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Holographic print from an architectural model

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<p>The purpose of this thesis was to make a case study about ordering and using of a holographic print. Senate-Properties and Pöyry formed a joint venture project in spring 2011 where a certain architectural model was to be printed into a hologram. Contemporary hologram is a specially made film product that creates an illusion of a floating three-dimensional model above and below the film. Information technology and special glasses are not needed for viewing.</p> <p>The objective was to learn about holography in detail and find out the required stages for preparing an architectural model for holographic printing. Zebra Imaging was selected as holographic print producer; however, it is possible to obtain holographic imager device for companies and campuses.</p> <p>Visual design of the hologram was made with Autodesk® 3ds Max® application. Different color schemes, textures and transparencies were applied to the architectural model. In addition, extra details were done to the model to find out the true resolution accuracy of a holographic print. The hologram was designed to be as informative as possible by highlighting certain elements. Final touch of the architectural model was done with a software that is specialized for framing the data and displaying previews from a hologram.</p> <p>The most important outcome was the actual ordering of the hologram and to examine it in practice. The suitability of a hologram for different purposes of use as a new kind of user interface was researched with many different practical experiments. It was possible to demonstrate an architectural model in a way that was not possible before this study. Self-made lighting solutions were adequate light sources for illuminating hologram. It would have been most advisable to order a light source that is specially designed for illuminating holograms.</p> <p>The results of this thesis will quicken holographic print orders in the future. The maximum benefit of a hologram is achieved when the workflow is organized and well defined. Price level of the holograms has been reduced outstandingly in summer 2011, which makes a hologram a more tempting choice for demonstrating three-dimensional graphics.</p>	
Keywords	holography, hologram, architecture, BIM, CAD

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Suuntautumisvaihtoehto	digitaalinen media
Ohjaajat	aluepäällikkö Mikko Hyytinen koulutuspäällikkö Harri Airaksinen
<p>Insinöörityön aiheena on tapaustutkimus holografisen filmitulosteen tilaamisesta ja käyttämisestä. Senaatti-kiinteistöt Oy ja Pöyry Oy käynnistivät keväällä 2011 yhteishankkeen, jossa eräästä arkkitehtimallista haluttiin tehdä hologrammi. Nykyaikainen hologrammi on erikoisvalmisteinen filmilevy, jonka ylä- ja alapuolelle muodostuu noin 25 cm korkea illuusio, kun se valaistaan yläpuolelta. Katseluun ei tarvitse tietotekniikkaa tai erikoislaseja.</p> <p>Tavoitteena oli perehtyä holografiaan ja selvittää, mitä työvaiheita vaaditaan, kun arkkitehtimalli halutaan muokata hologrammille sopivaksi. Hologrammin valmistajaksi valittiin amerikkalainen Zebra Imaging; yrityksiin ja oppilaitoksiin on mahdollista saada myös oma laite, jolla holografisia filmitulosteita valmistetaan.</p> <p>Hologrammin visuaalinen suunnittelu toteutettiin Autodesk® 3ds Max® -sovelluksella. Arkkitehtimalliin kokeiltiin erilaisia värityksiä, tekstuureja ja läpinäkyvyyksiä. Lisäksi arkkitehtimalliin tehtiin ylimääräisiä yksityiskohtia, jotta hologrammin todellinen tarkkuus selviäisi. Hologrammista haluttiin tehdä mahdollisimman informatiivinen. Viimeistely tehtiin hologrammeihin erikoistuneella sovelluksella, jossa arkkitehtimalli asetoitiin virtuaaliselle hologrammitasolle.</p> <p>Työn tärkein lopputulos oli hologrammin tilaaminen ja sen tutkiminen käytännössä. Hologrammin soveltuvuus erilaisiin käyttötarkoituksiin uudenlaisena käyttöliittymänä selvitettiin useilla erilaisilla käytännön kokeilla. Arkkitehtimallia pystyttiin nyt esittelemään sellaisella käyttäjäystävällisellä tavalla, joka ei tätä ennen ollut mahdollista. Omatekoiset valaisuratkaisut toimivat riittävän hyvinä valonlähteinä hologrammille. Suositeltavinta olisi kuitenkin ollut tilata hologrammeille suunniteltu erikoisvalonlähde.</p> <p>Tämän insinöörityöraportin tulokset nopeuttavat vastaisuudessa tehtäviä hologrammitilauksia. Hologrammista saa mahdollisimman suuren hyödyn, kun työvaiheet on eritelty selkeästi. Hologrammien hintataso on laskenut tämän insinöörityön teon aikana merkittävästi, mikä tekee hologrammin käytöstä yhä houkuttelevamman vaihtoehdon 3D-grafiikan esittämiselle.</p>	
Avainsanat	hologrammi, holografia, tietomalli, 3D-mallinnus, CAD

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Abbreviations and Terms

anaglyph	Three-dimensional image encoded in a single picture using two images.
backface culling	A method, which determines whether or not a polygon is visible to the renderer. It will dramatically speed up the creation process of a holographic print.
bézier	Mathematical path construction between two points.
BIM	<i>Building Information Modeling</i> . It is related to architecture where all objects have building data within the objects themselves.
CCD	<i>Charge-coupled device</i> . Usually a device which can convert beams of light into digital values.
clipping	Algorithm that defines to a renderer whether or not specific polygons will be rendered and from which angles.
diffuse color	Main color used for an object. Diffuse color is not necessarily same as the object color.
edge	Edge is between two specific vertices. Polygons consist of three edges.
HDT-C	<i>Holographic Definition Tool - Commercial</i>
hogel	Portmanteau from words holograph and element. Can also be referred to as holopixel (holographic pixel) or voxel (volume pixel) in patent text. One hogel contains color information from thousands of different angles selected by virtual camera renderer. Information is recorded as interference pattern. RGB color values in hogels are between 0 and 255. Monochrome hogel contains only shades of green color.
hogel plane	A physical flexible holographic surface which is usually mounted to inflexible plastic plate. Physical thickness is approximately 2 mm.
HVAC	<i>Heating, Ventilating and Air Conditioning</i> .
imager	Holographic film printer.
LED	<i>Light-emitting Diode</i> .
line	Basic shape element. Line elements are not visible to renderer by default.
multichannel	Multiple-scene hologram. Holographic print is multichanneled when its content varies from different viewing angles. Hologram is not multichanneled by a default. Typical multichanneled hologram has two or four channels, where each channel is one independent 3-D data set.

normal	Invisible vectors defining direction of surface face. By default surface face back is not visible to renderer unless Backface Culling option is turned on.
pointcloud	Output from 3-D scanner which creates three-dimensional surfaces using thousands of points.
polygon	A plane figure which consist of three vertices.
rat nest	A problem related to unwelded vertices and jumbled polygon edges. Object structure looks like a rat nest from renderer's viewpoint. An example can be found in Figure 6.
render	Visualized image of virtual camera that is produced using a renderer algorithm.
spline	Basic shapes such as line or circle which can be converted as editable spline. All three possible sub objects are vertex, segment and spline.
UV map	Texture map that is projected to a 3-D surface with UV-coordinates.
vertex	Point of a polygon or a shape.
ZScape™	A trademark owned by Zebra Imaging, Inc. It is related to computer software that has real-time user interaction with digital content on holographic and auto stereoscopic display monitors. Also related to software that is used for preparing three-dimensional content for holographic printing.

