Re-imaging displays

These types of display are the simplest ones within the range of autostereoscopic displays. They don't produce a stereoscopic image, they simply affect the appearance of another three-dimensional image in some way, by capturing and re-radiating the light from a three-dimensional object, maybe even to a new location in space.

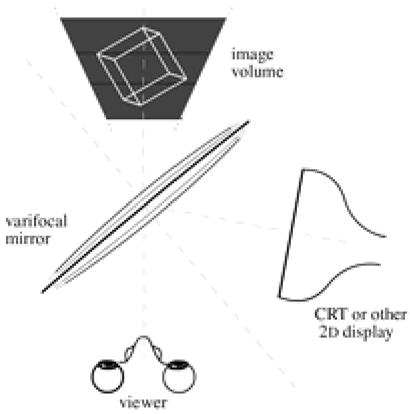
As an example, we have a simple mirror, which can change the direction of all rays of light entering it without changing the intensity or the color of the light itself. The mirror can be used to superimpose the light of two three-dimensional scenes and re-radiate the result. These autostereoscopic displays are the most commonly used on theme parks today, because they have a very low price and a high efficiency.

More complex re-imaging devices use lenses and mirrors with optical power that can translate the position of an object or distort it into a different three-dimensional shape.

3.2.2 Volumetric displays

These displays create a volume of space. They can address individual points explicitly in that volume of space and with it illuminate specific parts in it, drawing in it the three-dimensional data.

As an example of a volumetric display, we have the varifocal mirror display on the next figure:



- Figure 3.2.2 - Varifocal mirror display -

(Image taken from [18])

To create the volume of space, a mirrored membrane of varying optical power sweeps an image of a CRT through different depth planes of a volume. When the CRT display is synchronized with the mirror's oscillation, any point within the volume can be displayed. The greatest problem with varifocal mirror displays is building a high quality varifocal optic that can be oscillated at high frequencies.

All the volumetric displays share several properties, whatever optical or mechanical technology they use. First, they provide a high freedom on choosing the viewers position. Second, it's possible for the human eye to focus on the display points, providing the sense of ocular accommodation. This is possible because the display image emits a continuous, uniform, spherical wave-front. The disadvantage of this wave-front is, because it's uniform and omni-directional, view-independent shading of objects is not possible.

Another problem is that it is not possible to display occlusion of one part of the image volume by another, which makes it impossible to display photorealistic scenes, where occlusion is one of the most important depth cues.

For these reasons, volumetric displays are mostly used to display non-realistic data like wireframe images and icon-based displays. They are appropriate for this type of data because they can vector-scan only the regions of space that the object fills, eliminating the display bandwidth that would be necessary to rasterize the entire image volume.

3.2.3 Parallax displays

Unlike the explicitly three-dimensional input data used on the volumetric displays, on parallax displays the input consists on a stereogram, two two-dimensional projections of a scene, where the depth information is implicitly encoded as positional disparity between the two projections.

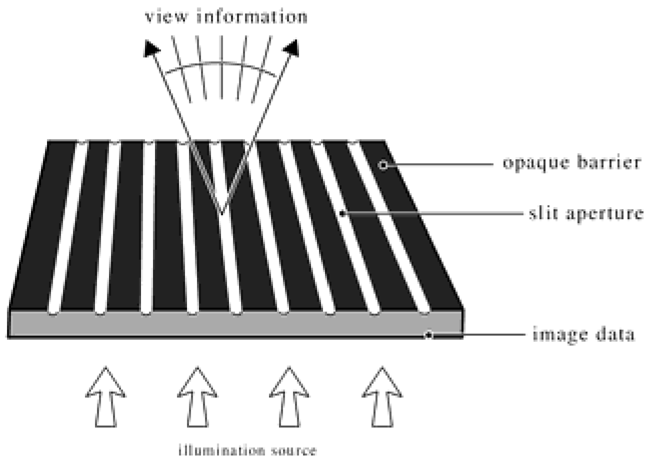
On parallax displays it's possible to show occlusion of one part of an object by another, making it possible to show photorealistic scenes. A disadvantage is that most parallax displays use information reduction techniques, diminishing or eliminating ocular accommodation depth cues.

Parallax displays are simply surfaces covered with display elements that can redirect light in several directions. With that, it's possible to send to each eye the correct two-dimensional projection of the scene.

3.2.3.1 Parallax barrier displays

A parallax barrier display is basically a simple image medium with an opaque material slotted with a series of regularly spaced vertical slits. This slotted material is known as *parallax barrier*. The image medium is placed behind the parallax barrier, with a regular distance from it. The slits in the barrier act as windows into the stripes of image that lie behind them. Exactly which stripe of image is visible depends on the horizontal angle from which the slit is viewed. A stereoscopic image pair is displayed on the image medium, interleaving columns of the two images, being one column of image for each eye, and also one column of image per slit. When the viewer stands on the right position, he will see the image for the left eye with the left eye and the image for the right eye with the right eye, producing a stereoscopic image, using the parallax barrier to block the opposite image from view.

On the next figure we can see a panoramagram, an improvement of the parallax barrier method that uses thinner columns on the parallax barrier, creating more views behind each slit, making the image appear to change more naturally when the viewer changes position.



- Figure 3.2.3.1 - Parallax panoramagram -

(Image taken from [18])

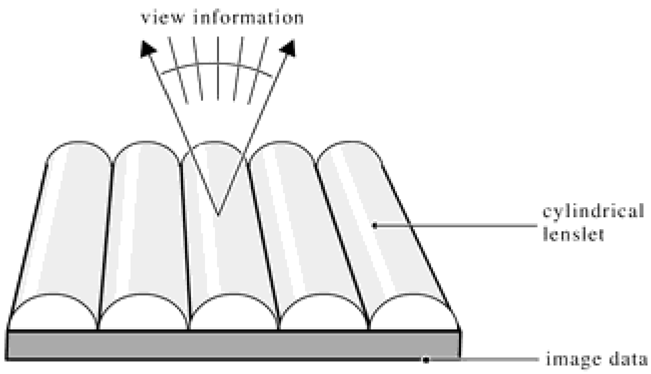
The parallax barrier has a side effect, which is that besides blocking the opposite image from view, it also blocks light from getting to the viewer. To solve this, parallax panoramagrams use banks of light, diffuse light located behind the image medium.

Another problem is, because spatial and directional information is spatially multiplexed on the image medium, if a viewer moves far enough to one side of the image, he will be able to look through the slit, seeing the data immediately on the side of the desired data. When this happens, the viewer will see the correct image with one eye, and the repeated image with the second eye, making the image appear to repeat its perspectives, which will appear as if the depth of the image would flip inside out, causing what is known as *pseudoscopic image*. Besides this, the resolution of the image limits the number of views that can be displayed. The spacing of the slits will determine the maximum spatial resolution of the display.

These images are not three-dimensional on the vertical direction, only on the horizontal direction. Vertically they are flat images. These types of displays are called HPO, *"horizontal parallax only"*.

3.2.3.2 Lenticular sheet displays

These types of display are similar to the parallax barrier displays, but instead of using the parallax barrier, they use narrow lenses to display three-dimensional information. On the next figure we can see a lenticular sheet display:



- Figure 3.2.3.2.I - Lenticular sheet display -
(Image taken from [18])

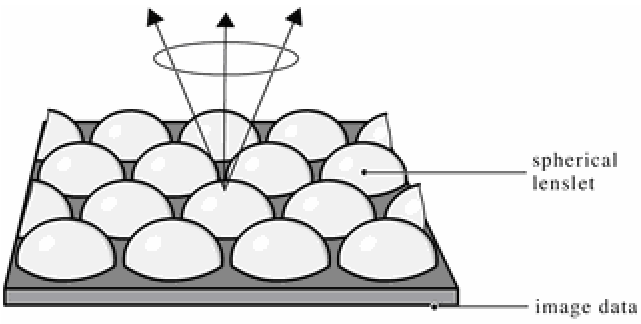
Just like on the parallax barrier display, on a lenticular sheet display the image medium also interleaves columns of the two images, but instead of slits, it uses lenses, being one lens for one stripe of image. The lenses direct light to different locations, directing each stripe of image to the correct eye, producing a stereoscopic pair. The advantage that lenticular sheet displays have is that the entire surface radiates light, because nothing is blocking the image, unlike the parallax barrier on parallax barrier displays.

The lenses are molded from plastic, and during that process their characteristics are defined, like width, distance between the image medium and the lenses (usually this distance is of one focal length behind the lenses), and their optical power.

