A SEMI-AUTOMATED SYSTEM FOR CAPTURING AND DISPLAYING 360 DEGREE STEREOSCOPIC SCENERY WITH MOTION PARALLAX

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Abstract

The project builds upon previous research. Here the technical realization of a semi-automation system is researched that is designed to reposition a 360 degrees camera in space to capture images, that can be turned into various kinds of stereoscopic 360 degree panoramas in VR. The concept of a bigger off-center distance has been proposed for these recorded images and this stereoscopic image synthesis method has been tested, with three other methods in regards of Comfort, Depth and Realism. A test focused on gathering ordinal data has been conducted on 24 people and the results have proven this display method significantly the best against nearly every other display method. The camera-positioning semi-automated system turned out to be an improvement in comparison to the earlier model.

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1. Introduction

> According to an old Chinese story, the ancient Chinese have accidentally stumbled upon the wheel at one time, inventing it. Being of contemplative and philosophical in nature, they started wondering: what will happen, once this wheel starts rolling?
>
> What will happen in its wake of rolling, where will it stop? After thinking about if for a while, they reached a conclusion, that it is more favorable for everyone if the wheel does not roll at all, therefore they discarded it, and went on with their lives. [1]

In 2017 regardless the world is a vastly different place. China is the number one producer of consumer electronics[2] and the emerging technology of immersive Virtual Reality (VR) systems is about to reshape the world.

The recent trend of revisiting immersive VR technologies was started with the Oculus Rift[3], a a VR Head Mounted Display’s (HMD) appearance in 2012, and as of today the trend has not slowed down: significant technological releases occurred, such as the Google Cardboard[4], HTC Vive[5] or the Playstation VR[6] systems. These VR systems offer the user the unique experience of mediating a virtual environment by taking over some aspects of the user's sensory system (mainly audiovisual) and provide artificial stimulus that supports the illusion of being present in the virtual space.

The content of these immersive VR experiences conventionally consist of 3 dimensional, computer generated imagery, but another approach for creating a Virtual Environment (VE) is through photographic processes.

This research is a continuation of the previous semester's work I have worked on with Jakob Memborg. In our 2016 paper “Displaying and Navigating in a Virtual Environment of 360 Degree Images with Stereoscopy”[7] a capturing and displaying system were developed for photographic VR, and the effects of three display methods were investigated: Monoscopic, Monoscopic with motion parallax, and Stereoscopic with motion parallax.

Two of these display methods built upon multiple images gathered by a camera that has been translated in space throughout taking the images, following a circular path.

The current research builds upon the solutions, approaches and findings of the previous project, by aiming to create a more efficient and accurate image capturing system that is capable to provide sceneries in a way that more closely resembles the human experience of looking around in a space, and through examining the effects of this stereoscopic image synthesis method.

The goal of this research to design a semi-automated camera positioning system and to figure out whether this new stereoscopic display method is significantly different from other methods, including some previously investigated approaches, in regards to Comfort, Depth perception and Realism.

2. Background

In this chapter necessary concepts and vocabulary of the project is explained.

2.1. Virtual Reality

Virtual Reality(VR) is the umbrella term for technologies that are meant to provide its user with the sensation of being present at a virtual space[8]. The goal of VR in technological terms is to provide the human senses with satisfactory artificial stimulus. The closer a system is to successfully achieve it, the more immersive that system is[9]. The current generation of HMD's are shown to be providing high levels of immersion in comparison to other existent VR technologies[10].

2.2. Virtual Environment

The Virtual Environment (VE) is the environment the user is subjectively transported through a VR system.

The VE is generally computer generated to a large extent, such an approach enables the system to provide stereoscopic visual content for each individual eye of the user, and easily accommodate the virtual environment to the movements of the human head. Therefore once the human head is being tracked (as it is highly effectively done by the aforementioned virtual reality solutions) the 3 dimensional computer generated virtual environment can easily be utilized in a manner that accurately follows the rotation and translation in 3d space that might occur. This connection between the human actor and the generated scenery is essential for the establishment of the illusion of being present in the virtual environment, as the provided stimulus of the system should satisfy the requirements of the human actor in order to successfully achieve the illusion of being present in the space[9]. An example for this technology is Valve's LAB[11].

An alternative to computer generated VEs, is the utilization of photographic methods.

In this approach physically existing scenes are being photographically captured, and these photographs are represented in a manner that constitute as the VE. This approach on one hand can highly efficiently mediate the illusion of being present in a space due to the high level of visual realism, but also is highly limited in nature and inherently static in comparison to computer generated VEs. An example for this is Youtube's video player running a 360 panorama video[12]. Pure photographic approaches for VEs are either monoscopic or stereoscopic in nature, but do not support motion parallax.

The completely computer generated and completely photographic VE's are two ends of a spectrum, there are multiple steps in-between: computer generated VE's often feature photographic content as textures, and the process of photogrammetry can efficiently combine the strength of both. Photogrammetry is the process of comprehension and reconstruction of underlying 3d shapes of photographs[13]. Therefore the photo-realistic textures can be combined with accurate 3d meshes. An example of this technology is the exploration-based software Destinations[14].

2.3. Depth Perception

Depth Perception is the process of the human brain of comprehending and interpreting space based on the various depth cues it receives. The depth cues are sorted in three categories: Oculomotor (sensation based on muscular tension within the eye), Monocular (based on one eye) and Binocular (based on two eyes)[15].

There are two main depth cues of interest in regard to the research objective of this paper: motion parallax and stereopsis.

Motion parallax is a motion-produced, monocular depth cue. It occurs when the position of the eye moves and objects at various distances move at various degrees: closer objects move faster, while objects at further away distances move slower. This gliding effect is a central depth cue for many animals and has been used in robotics to determine distances[16].

Stereopsis is the depth impression resulting from binocular disparity – the difference of position between the two eyes. Since information is being received from two positions a synthesis of these two images result in information about the three dimensional space. Humans possess varying degrees of stereopsis[15]. According to Richards about 15% of the population cannot see-, or has severe problems using the depth cues of stereopsis[17].

2.4. Cybersickness

Cybersickness is the phenomena that can occur once someone is exposed to VR. The symptoms are very similar to motion sickness and generally are caused by non-satisfactory sensory stimulus to the human brain[18]. People are affected to cybersickness at varying degrees, and can be manifested by varying signs of sickness, such as dizziness, nausea and headaches.

A flaw inherent in current VR HMD's is the vergence accomodation conflict[19]. It occurs when the vergence and accommodation distances of an object do not match. The vergence distance refers to the perceived distance of an object, and the accommodation distance to how far the eyes have to focus in reality. In everyday reality these distances are usually identical, however once the eye is perceiving the surroundings through a flat display surface it causes the accommodation distance to be uniform.

This leads to the user focusing constantly on one plane, while receiving conflicting visual stimulus about the vergence of the surroundings. As this phenomena might lead to cybersickness the minimum camera-object distances should be kept in consideration[20].

3. Related works

3.1. Creating panoramic stereoscopic scenery

Mutlitple systems have been created for capturing panoramic stereoscopic scenery.

Omnidirectional stereoscopic panorama stands for a stereoscopic panorama, that does not demand head tracking for displaying it, there is one texture for left and another texture for the right eye[21]. The original system is based on synthesizing these images by moving a camera around, with an offset to its pivot point. Light is being processed through two slits, which are displaced from each other. Each slit records a 1 pixel wide image at a time, and in a similar manner of how photographic scanners work. At the end of a revolution around the pivot point enough information is gathered for the generation of a left, and a right eye image in the form of stereoscopic cylindrical textures.

Systems along the same concept have been created with different technical approaches:

Bourke documents a system that utilizes an automated rotating system in combination with a double lens film camera[22].

Peleg et al. have proposed the use of a system that along the same idea using a high resolution video camera with a wide angle lens to generate a stereoscopic panorama[23].

Some of the recently announced VR based 360 cameras are also capable of recording stereoscopic vision: The Nokia OZO[24], the Jaunt One[25], the Eye camera rig[26], or the GoPro Odyssey[27] capture images using multiple cameras, and using this information in post processing potentially can generate stereoscopic textures for 360 degrees panoramas.

Due to the complexity and specialized nature of the equipment, these systems are far from affordable. The Nokia Ozo costs 40.000 USD[28], a Google Halo Jump is being sold for 17.000 USD[29] as of 2017 may.

3.2. Our previous research

As mentioned in the introduction, this project is the continuation of the previous semester's work. The goal of the project was the investigation of the feasibility of creating 360 degree stereoscopic panoramas with motion parallax using one 360 degree camera.

In this project both a hardware and a software solution has been created to attain this goal.

The capturing system consisted of a tripod, that incorporated an aiming system for manual placement on the horizontal plane, on a circle with a 6.3 centimeter diameter. (See Illustration 1).This circle was designed to record images, that could simulate the movement of the human eyes in a three dimensional space. The camera used was a Ricoh Theta S[30].

Illustration 1: The previous system

The software solution was designed in the Unity game engine[31], and consisted of various spheres having the appropriate individual textures attached to them. These spheres constituted as the VE, and making use of the tracking of the HMD, it linked the transparency of these spheres with the alignment of the head. As the participant rotated his head, the various appropriate textures were provided for his viewing. For displaying the VR a HTC Vive was used.

Two preliminary experiments were conducted: one defined the minimum camera-object distance to be maximum 90 centimeters to avoid discomfort, the other has concluded that there is no significant different between the use of 24 images in comparison to 48, when the closest object are 1 meter away in the distance.

Three various display methods were developed: a Stereographic with motion parallax, a Monoscopic with motion parallax, and a Monoscopic without motion parallax.

An experiment was conducted to find whether there are significant differences between these display methods. The test did not result in significant differences, but indicated a tendency towards the Stereoscopic method and motion parallax in regards of containing depth cues of a higher degree.

Another angle of the research was focused on a teleportation system in a photographic VE, but this is not relevant to the research interest of this report.

4. Materials and Methods

4.1. Technological and research goals

The project aims to achieve two goals: To develop an improved, semi-automated system for capturing 360 degree images for stereo synthesis, and to create and evaluate a new kind of stereoscopic image synthesis method, which is inspired by the Stereoscopic display method from the previous semester, but is altered in a manner, to more accurately accommodate to the human body's motion of looking around.

The goal of this development only a partially automated image capturing process: complete automation would demand communication between the repositioning system and the camera, and this is beyond the scope of this project.

The achievement of the new stereoscopic image synthesis method can be realized by rendering the circle bigger, which defines the points where images are recorded. In the previous semester's stereoscopic method, the eyes were simulated to be strictly rotating around a central axis. This simulation is both unrealistic, and due to the comparatively low amount of displacement occurring for the eyes, constraints one of the examined depth cues: motion parallax.

Increasing the radius of the circle is theorized to lead to a higher degree of depth perception and realism, due to more accurately representing the human anatomy and providing an increased amount of depth information.

The average human interpupillary distance varies between genders and individuals, but the gender independent adult interpupillary distance is 6.3 centimeters[32], and this should be consistent throughout both the Small Radius Stereo Parallax (SRSP) and the Large Radius Stereo Parallax (LRSP) as well. This means, that the same method of providing images of polar opposite locations of the circle is not feasible for the LRSP, as the same approach would result in interpupillary distances greater than 6.3 centimeters.

Instead, two points of 6.3 centimeters distance should be respectively used as left and right textures for the stereo synthesis.

The radius for the LRSP method should be equivalent for the center of human head – eye distance, whilst looking around in an environment.

Further on, two other display methods will be tested: Large Radius Mono Parallax (LRMP) and Single Point Mono (SPM) for learning about the possibilities of the system, the importance and nature of depth cues for our case. These methods are derived from the first two display methods: the LRMP is the monoscopic version of the LRSP, therefore the difference is that both eyes are to be provided by identical images. This change eliminates the stereopsis element from the method, and puts emphasis on the motion parallax.

SPM is the sensory representation of a single texture on a sphere map, therefore this version lacks both stereopsis and motion parallax.