File formats used in thesis

DWG	<i>Drawing</i> . A binary file format that is used for storing two- and three-dimensional design data with metadata. Used mostly in CAD software.
DXF	<i>Drawing Exchange Format</i> developed by Autodesk®.
IFC	<i>Industry Foundation Classes</i>
MAX	Autodesk® 3ds Max®'s own proprietary binary file format.
MTL	<i>Material Template Library</i> . An MTL file is an auxiliary file containing definitions of materials that can be accessed by OBJ file.
MS	MAXScript file. Scripting language used in Autodesk® 3ds Max®.
OBJ	A geometry definition file. See Appendix 8.
RVT	Autodesk® Revit® Architecture file for storing BIM mode

1 Introduction

This is a practical case study of the process of creating a digital holographic print from an architectural model. Senate-Properties's one of the first real estates where BIM (Building Information Model) was used to cover all stages of the building process was the Lohipato unit of Tervaväylä School that offers a comprehensive school level education, rehabilitation services, accommodation for disabled and neurologically ill children and youths. [6, 7, 20]

The main research objective was to find out what kind of work progress is required when holographic print is made from an architectural model. The secondary objective was to design the architectural model to be as informative hologram as possible. The school has many unique features that required being highlighted in the hologram. These features were for example roof railings, a therapy pool and a wheelchair accessible classroom. The hologram was made to demonstrate the school to people who are not familiar with the building. [6, 7]

Zebra Imaging was selected as the holographic print producer as it has the most advanced technology in field of holography and it does not have any major competitors to be reckoned with. Zebra Imaging, Inc. is a privately held company, which employ currently 63 persons. The headquarters is located in the United States of America, Texas. Graduates of the Massachusetts Institute of Technology's Media Laboratory founded Zebra Imaging in 1996. [8, 21]

The second chapter is focused on technology, software and hardware that Zebra Imaging uses. Patents are described briefly to clarify the possibilities and limitations of holography. The third chapter covers the workflow when preparing three-dimensional data for a digital holographic print. The fourth chapter gives comprehensive idea of the ordering process of hologram from Zebra Imaging. The end of thesis covers practical use of holographic print and possible research possibilities in the field of holography.

2 Holography

2.1 General information on holography

Holography was discovered in 1948 – over a decade before laser was invented. Lasers revolutionized the field of holography as the light source was coherent and it was possible to produce sharp three-dimensional holographic images. The word holography can refer to almost anything that reflects light in some special way, for example a ribbon in euro bills, credit card hologram or the seal of quality in expensive product packages. This thesis covers only specific type of digital reflection holographic prints. Classical holography requires a real physical object, which is usually 1:1 size of the holographic film where the holoqram is made. Zebra Imaging's digital holographic print is made from three-dimensional digital data and does not require any digital devices nor 3-D glasses for viewing. Holographic image is reconstructed by single point light source that is preferably a halogen or LED (Light-emitting Diode). Reflection hologram means that light source is at the same side of the holographic surface as its viewers. [16]

On the contrary to reflection holograms, transmission holograms are not covered in this thesis as they has their very own purposes and they work differently. The main difference is that a transmission holoqram requires more specific lighting than a reflection hologram. Required light source is typically a laser instead of white light. [3 p.49-63] It is noteworthy that digital holography in common should not to be confused with Zebra Imaging's digital holography technology. Usually digital holography requires a real physical object and that is not the case in this thesis. [5 p.21-28]

Zebra Imaging's digital holograms can be created from computer generated three-dimensional data which is recorded to high-resolution photosensitive holographic film by laser beams. It is all about small holographic elements that are called hogels.

Figure 1 visualizes the process of hogel recording. A wide laser beam comes from top through 1024 * 768 resolution LCD (Liquid Crystal Display) panel where hogel data is set in hogel perspective. Then the converging lens focuses the beam into one hogel where a reference beam is present at the same time. This is made with pulse lasers. Interference between these two laser beams is recorded into hogel. The interference is

in a microscopic scale that the human eye cannot see. This process is repeated rapidly to each hogel separately to make the hologram. A hologram creates an illusion of three-dimensional object which floats approximately 20-25 centimeters above and below the hogel plane. Appendix 11 contains a photo of hologram. [3 p.63, 11]

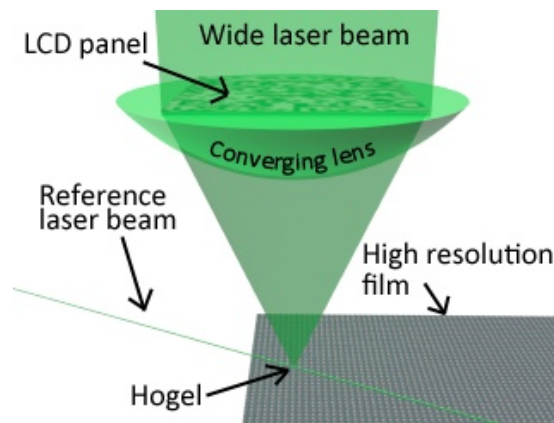


Figure 1: A diagram of hogel recording process

Holographic image is reconstructed when light is reflected from the holographic film material and seen by a spectator. Holograms look the best when viewed indoors with proper lighting. Specific type single point halogen or LED light is mandatory to create the three-dimensional illusion. Direct sunlight is not a recommended lighting option in northern or southern meridian areas. In another words; when shadows are large the sun does not probably shine directly from above. An invention has been made to make sunlight as proper source of light. [11, 13]

“ One aspect of the present invention includes a system for illuminating relatively large scale holograms with a controlled angle beam of sunlight.” [13]

Plain sunlight may cause distortion and undesired visual appearance to the hologram. Cloudy weather has been also taken into consideration in the invention. When moving light source, as the sun is not available or it is cloudy, an artificial light will illuminate the hologram. Lighting of hologram is discussed more closely in chapter 5. [13]

2.2 Software and hardware by Zebra Imaging

At the early stages of this project there was only limited amount of information available about software. I was able to download software only from protected hyperlink by Zebra Imaging's staff. Currently there are two publicly available softwares that are ZScape™ Exporter and HDT-C (Hologram Definition Tool - Commercial). The selection between these two softwares depends on what kind of 3-D graphics software you are using primarily. ZScape™ Exporter is for ESRI® ArcScene users specialized in GIS (Geographic Information Systems) software and geodatabase management applications. However this software is not covered in this thesis. [8]

The HDT-C is the most important software for a great majority of users. The idea of the program is to get a nearly realistic preview of your intended hologram from different viewing angles. The main features are for adjusting

- hogel plane size and orientation,
- multiple hogel plane tiles,
- field of depth,
- lighting,
- shadows and
- scaling of the three-dimensional data. [8]

If some portions of your 3-D data do not render correctly in HDT-C, it will not render to the physical hologram itself either. Transparency of the 3-D data is not displayed unambiguously in the software, as it may not represent the true transparency in the final holographic print. User interface of the HDT-C program can be seen in figure 2. [8]