The final quality of the lenses determinates the optical aberrations that will be viewable on the final picture, and the optical power of the lens controls the angle of view through which the final image can be seen. The greatest difficulty is to create high quality and affordable lenticular sheets.

As well as parallax barrier displays, only horizontal parallax is displayed here.

Another type of display, the integral photograph or integram, uses spherical lenses instead of cylindrical ones to present horizontal and vertical parallax, producing a full parallax image. These types of display are less common than the cylindrical ones, because even more of their spatial resolution if sacrificed to directional information. On the next picture we can see an integram's spherical lens array.

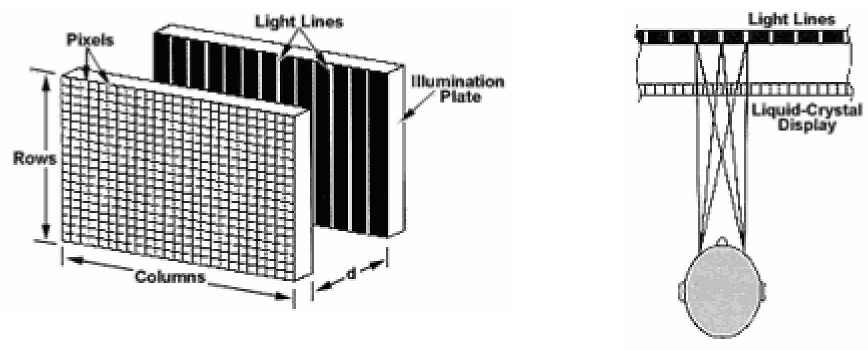


- Figure 3.2.3.2.II - Integram -

(Image taken from [18])

3.2.3.3 Parallax Illumination – DTI Real Depth 3D™ [19]

This technology is similar to parallax barrier displays, but instead of having a physical barrier with slits in front of the display, it has a special illumination pattern and optics behind the LCD screen, which make the alternate columns of pixels only visible by the correct eye, provided that the viewer is directly in front of the screen, or in certain areas off to the side.

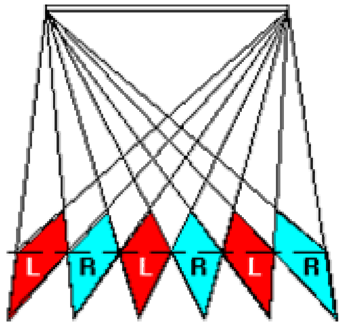


- Figure 3.2.3.3.I - DTI's parallax illumination -

(Figures taken from [19])

The stereo pair is multiplexed by having the left image on the odd numbered columns and the right image on the even numbered columns. The special illumination plate located behind the LCD screen uses light from compact and intense light sources, optically generating a lattice of very thin, bright, and uniformly spaced vertical light lines. The line spacing is chosen according to the number of pixel columns displayed on the LCD, and the disparity of our eyes makes us see the odd columns with the left eye, and the even columns with the right eye.

Just like the parallax barrier displays and the lenticular displays, also on this display the distance between the screen and the illumination plate will generate several viewing zones. The number of viewing zones will be decided in part by the distance between the illumination plate and the LCD screen.



- Figure 3.2.3.3.II - Viewing zones of the DTI parallax illumination -
(Figure taken from [19])

The correct stereoscopic image will be seen if the viewer is in any position where the left eye is in a left eye zone, and the right eye is in a right eye zone, allowing the use of several viewers simultaneously.

3.2.4 Holograms

While a photograph has an actual physical image, a hologram contains information about the size, shape, brightness and contrast of the object being recorded. This information is stored as microscopic interference fringes, during the holographic exposure process.

The light reflected by a three dimensional object forms a pattern that is also three dimensional. In order to record the whole pattern, the light used must be highly directional and must be of one color. Such light is called coherent. Because the light from a laser is of one color, and leaves the laser with one wave in perfect step with all others, it is perfect for making holograms.

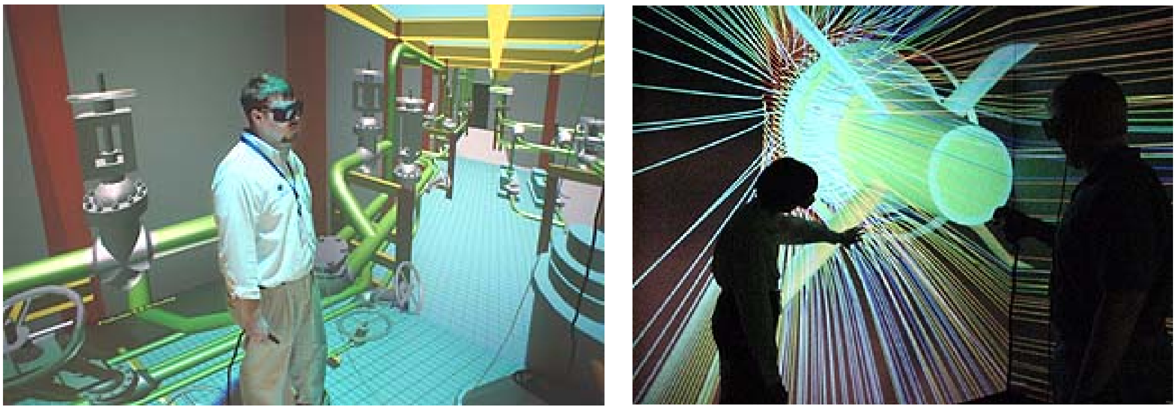
When you shine a light on the hologram, the information that is stored as an interference pattern takes the incoming light and re-creates the original optical wave-front that was reflected off the object. Your eyes and brain now perceive the object as being in front of you once again.

Because holograms can be very realistic, the term "hologram" has been misused by people when addressing any display that is vaguely three-dimensional, or even not three-dimensional at all. So, display holograms are image-bearing diffractive optical devices.

3.3 Virtual Reality caves

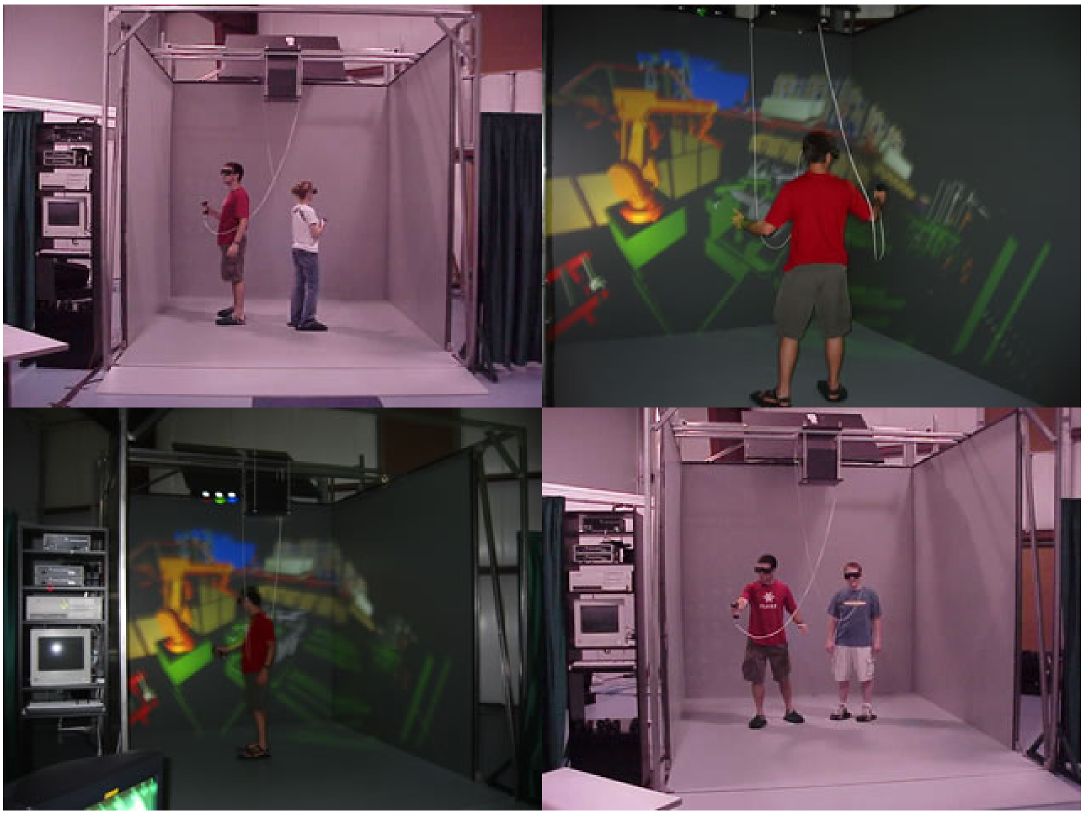
Virtual Reality caves are immersive displays, composed by square rooms with 3x3 meters of wall size, with flat walls, where in each wall and ceiling, a stereo image is back-projected, surrounding the viewer and giving him a feeling of immersion. The viewer explores the virtual world by moving around inside the cube, while the images blend real and virtual objects naturally in the same space so that those individuals have an un-occluded view of their bodies as they interact with virtual objects. Image management is required so that the scenes on each wall fit together seamlessly to replicate the single surrounding environment. Because the system uses back projection, the viewers have to wear active shutter glasses. These systems support several viewers at the same time, but only the viewer with the tracker device will have a perfect composed image, because only one tracker device can be used at the same time. The tracker device adjusts the images of the walls according to the viewer's movement.