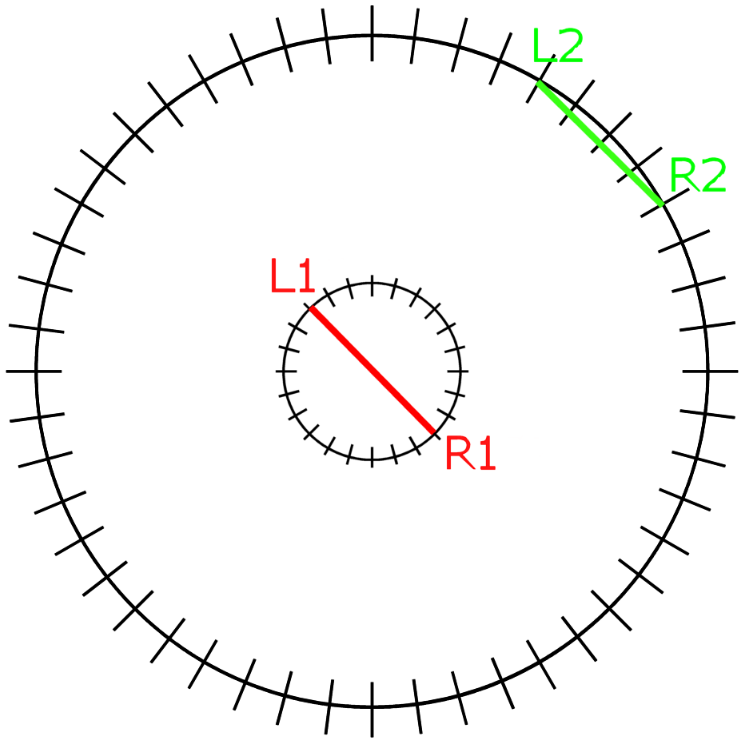


Illustration 2: SRSP(red) and LRSP(green)

Illustration 2 shows the top view of the positions for a 24 image model for SRSP(red) and LRSP(green).

The display methods are to be examined in regards to three criteria: Comfort, Depth and Realism.

4.2. Defining the off-center distance for the LRSP method

A preliminary experiment has been conducted about the human anatomy in order to measure the distance between the pivot point of the head and one of the eyes. The result of this experiment was used to design the turntable system and served as the model for the LRSP display method.

The experiment design consists of giving the participants a pair of glasses that is being marked according to the participant's specific anatomical traits: yellow markers are being placed to mark the location of the iris along the line defined by the position of the eyes. The three marks determine the orientation of the head and the position of the eye. Using an overhead camera we can reach conclusions about the intended measurement.

4.2.1 First experiment

The first experiment consisted of the aforementioned pair of glasses, an overhead standard definition web-camera mounted on the approximately 3 meters tall ceiling. The adult male participant was instructed to take a turn around his center point, and his movement was documented as a video recording.

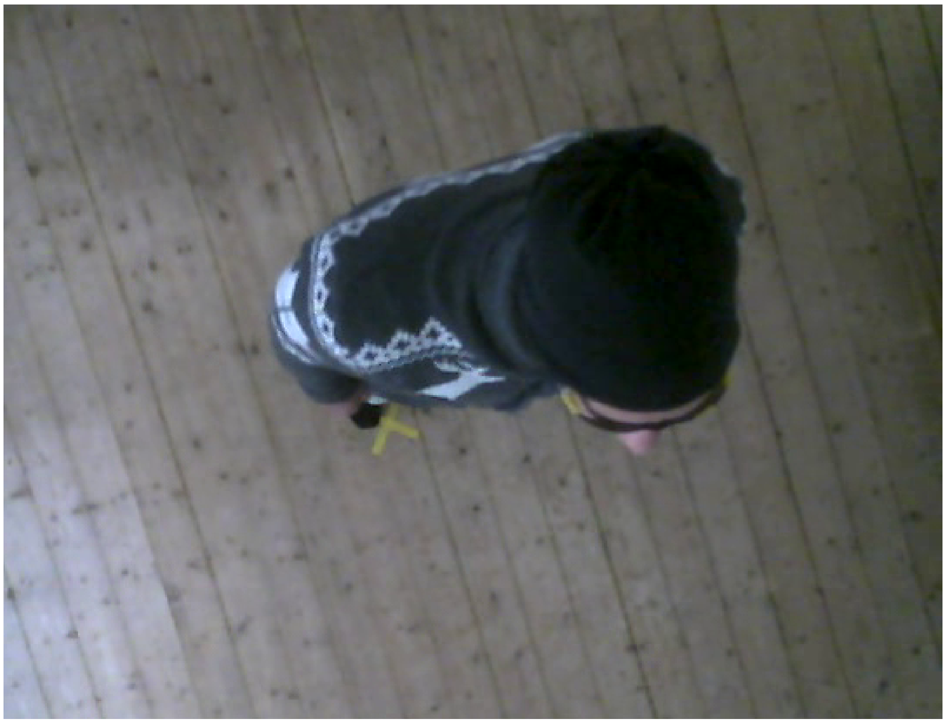


Illustration 3: Demonstrating the issue with the first off-center distance experiment

Two problems surfaced after conducting this experiment:

On one hand the participant's movement pattern was complex than expected. Although the participant was instructed and has attempted to remain upright, the torso of the participant was skewing vertically, and his relative angle to the camera's plane has been constantly shifting as well. This was a result of him naturally turning around, with the aid of repeatedly repositioning his legs, as seen on Illustration 3.

Another problem with the experiment was the inadequate image quality and the wide-angle focal length of the web-camera, this setup turned out to be inaccurate for measurements of this nature.

It has been concluded that for the natural motion pattern of turning around a central point is overly complex for this project's technological boundaries, therefore the experiment was decided to be repeated with a more constrained motion of looking around. The intention with this altered movement pattern was to get a measurement that could let us simulate a natural human motion of looking around to the best of our technological boundaries, which is a circular motion of the camera.

4.2.2 Second experiment

The experiment has been repeated along the same conceptual lines in an improved manner, with a different participant. The participant was instructed to keep his shoulders locked in place while looking from one side to the other. The recording has been done at an approximately 10 meters height using a full frame mirrorless camera with a 135mm telephoto lens. Video recording has been done at 4k resolution at 30 frames per second at 1/500th shutter speed.

Illustration 4: One of the images that has been used to measure the off-center distance

The telephoto lens was chosen for achieving increased spatial compression, 4k resolution for more detailed data to work with, and a comparatively high shutter speed for avoiding motion blur of any kind.The files were investigated afterwards and 5 frames were chosen, representing the participant looking at five different directions: left, diagonally left, forward, diagonally right, right. (See Illustration 4)

The pixel coordinates of interest (the 3 points defined by the markers on the glasses) were imported into AutoCAD[33], and the location of the irises and the sagittal axises of the head locations were defined, as seen on Illustration 5.

The intersecting points of the five sagittal axises were averaged out and this defined a unified central pivot point of the head. Measurements were taken from this central point towards the locations of the irises and these measurements were again averaged through their arithmetic mean.

The experiment resulted in an off-center distance of 10.0334 centimeters, and this is the measurement that the following steps of developing the LRSP model were based on.

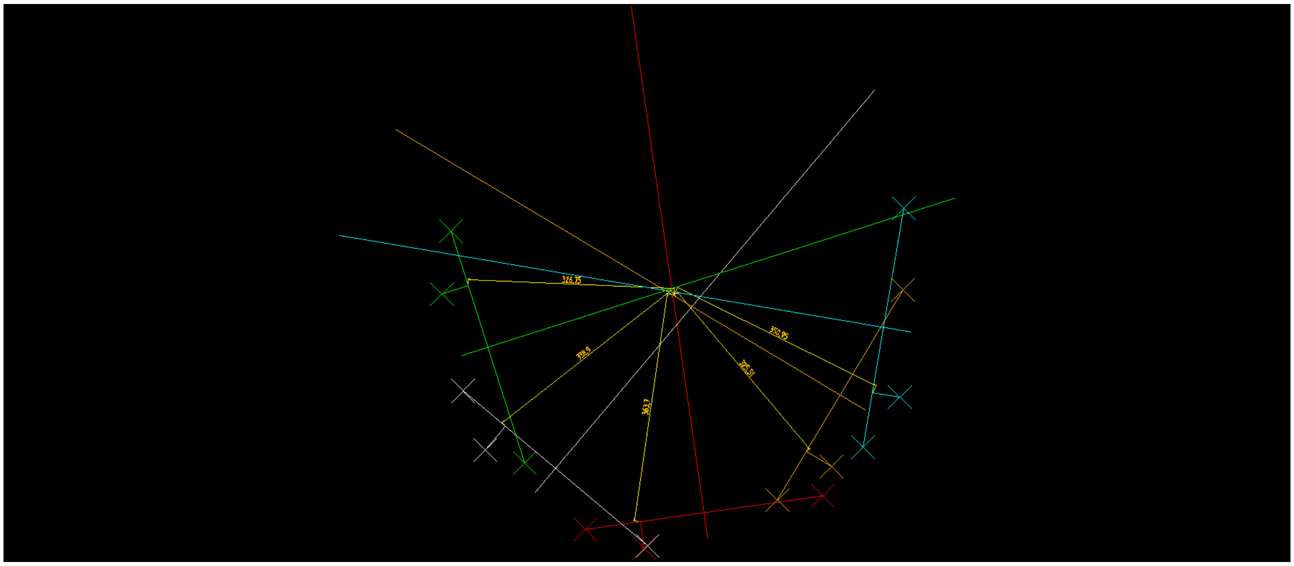


Illustration 5: The measurement calculated in AutoCAD

4.3. Developing the semi-automated system

4.3.1. Conceptualization of the semi-automated system

One of the central focuses of this project is to create a semi-automated system that is capable of moving the camera to spatial locations of our design during the recording process.

There are multiple severe downsides of the image capturing process we utilized in the previous semester: Most importantly the system demanded the camera to be manually replaced between each shot. This replacement process included both a translation in space on the horizontal plane, and the accurate angular alignment between the shorts, as the camera was meant to be facing the same direction throughout the recordings.

The manual aspect of moving the camera had multiple downsides:

It was extremely time and work consuming. The person operating the recording system is not meant to be visible on the images, thus it resulted in constant walking to- and behind a surface that served as a cover for the operator from being photographed.

Further more this method of operation demanded a high level of concentration from the operator's part as the positioning of the camera was completely manual. This nature of the method also opened up a significantly high level of likelihood for errors to manifest: there was no safeguard for detecting possible errors in position and orientation, and the constant movement of the operator in the captured environment could easily lead to accidental changes in the scene. Accidents of this nature have occurred multiple times in the previous semester and resulted in a restart of the capturing process once something has accidentally changed in the environment: for example a chair has been moved in the process from walking to and from the camera.

By redesigning the capture system another important aspect was made possible to improve: the previous system was designed in a manner that the camera was constantly facing the same direction throughout the capturing process. It was established in this manner to keep the alignment between the images constant, thus when cycling through them inside the VR it would not be visible when one image transitions into another. This design choice leads to issues when combined with a 360 degrees camera that uses non-perfect image stitching. Along the stitching plane artifacts can occur, which are heavily dependent on the nature of the images, thus can lead to inconsistencies throughout multiple imagess. Due to the design of the previous system, it was unavoidable to show this stitching line in the visible portion of the vision for some of the represented images.

By redesigning the system it became possible to approach the movement of the camera in a manner that overcomes this problem by keeping the stitching plane perpendicular to the represented image's center, once assigned to a spherical mesh as texture.

4.3.2. First design idea

An early design idea followed conceptually the first system: the camera was meant to be orientated in one direction while being translated on the capturing plane. The design included two rail systems, running perpendicular to each other. The system consisted of two motors that would move the camera along the two axises using the rails. This method of motorization was inspired by affordable contemporary 3D printing systems, such as the Prusa i3[34]. For these models the plastic extruder is being moved on two axises along the same principles.

Although the system appeared to be functional for the simple spatial translation of the camera on a plane, it did not address the stitching issue inherent from the first system.

4.3.3. The turntable design

The design was aimed to both automate the movement of the camera and to overcome the stitching issue. The circular nature of the movement required by the camera is easily accommodated to the concept of a turntable. Both the desired path for the camera and the motion of a turntable is circular, therefore the two variables defining the position of the camera's location can easily be altered: the off-center distance determines the size of the circle, and through the rotation of the turntable the camera can be conveniently moved to the desired point on the circle.

This design gets rid of the need for the camera to have a constant orientation, it turns instead along the circle and therefore can face in a way that the stitching plane of the 360 degree panorama is not visible once the images are loaded as the VE. The downside of this design choice is that the images will not be naturally aligned, but this can be easily countered by automated scripting inside Unity, as the images are at a constant offset with each other this way by design.