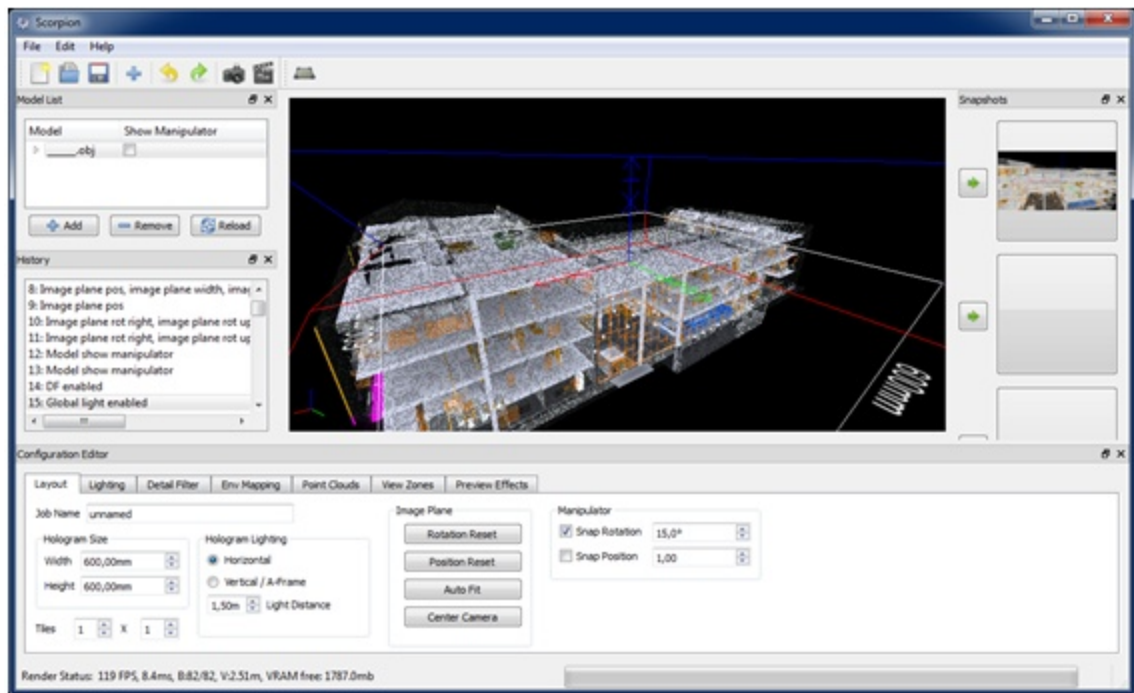


Figure 2: Screenshot from the user interface of the HDT-C program

Both of these softwares require Microsoft Windows XP, Vista or 7 operating system and NVIDIA® GeForce or AMD Radeon™ 3-D display adapter with up-to-date video drivers. ZSpace™ Exporter is currently available only for 32-bit operating system. HDT-C works on both 32 and 64 bit operating systems. [8]

The holograms, however, are produced by using a machine called holographic imager that is seen in figure 3. If a company or a campus needs to produce hundreds or thousands of prints, the best solution is to rent or buy the imager from Zebra Imaging, Inc. Surely it will be quite expensive but still much cheaper than to order hundreds of holograms directly from the company. [8]



Figure 3: Holographic imager machine [8]

To own an imager is also a more secure option, as you are able to create holograms without the need to send any sensitive 3-D data to be seen by other unknown people. Imagers can print A1 size holograms in less than three hours. It can be left printing overnight on its own. These imagers are designed to have replaceable components and employees from Zebra Imaging, Inc. can come to visit and replace parts. The holographic film that the imager uses is roll fed. [8]

2.3 Patents

Zebra Imaging, Inc. has over 30 approved patents worldwide. This chapter covers only those patents that are useful to the reader. When one knows a little about these patents, will get a better idea of possibilities and limitations of this kind of technology. Patent references are taken from USPTO (United States Patent and Trademark Office) and JPO (Japan Patent Office) web pages. Pending patents, patent applications as well as granted patents are discussed below. Many Zebra's patents are related to their active digital hologram display, but since they are not covered in this thesis, they are not mentioned in this chapter.

The next four paragraphs present a short description about the patents that are listed in table 1. A system is developed to illuminate the hologram with moving light source. The system includes a heliostat device that keep track on the moving light source and rotates the deflection mirror to the direct light. When moving light source is not available, it will illuminate the hologram with artificial light. [13]

A device that is used to create holograms has the ability to print variable size and resolution images from three-dimensional computer models. Basic principles are moving the reference beam along with the object beam unit that is pointed to one point to the holographic surface. The object beam is passed through rendered image and the computer will calculate the exposure time of the laser. [14]

The material that the hologram is recorded into, is coupled to a plastic surface. A tiny portion of this recording material is exposed under a coherent light source to create a holographic element, hogel. Usually this coherent light includes an interference pattern that is a combination of two laser beams. [15]

The main point of inventing pulsed-laser systems is to create accurate and high-resolution holographic stereograms. A holographic imager has a certain printing direction and pulsed-laser system guarantees accurate timing of hogel recording. There are tiny dead spots between hogels in which the laser cannot record. Thus, the laser must be turned off when it is over these dead spots. [16]

Table 1: Four important patents in order of patent issue date where patent assignee is Zebra Imaging, Inc. [13, 14, 15, 16, 17]

U.S. patent	Title
7,505,186	Pulsed-laser systems and methods for producing holographic stereograms
6,710,900	Holograms exposed and processed on plastic substrates
6,661,548	Method and apparatus for recording one-step, full-color, full-parallax, holographic stereograms
6,407,832	Light source following optical system for hologram illumination

Zebra Imaging is currently a 15-year-old company and many inventions in the field of holography were done before that. Therefore, there are lots of other companies' patents that Zebra Imaging uses. It is unnecessary to put too much detailed information about these patents in this thesis, as they are publicly available on the Internet.

1. Google patent search: <http://www.google.com/patents>
2. USPTO search: <http://patft.uspto.gov/>

Present patents concerning new inventions in the field of holography are dramatically different compared to the past. when the size of holographic film had to be in a 1:1 related to the subject the hologram was made of. Currently, there is no such limitation as lenses are much more advanced and creating of hologram does not require a physical object. Thus, it can be done from three-dimensional, computer-generated data. Diagrams about holographic printers are found in US patents 6,661,548 B2 and US patent 6,930,811 B2. [14, 18]

3 Preparing the data for a holographic print

3.1 Initial state of the project

The three-dimensional data must be in specific file format and should contain only data, which is relevant to the final use of the hologram. The intended purpose of the use should be determined in as early stage as possible. At first the data should be cleaned up from any excess data and after that visual design is the next reasonable stage. When the data is visually good in HDT-C software, the hologram can be ordered.

I started to research BIM (Building Information Modeling) of the school building after two meetings at the Pöyry, Ltd. headquarters, Vantaa, Finland. The model included only basic building structures with more focused on HVAC (Heat, Ventilation and Air Conditioning) and electricity elements. The BIM of Tervaväylä school, Lohipato unit was in IFC (Industry Foundation Classes) file format. The IFC is a vendor neutral and widely used standard for storing BIM data. It contains semantic information of BIM models' physical geometry, properties and relationships to other objects. The main point in using IFC is to describe building elements regardless of the software used. It also enables easier BIM workflow between different IFC capable softwares. For example, Autodesk® AutoCAD®, Autodesk® Revit® Architecture and Solibri Model Checker™ are software that support IFC. Solibri Model Viewer software was used to open the files for viewing purposes only. Autodesk® AutoCAD® was used to convert the IFC files to file format which Autodesk® 3ds Max supports. Autodesk® 3ds Max® does not have the ability to open IFC files. [8, 10, 19]

Homepages of mentioned software are

- Autodesk® AutoCAD® [<http://usa.autodesk.com/autocad/>],
- Autodesk® Revit® Architecture [<http://usa.autodesk.com/revit-architecture/>],
- Autodesk® 3ds Max® [<http://usa.autodesk.com/3ds-max/>] and
- Solibri Model Checker™ [<http://www.solibri.com/solibri-model-checker.html>].

The most significant project meeting was held in Oulu, Finland on 14th May 2011. It was agreed that a holographic print would be ordered which was not certain before this meeting. Another important decision was that an architectural BIM model will be used in the hologram instead of technical BIM IFC files. An architecture model had

significantly more details of the building itself but without HVAC elements. Even though HVAC elements were not present, the architectural model was still based on BIM data but it focused more on the visual appearance of the building. The research continued with one Autodesk® Revit® file the size of which was approximately 40 megabytes. IFC files were not used afterwards. Appendix 5 contains an image about the architectural model that is a rendered image from Autodesk® Revit® Architecture.