On the figures below, we can see several examples of this technology:



- Figure 3.3.I - Fully immersive display cave -

(Images taken from [20])



- Figure 3.3.II - Display cave -

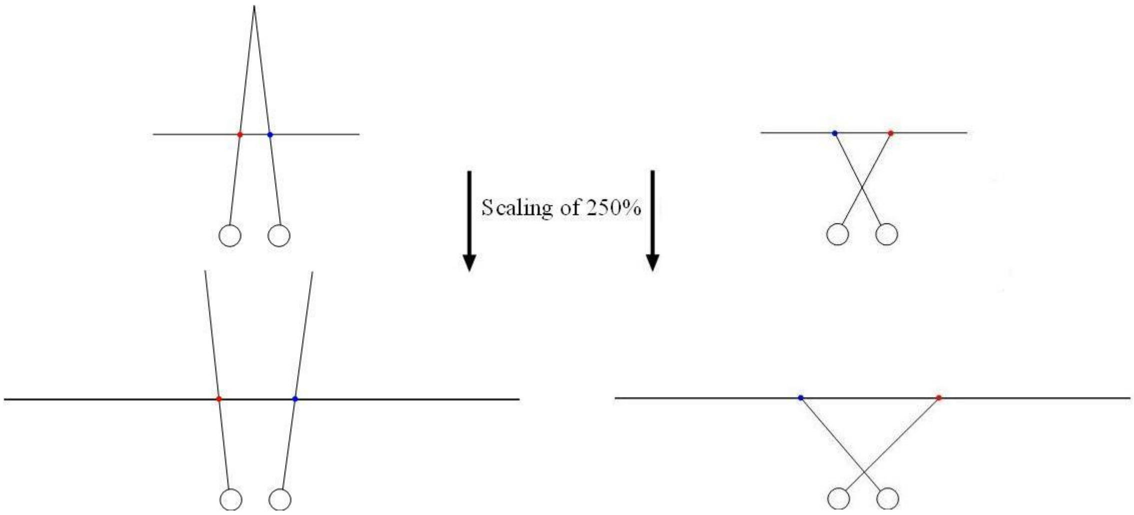
(Image taken from [21])

4. Problem explanation

Rendered stereoscopic scenes suffer from a scaling problem. When a stereoscopic scene is scaled, the parallax values change, being the module of the parallax values directly proportional to the size of the screen.

If the size of a scene is gradually enlarged, there will be a point from where the module of the parallax values will exceed the retinal disparity values, causing divergent parallax or very strong negative parallax, making it impossible for the human eye to fuse the stereoscopic pair, causing terrible discomfort to the viewer.

On the next figures we can see the result that the enlargement of the scene has on the parallax values:

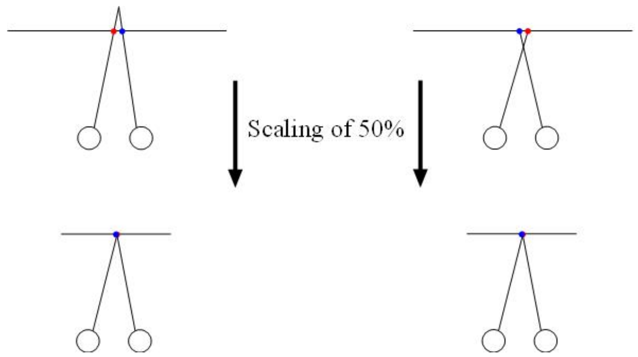


- Positive parallax values - (divergent parallax)

- Negative parallax values - (very strong negative parallax)

- Figure 4.I - Results of scaling the screen to 250% -

On the other hand, if the size of a scene is gradually decreased, from a certain point the parallax values will be so small that the points will appear to be on the same position, or they will even be on the same position, eliminating the stereoscopic depth cue, as we can see on the next figure:



- Positive parallax values - - Negative parallax values -

- Figure 4.II - Results of scaling the screen to 50% -

When a stereoscopic scene is produced, the final visualization technology is taken into consideration, so that throughout the entire scene, all parallax values will be within the normal values. By knowing the size of the final screen on which the scene will be projected, as well as the positions of the viewers, the entire scene is constructed with the parallax values within the acceptable values.

The practical result of not being able to scale a stereoscopic scene is that a particular scene can only be viewed on a particular size screen. This makes it impossible to view the scene on another type of display, narrowing the number of people who can see the scene, making a major drawback on several aspects, like the commercial one, for example. This is one of the main reasons for stereoscopy not being present on our daily life, in television, personal computers, cinema, and other display mediums.

5. Performed work

The goal of this project was to find a solution through the experimental point of view for scaling rendered stereoscopic scenes, possibly with some compromises.

A solution is presented, relying on the fact that screen parallax is directly connected to the distance between the viewer and the screen, when perceiving stereoscopic depth. If parallax values are kept within a certain range during the whole scene, they will allow the viewers to see only one fused image for each presented stereoscopic pair.

5.1 Problem approach and solutions

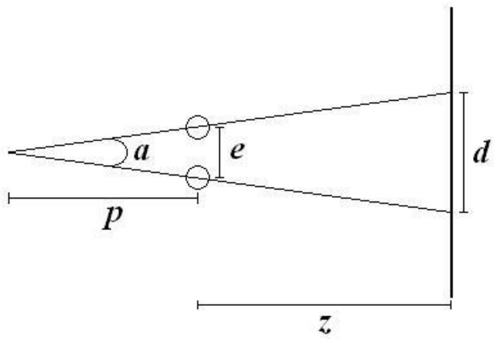
The main problem with scaling stereoscopic scenes is the direct influence that it has on the convergence angle of the viewers. For a scene to be viewed without problems, the convergence angle has to be always within acceptable values. These acceptable values are the maximum angle to where the eyes can converge outward, and the maximum angle to where the eyes can converge inward. All angles between these two values are within ***Panum's fusion limits*** [1]. All angles outside Panum's fusion limits will cause the viewers to see double images, causing what is known as ***diplopia***.

Because the scaling of stereoscopic scenes has a direct influence on the convergence angles, we need an estimation for Panum's fusion limits.

To calculate the convergence angles, two models are used. The variables used on the models are:

- z = Distance from the viewer to the screen
- p = On the divergent parallax model: distance from the point where the convergence angle is calculated to the viewer's eyes;
  On the negative parallax model: distance from the point where the convergence angle is calculated to the screen;
- d = Parallax, left point minus right point (LP-RP);
- a = Convergence angle;
- e = Eye disparity.