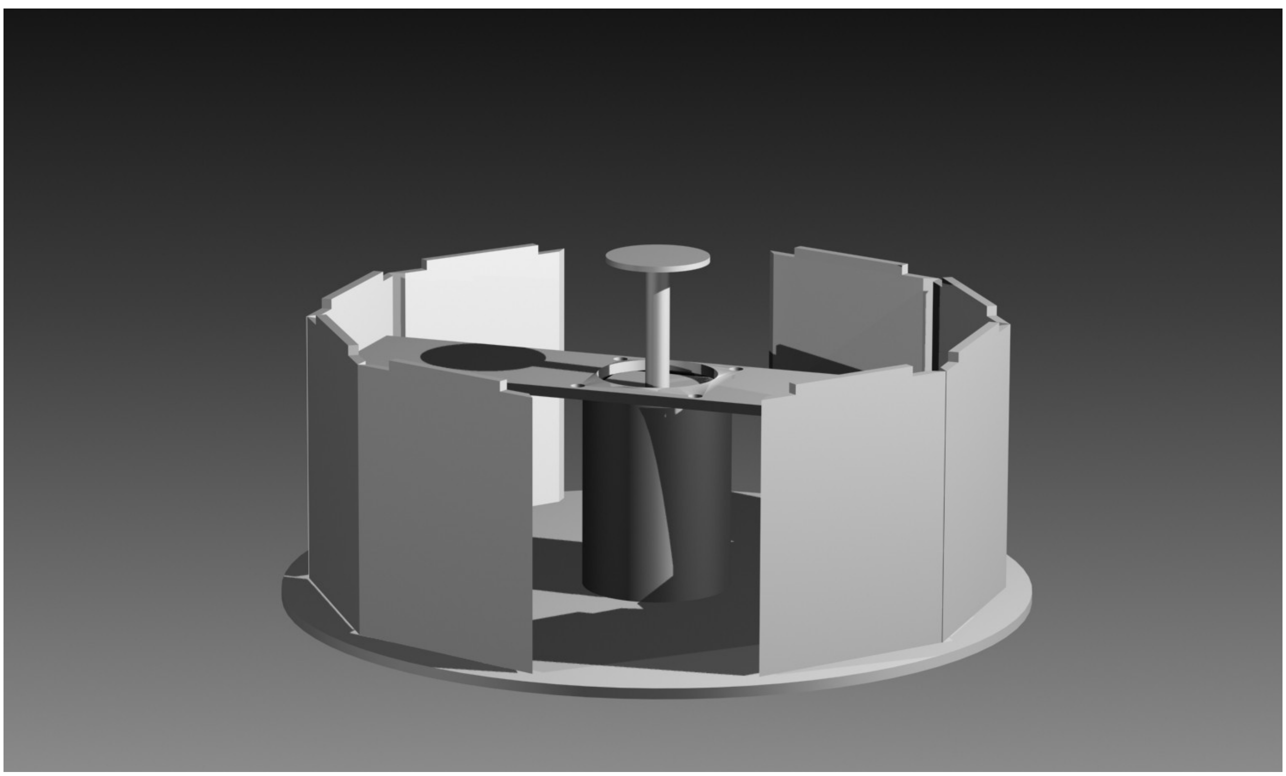


Illustration 6: 3D rendering of the base of the automation system

The turntable design can be conveniently used for both the SRSP stereo-synthesis of the images used in the previous semester, and for the LRSP method.

The movement of the camera differs for the two display methods: The SRSP has a 3.25 cm off-center distance and the lenses of the camera stand at a 90 degrees angle in relation to the center of the turntable. The LRSP method should have a 10.51 cm off-center distance and the camera should be oriented towards the center of the turntable for the desired image synthesis.

4.3.4. Hardware elements of the turntable system

The system demands the following core elements: 360 degrees camera, a turntable, a motor, a motor controller and a telecommunication system for remote operation.

For capturing images two cameras were considered: the Ricoh Theta S and the Samsung Gear 360[35]. Both cameras capture two images and synthesize them in camera into a equirectangular texture. The equirectangular projection is a mapping of a spherical surface onto a rectangular surface, therefore a 360 degree panorama can be translated into a conventional, rectangular digital image.

Comparing the two cameras the Ricoh Theta was deemed to be superior for the project: Both cameras offer remote operation through mobile devices, but it is only the Theta that has full manual controls for the exposure settings and the white balance. As the Gear 360 does not allow the white balance to be set manually, it posed a potential source of error for the capturing process, as the automated white balance algorithm of the camera is not known.

For the turntable, a plastic 25 centimeter big plastic unit was chosen. Its minimalistic design consists of two elements: a top and a bottom. The two elements are in contact with each other through ball bearings that are meant to minimize friction while being in motion. Affordable units like these are generally being sold for both domestic and professional purposes. The unit was disassembled for the purposes of the project, and a central plastic element was replaced in order to mount it on a motor.

Multiple systems were tested for the motor: the development started with the testing of multiple 360 servo engines. While these motors were highly responsive, they lacked accuracy, which is a crucial element of the device that was to be created.

After further research into motors it was decided utilize a stepper motor, as these motors through the use electromagnetic coils and current can achieve high levels of accuracy.

A powerful 3.96 volts 2.2 amps Wantai 57BYG621 stepper motor was chosen to be used for this project. This motor has 200 steps, which is 1.8 degrees per step. Although previous testing was not done at this point in regards to the minimum number on required images to avoid ghosting, the maximum of 200 steps was expected to be suitable for the system, as for the system of the previous semester 24 images were satisfactory for the SRSP method.

Testing took place to determine whether the motor is strong enough to securely operate the system. The motor was tested under weighted load of 2 kilograms, a weight that greatly exceeds the Ricoh Theta S camera which is 125 grams. The motor passed this test and was deemed to be suitable for the purpose of the project.

For controlling the system two approaches were investigated for use: an Arduino board[36] and a Raspberry Pi[37]. After evaluating the capabilities of these boards and the requirements for this project, an Arduino Uno was deemed to be suitable, as the extra processing power of the Raspberry Pi was not needed.

The HC05 bluetooth module was chosen to be used for telecommunication between the operator and the turntable system. Using this unit it was made possible to connect to the Arduino board through a mobile phone and both send commands to it, and receive feedback in regards to the position of the turntable.

For connecting to this unit through a mobile device, the ArduDroid[38] controller was used. ArduDroid is a Android based app for connecting a smartphone with the HC05. In ArduDroid three operations were assigned to its interface: turning clockwise, turning anti-clockwise, and resetting the step counter.

The step counter is a variable designed to that increases/decreases based on the number of steps the motor has done. This way it becomes an indicator of the stage the image capturing process is in. It increases by one every time the motor turns clockwise, and becomes reduced by one when it turns anti-clockwise.

Although this feature is very simple and straightforward, it incorporates another development. In the previous image capturing system it was necessary to keep the number of manual steps in mind one has made whilst moving the camera.

For driving the motor the on-board power of the Arduino Uno board was not satisfactory. Therefore an external stepper motor driver was utilized. Both the A4988 and DRV8825 were tested, and the latter was deemed to be more reliable.

The motor is being driven by an external power source, as the Arduino Uno was not capable of providing enough current to operate it through the DRV 8825 driver. It was decided therefore to provide power to the driver through an external 12V adapter.

4.3.5. Designing the automation system

Once the required elements were assembled and tested, an external structure was designed with the purpose of keeping all the elements in place, shielding them, creating means to connect the device to a tripod, and attach a circular wooden plate on top of the plastic turntable as an extension platform.

It was decided to laser-cut the elements of this structure of 4 millimeter MDF plates. Once the material was investigated for structural integrity, the design process began in Autodesk 3D Studio Max[40].

The goal of the design was to keep all the electronics and the motor inside a protected area, while accurately positioning the plastic turntable over it. On top of this plastic turntable a wooden plate was placed as the extended top. This surface was meant to serve as a platform for mounting the camera. The camera was designed to be elevated above the turntable by a 6.35 millimeter steel pole that connects with the thread of the camera. This serves the purpose of reducing the apparent size of the turntable in the images afterwards and this way enabling more of the environment to be seen.

A conventional 6.35mm threaded hole was placed at the bottom of the structure for the ability to mount it on a conventional tripod meant for photographic equipment.

The sides of the structure are intended to be both stable, but also let easy access for the electronic parts, in case there is a need to do some modifications or fixes on the system.

There are eight side pieces in total, two of them holding an elevated platform with the function of keeping the motor in place.

The process of creating the structure inside 3D Studio Max was done in the following steps:

the already existing physical elements were measured, using these measurements they were modeled as 3d meshes, and afterwards the accurate structure around them was modeled. The measurement process was done with a digital caliper. The 3d objects inside 3D Studio Max were created with 4 mm thickness in line with the target material 4 mm MDF, and the shapes were modeled as splines for maximizing compatibility with the laser cutter.

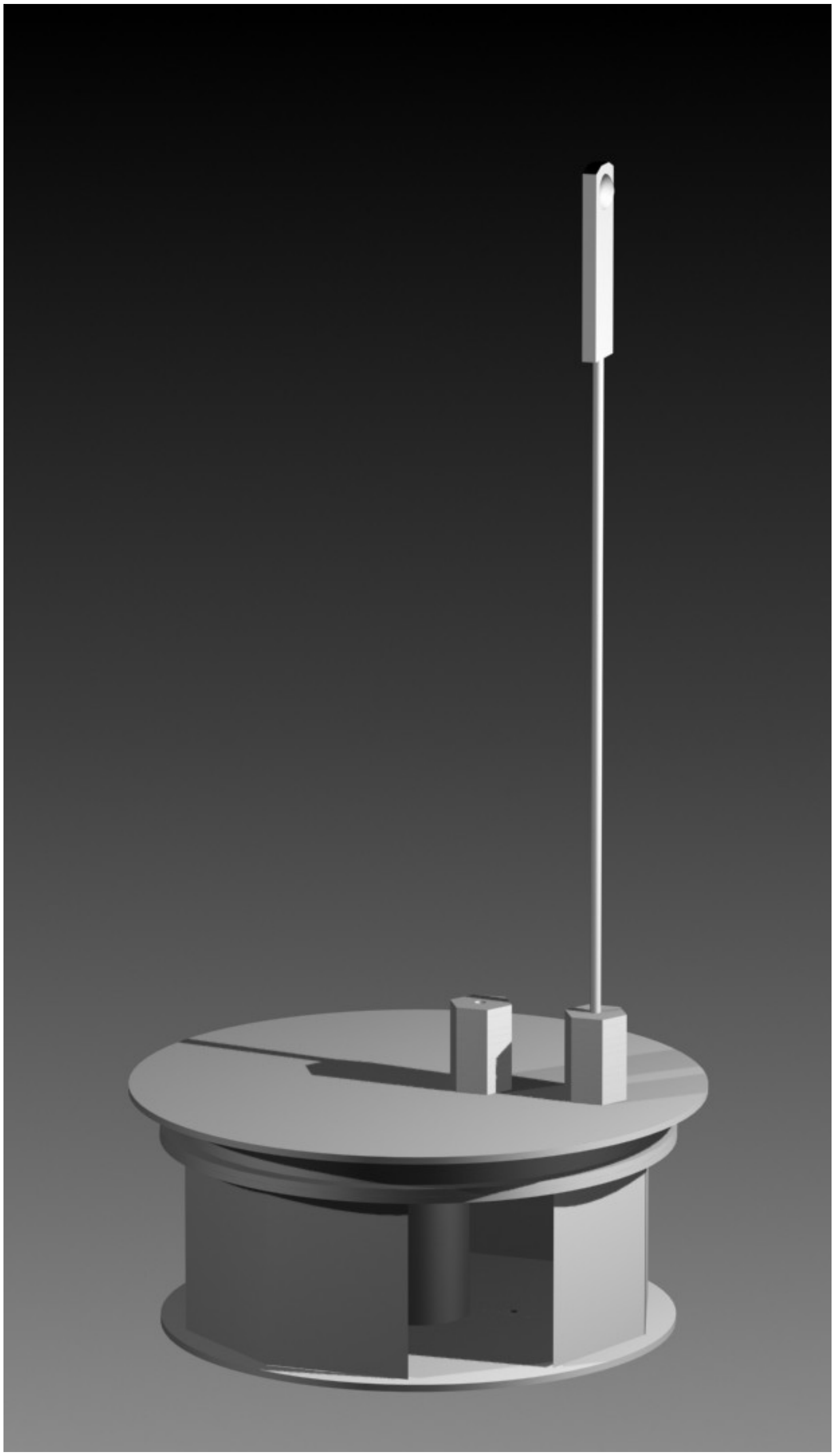


Illustration 7: 3D rendering of the final design

Once the structure was finished the various shapes were arranged on a horizontal plane and exported as the vector based .ai file format.