3.2 Excess data cleanup

If your three-dimensional data looks good in HDT-C software, the excess data cleanup may not be required in the intermediate phase. As you might already have a 3-D model of the building, factory or perhaps your future house, it is only natural that the model is as detailed as possible. All the details may not be appear in the hologram, as there is a particular, limited resolution. There might be unnecessary data related to your hologram or there can be invisible objects. Overdetailed objects are a big issue when viewing and editing the model with 3-D graphics software. Some objects may have problems with polygon face normals. These topics are discussed more closely in this chapter.

After the intended purpose of use of the holographic print has been confirmed all the way, excess geometrical data can be removed from the 3-D model. In this study, the original architecture model contained over 30 000 unnecessary shapes which were not needed in the hologram, hence they were deleted. Shape objects are invisible by default by the 3-D graphics software renderer. These line and spline (or beziér line) shapes were mostly 2-D architectural floor plans. Note that vector lines and mesh lines were not necessarily the same object in the same location. Numbers in Table 2 are rounded to nearest hundred and they refer to object number, not the number of polygons. It is a mere coincidence that the amount of mesh and vector lines are the same. Physically, they were from different portions of the 3-D data. However, there were some areas where vector and mesh lines were at the same location.

Table 2: Irrelevant objects in the scene in the architectural model

Object type	Amount	Deleted/Modified
Vector lines (invisible to renderer)	17,500	All deleted
Mesh lines (renderable lines)	17,500	All deleted
Topography (grass, soil, asphalt)	1,200	Modified and partially deleted
Compound (stone or concrete fence)	8,000	Partially deleted

One important step was to decide how much unnecessary yard area (terrain) should be cropped out of the print. In this case the boundaries were cropped to a slightly bigger area than the dimensions of the building itself. The idea was to focus in the building itself by cropping the yard area as much as possible. Appendix 6 shows the exact area that was cropped to the final hologram. Terrain vertex points had to be edited manually one at a time. The terrain structure must remain rigid after it has been edited. Otherwise problems will occur while exporting the 3-D data even though the surface might look great in the 3-D software and preview renders.

After deleting thousands of unnecessary objects and cropping the area, there were still over 2.6 million polygons in the scene. The 3-D model was still really slow to view with a state-of-the-art personal computer. Screen frame rate was approximately 10 FPS. A closer examination of the 3-D model afterwards revealed many overdetailed objects such as folding doors, computer keyboards and dining hall light spheres. They had to be simplified. The quickest way would have been to use 3ds Max's[®] Optimize-modifier (which is the opposite of the Tessellation-modifier) to reduce polygon count with an automated computer algorithm. However, it was decided that geometrically simple and polygon glutton objects would be done from the start by manual 3-D modeling, as they are rather simple models. It guaranteed both low polygon count and good quality. 3ds Max[®] viewport's frame rate improved outstandingly (to over 60 FPS) after polygon glutton objects were replaced. The use of Optimize-modifier can cause undesired results when optimizing three-dimensional data for holographic print. Optimization was done for two major reasons. Firstly, the scene should be viewed smoothly in Autodesk[®] 3ds Max[®] and secondly, the exported OBJ file should contain as little geometrical data as possible. [10]

3.3 Bring out invisible data

Invisible three-dimensional data may or may not occur in the scene depending on export and import settings. In this study objects without a visible surface were discovered when multiple test renders were made in Autodesk® 3ds Max® from multiple different angles. They were clearly visible in the renders but not in the viewport. By selecting all objects and taking closer look to objects bounding box boundaries; it showed that these objects were visible in render but not in viewport as seen in Figure 4.

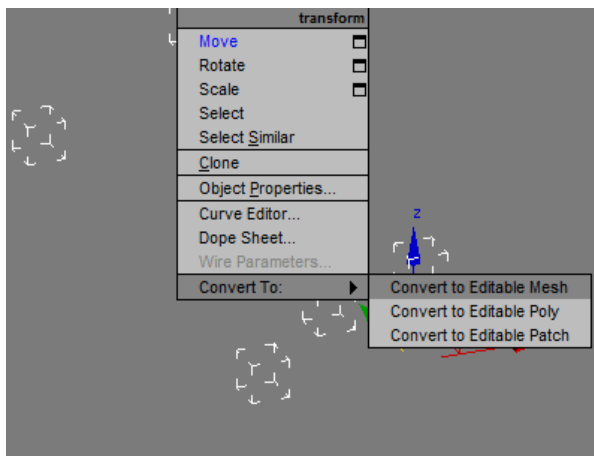


Figure 4: Dining hall light fittings were invisible in the viewport of Autodesk® 3ds Max®

The first and the best solution by so far was to convert the objects to Editable Mesh. Another solution would have been to adjust export settings in Autodesk® Revit® Architecture and import settings in Autodesk® 3ds Max®, although it would be more time consuming because export and import settings are very case-specific. Each test run (export and import sequence) takes from one to five minutes and there are numerous unique combinations settings. In my opinion such time-consuming trial and error procedure can be avoided by understanding better the 3-D graphics software export and import setting parameters. This kind of important workflow sequence should not be based on luck.

3.4 Visual design of the hologram

When preparing the 3-D data for a holographic print, it is very important to know that the resolution is currently approximately from 25 to 30 DPI (Dots Per Inch). You can imagine the 3-D data in the hologram consisting only from elements size of 0.71 cubic millimeters. Basic elements in the hologram are hogels and they are not comparable with pixels in LCD panel. Dimensions of the hologram that was ordered were 18" * 24". In X-Y-space it is approximately 860 * 640 pixels. Because of this resolution, it is not possible to print too detailed three-dimensional data in the hologram. For a comparison, a common systems camera takes images in 240 DPI. Figure 8 in chapter 3.5 contains a close-up image of the hologram. [1 p.36-38, 2 p.27-29, 12]

Own textures can be used but they are not recommended. Holographic print has its limitations and it is not certain how the texture will look like in the final print. Procedural materials are recommended to enrich the visual style of your model. They are based on mathematical formulas and do not need any actual texture file, although they can be rendered as texture while exporting 3-D data. Typical procedural texture names are checker, dent, gradient, tile, cellular, falloff, noise and brick. It is very important to adjust correct parameters in the procedural materials. [4 p.562-587, 8, 10]

The more textures are added to a scene, the more likely you are to encounter a problem. However, this does not mean that the best visual style is achieved without textures. The key point is to keep texturable object surface as simple as possible. Plain color instead of texture is recommended for complex surfaces. It is also recommended to use discreet gradient colors for improving contrast. Avoid big surfaces with only one flat color. Surface color can be varied using procedural textures. However, in this study most of the surfaces were just plain color and surfaces in the actual hologram looked good, although big surfaces were mostly transparent and small surfaces opaque. The materials are described in appendix 7.

Many objects in the school building were reference objects. In practice it meant that when applying material to a specific object, all similar objects were changed instead of one. It was not necessary to make each object unique. A reference object would have been changed to unique only if it was mandatory to have different color furniture and

walls around the model. UV-maps should always be kept as simple as possible to avoid any graphical defects. All textures must be tested in Zebra Imaging's own graphic software where true UV-maps can be seen after 3-D data has been exported as OBJ file format. [8]

Transparent objects should be used only when necessary. Object transparency should always support informativity of the hologram and it should never be used without reason. An object that has no transparency, will have the best visual appearance. An opaque object emits physically more light photons to the viewer's eye. The following quotation is from Zebra Imaging's guide document. [8]

"When rendering transparent objects, be aware that the renderer will only render through a total of 4 surfaces. If you see black in transparent areas, the likely cause is that you have exceeded this limit. The limit may be increased in the future." [22]

The hologram had a few black areas due exceeding the limit. When viewing the hologram through a rooftop to the therapy pool from a certain direction, a small dark area can be seen. This phenomenon was not photographed for this thesis.