On the next figures we can see the model and mathematical formula used to calculate the maximum convergence angle when our eyes converge outward:



- Figure 5.1.I - Model for divergent parallax values -

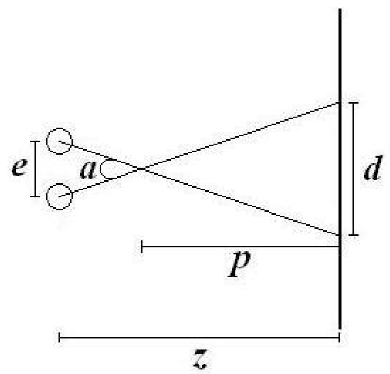
$$p = \frac{z}{\left(\frac{|d|}{e}\right) - 1}$$

- (F1) -

$$a = 2 * \arctan\left(\frac{|d|/2}{z+p}\right)$$

- (F2) -

For the maximum convergence angle when our eyes are converging inward, the model and mathematical formula used are:



- Figure 5.1.II - Model for negative parallax values -

$$p = \frac{z}{\left(\frac{e}{|d|}\right) + 1}$$

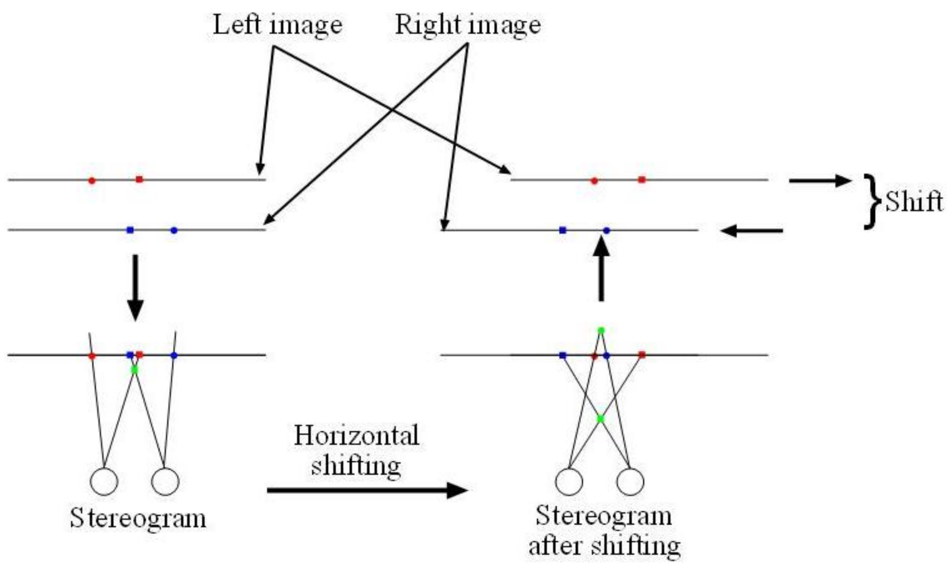
- (F3) -

$$a = 2 * \arctan\left(\frac{e/2}{z-p}\right)$$

- (F4) -

The proposed method to scale stereoscopic scenes works on both models, and it controls the convergence angle by adjusting the position of the viewer, defining the distance between the viewer and the screen. For this, it’s necessary to know the maximum parallax values of the entire scene, both positive and negative. To prove this method, experiments were done, which will be presented on the next chapter of this report.

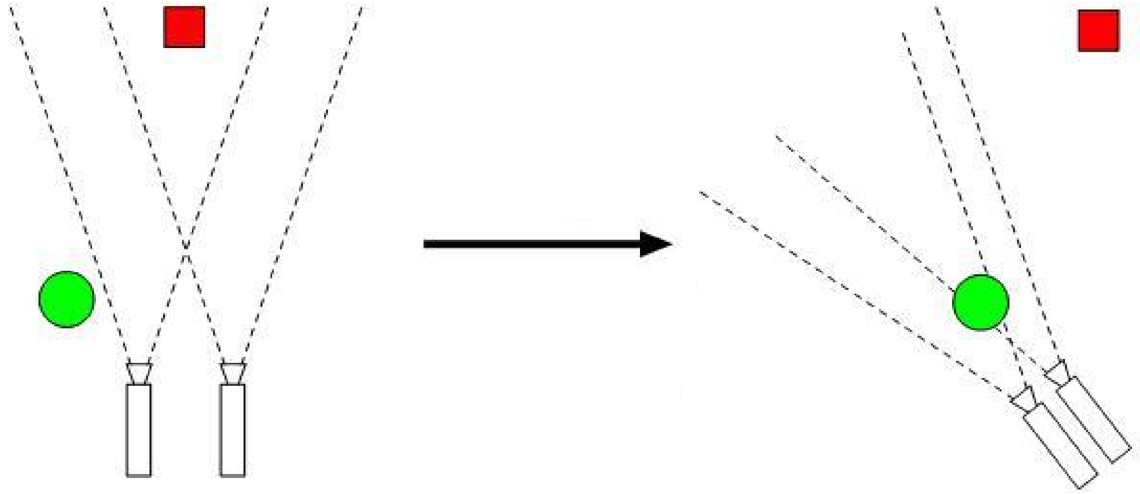
Another method can be used to control parallax values, which is to shift images horizontally inward or outward, depending on the desired result on the parallax values. By shifting the images inward, negative parallax values will increase, and positive parallax values will decrease, by shifting them outwards, the opposite effect will occur. Because of its inherent nature, this method is very limited, and used alone it doesn’t have too many positive results. Also, from a certain point, positive parallax values can convert into negative parallax values, and negative parallax values can convert into positive parallax values, depending on the type of horizontal shifting. Used in conjunction with the first method, it can provide some help when controlling the convergence angles when the size of a scene is enlarged. When the size of a scene is decreased and the parallax values are so small that the points appear to be on the same position, as seen on the Figure 4.II, shifting the images outward can solve the problem. We can see the result of the horizontal shifting on the next figure:



- Figure 5.1.III - Horizontal shifting of a stereoscopic pair -

On the figure above, the stereogram had divergent parallax on the point represented by the circle, and very small negative parallax on the point represented by the square, so the first wasn't possible to fuse. By shifting the images inwards, the positive parallax value was reduced and the negative parallax value increased, making possible the fusion of both points. This method worked on this example because the point with negative parallax had a very low negative parallax value, if the parallax value would be higher, after shifting the images, it would be impossible to fuse this point, because it would have an extremely large negative parallax value.

When working with interactive software that has a stereoscopic output, another method to control parallax values can be used, before the rendering process: the distance between the cameras can be adjusted every time their position changes. Every time the cameras move, the distance between them can be re-calculated bearing in mind the distance from the cameras to the closest viewable object and the size and resolution of the final output screen. The side-effect caused by changing the distance between the cameras dynamically is that the perspective will change constantly, giving the impression that objects are moving closer to us or farther from us when we are simple rotating the camera on the same position, for example. This will cause headaches and indisposition after only a few minutes of viewing the scene. This method was not tested in exhaustion and its experiments are not included on this report, because the method cannot be used with already rendered stereoscopic scenes, which is the study object of this report.



- Red square as the closest viewable object - - Green circle as the closest viewable object -

- Figure 5.1.III - Cameras rotate and adjust -

5.2 Experimentation

The main goal of these experiments was to prove that stereoscopic scenes could be scaled, maintaining the depth perception without diplopia by adjusting the distance of the viewer to the screen. The other goals were, to find an estimation for Panum's fusion limits, and to study the inherent properties of stereograms.

For the experiments, two types of stereograms were used: stereograms of a natural scene, made with one digital photographic camera; and computer generated stereograms. The natural scene stereograms have negative parallax, and they were used to study the maximum convergence angle when our eyes look inward. To study the maximum convergence angle when our eyes look outward, computer generated stereograms were used.

From the original stereograms, scaled versions were made, resulting in different parallax values. These scaled versions were visualized by several persons, and for each person, in each stereogram, the person's convergence limit on a particular image point was registered.

Each person visualized the samples individually on the stereo-wall described on the chapter 5.2.3, and the samples were shown in ascending order, relative to the parallax values. This order of samples was chosen because the eyes get accustomed to high parallax values with time, and it was desired that this effect would have the smallest role possible on the experiments.

For each sample, the person was placed far from the screen and approached gradually, forcing the convergence angle to increase. When the person's limit of fusion was reached, the distance from the subject to the screen was recorded.

All subjects had approximately the same results of fusion limit, so to calculate the maximum convergence angle, as a retinal disparity value, the international standard value according to [22] for the eye distance was used, 63.5 mm.

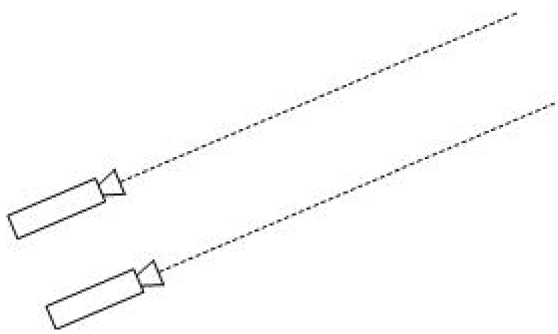
The results on table 5.3.1 and table 5.3.2 are relative to the measurements made on the stereo-wall described in the chapter 5.2.3.

5.2.1 Camera settings for the natural scene stereograms

Only one camera was used to make the stereograms, an Olympus C-4040 Zoom, with a tripod to control the exact position of the camera. The pictures were made with a resolution of 3200x2400 pixels.