The first prototype was cut out using the EzCutter200, afterwards the final structure was cut using the Eurolaser XL-1600 due to its increased efficiency.

The part connecting the motor with the turntable was designed in 3D Studio Max as well, but due to its particular shape it was 3D printed using an Anet 8 printer.

The cut out MDF pieces were glued together, and the motor has been bolted to the desired MDF platform. Originally it was intended to bolt the 3D printed piece to the motor as well, but it turned out to be cumbersome to assemble and resulted in some play between the elements. As a more accurate solution the 3D printed attachment piece was glued to the rotor element of the motor. The attachment piece was taped to the top element of the turntable. A MDF ring was glued on top of the top element of the turntable, and a MDF circle of 32 centimeters diameter was placed on top of that. This surface has been spray-painted black to reduce the visual impact of the unit from the camera.

Two points were marked on the MDF circle at appropriate distances from the center of the circle, one for the SRSP, the other one is to the LRSP. The use of multiple layers of cut out rings made it possible to mount the steel rod on top of the turntable.

4.3.6. Adapting the results of the off-center experiment to the hardware

Once the device was assembled a trial run was conducted. At 100 images, at the closest object-distance of 90 centimeter some ghosting has been observed, due to the high extent of animation taking place between frames. This made it necessary to increase the number of images taken to the maximum of the system. At 200 images the ghosting was observed to be gone at images at a 90 centimeter meter distance.

This project uses 6.5 centimeters as its interpupillary distance due to a human error of incorrectly recalling this number. This mistake resulted only in 2 millimeters of difference compared to the baseline defined by Dodgson, which can be considered insignificant, as the interpupillary distance of most of the adult human population vary from 50 to 75mm[32].

For defining the exact off-center distance for our purposes it was required to find a distance, that accommodates to both the 200 steps and to the 6.5 centimeter interpupillary distance, while it is as close to the the measured 10.51 centimeters as possible. For the purposes of the experiment it was decided that not turning the interpupillary distance into independent variables across the iterations is more important, than the very exact results of the off-center human anatomy experiment.

For finding this distance a 200 sided polygon with 10.51 centimeters diameter was created in 3D Studio Max, and using a ruler a distance between two vertexes was looked for that most closely resembled the 6.5 centimeters. This distance was between the 1st and the 21st vertex, and thus this is the given angle that will result in the radius that closest resembles the 10.51 centimeters once altered. This angle defined by these points is 37.8 degrees. Once this is known the middle point of the segment that is between the 1st and the 21st vertex, the center point of the circle, and the position of the 21st vertex determine a right-angled triangle.

$$sin18.9 = \frac{3.25}{r}$$

As the result we can conlude thtat a 200 sided polygon with this radius of 10.0334 centimeters is capable of modeling an interpupillary distance of 6.5 centimeters, with the displayed offset of 21 images between the left and right eyes. The finished system therefore has two positions for the cameras: one with 3.25 centimeters for SRSP, and 10.03 centimeters off-center for the LRSP.

4.3.7. Software

The software aspect of the project is realized in Unity. The system consists of a virtual camera situated in the middle of multiple sphere meshes. These spheres are individual game objects and their transparency changes according to the orientation of the virtual camera. The virtual camera follows the tracked motion of the HMD.

Each sphere is assigned with a different equirectangular texture and is being seen at a given camera angle only. The alignment of the in-camera position with the proper textures is crucial, as otherwise erroneous visual input is being provided through the HMD and the uncalibrated sphere-virtual camera relation can result as incomprehensible stereoscopic information. Such unnatural visual stimulus is likely to lead to cybersickness.

The x,y,z position of the spheres are constant in relation to the participant's head position, rendering the participant's interaction with the VE to be spinning inside it.

The system has been developed during last semester and has been modified to be utilized for the changes in this semester's project:

The limitation of 100 spherical gameobjects per location was extended to 200 inside the script that is responsible for the fading process.

Another change that needed to be addressed was the extension of the script that imports the textures and constructs the appropriate game objects . By altering the phase between left and right images both the SRSP and LRSP display methods can be modeled. While the SRSP uses polar opposite images (images 0 and 100, or 84 and 184 as an example), the LRSP operates with a smaller difference of 21 images (images 0 and 21, or 101 and 122 as an example).

The system uses the HTC Vive HMD for displaying the VR to its users.

4.4. Locations

4.4.1. Design and requirements

Two locations were captured for the experiment. Both of the locations were chosen and altered according to the same requirements:

For the choosing / designing of a location an important factor was the demonstration of objects in various distances from the camera. As one of the main focuses of the study is depth perception of locations using various stereoscopic and monoscopic image synthesis methods, it was crucial to include objects at both close and further proximities from the camera. This decision provides a good environment for achieving motion parallax and stereopsis. Both of these phenomena demand close objects, and motion parallax especially depends on the presentation and relation of camera-wise close and distant objects. Therefore it was decided to represent objects both close and distant to the camera.

Using internal testing we conducted in the previous semester that the objects close to the camera shall be placed closest at 90 centimeters to avoid discomfort. Therefore the closest objects in the scene were placed at this distance, and objects were distributed throughout the distance spectrum from 90 centimeters to approximately 25-40 meters depending on scenes.

A criteria of the locations was the controllability of of light conditions in the space, as this is essential for the end result.

4.4.2. Location 1

Location has been chosen inside KUL, a café in Nordkraft Aalborg. The location of the camera was placed inside the bar, on a spot where it was surrounded by a ring of closer objects. This provided larger horizontal surfaces at various depths to support depth perception through stereopsis and motion parallax, and the setting of various objects according to the the above mentioned proximity criteria of 90 centimeters to 25 meters. The edges of the bar are at around 2 meters of distance, while one opening has a wall surface at around 8-10 meters distance, the other opening of the bar presents surfaces at 20-25 meters distance. This design provided depth cues by both close objects (2 meters) and further away surfaces at different degrees (8-10 meters and 20-25 meters).

The location also provided a reflective glass door of a refrigerator, which was intended to provide animated reflections once the images are being cycled through.

Some objects were intentionally positioned in the scene: a chair has been placed nearby the camera, and a candle holder has been positioned on the top of the bar to serve as a foreground element against the background wall.

4.4.3. Location 2

Location two followed similar design choices as Location one, but in this case a radical depth difference was represented in the scene. This location is a rehearsal/concert space inside Nordkraft in Aalborg. Both the closest (90 centimters distance) and furthest (40 meters) distances are represented very close to each other in one aspect of the setting. This extreme difference in depth was achieved by placing a microphone stand very close to the camera, and having the end of the hall being its background. The relative size of the microphone is much smaller than its background, therefore represents a new kind of depth relation in regards to Location 1. The camera following the 90 centimeters design decision is surrounded by musical instruments: a synthesizer, a drum set and a guitar. On the concert hall chairs have been placed in three rows, followed by rows of tall round tables. The placement of these objects were intentional to provide motion parallax at a further proximity.

4.5. Recording of the images

The images were recorded at night to avoid any possible light leakage into the scene, and to provide a static environment to work with, as this is a crucial element of the project. The final versions of the two locations were recorded on two different days, as the recording of these scenes were lengthy due to the required number of 200 required images for each scene. This meant that the recording of one iteration of one scene took around an hour (that is 200 images of the scene + 30 more images as a safety margin), and the camera had to be charged for another one and half hours, so it could record the same number of images again.

Illustration 8: Equirectangular texture of Location 1

This meant that the setup and the recording of the scene both at a smaller and larger radius took around four and half hours.

The use of tripod has been dismissed, as it did not turn out to be stable enough on the long run, so the camera positioning system was placed on a 1 meter tall platform, rendering the simulated eye height to 1.70 meters, which is an ordinary human height for both sexes.

When recording the scenes, various safety measures were taken: the rooms were light insulated to the best of their capabilities, which meant that the great windows were covered by blinds. Even though the recording session was at a late hour, a wide array of external environmental conditions posed interference with the recordings: cars driving by, external lamps changing, dawn breaking, et cetera.

Further on most objects that showed any form of animation were removed or turned off: a large clock was removed from the wall, and the coffee machine was unplugged.

The turntable system was provided by electricity, and the end of the extension cord was placed as close to the platform of the system as possible to minimize its visual representation in the recorded images.

4.6. Post processing the equirectangular textures

Once the recording was finished the images were checked for consistency on a computer, and once deemed to be functional, imported to Adobe Photoshop for alignment. Although the original goal of the system was an accurate turntable that could be automatically aligned in post by changing the offset of the textures inside Unity, this has not been achieved. For this to be a functioning solution the turntable should have such a level of accuracy, so the automatically offset textures would align

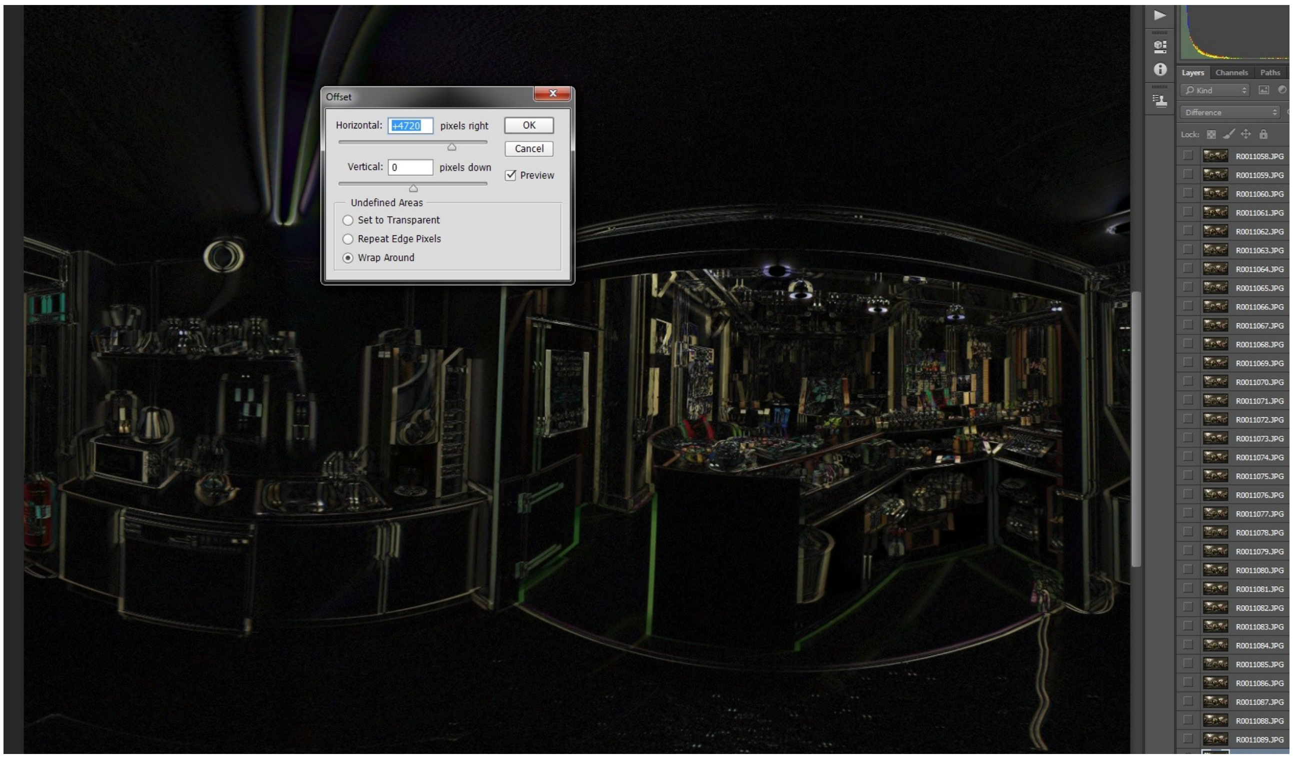


Illustration 9: Screenshot of the alignment process in Adobe Photoshop

with each other on a 1 pixel level accuracy. This has not been achieved: although generally reliable, sometimes there can be 10 to 20 pixels of unstructured displacement error between images. This is due to some play between the rotor of the stepper motor and the attachment unit of the turntable. Therefore even though the turntable steadily travels the 200 steps each rotation, the sub-movements of this full rotation are not reliable on a 1 pixel basis. As this would naturally result in a disconnection between sub-sequential textures, the textures were aligned manually using Adobe Photoshop's offset filter.