Transparency had a specific purpose in this case study hologram. All rooms in the school building had to be demonstrated in the hologram; it would have not been sensible without transparent elements. After the basic color scheme of the objects was decided, the visual design of transparency started. It had to be decided which elements should be transparent and by how much. The sum of transparent layers especially in holography has logarithmic nature as shown in table 3. Think of four plastic objects that have 25 % transparency. When you place these plastic objects one on the other, you can still see through all of them. Four times 25 is 100, but four times iterated 25% transparencies are 69%. This means that the stack of four plastic objects is still 31% transparent.

Table 3: The sum of transparent layers with 25% step iteration. Each iteration is 25% less transparent than the previous iteration.

iteration	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.
%	25	44	58	69	76	82	87	90	93	95	96	97	98	98

Three main versions were made from this architectural model that was sent to Zebra for creating the proof shots. The first version was too opaque and the second version

too transparent. The third version was the perfect mix of the two first versions, as there were over ten different kinds of transparency levels that were closely considered. The architectural model included window objects but they were deleted at the beginning. Because windows seem like 100% transparent, there was no reason to keep them at all. All ceiling objects also had 100% transparency because they made the visual style look worse. The visual design of transparent elements is clarified in appendix 4. If you have red-blue 3-D glasses available, an anaglyph 3-D version is available in the appendix 3.

Hogel plane is the holographic surface where hogels physically exist. See appendix 2 for an example of location of a hogel plane. It must be determined virtually in the HDT-C program.

"Objects that lie directly on the hologram surface, and that as a result occupy a lot of hogel space, may result in tiny imperfections due to clipping at the surface. When possible, try and keep large amounts of your geometry just a millimeter or so off the image plane." [8, 22]

It was necessary to place the hologram on a low table to make possible for the viewer to look the hologram sloping downwards around the table. The horizontal format is illustrated in the upper image of appendix 2. Another option would have been to place the hologram to the wall or A-framed table stand that is called incline format as shown in the bottom image of appendix 2. The incline allows the viewer to see the three-dimensional data in front of it rather than above it as in the horizontal format.

3.5 Exporting issues

The most common problem in exporting is the direction of polygon normals. Some polygon face normals can be flipped over in an unexpected way. Because a hogel contains information from thousands of angles, graphic problems visible in your 3-D software will be seen in the holographic print as well. The best way to discover any defective normals is to make multiple test renders from many angles.

When using complex architectural files that contain lot of data, there is a high risk of forming so-called rat-nested objects during the export procedure. The word rat-nest refers to a situation where three-dimensional object data is not rigid and correctly organized. When object edges are tangled, it resembles a rat nest. It may be an

unnoticeable problem in 3-D software's viewport but it might be visible in the holographic print and the 3-D software's renderer as well. See figures 5 and 6.

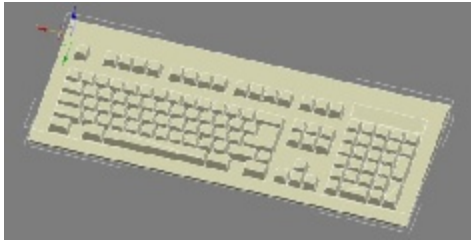


Figure 5: Screenshot from 3-D software



Figure 6: Render from 3-D software

The used architecture file in this study included a model of keyboard which was rat nested. All keyboard models were replaced with simple flat cuboid for two reasons. Firstly, the object was rat-nested and secondly, the details in the keyboards would not have been visible in the hologram. So, in the final scene they were just keyboards without any keys. As mentioned in the beginning of chapter 3.4, the hologram has a specific resolution. Life size of a regular keyboard is 20" * 8". Therefore, the keyboard would cover as small as 6 * 4 hogel area in the hologram.

Textures should be only standard type material without any fancy effects such as reflections or refractions. All textures must always be only in the first UV-channel and only one UV-channel can be present in the scene. Multiple UV-channels are not accepted. Compare figures 10 and 11 in chapter 4.2 to see an example of UV-map. [10, 22]

Figures 7 and 8 show the same northeast side entrance of the school building. Physical size of the concrete slab is approximately three square meters. In the hologram, the size is 460 square hogels, which is approximately 6.5 square centimeters. This does not yet mean that small details cannot be presented in hologram because there is slightly too much transparency in the textures used in the hologram.

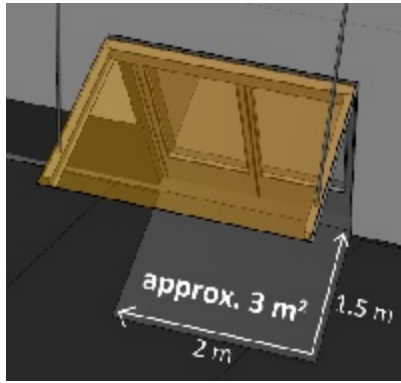


Figure 7: Side entrance of the school building in the Autocad® Revit® Architecture

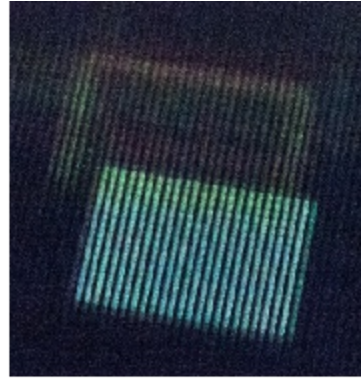


Figure 7: Side entrance of the school building in the hologram

When the hologram was measured and the result was compared to the real world, a proportion ratio between these could be determined. The measuring method is shown in figure 19 in chapter 5.2. The results are listed in table 4 where the measured item is compared to the real world. The variations between different ratios have occurred from a measuring error. If the measuring of the hologram had been exact, the ratio between each measurement would be the same. The median between ratios is 129 and the average is 128. This can be rounded up to 130, thus the proportion of the hologram is approximately 1:130. One centimeter in the hologram equals 130 centimeter in real life.

Table 4: The results of the measured hologram

Location	Hologram [mm]	Real world [mm]	Ratio
length of the glass roof on the main entrance	210	27,000	129
length of the stone wall in front of the main entr.	178	22,888	129
length of the therapy pool	112	14,000	125
width of dining hall's glass wall	108	13,644	126
length of the bicycle shelter	86	11,085	129
width of the side entrance of the school	16	2,010	126
width of the side entrance ramp	12	1,500	125
width of the stairs	9	1,200	133
diameter of the dining hall light sphere	3	400	133

When the architectural model was exported from Autodesk® Revit® Architecture, there were problems with Accustudio Accurender textures. Figure 9 shows which textures were unable to export. All materials that began with a name "accu" did not export successfully.

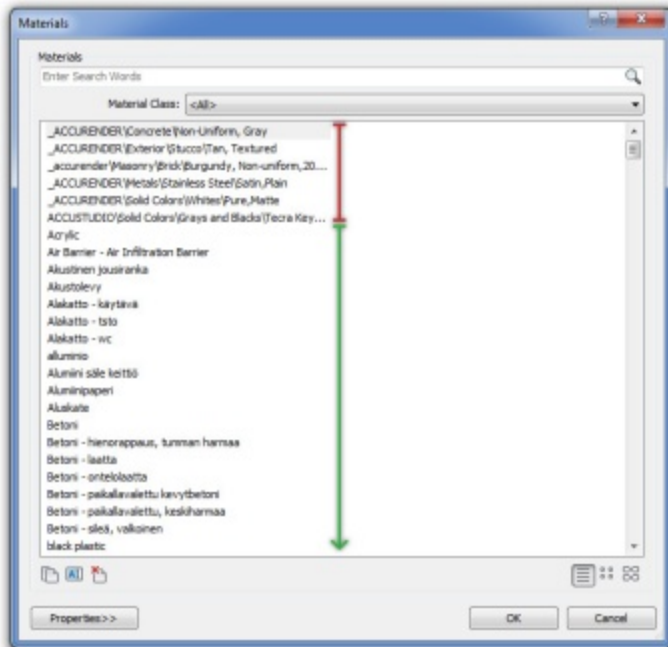


Figure 8: Autodesk® Revit® material export issue

This material export issue made the visual design of the hologram more difficult as the original materials were not fully present in the exported model. The reason was simply that Accurender software and textures were not available in the computer used for preparing the hologram. Problems during exporting regardless of the used software are commonly case-specific. Everything should be kept as simple as possible.