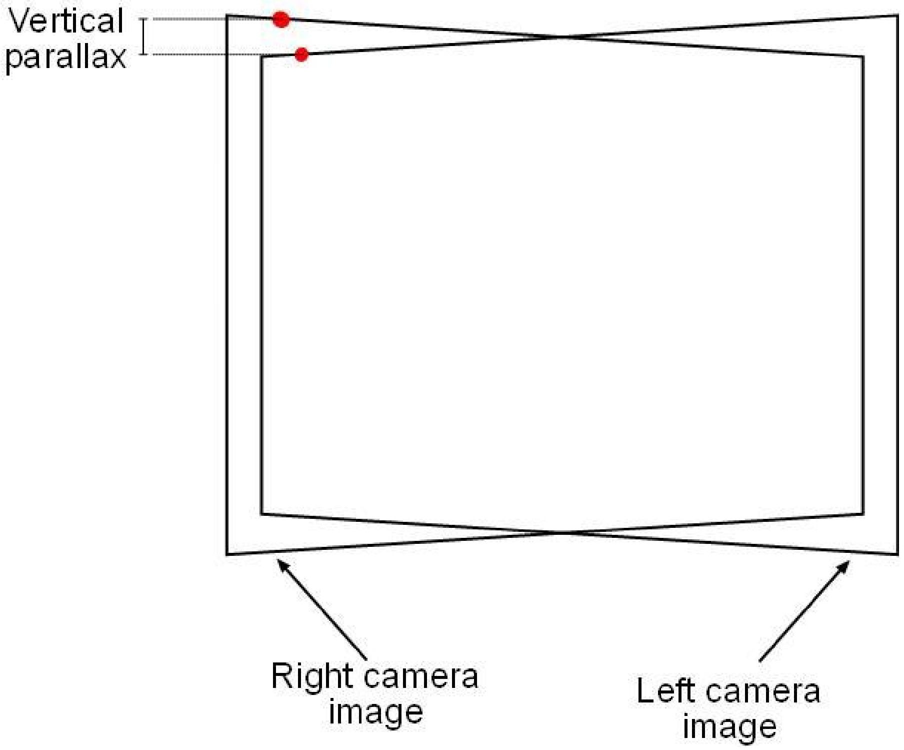
- Figure 5.2.1.I - Olympus C-4040 Zoom -
(Image taken from [23])

As an ideal camera setting, two basic rules should be followed. First, the image axes of the cameras should be parallel, according to [22, 24], as we can see on the next figure:



- Figure 5.2.1.II - Cameras with parallel axes -

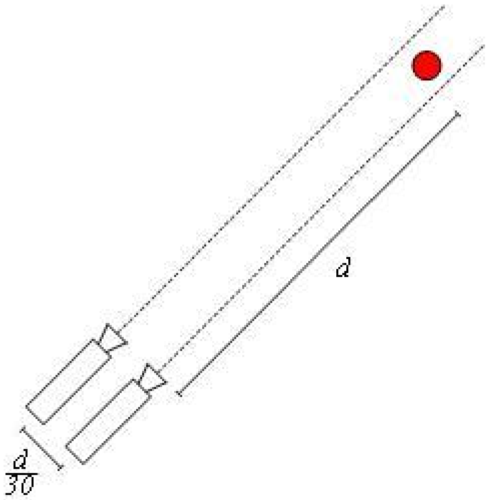
The reason for this rule is, when the axes of the cameras cross, the stereoscopic pictures will produce vertical parallax. Because retinal disparity is horizontal, points in stereograms with vertical parallax will not be fused by the brain. On the next figure we can see the result of making stereograms with the axes of the cameras crossed, originating vertical parallax:



- Figure 5.2.1.III - Vertical parallax -

Because only one camera on one tripod was used, the placement of the camera was not perfect, and the stereograms that were made show a slight vertical parallax on the edges. For that reason, the studied point is on the middle of the stereograms, without vertical parallax.

As a second basic rule, the distance between the cameras should be about 1/30 of the distance to the nearest object, according to [22, 24]. This rule was followed on the stereograms made on these experiments.



- Figure 5.2.1.IV - Optimal camera distance -

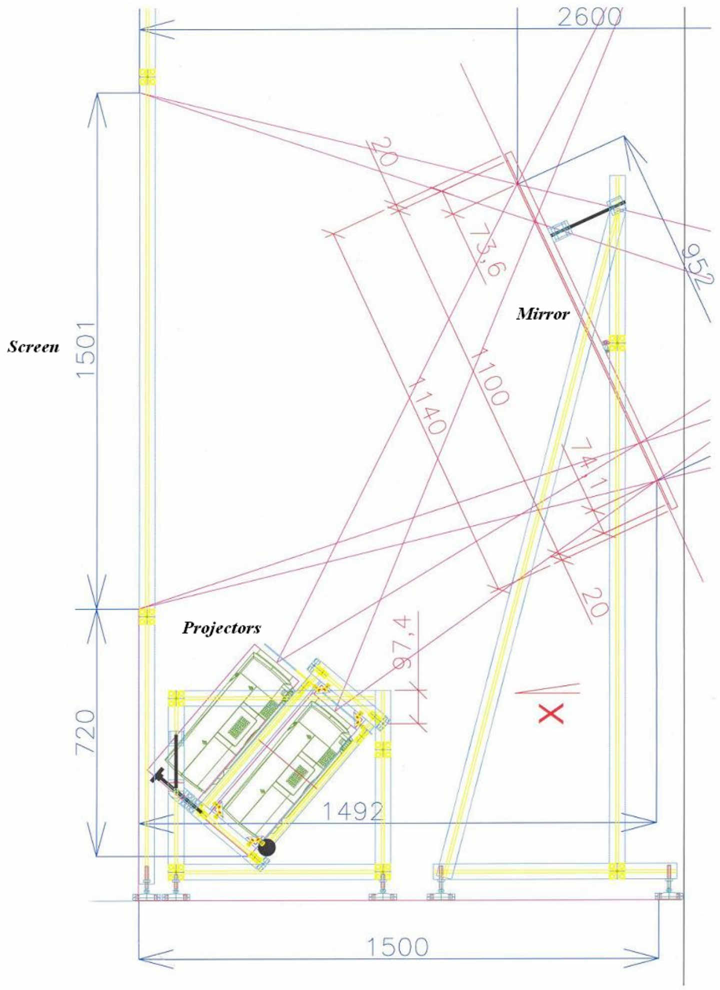
5.2.2 Computer generated stereograms settings

To create this type of stereograms, an application developed in C++ was used. This application was build on the Computer Graphics Department on the University of West Bohemia in Pilsen, by Zbyněk Novotný. The application reads a data file with the mesh of an object, inserts two cameras in the scene, and opens two windows, each window with the output of each camera. Some parameters of both cameras can be controlled in real-time, but for these particular tests, only two were changed: the axes of the cameras, which were set to parallel; and the distance from the cameras to the object, which has the same practical effect as a scale change, because only one object was in the scene. The reason for changing the distance from the cameras to the object to simulate the scaling effect is that the stereo-wall used for the experiments works with 1024x768 pixels as a maximum resolution, and if the final rendered image would be scaled, the pixel size limitation would cause an error on the measurements which would result in completely different values for the maximum convergence angle. The stereograms were then created by simply capturing the image of the screen.

5.2.3 Stereo-wall used on the experiments

A stereo-wall was used to analyse the stereograms. The stereo-wall uses back-projection with two projectors, using a mirror as a re-imaging display, joining the two images and reflecting them into the screen. The stereo-wall used has the following characteristics:

- Resolution......: 1024x768 pixels
- Pixel size........: 1,95 mm
- Screen width ..: 2001 mm
- Screen height..: 1501 mm



- Figure 5.2.3 - Side view diagram of the stereo-wall -

(Image taken from the stereo-wall's user manual)