This was done by stacking 201 sub-sequential images into layers and aligning them with each other according to their orientation.

The process consisted of checking the image's central point, setting the layer's blending mode as difference, and then aligning it, so there is the least amount of difference between the images. (See Illustration9) The horizontal translation of the images were done through the offset filter, which provided continuous texture translation, the movement of the texture by automatically attaching the non visible areas of the image back to itself, so no information was cropped off.

Once all the images were aligned in relation to neighboring layers, the offset between the 201st and the 1st layer has been measured and this distance has been equally distributed along the 200 layers, so the textures would be aligned at a continuous cycle.

Although safety measures were taken, four images demanded further post processing due to changes in the environment: a lamp has turned on at the distance at one of the locations. This resulted in an around 20*50 pixels big temporal artifact. These four frames were successfully fixed by copy-pasting pixels from other, non-affected frames of the same spot.

Illustration 10: Equirectangular texture of Location 2

4.7. Assembling the scenes in Unity

Once the textures were post-processed, they were imported into Unity and using the enhanced import-script system the scenes were assembled.

The LRSP method has the appropriate textures assembled to the left and right eyes with the phase of 21 images. The SRSP has the appropriate, diagonally located textures assembled to the left and right eyes. The LRMP method is the monoscopic version of the LRSP method, so both the left and right eyes have been assigned to only one texture. The SPM method consists of a single image taken from the SRSP sequence, as this sequence is the closest to the central point of the circle.

The assembled game objects were assigned a number, and a script has been created that enabled turning on and off the various iterations through pressing the the given number on the keyboard.

Upon importing the file textures into Unity it became apparent that on Location 2 during the small radius recording the pole extending the camera from the turntable was not absolutely vertical, but had a small skew. Due to the way the SRSP image is being synthesized it resulted on the right eye's visual stimulus being slightly higher than the left one. This issue has been addressed by raising the hight of the right eye's spheres. This solved the misalignment issues facing the camera, but resulted in a slight distortion in the peripheral vision in this iteration.

5. Performance of the camera positioning system

Once the system has been finished it has been tested and compared against the previous system, developed the last semester. As a conclusion, as intended, the system greatly exceeds the previous system's capabilities, but also introduces a few downsides, that should be addressed in future iterations.

The automation of the image capturing process makes the operation both vastly easier and less time consuming: at it's current stage 24 images can be taken in approximately 5 minutes in comparison with the previous system, that demanded 25-30 minutes, depending on environmental conditions, as the operator was required to physically go to the image recording system to move it, then go into a place where he/she is not visible on the camera. This is a 5 to 6 times improvement in speed. This

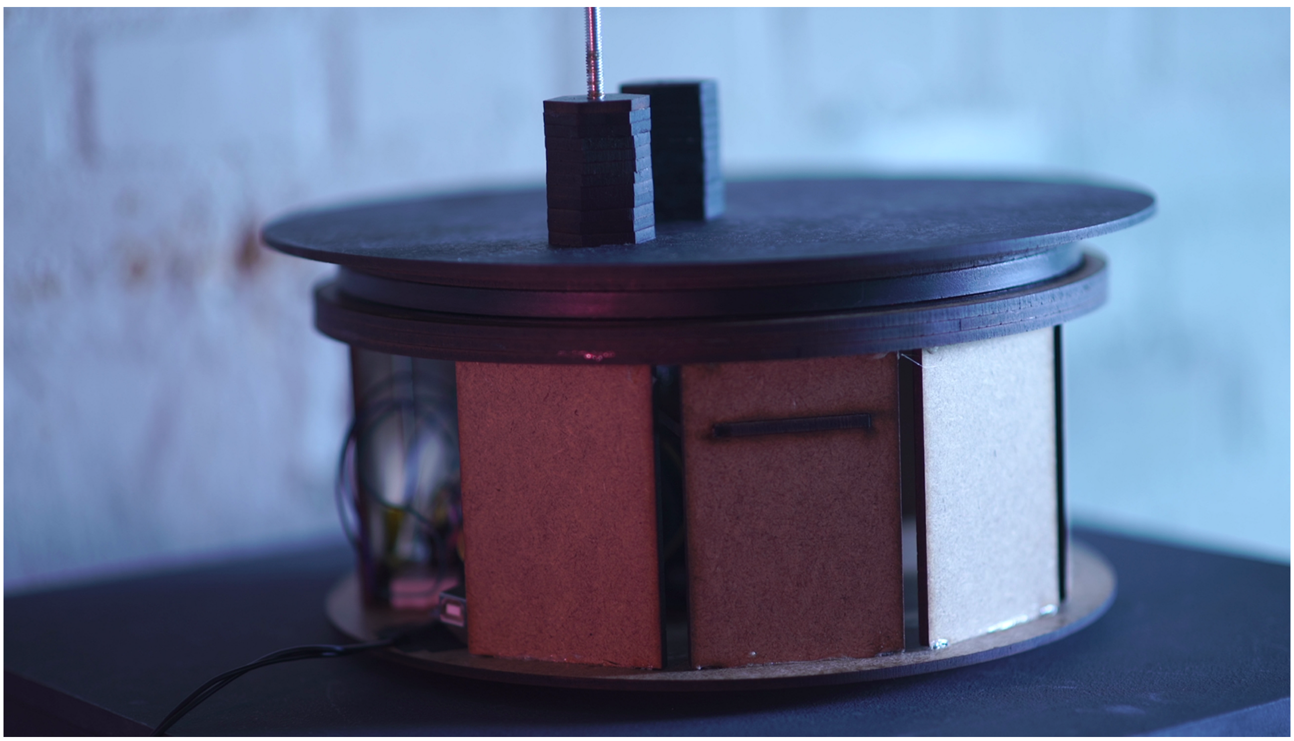


Illustration 11: The completed semi-automation system

speed can be further increased to 3 minutes 30 seconds by creating a more stable connecting rod between the turntable and the camera.

The new system achieved the goal of capturing images in a manner that avoided any stitching artifact to be visible, thus increased the level of quality of the perceived images by getting rid of stitching artifacts in the user's field of view.

A downside of the new system in comparison to the previous one is the introduction of image alignment procedures. The addressability of this problem is highly connected to the accuracy of the turntable system. In case of a highly accurate turntable system is achieved the alignment could be solved in a very simple, and non-resource demanding manner by simply translating the texture's position horizontally. As this was not achieved, it resulted in work-intensive post processing of the textures.

The goal of a remotely operating system has been achieved, the system has worked without problems in this regard.

A potential issue that has emerged during working with the camera is the inadequate performance by the rod extending the camera above the turntable. This piece's accuracy has turned out to be highly important for the efficiency of the system. In case the metal rod is not completely perpendicular to the surface of the turntable spatial distortions can occur of the recordings. These problems can be addressed in post processing, but this process greatly increases the workload of constructing a virtual scene.

The tripod mounting position of the system should be reassessed as well. While it is a highly useful feature, it's location and the choice of materials resulted in the system resonating for a lengthy time after the motor in the turntable has been initialized, and ultimately it was decided to abandon the use of a tripod while recording the scenes, and place it on top of a platform.

6. Experiment design

The experiment investigates the effects of the four display methods on two locations: LRSP, SRSP, LRMP, SPM on Location 1 and Location 2.

Through the test 24 participants are tested, which is the permutation of 4, the number of various test conditions. The experiment takes place on an individual basis.

This place of the experiment is sound insulated place to aid the concentration of the participants. It is also made sure that the environment is comfortable: the space is orderly, it has room temperature and fresh air.

Upon arriving into the room the participants are asked to fill out a short form about their age and whether they have used VR before.

This is followed by a process of comfortably mounting the HMD on participants and making sure that their vision was clear, by asking them to look at the sharp text in the distance, that is an inherent element of the HTC Vive system. The participant was instructed to go to the middle point of the space, defined by the HTC Vive's system, marked by a white target in the VE. This point is defining a central point that is multiple meters in all directions away from the boundaries of the HTC Vive's tracking area, and of any physical objects that could interfere with the player's motion.

Once this security measure was taken a three step stereopsis test was inducted.

The goal of this test was to filter out any possible participants who might lack the ability for stereopsis. Both images supporting expressive stereopsis, and flat images were presented to the participants. Both images were shown to the participant and it was asked, whether they have seen any difference between the images. The participant succeeded if he/she could explain that the difference lies in the depth information of the image, and could successfully identify the difference in all three steps. In case the participant has failed the test he/she has been disqualified, due to not having adequate ability for stereopsis to participate in the experiment.

As the next step the participants were introduced to the basic concept of the experiment, and were asked not to try to go anywhere in their environment, with the exception of spinning around, a motion, that has been encouraged by the conductor. This was done as the system only accommodates to the spinning around one's pivot point, attempting to move in the space could potentially induce cybersickness due to the disconnected nature of the sensory input.

The test uses within-subject test design, all participants are presented with the same four different methods at two locations, but in a counter balanced and randomized order. For the actual order of the experiment see it at appendix.

To avoid cybersickness and any strain of the eyes, the participants are asked to close their eyes upon the changing of scenes. This is done due to the changing nature of the environment between display methods (different kinds of stereoscopic image synthesis, the change of relative distances in relation to objects) . The various scenes are also set up in a misaligned manner, therefore once the participant opens his/her eyes it was necessary for them to refocus on objects. The conductor is to consistently remind the participants throughout the entire experiment to close there eyes whenever a scene is changed.

Once the participant makes it clear he/she understands the instructions, the participant is asked to close his/her eyes and the first scene is loaded.

The participants are asked to look around, experience the environment around them, and gather their impressions.

Through the ranking preference of the participants ordinal data is collected, and through observation the conductor is noting relevant qualitative data.

After being presented by the four different methods of one given location, the participants are asked to rank what they have seen according to three criteria: Comfort, Depth perception, Realism.

The methods are presented to participants in a counter-balanced manner for the first time, and it was possible for them to revisit previous scenes in any order they desired.

Special attention is paid on the communication with the participant, if the conductor experiences hesitancy from the participant's part, a go-through of the scenes is recommended, so the participant can make a more accurate choice and would not feel pressed for answering the question. This is utilized to safeguard the quality of the answers. Once the participant has ranked the scenes along these three criteria, the next location is loaded and he/she is asked to repeat the same process one more time.

The order of the two locations were also arranged in a counter-balanced manner, 12 participants are first presented by Location 1, 12 other participants by Location 2. The Location 1 and Location 2 iterations are linked together in a randomized manner to avoid any carry-over effects in their combination. These answers are documented by the conductor along with sentences, opinions of the participant that is deemed to be valuable for the research.

The order the participants were asked to rank the various criteria is also randomized, similarly to reduce any possible carry-over effects.

Once the participants have finished ranking both of the locations, they are asked to remove the HMD and pick a fruit of their choice in return for participating in the experiment.

The data is to be analyzed using Friedman's test to detect significant differences in regards to a criteria amongst the four methods. If the test deems successful, the pairs are to be analyzed using the Wilcoxon signed-rank test[42].