4 Holographic print ordering process

4.1 Types of available holograms

Holographic prints are available as monochrome or full color. A monochrome version is based on shades of green. Benefits of monochrome print are easier production and cheaper price. Holograms in the full color print are RGB values between 0 and 255. Prints are available in five different standard sizes but it is possible to place multiple prints next to each other to create large tiled print. Maximum standard size is 24" * 24" but larger prints are available as custom request.

The workflow of the ordering process was slightly different when the hologram of this case study was ordered in May 2011. The old ordering process is described in appendix 1 as a flowchart. Currently, there is less e-mail based communication with Zebra Imaging because their official website has the possibility to upload your three-dimensional data as compressed zip file. Table 5 shows standard print sizes, resolution and prices in August 2011. Table 6 refers to old standard print sizes and prices in May 2011 when the hologram (18" * 24") was ordered. Hologram size of 12" * 12" was available only as a gift copy in May 2011 and it was mandatory to order at least four copies. All prices in tables 5 and 6 are for full color prints, as monochrome version was not even considered. Prices are rounded to the nearest ten. [8]

Table 5: Standard print sizes, resolutions and prices in August 2011. (EUR/USD 1.445) [8]

size [in]	size [cm]	resolution [pixels]	price USD	price EUR
12 * 12	30 * 30	430 * 430	600	410
12 * 18	30 * 45	430 * 640	1,000	690
18 * 18	45 * 45	640 * 640	1,400	970
18 * 24	45 * 60	640 * 860	1,700	1,180
24 * 24	60 * 60	860 * 860	2,000	1,380

Table 6: Standard print sizes, resolutions and prices in May 2011. (EUR/USD 1.428)

size [in]	size [cm]	resolution [pixels]	price USD	price EUR
12 * 18	30 * 45	430 * 640	1,500	1,050
18 * 18	45 * 45	640 * 640	2,000	1,400
18 * 24	45 * 60	640 * 860	2,500	1,750
24 * 24	60 * 60	860 * 860	3,000	2,100
24 * 36	60 * 90	860 * 1290	3,500	2,450

Zebra Imaging gives instructions, quotes and additional information documents by e-mail. All international purchases must be prepaid based on estimate quote. Purchases made within US can be paid after the product has arrived to the customer. The quote includes separately

- additional lighting options,
- handling and shipping,
- tax,
- customs and
- the hologram. [8]

Considering how useful holographic print can be, it is actually quite cheap from the viewpoint of industry and companies. To the man in the street it may appear as an expensive product. The classic architectural miniature that is made from plastic and cardboard is difficult to transport and it takes a long time to produce it not to mention that it is quite expensive as well.

4.2 Data transfer and graphics approval

Currently Zebra Imaging has a quite easy-to-understand workflow. First you need to visit Zebra Imaging's homepage (<http://www.zebraimaging.com/>) and get some information about holograms. Then you must prepare your 3-D data and export it as OBJ file. After that, load the OBJ file to the HDT-C program, frame your hologram and adjust lighting. The final step is to save the data and upload it to Zebra Imaging. If the file size is over 100 MB, you need an FTP account to Zebra Imaging. It is recommended to send reference pictures about your project along with the mandatory OBJ and MTL files. Although the OBJ file is the most important one, MTL file is also very important even when no textures are used. The content of OBJ and MTL files are described in appendices 8 and 9.

Following proceedings were made on 13th May 2011. An FTP account was created by Zebra Imaging right after they learned that we needed a holographic print. We provided them also high-resolution visual references during the data transfer. The transfer rate was 200 KBps, which meant that 50 MB file took about four minutes to upload to Zebra Imaging's FTP server. Then we waited for the proof shots and video

preview. We did not approve of the proof shots (shown in figure 12), as they were too bright and the brick wall texture was too big. After this we had access to download the HTD-C program for creating own proof shots and video previews. On the second attempt we did not approve it either, as the hologram (figure 13) was definitely too transparent. The brick wall texture can be compared between figures 10, 11 and 12. The third attempt was a success as the expectations and requirements met. There was a correct color scheme and transparency. Graphics approval was an important stage of the order process as it meant that the hologram had gone to the production thus the estimate quote must be paid anyway.



Figure 9: Brick wall, real world photo [20]

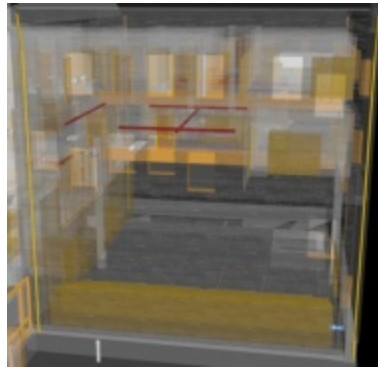


Figure 10: Brick wall, Autodesk® 3ds Max® render



Figure 11: Brick wall, HTD-C proof shot (version 1) preview render

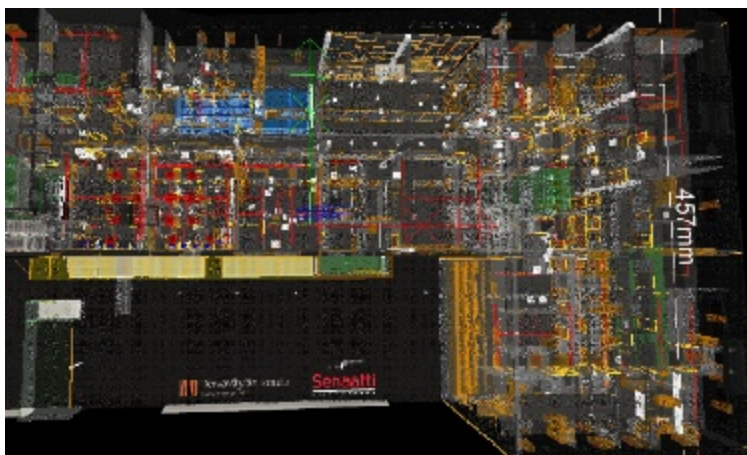


Figure 12: HTD-C proof shot (version 2) that was too transparent

Figures above explain why we did not approve of the first proof shots. Figure 11 shows that the brick wall texture was designed to be very similar to the real world, but with transparent walls. The texture is repeated in U and V coordinates multiple times. Figure 12 shows clearly that UV map parameters were re-set during the export procedure and thus, the UV map tile repeat is incorrect.

The basic workflow during the ordering process of this hologram was

1. communicating with Zebra,
2. obtaining access to Zebra's FTP server,
3. sending the data to the FTP server,
4. receiving proof shots and video preview,
5. accepting proof shots and
6. receiving the hologram.

Communicating with Zebra was done by email that included information about our intended hologram. Delays between replies were fast; less than ten minutes on the first day. Afterwards emails were not replied that quickly, however they were answered within a day or two. After Zebra approved our holographic print order about the architectural model, we got an FTP account that we used for uploading the data and reference images about the building. Uploading of the data (approximately 65 megabytes) took under ten minutes.