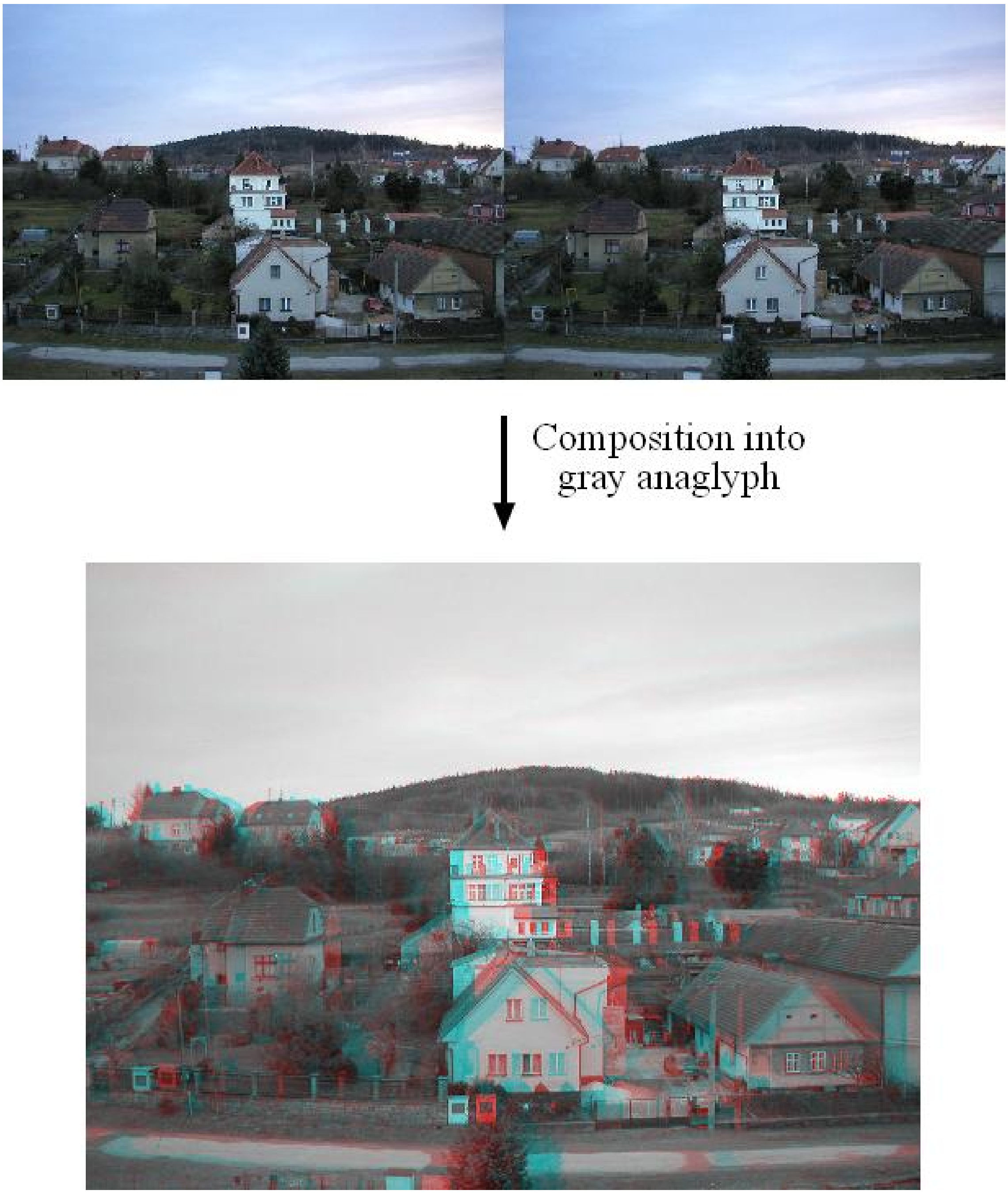
5.3 Results

All stereogram figures in this chapter have the composed anaglyph bellow the stereo pair. These anaglyphs can be viewed with glasses with a red filter on the left eye and a blue or cyan filter on the right eye, but because they are gray anaglyphs, the composed image will be black and white.

5.3.1 Maximum convergence angle for negative parallax

In order to scale the original image, two methods were used: the first one was to down-sample the size of the pictures; the second one was to cut a central part of the original picture. A combination of these two methods was also used.

Three samples were made from the original picture. On all samples, one specific point was studied and measured, and the subjects were asked to evaluate that specific point. The studied point is the top of the roof on the nearest white house on the following image:



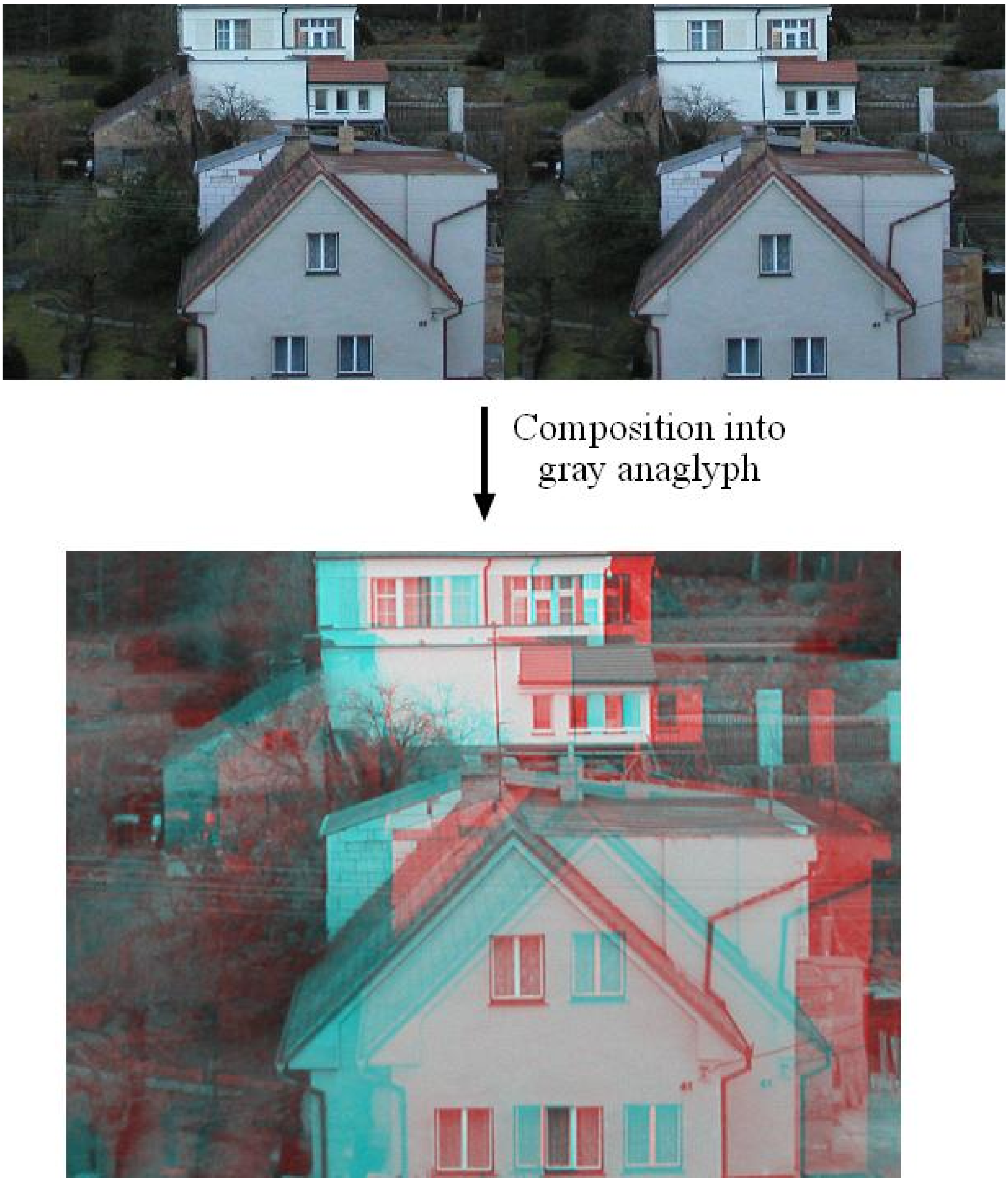
- Figure 5.3.1.I - Original stereogram with negative parallax values and gray anaglyph composition -

The first sample was a down-sample of 32% from the original image, and simply the size of the image was changed, from 3200x2400 to 1024x768 pixels.

On the second sample, a down-sample of 71% from the original image was made, changing the size of the image from 3200x2400 to 2272x1704 pixels. From the down-sample result, a cut was made on the central part, with a size of 1024x768 pixels.

- Figure 5.3.1.II - Central cut from the 71% down-sample of the original stereogram -

As a final sample, a cut was made from the original image, on the central part, providing the highest parallax values of all three samples. The cut has a size of 1024x768 pixels.



- Figure 5.3.1.III - Central cut from the original stereogram -

The convergence angles were calculated with the formula (F4).