7. Results

7.1. General information about the sample group

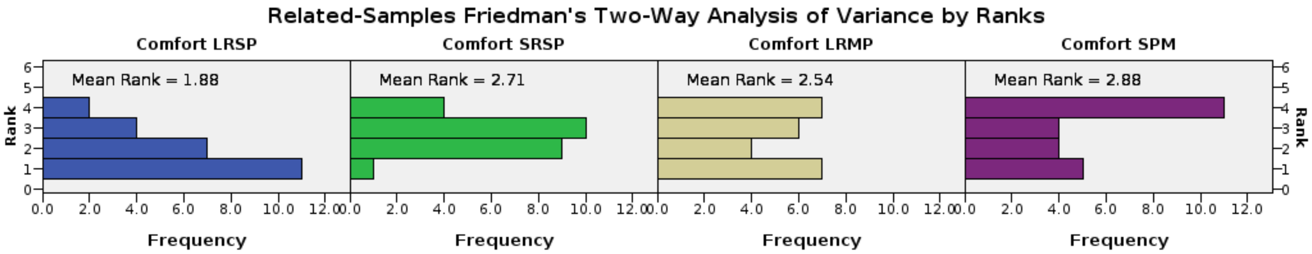
For the stereopsis test 28 people were tested, and 4 people did not pass this test. This 14.3% is in line with Whitman's findings of 15%[17]. Two out of these four participants were aware of some sort of a medical condition that would limit their vision, two were not aware of such.

The main test were undertaken by 24 people, 12 male and 12 female participants. The arithmetic mean of their age is 23.67, with a standard deviation of 3.58. Out of 24, 18 people have tried VR before and 6 have not.

The experiment reached completion with all the participants, and 2 out of the 24 showed signs of cybersickness. Out of these two, one participant had to remove the HMD and take a break at one point, but after 15 minutes of rest willingly finished the experiment and showed no signs of distress upon leaving.

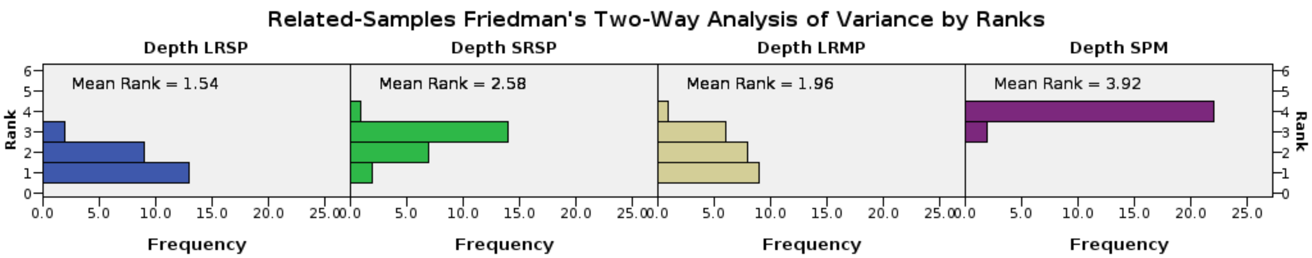
7.2. Results for Location 1

7.2.1. Location 1 - Comfort



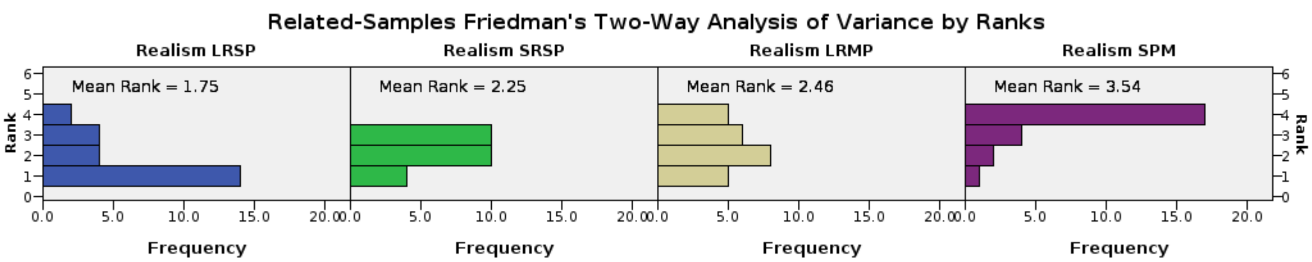
The Friedman test was significant at p=0.40

7.2.2. Location 1 - Depth perception



The Friedman test was significant at p=0

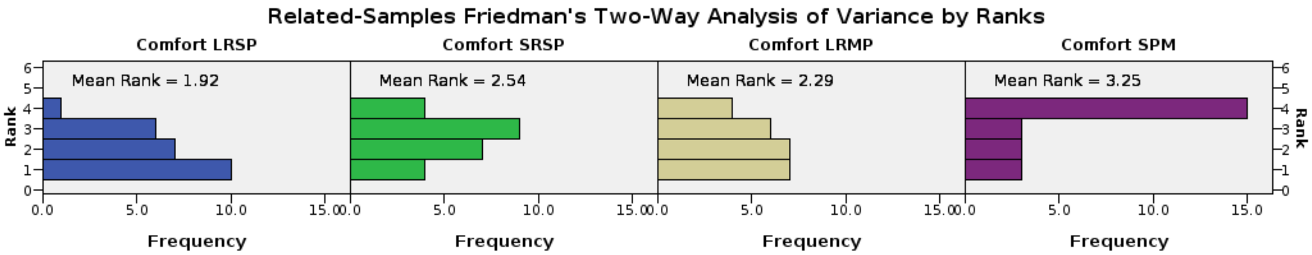
7.2.3. Location 1 - Realism



The Friedman test was significant at p=0

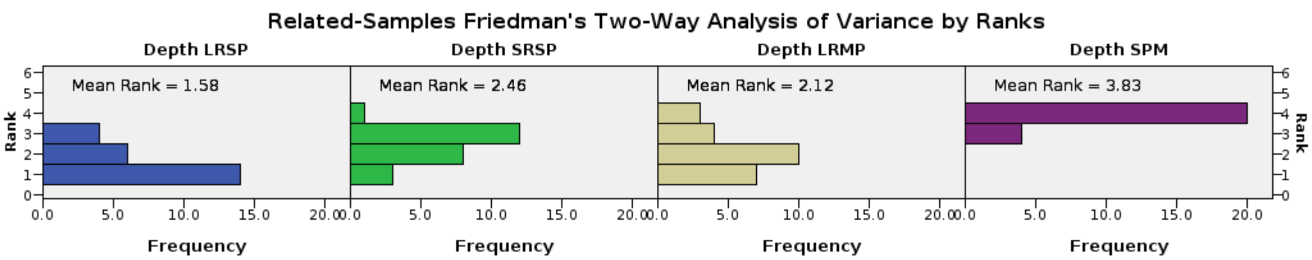
7.3. Results for Location 2

7.3.1. Location 2 – Comfort



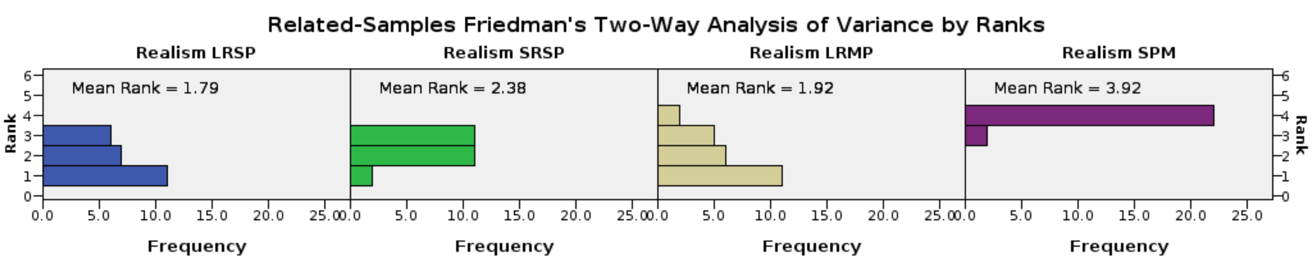
The Friedman test was significant at p=0.003

7.3.2. Location 2 – Depth perception



The Friedman test was significant at p=0

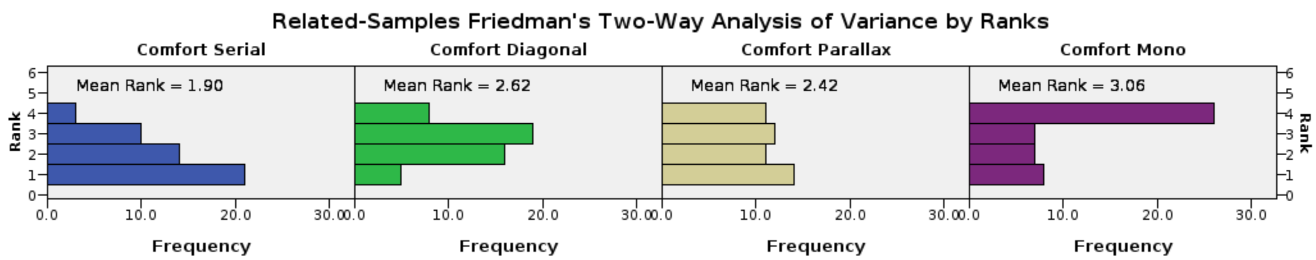
7.3.3. Location 2 – Realism



The Friedman test was significant at p=0

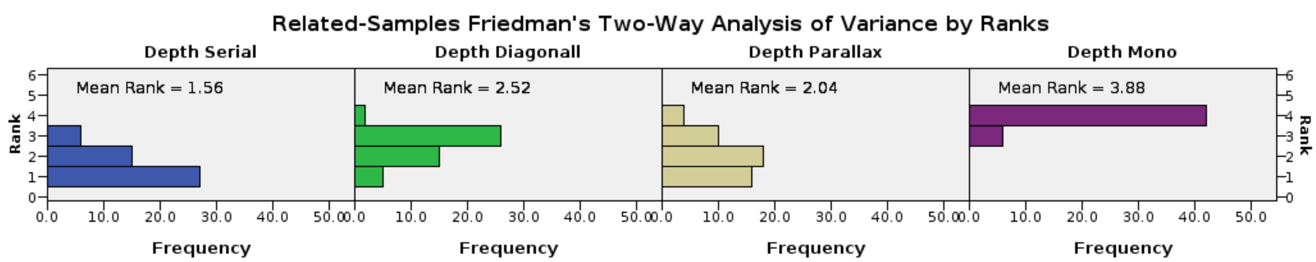
7.4. Results for Unified data

7.4.1. Unified data – Comfort



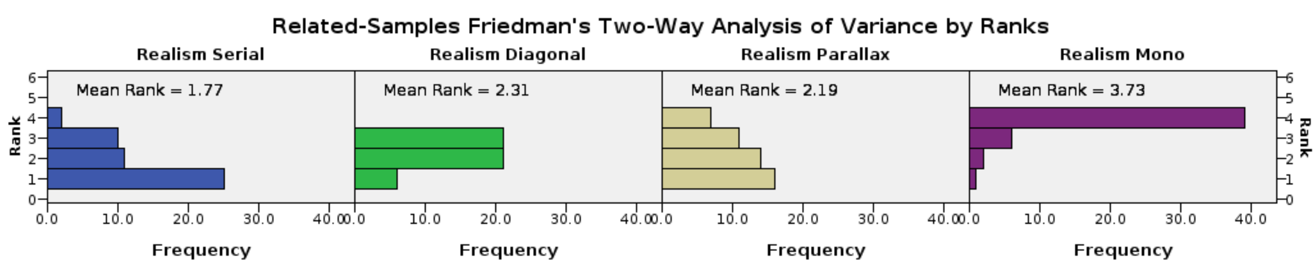
The Friedman test was significant at p=0

7.4.2. Unified data – Depth



perceptionThe Friedman test was significant at p=0

7.4.3. Unified data – Realism



The Friedman test was significant at p=0

7.5. Results for Wilcoxon tests between pairs

Dataset	Aspect	Method 1	Method 2	p value	Rejection of null hypothesis
Location 1	Comfort	LRSP	SRSP	0.009	yes
Location 1	Comfort	LRSP	LRMP	0.062	no
Location 1	Comfort	LRSP	SPM	0.023	yes
Location 1	Comfort	SRSP	LRMP	0.588	no
Location 1	Comfort	SRSP	SPM	0.565	no
Location 1	Comfort	LRMP	SPM	0.023	yes
Location 1	Depth	LRSP	SRSP	0	yes
Location 1	Depth	LRSP	LRMP	0.05	yes
Location 1	Depth	LRSP	SPM	0.001	yes
Location 1	Depth	SRSP	LRMP	0.041	yes
Location 1	Depth	SRSP	SPM	0	yes
Location 1	Depth	LRMP	SPM	0	yes
Location 1	Realism	LRSP	SRSP	0.113	no
Location 1	Realism	LRSP	LRMP	0.061	no
Location 1	Realism	LRSP	SPM	0	yes
Location 1	Realism	SRSP	LRMP	0.652	no
Location 1	Realism	SRSP	SPM	0	yes
Location 1	Realism	LRMP	SPM	0.008	yes