The ordering process of the hologram is currently under continuous developing. Orders within United States can be done easily in Zebra Imaging Online Store; however, all international purchases must be requested by email from Zebra Imaging. More detailed workflow is described in appendix 1 as a flow chart. [8]

Current workflow for international purchases are

1. to complete the International Customer Information Form,
2. receive FTP account details and download HDT-C or ZScape™ Exporter,
3. fill in payment information form if your order has been accepted,
4. approve proof shots and preview video,
5. pay the order and
6. receive the shipment. [8]

4.3 Transportation of the hologram

FedEx delivered the holographic print a few days earlier than scheduled. You will receive a FedEx tracking number when your shipping is on the way. Normally the shipping would include also Zebra Imagings certified lighting equipment. Additional lighting was not ordered in this case. The hologram was well wrapped thus unlikely to be damaged during transportation. [8]

Only smallest prints can be taken into an airplane as hand luggage item, anything from medium size to large is too big. The hologram can be also ordered in rolled form as a special request, it increases the portability of the hologram. X-ray will not cause damage to the holographic surface. Usually cardboard packaging is enough when shipping a hologram. But when a hologram is shipped quite frequently for some reason, it is wise to put multiple layers of cardboard around the hologram. Plastic case would be safest but weight would be an issue when shipping. Also, take into consideration that lighting solution may be heavy with metal stands. Flashlight type on lighting is recommended only when the holographic surface is small enough. Freehand lighting is not necessarily the best solution even when travelling with hologram and using a relatively small hologram. When you point the light at the hologram, you have only one free hand and if you point your free hand to the hologram, the light source is definitely moving a little.

5 Using of holographic print

5.1 Lighting the hologram and taking photographs

The first impression was somewhat mystic right after opening the package. Proper lighting was not yet set-up. Three-dimensional illusion was not present within the hologram when there was very bright ambient lighting. Right after the hologram was placed on low table perpendicularly under a bright studio halogen lamp, the three-dimensional illusion popped out and it gave us good impressions. But after studying it closely for a few minutes, we started to feel quite disappointed, as the 3-D data was sharp only nearby the holographic surface. Floors of the building from two to five were indeed strongly blurred. At this time I was not aware that light source as seen in figure 9 dissolved and scattered the light too much.

As we could not find any reasonable or working lighting solution within the school, we had to go shopping for a light. The light that was bought is shown in figure 15. It should preferably be a powerful halogen light or as powerful LED light as possible. Most of the present LED lights tend to have three, five or more LEDs within one physical light that is bad for a hologram because every point of light creates its own holographic illusion. It was tested in school that when you have two bright LEDs above the hologram, it clearly did create two holographic illusions. Distance between these LEDs was approximately five centimeters. When the distance was reduced to one centimeter, it caused obvious blurring to the holographic illusion.

Mr. Esa Halmetoja from Senate-Properties had also tested different options for illuminating the hologram. Different kind of halogens and LED lights were tested. The best result was achieved by combination of a powerful halogen light and light fiber that was pointed directly above the hologram.

Magnifying glass was tested with multiple different light sources. When light was focused to smaller area, the holographic illusion was remarkably sharper and clearer. The difference of using a magnifying glass was much more greater to bare eye as the picture in figure 14 shows.



Figure 13: Hologram under halogen light, which is focused with magnifying glass

The personnel in Zebra Imaging, Inc. suggested three times that we should order official Zebra certified lighting. We made wrong assumptions about our lighting equipment. All halogen lights will not do the trick as they usually have reflective surface next to the light source itself. Photos and videos were shot at Helsinki Metropolia University of Applied Sciences, Leppävaara. The school's own studio had different kind of light sources. None of those lights worked as a proper light source for a hologram. Figure 14 is an example of wrong type of halogen light for illuminating the hologram and images in appendix 10 shows how the hologram looks under this type of halogen. Correct LED light is the black object in the figure 15 nearby television.



Figure 14: Wrong type of halogen light

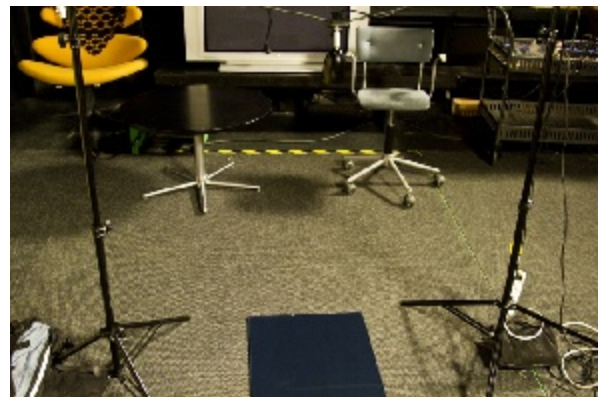


Figure 15: Experimental lighting stand with correct type of LED light

A Metropolia trainee Frans Tihveräinen helped me with photographing and filming the hologram as seen in figures 17 and 18. Matti Peltoniemi, who works as a project engineer in our school, borrowed two high definition capable video cameras (Canon Legria HF S100) and one systems camera (Canon EOS 7D). Mr. Tihveräinen took most of the photos and shot a video using Steadicam™, which is a mechanical camera stabilizer. I took a few stereoscopic still pictures. Mr. Tihveräinen used also his own systems camera (Canon EOS 5D Mark II).



Figure 16: Mr. Frans Tihveräinen using Steadicam™ while shooting video



Figure 17: Mr. Frans Tihveräinen shooting still photos

The most interesting thing while shooting photos from a hologram was that autofocus did not work properly. Manual focus gave the best images, as systems cameras could not interpret the holographic illusion the way a human eye can. Another challenge was the insufficient power of the light sources that we used. A camera objective gathers the light very differently from the human eye that causes a condensed field of vision. It was challenging to find a perspective where the whole holographic illusion would be visible to cameras.

5.2 Holographic user interface

When a person approaches a hologram for the first time in his/her life, he or she is able to use it as a new kind of user interface immediately quite intuitively without knowing about the technology behind it. Basically the only requirement for viewing a hologram is a correct type of light source and as little ambient light as possible. Basically, it works in a speed of light without having to deal with computers or special viewing equipment. A major limit is the viewing angle that is 45 degrees from every direction. If you try to look at the hologram too much from the side, the illusion disappears. Of course there is also an incline version that can be mounted to wall and seen from the side. Figure 19 shows an example of how the holographic user interface can be used.



Figure 18: Hologram dimensions can be easily measured with a ruler

It is also possible to draw directly to the holographic plate with drawing ink, preferably with whitish color. Transparency (plastic film) should be placed first above the holographic plate. It is important to remember that abrasion can damage the holographic plate. Drawing ink was not tested to the hologram during this research. [8, 9]

The dust above the holographic surface did not affect the holographic illusion at all. It was just a cosmetic issue. Figure 20 shows only how the dust appears above hogel plane and not the three-dimensional illusion.



Figure 19: Dust over a hogel plane

When selling your architecture related idea to a new potential customer, consider what kind of impact or impression you are able to give by using a hologram. When comparing a hologram as a media presenting method to 3-D television or classic architecture model made from cardboard, plastic and paint, it is rather clear that hologram will leave better first impression not just because it is a new kind of media but also because it is visually illustrative. [9]

6 Conclusion

The most important matter in this kind of project is to make clear at the very beginning where the holographic print will be used and by whom. Unnecessary go-between persons should be avoided during the project. Communication between the customer and Zebra Imaging should start by emailing to Zebra Imaging and telling about the project. When ordering a hologram within United States, the communication involves fewer emails and can be done mostly in the Zebra Imaging Online Store. It is essential to not make any assumptions of how the hologram works. Even when ordering the very first digital holographic print, you should be well aware of how it works and what requirements the print has. For a project such as this study, one needs to define the purpose for the hologram. Besides money, 3-D model and knowledge about 3-D graphic software it is important to have a place where you can view the hologram. If you have a reason to print thousands of holographic prints, an own imager device can be obtained to your company or campus by contacting Zebra Imaging.