The results were the following:

Stereogram	**Parallax value (absolute value)**	**Minimum distance**	**Value of *P***	**Convergence angle (degrees)**
Figure 5.3.1.I (1024x768 pixels)	36 pixels = 70.2 mm	700 mm	367.539267 mm	10.91040563
Figure 5.3.1.II	74 pixels = 144.3 mm	1050 mm	729.1385948 mm	11.30231428
Figure 5.3.1.III	104 pixels = 202.8 mm	1300 mm	990.0112655 mm	11.69603482

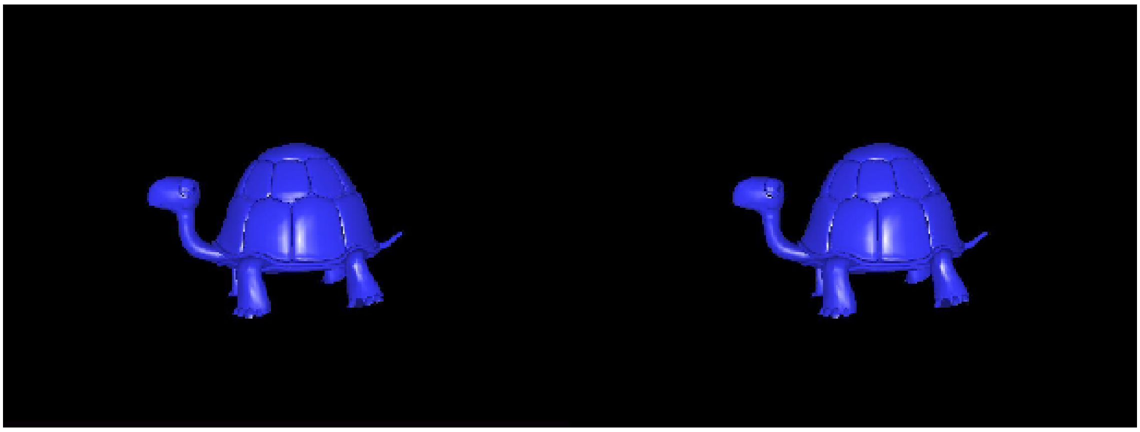
- Results table 5.3.1 -

For stereograms with negative parallax, viewers should be able to fuse both images to a limit of 11° convergence angle.

5.3.2 Maximum convergence angle for divergent parallax

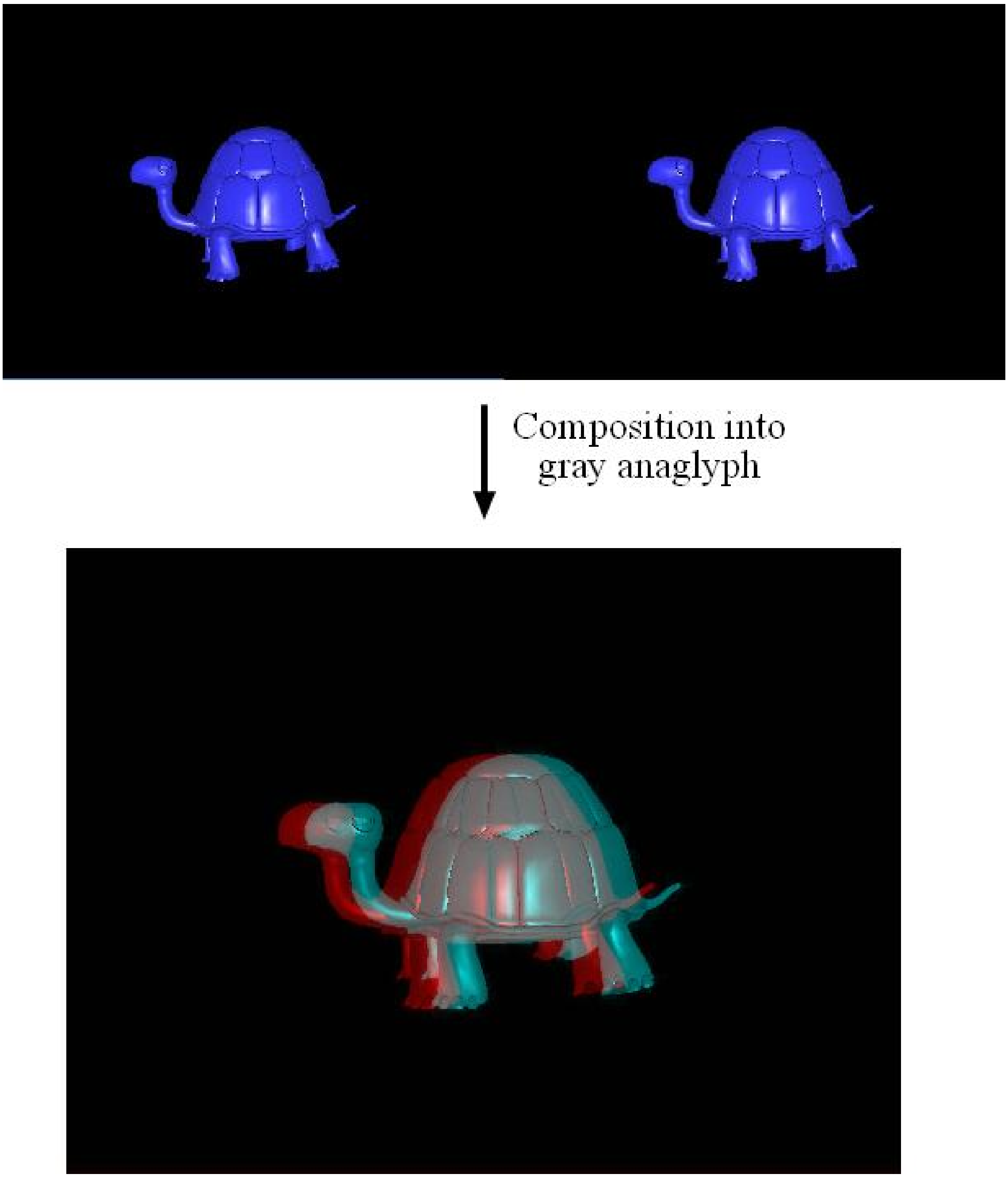
On these tests, instead of scaling the whole scene, only the distance between the cameras and the object changed. Because only one object is in the scene, the practical effect of changing the distance from the cameras to the object is the same as if the stereogram would be scaled. The reason for choosing this method was previously explained, on the chapter 5.2.2.

The studied point is the centre of the eye of the turtle on the following image:

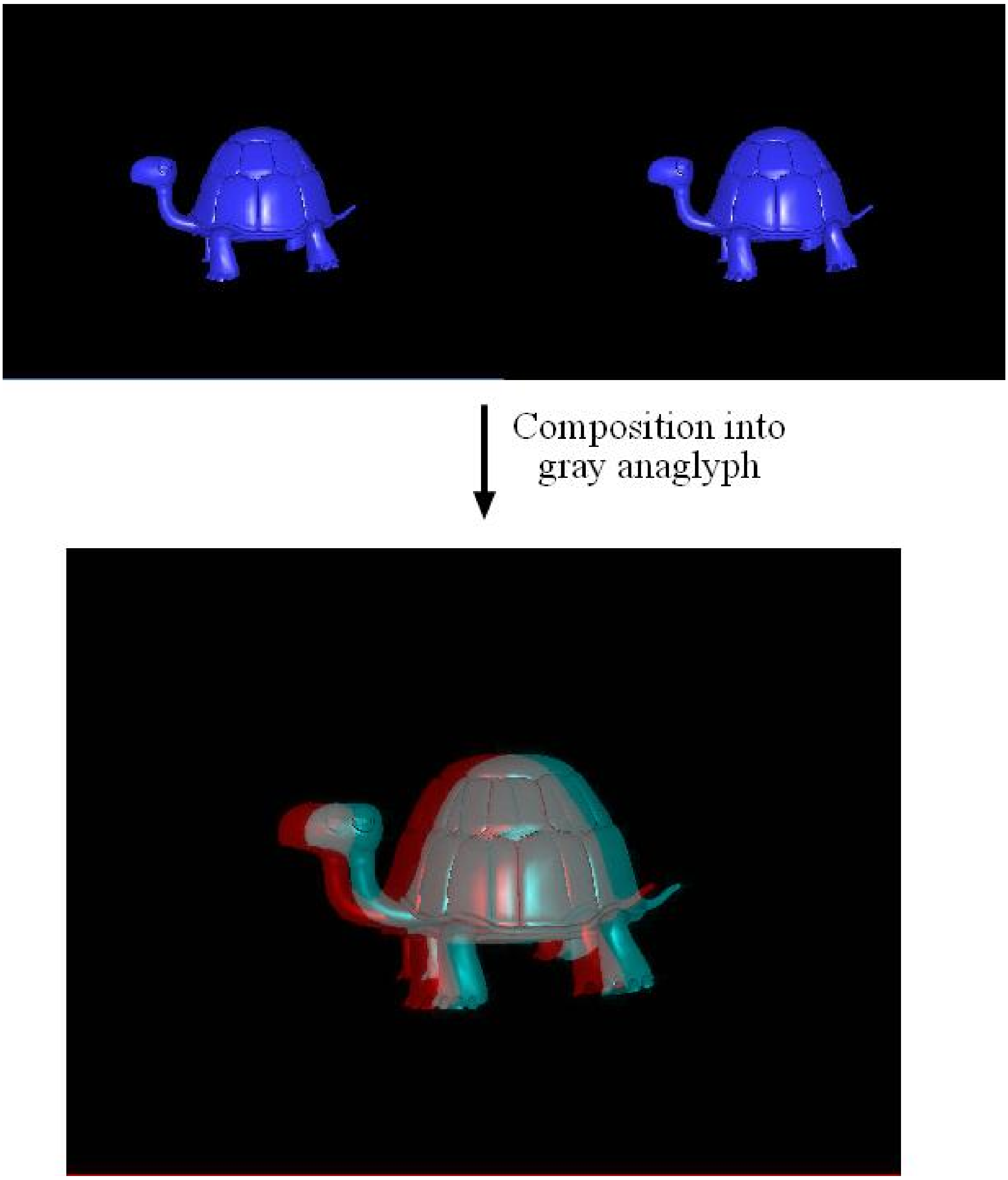


- Figure 5.3.2.I - Original stereogram with divergent parallax values -

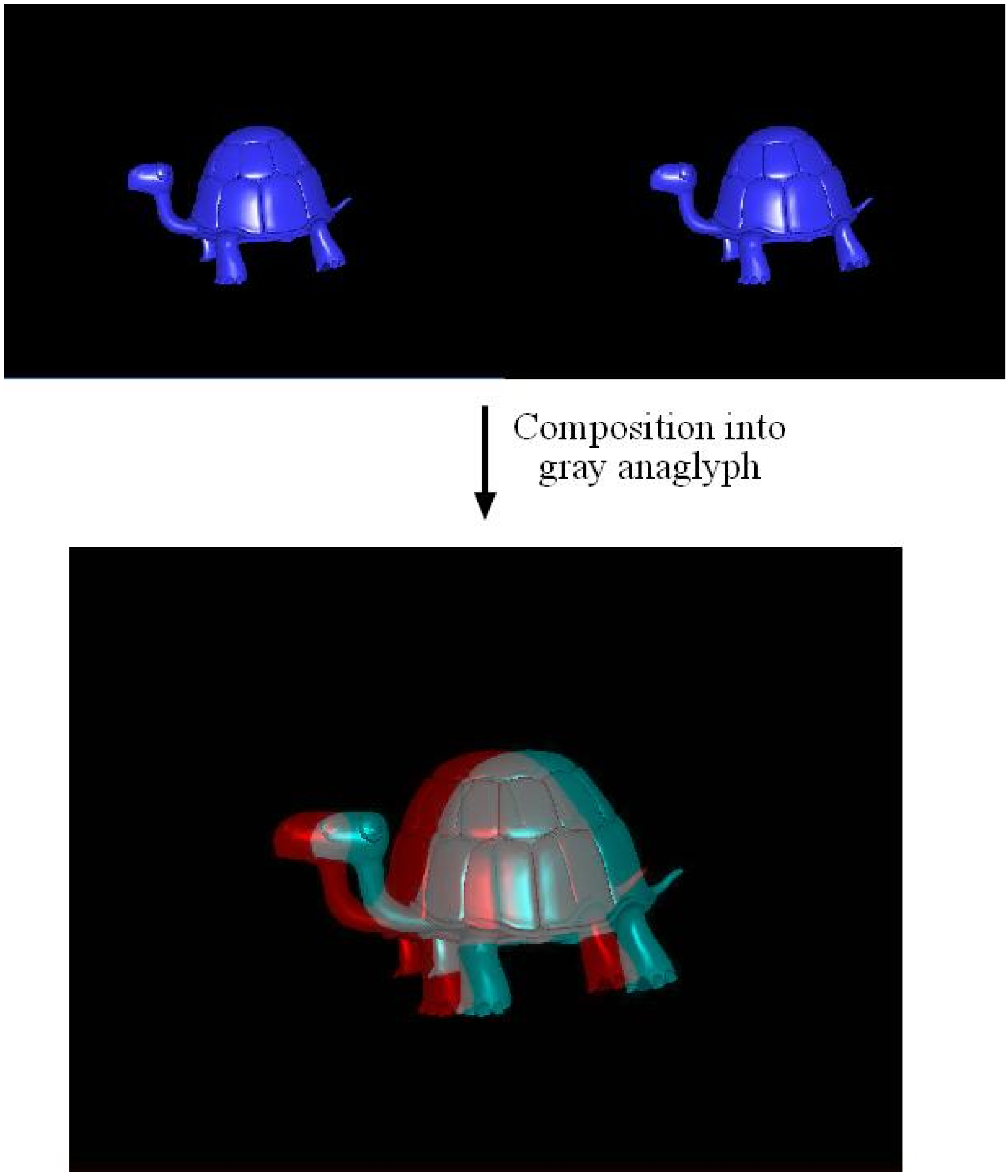
On the next figures, we can see the three stereograms used in this experiment:



- Figure 5.3.2.II - Stereogram and anaglyph with the lowest divergent parallax value -



- Figure 5.3.2.III - Stereogram and anaglyph with the middle divergent parallax value -



- Figure 5.3.2.IV - Stereogram and anaglyph with the highest divergent parallax value -

The convergence angles were calculated with the formula (F2).

The results were the following:

Stereogram	**Parallax value (absolute value)**	**Minimum distance**	**Value of *P***	**Convergence angle (degrees)**
Figure 5.3.2.II	35 pixels = 68,25 mm	1300 mm	17378.94737 mm	0.209349731
Figure 5.3.2.III	41 pixels = 79,95 mm	4200 mm	16212.76596 mm	0.224408183
Figure 5.3.2.IV	48 pixels = 93,6 mm	6100 mm	12868.77076 mm	0.282721224

- Results table 5.3.2 -

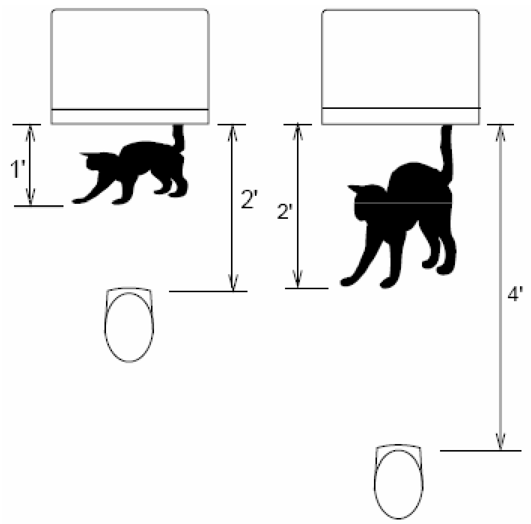
For stereograms with divergent parallax, viewers should be able to fuse both images to a limit of a 0,2º to 0,3º of maximum convergence angle.

6. Summary and conclusions

The main goal was proved through the performed experiments, in which all scaled versions of the original stereograms were possible to fuse from a certain distance without diplopia.

An estimation for Panum's fusion limits was found, and it's advisable that all stereoscopic scenes are made with these values as a maximum reference. Ideally, stereoscopic scenes shouldn't have divergent parallax values, because that doesn't happen on the real visual world, and our eyes are not used to that type of convergence angles, so it will cause some discomfort, and with prolonged visualization it will cause headaches.

As a final conclusion, adjusting the distance from the viewer to the screen, it is possible to scale a correct stereoscopic scene. A correct stereoscopic scene is a scene that viewed from a certain distance, has all parallax values within Panum's fusion limits. When a scene is being enlarged or decreased, the objects will elongate or diminish, as we can see on Figure 6. So, in order to avoid this side-effect, the convergence angles should be maintained when choosing the new position for the viewers. This will maintain the same image perspective as the original scene.



- Figure 6 - Cat elongating when the viewer is more distant -

(Image taken from [2])

As said before, this project is a part of a larger scale project conducted in part on the University of West Bohemia in Pilsen, Czech Republic. The project is divided into five major parts concerning a 3D scene: capture; representation; transmission; display; and interaction. The contribution of this project to the 3DTV project goes to the display part, to which eventual problems and solutions on the scaling of the final three-dimensional scenes are presented, allowing the use of different size stereoscopic display mediums, and also some insight on the available display technologies is presented.

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