Dataset	Aspect	Method 1	Method 2	p value	Rejection of null hypothesis
Location 2	Comfort	LRSP	SRSP	0.067	no
Location 2	Comfort	LRSP	LRMP	0.291	no
Location 2	Comfort	LRSP	SPM	0.001	yes
Location 2	Comfort	SRSP	LRMP	0.533	no
Location 2	Comfort	SRSP	SPM	0.094	no
Location 2	Comfort	LRMP	SPM	0.026	yes
Location 2	Depth	LRSP	SRSP	0.008	yes
Location 2	Depth	LRSP	LRMP	0.098	no
Location 2	Depth	LRSP	SPM	0	yes
Location 2	Depth	SRSP	LRMP	0.249	no
Location 2	Depth	SRSP	SPM	0	yes
Location 2	Depth	LRMP	SPM	0	yes
Location 2	Realism	LRSP	SRSP	0.031	yes
Location 2	Realism	LRSP	LRMP	0.747	no
Location 2	Realism	LRSP	SPM	0	yes
Location 2	Realism	SRSP	LRMP	0.139	no
Location 2	Realism	SRSP	SPM	0	yes
Location 2	Realism	LRMP	SPM	0	yes

Dataset	Aspect	Method 1	Method 2	p value	Rejection of null hypothesis
Unified	Comfort	LRSP	SRSP	0.002	yes
Unified	Comfort	LRSP	LRMP	0.035	yes
Unified	Comfort	LRSP	SPM	0	yes
Unified	Comfort	SRSP	LRMP	0.418	no
Unified	Comfort	SRSP	SPM	0.098	no
Unified	Comfort	LRMP	SPM	0.04	yes
Unified	Depth	LRSP	SRSP	0	yes
Unified	Depth	LRSP	LRMP	0.027	yes
Unified	Depth	LRSP	SPM	0	yes
Unified	Depth	SRSP	LRMP	0.023	yes
Unified	Depth	SRSP	SPM	0	yes
Unified	Depth	LRMP	SPM	0	yes
Unified	Realism	LRSP	SRSP	0.009	yes
Unified	Realism	LRSP	LRMP	0.109	no
Unified	Realism	LRSP	SPM	0	yes
Unified	Realism	SRSP	LRMP	0.467	no
Unified	Realism	SRSP	SPM	0	yes
Unified	Realism	LRMP	SPM	0	yes

7.6. Mean ranks sorted along absolute difference of mean ranks

Aspect	Method	Mean rank Location 1	Mean rank Location 2	Abs. Diff. Of mean ranks
Realism	LRMP	2.46	1.92	0.54
Realism	SPM	3.54	3.92	0.38
Comfort	SPM	2.88	3.25	0.37
Comfort	LRMP	2.54	2.29	0.25
Comfort	SRSP	2.71	2.54	0.17
Depth	LRMP	1.96	2.12	0.16
Realism	SRSP	2.25	2.38	0.13
Depth	SRSP	2.58	2.46	0.12
Depth	SPM	3.92	3.83	0.09
Comfort	LRSP	1.88	1.92	0.04
Depth	LRSP	1.54	1.58	0.04
Realism	LRSP	1.75	1.79	0.04

7.7. Distribution of rankings sorted along absolute difference of standard deviations

Aspect	Method	Std. Dev. Location 1	Std. Dev. Location 2	Abs. Diff. Of Stdandard Deviations
Realism	SPM	0.833	0.282	0.551
Realism	LRSP	1.032	0.833	0.199
Comfort	SRSP	0.806	0.977	0.171
Comfort	LRMP	1.215	1.083	0.132
Depth	LRSP	0.658	0.776	0.118
Comfort	SPM	1.227	1.113	0.114
Depth	SPM	0.282	0.381	0.099
Depth	LRMP	0.908	0.992	0.084
Comfort	LRSP	0.992	0.929	0.063
Depth	SRSP	0.717	0.779	0.062
Realism	SRSP	0.737	0.647	0.09
Realism	LRMP	1.062	1.018	0.044

8 Findings and discussion

Comparing the results between the two locations it can be stated, that both locations show very similar tendencies in regards to display methods, with a few exceptions.

The mean rank of the LRSP method is decisively in the lead along all three aspects at both locations with very consistent results, with a maximum difference of mean ranking of 0.04 in regards to Depth perception. While the mean rank of LRSP in regards to Depth has not changed much, the standard deviation of the rankings is considerably lower for Location 1.

A considerable difference of distribution of ranks in LRSP occurs in regards to Realism between the locations.

Although the mean ranks are very close, the ranking of Realism measured on Location 1 is more polarized than on Location 2. On Location 1 LRSP has been ranked first 14 times and last twice, on Location 2 it has been ranked first 11 times and has not been ranked as last. There is a 0.199 difference in the standard deviation between locations.

Another considerable difference in the distribution of the rankings of LRSP can be found in regards to Depth. Although the amount of first ranks is rather similar, 13 on Location 1 and 14 on Location 2, the rankings on Location 1 are less polarized: it has been ranked second 9 times, and third twice, Location 2 has been ranked second 6 times and third 4 times. There is a 0.118 difference between the standard deviations.

A major change occurred in LRMP’s and SPM’s mean rank in regards to Realism. LRMP has gained 0.551 in mean rank at Location 2, while SPM scored 0.38 lower in the same regard.

SPM’s drop in Realism in Location 2 shows correlation with its drop in scores in regards to Comfort. The same connection can be seen on LRMP’s relevant Realism and Comfort scores. The same connection cannot be found however in SRSP, as its increase of Comfort is not followed by an increase of Realism.

SPM’s standard deviation has lowered at Location 2 in regards to Realism from 0.833 to the very low 0.282, which is clear indication that the participants had a decisive opinion about its ranking.

SRSP’s distribution has considerably changed as well in regards to Comfort, Location 2 has a more bell-like shape, while Location 1 lacks the high ratings for such. This is in combination with a considerable change of the mean ranks, 2.54 versus 2.71, which means that the participants have more confidently rated Location 1 lower than Location 2.

For better comprehension of the ordinal data, the statistical findings should be interpreted through the results of the qualitative data.

A comment that was mentioned multiple times by participants is that the LRMP has “too much motion” on Location 1. People who have made such comments (Participant nr. 2, 8) has ranked it 4th and 3rd for Comfort. No such comment was made for Location 2. Participant nr. 19 noted “I am losing my balance” in regards to LRMP.

High degrees of motion parallax leading to a higher sense of Depth perception and discomfort are supported by the ordinal data: as it has been earlier pointed out, LRMP has a lower mean rank for Comfort and a higher mean rank of Depth in Location 1 in comparison to Location 2.

The connection between these aspects can be explained by the decreased extent of motion parallax on Location 2 in comparison to Location 1. This finding makes sense, as the distinct foreground /background ratio is higher for Location 1, with large surfaces to be on different depths for parallax, particularly the inner side of the bar against the far away walls of the space.

Another thing worth considering is the nature of the method: both eyes are being provided by motion parallax information from a single point, which normally in reality does not occur. Therefore this sensation could be easily experienced as an over-exaggeration of the natural parallax phenomena.

It is worth noting that the participants reacted in different ways towards the LRMP method as for Comfort it can be seen at the distribution of the rankings. While some people found it rather uncomfortable, participant number 4 got visibly excited about it. He was conceptually aware of the phenomenon and highly enjoyed its technical representation, ranking it first five times, and ranking it second once.

The difference in the distribution of ordinal data of LRSP's Depth can be explained through the high ratings of LRMP in the same regard. The relatively high number of first ranks for LRMP in Depth for Location 1 can be accounted for widening the distribution of LRSP's rankings.

Following this logic, the wider distribution of data for LRSP's Realism can be partially explained by the increased preference of LRMP.

A noteworthy comment has been addressed to the LRSP and LRMP methords by participant nr. 11, who noted that "The head does not tilt, that's why it's uncomfortable.", which is a logical explanation for lower ranks in regards to Comfort.

An explanation of why some people preferred LRMP over LRSP for Realism can be found in comments for LRSP, stating "Everything is going a bit up" and "There is some wonkyness to it" (Participant nr. 11 and 22).

These comments can be explained to a certain extent by the method providing two different images to the eyes. Although the system generally avoids stitching artifacts, due to the nature of the synthesized images, some artifacts might have influenced some visible pixels as well. Further more there could be other artifacts present in the space: light condition changes or minor structural inconsistencies of the turntable system.

Monoscopic methods avoid these issues out of their nature. Participant nr. 11 reflects on SPM as "Everything is dialed down a bit, but it works better" in regards to Comfort. Participant nr. 16 stated that "Things are more in place, not moving so much". Participant nr. 17 noted "You don't get nauseous" .

Another comment that has been gathered in relation to LRSP's Realism relates to the experienced size of the environment: "I am feeling too low", "Everything is a bit smaller"(in comparison to SRSP), "Things are tinier", "Everything is small". (Participant nr. 11, 15, 16, 23 respectively). Although some of these statements are consistent with the ratings, participant nr. 23 has ranked LRSP this for Location 2, but first for Location 1.

A convenient interpretation of these comments could be related to an erroneous interpupullary distance, but this aspect has been double checked and no issues were found with the setup.

An explanation could be related to the off-center distance and its effects on individuals with various physical attributes and movement patterns. Possibly people do not perceive the size of surrounding objects in a uniform manner based on the off-center distance of the camera.

This theory is supported by participant nr. 23's comment stating "Everything seems human scaled" in regards to SMSP.

Possibly an overly-heightened degree of depth-cues translate to alterations of the size of the surrounding objects. It's worth noting though, that no similar comments were made to the LRMP method, although it is missing a depth cue in comparison.

SPM has been ranked last in all regards throughout the experiment, but a considerable negative change occurred in regards to Comfort and Realism on Location 2.

Participants have expressed the Location 2 SPM being "strange" and "unrealistic". A common way to describe the sensation of it was it was "I feel like I am standing on a pedestal" or it being "too tall". (Participant 9, 13, 15, 17, 18, 23) Location 1 was better received, but it has also been commented as being "unsettling". (Participant nr. 17)

People making such comments have nearly without exception ranked SPM last in regards to Comfort and Realism.

This strongly indicates that something in the environment triggered such a response. One element inducing the effect could be that the turntable received more light, thus it became a more visually apparent component of the scene.

Another explanation for this phenomena may lie in the fact that the camera was more closely surrounded by objects in Location 2 in comparison to Location 1, which in combination of the lacking depth cues of the other methods resulted in a distorted depth interpretation of the environment. As the participants were exposed to all the various methods, such depth cues might have become essential elements of the environment of exposure, and their lack therefore resulted in a decreased experience of Comfort and Realism.

This argument cannot be pointed out causally based on our ordinal data though, as even though the participants were exposed to the various methods in a counterbalanced manner, each participant has requested to revisit these scenes at least once for making an accurate judgment in ranking the methods.

Due to the missing depth information of stereopsis and motion parallax, close objects could have been interpreted being largely out of scale.

A related comment was made by participant nr. 7, who explained that "The microphone stand is hanging under the chairs". These objects were approximately 8-10 meters apart, therefore this abstract interpretation of space tis a clear sign of missing depth information.

As Location 1 does not contain objects so prevalently in the foreground, so these effects were likely less prevalent.

It's worth noting that participant nr. 22 has decided to test the spatial accuracy of the represented environment by reaching out his arm and imagining he is holding a teapot in his hand. He has chosen LRSP as the highest ranked method for Realism and Depth for both locations.

9. Conclusion

Based on our findings and the experiment, we can conclude, that the automation system is capable at capturing series of images that can be synthesized into the various discussed display methods.

The automation system is 5 to 6 times faster than the image capturing method used in the previous semester. Although the design seems to be very promising, further effort needs to be taken to increase the speed and accuracy of the turntable system.

Based on the results of the experiment we can make the following statements:

LRSP is better than any other display method for Comfort, Depth perception and Realism, with the only exception being, LRMP, where the difference is not significant in regards to Realism.

SRSP provides better Depth perception than SPM and is more Realistic than SPM.

LRMP provides better Depth perception than SRSP and SPM, and is more Comfortable than SPM.

SPM is is the worst at Comfort, Depth and Realism amongst these methods.

LRSP is a feasible display method for photographic stereoscopic 360 degree environments, although further research must be taken to address the experience of some of the participants, that consisted of images being perceived smaller.

LRMP has received both positive and negative feedback in regards to its Comfort, but it has received appreciation for its ability to provide Depth perception.

Although the results might indicate motion parallax being a more prevalent depth cue than stereopsis, it’s worth noting that the simulation of the LRMP display method does not occur in nature, while SRSP can. Therefore the relationship of stereopsis and motion parallax should be further investigated as well.

10. Further development

The automation system should receive increased accuracy and stability, so its running speed could be increased as well. A more accurate system would also mean less post processing with the alignment of the images.

For the LRSP display method a 360 camera is not necessarily a prerequisite, a superwide-angle camera could be able to substitute the Ricoh Theta S. In this case a faster and better image quality image capturing system could be incorporated into the system, which besides increasing the speed of the system, could also result in image quality increases as well: increase in dynamic range, noise performance, resolution, the possibility to store raw data, etc.

With incorporating a new camera in would be possible to achieve total automation in comparison to the current partial one, as the elements of the system could be tightly integrated with each other.

The automated camera-positioning system could also run off a battery, which would make its operation less constrained.

For research purposes the connection of the off-center distance and the responses of the participants should be further researched. This could happen in combination with anatomical measurements of the participants, to find any possible correlations. This research could also shed some light upon the phenomena of some people experienced the objects comparatively small in the VE.

A new image handling system could be also developed, so only necessary textures would be stored / had to be computed by the computer. This would increase the performance, and probably the degree of Comfort and Realism as well.

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Appendix A

Experiment setup: the order of exposure to different methods and order of criteria to rank

1	Mono	Mono with parallax	Diagonal Stereo	Serial stereo		Comfort	Depth impression	Realism
	Serial stereo	Mono with parallax	Mono	Diagonal Stereo		Depth impression	Comfort	Realism
2	Diagonal Stereo	Mono	Mono with parallax	Serial stereo		Depth impression	Comfort	Realism
	Mono with parallax	Serial stereo	Mono	Diagonal Stereo		Realism	Comfort	Depth impression
3	Mono	Mono with parallax	Serial stereo	Diagonal Stereo		Depth impression	Comfort	Realism
	Diagonal Stereo	Mono	Serial stereo	Mono with parallax		Realism	Depth impression	Comfort
4	Diagonal Stereo	Mono with parallax	Serial stereo	Mono		Realism	Comfort	Depth impression
	Diagonal Stereo	Serial stereo	Mono with parallax	Mono		Depth impression	Comfort	Realism
5	Mono with parallax	Mono	Serial stereo	Diagonal Stereo		Realism	Depth impression	Comfort
	Serial stereo	Diagonal Stereo	Mono	Mono with parallax		Depth impression	Realism	Comfort
6	Mono	Diagonal Stereo	Mono with parallax	Serial stereo		Comfort	Depth impression	Realism
	Mono	Mono with parallax	Diagonal Stereo	Serial stereo		Realism	Depth impression	Comfort
7	Mono	Diagonal Stereo	Serial stereo	Mono with parallax		Comfort	Realism	Depth impression
	Serial stereo	Mono	Mono with parallax	Diagonal Stereo		Depth impression	Realism	Comfort
8	Serial stereo	Mono with parallax	Mono	Diagonal Stereo		Realism	Depth impression	Comfort
	Serial stereo	Diagonal Stereo	Mono with parallax	Mono		Comfort	Depth impression	Realism
9	Mono with parallax	Serial stereo	Mono	Diagonal Stereo		Depth impression	Realism	Comfort
	Mono with parallax	Diagonal Stereo	Serial stereo	Mono		Comfort	Realism	Depth impression
10	Mono with parallax	Serial stereo	Diagonal Stereo	Mono		Comfort	Depth impression	Realism
	Mono	Serial stereo	Mono with parallax	Diagonal Stereo		Depth impression	Comfort	Realism
11	Serial stereo	Mono	Mono with parallax	Diagonal Stereo		Realism	Comfort	Depth impression
	Mono	Mono with parallax	Serial stereo	Diagonal Stereo		Comfort	Realism	Depth impression
12	Serial stereo	Diagonal Stereo	Mono with parallax	Mono		Depth impression	Realism	Comfort
	Mono with parallax	Serial stereo	Diagonal Stereo	Mono		Realism	Comfort	Depth impression
13	Diagonal Stereo	Mono with parallax	Mono	Serial stereo		Comfort	Realism	Depth impression
	Diagonal Stereo	Mono	Serial stereo	Mono with parallax		Realism	Comfort	Depth impression
14	Mono with parallax	Diagonal Stereo	Mono	Serial stereo		Depth impression	Comfort	Realism
	Mono	Serial stereo	Mono with parallax	Diagonal Stereo		Comfort	Depth impression	Realism
15	Mono	Diagonal Stereo	Serial stereo	Mono with parallax		Comfort	Depth impression	Realism
	Diagonal Stereo	Serial stereo	Mono with parallax	Mono		Realism	Depth impression	Comfort
16	Mono with parallax	Mono	Diagonal Stereo	Serial stereo		Comfort	Realism	Depth impression
	Serial stereo	Mono	Diagonal Stereo	Mono with parallax		Comfort	Depth impression	Realism
17	Serial stereo	Mono with parallax	Diagonal Stereo	Mono		Comfort	Realism	Depth impression
	Serial stereo	Mono with parallax	Diagonal Stereo	Mono		Depth impression	Realism	Comfort
18	Mono	Serial stereo	Diagonal Stereo	Mono with parallax		Depth impression	Realism	Comfort
	Mono with parallax	Mono	Diagonal Stereo	Serial stereo		Depth impression	Comfort	Realism
19	Mono	Diagonal Stereo	Mono with parallax	Serial stereo		Comfort	Realism	Depth impression
	Serial stereo	Diagonal Stereo	Mono	Mono with parallax		Realism	Depth impression	Comfort
20	Serial stereo	Mono	Diagonal Stereo	Mono with parallax		Realism	Depth impression	Comfort
	Diagonal Stereo	Serial stereo	Mono	Mono with parallax		Comfort	Realism	Depth impression
21	Diagonal Stereo	Mono	Mono with parallax	Serial stereo		Depth impression	Comfort	Realism
	Diagonal Stereo	Mono with parallax	Mono	Serial stereo		Depth impression	Realism	Comfort
22	Mono with parallax	Mono	Serial stereo	Diagonal Stereo		Realism	Depth impression	Comfort
	Mono with parallax	Diagonal Stereo	Mono	Serial stereo		Realism	Comfort	Depth impression
23	Diagonal Stereo	Mono with parallax	Serial stereo	Mono		Depth impression	Realism	Comfort
	Mono	Serial stereo	Diagonal Stereo	Mono with parallax		Realism	Comfort	Depth impression
24	Diagonal Stereo	Serial stereo	Mono	Mono with parallax		Realism	Comfort	Depth impression
	Mono with parallax	Diagonal Stereo	Serial stereo	Mono		Comfort	Depth impression	Realism

Appendix B

Ordinal data

Location 1

	Comfort				Depth				Realism			
	LRSP	SRSP	LRMP	SPM	LRSP	SRSP	LRMP	SPM	LRSP	SRSP	LRMP	SPM
1	3	4	1	2	2	3	1	4	2	3	1	4
2	1	3	4	2	1	3	2	4	1	3	2	4
3	1	2	4	3	1	3	2	4	1	2	3	4
4	2	3	1	4	2	3	1	4	3	2	1	4
5	3	2	4	1	2	3	1	4	2	3	1	4
6	1	2	3	4	2	3	1	4	1	2	3	4
7	1	2	3	4	2	3	1	4	1	2	3	4
8	4	2	3	1	1	4	2	3	4	2	3	1
9	4	3	1	2	2	1	4	3	2	1	4	3
10	1	2	3	4	1	2	3	4	1	3	2	4
11	2	3	1	4	2	3	1	4	1	3	2	4
12	3	2	1	4	3	2	1	4	3	2	1	4
13	1	4	2	3	2	3	1	4	1	3	2	4
14	1	3	2	4	1	3	2	4	1	2	4	3
15	2	1	4	3	2	1	3	4	4	1	2	3
16	3	2	4	1	1	3	2	4	3	1	4	2
17	1	3	2	4	1	2	3	4	1	2	3	4
18	2	3	1	4	1	3	2	4	2	1	4	3
19	1	2	3	4	1	2	3	4	1	3	2	4
20	2	3	4	1	3	2	1	4	3	2	1	4
21	2	3	4	1	1	3	2	4	1	3	4	2
22	1	4	3	2	1	3	2	4	1	3	2	4
23	1	3	2	4	1	2	3	4	1	2	3	4
24	2	4	1	3	1	2	3	4	1	3	2	4

Location 2

	Comfort				Depth				Realism			
	LRSP	SRSP	LRMP	SPM	LRSP	SRSP	LRMP	SPM	LRSP	SRSP	LRMP	SPM
1	1	4	3	2	1	3	2	4	1	3	2	4
2	1	2	4	3	1	2	3	4	1	2	3	4
3	1	2	4	3	1	3	2	4	1	2	3	4
4	1	3	2	4	2	3	1	4	2	3	1	4
5	2	4	3	1	2	3	1	4	2	3	1	4
6	1	3	2	4	1	2	3	4	1	3	2	4
7	3	2	1	4	3	2	1	4	3	2	1	4
8	3	4	1	2	2	1	4	3	1	2	3	4
9	3	2	1	4	2	3	1	4	3	2	1	4
10	1	3	2	4	2	3	1	4	2	3	1	4
11	2	3	1	4	1	3	2	4	2	3	1	4
12	3	2	1	4	3	1	2	4	3	2	1	4
13	2	3	1	4	1	3	2	4	2	3	1	4
14	1	3	2	4	1	3	2	4	1	3	2	4
15	2	1	3	4	1	2	4	3	1	2	4	3
16	3	1	2	4	3	1	2	4	3	1	2	4
17	4	1	3	2	3	2	1	4	3	2	1	4
18	1	3	2	4	1	3	2	4	1	3	2	4
19	1	2	3	4	1	4	2	3	1	3	2	4
20	2	3	4	1	2	3	1	4	2	3	1	4
21	1	2	3	4	1	2	4	3	2	1	3	4
22	2	3	4	1	1	2	3	4	1	2	4	3
23	3	1	2	4	1	2	3	4	3	2	1	4
24	2	4	1	3	1	3	2	4	1	2	3	4

Appendix C

Qualitative records

No.2	Location 1	LRMP "It has too much depth!"
No.3	Location 1	LRSP "It is more natural."
No.4	Location 1	Got visibly excited by parallax and was aware of phenomenon.
No.7	Location 2	SPM Abstract interpretations of space on Mono -> Mic stand hangs under the chairs
No.8	Location 1	LRMP "Changes more intensely, but more stable"
		LRSP "It is more 3D than reality"
No.9	Location 1	LRMP "Too much motion"
		LRSP "Some wonkyness to it...sea sickness"
		SPM "Very high up on a pedestal"
No.11	Location 1	SPM "Dialed down a bit, but works better for comfort"
	Location 2	SRSP "Harder to judge distance"
		LRSP "Head does not tilt, that is why it's uncomfortable"
No.12	Location 1	Removed helmet
No.13	Location 2	Finding SPM strange
No.14	Location 2	SRSP "Feeling higher"
	Location 1	LRMP "Ceiling is too high"
No.15	Location 1	SRSP "It feels realistic size-wise, except for feeling small in a small environment"
		LRSP "I am feeling to be the right size, but things are small around me"
No.16	Location 1	LRSP "Things are tinyer"
	Location 2	LRMP "Things are more in place, not moving so much"
No.17	Location 2	SPM "You don't get nauseous"
	Location 1	SPM "It's unsettling.."
No.18	Location 2	SPM "Too tall"
	Location 1	SRSP "Size of things is more normal"
No.19	Location 2	LRMP "Feels like I'm losing my balance"
No.22	Location 2	LRMP "Everything moves a bit too much!"
		Testing distance by reaching out with his arm.
No. 23	Location 2	"Everything is small!" SR3
		SPM "I am standing super high" CM 4