This case study revealed a lot of information about holography that could not have been obtained without working with one's hologram. If the details are really important, the biggest or multiple tiled holograms are suitable options to avoid the limitation of the holographic resolution. Surfaces of the objects should not be flat color. Also, using of textures may cause time-consuming problems. Colors, textures, text and transparency should be used wisely and for a reason. The final touch comes from the light that illuminates the hologram.

Books related to digital holography were only supporting the theory behind holography but none of them said anything about the technology which Zebra Imaging uses. Only the main principle theories were the same. The biggest surprise were the issues concerning transparency of the school building in the hologram. It was supposed to be transparent in the first place but some may say that it came a little too transparent. The project ended up really well and it is really interesting to see first floor straight through a roof.

One should read Zebra Imaging Terms of Sale very carefully when placing an order. The contract is valid only after Zebra has approved the order. When a hologram is shipped by the Zebra Imaging, the company is not responsible for the product anymore. FedEx is commonly used for international shipping from Zebra Imaging but the customer still bears the possible risk of loss of the hologram during the shipment. When the hologram is shipped to non-US address, the order must be pre-paid before it can be shipped. From such data that has not been marked as proprietary, Zebra is authorized to create holograms from your data for marketing and promotional purposes. Customer data is usually deleted after 14 days from the creation date of the hologram.

Generally speaking the project finished successfully as the desired hologram was ordered and it is currently in use. It could be done more rapidly but in this case it was not necessary. New hologram orders can be done within a few weeks by the help of this thesis. The most time consuming part was to prepare the three-dimensional data set for a holographic print. Also, the light source that was not powerful enough to illuminate the hologram was a problem during this project. A proper and powerful light source was found by the end of this project.

As this thesis covers only specific type of reflection hologram, further possible studies could include Zebra Imaging's ZScape™ active holographic display or multichannel hologram. Another good field of study would be augmented reality combined to holography. Also, Zebra Imaging's edge lit hologram was not studied in this thesis.

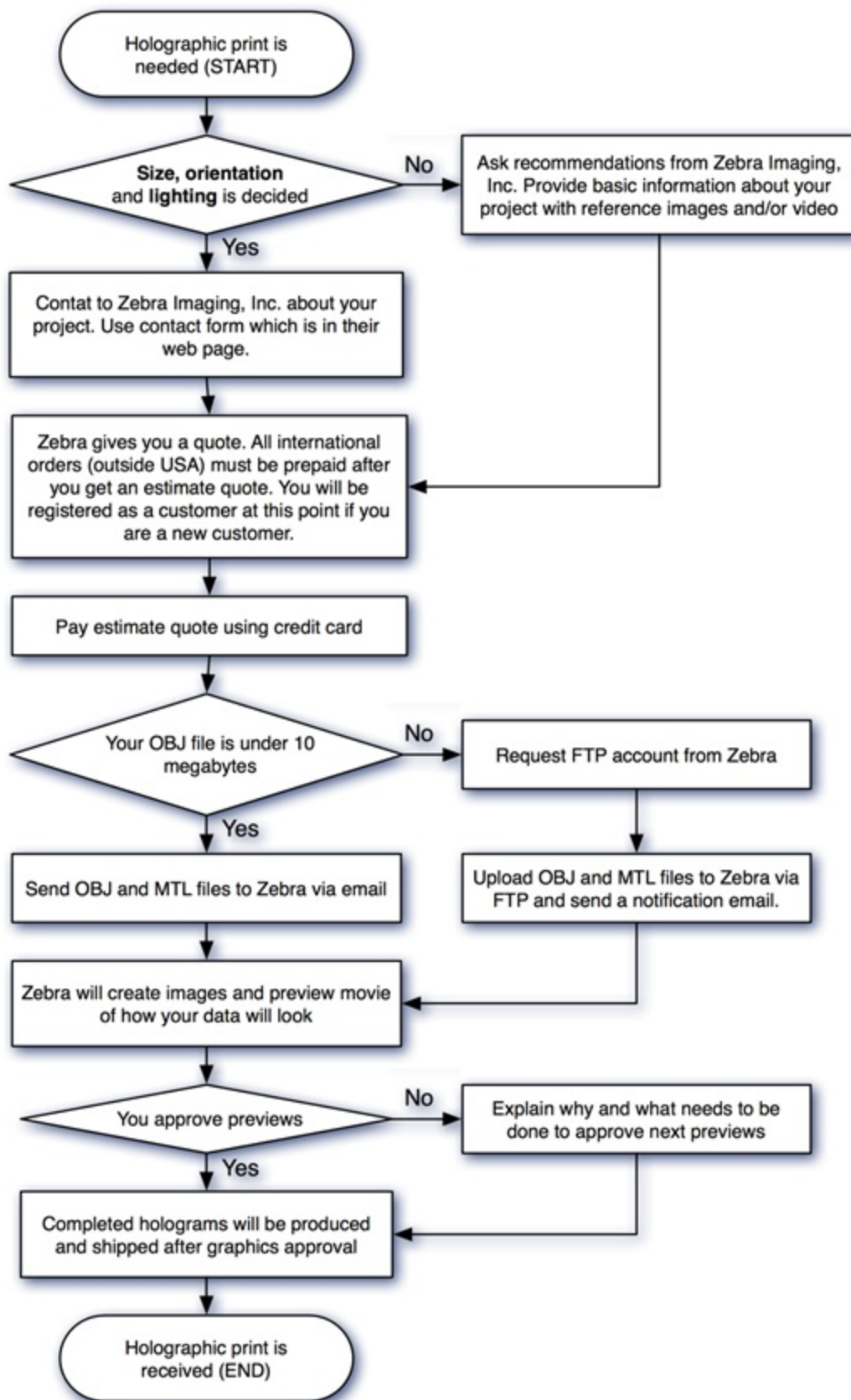
Usually, people are strongly interested in this kind of technology but there is always someone who does not see this as a good way of representing three-dimensional graphics. Holograms in the future can possibly show a bigger three-dimensional illusion from a smaller film with higher resolution. It might also become less critical what kind of light source is used for illumination.

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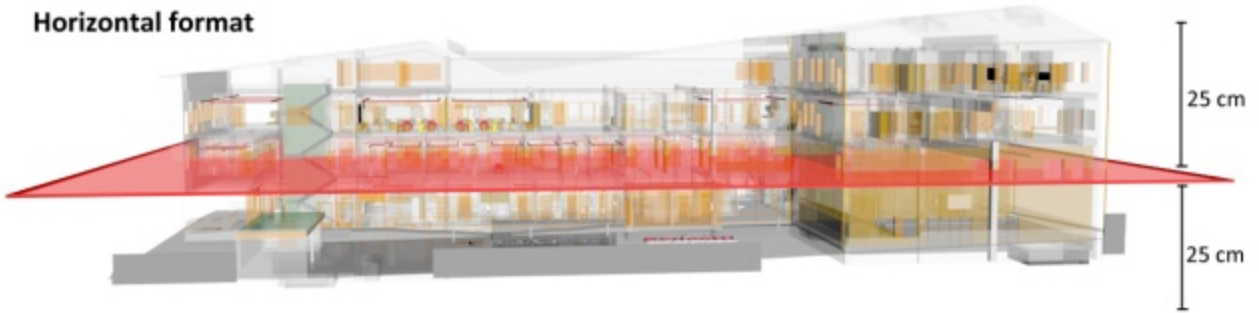
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Appendix 1: Flow chart of the ordering process

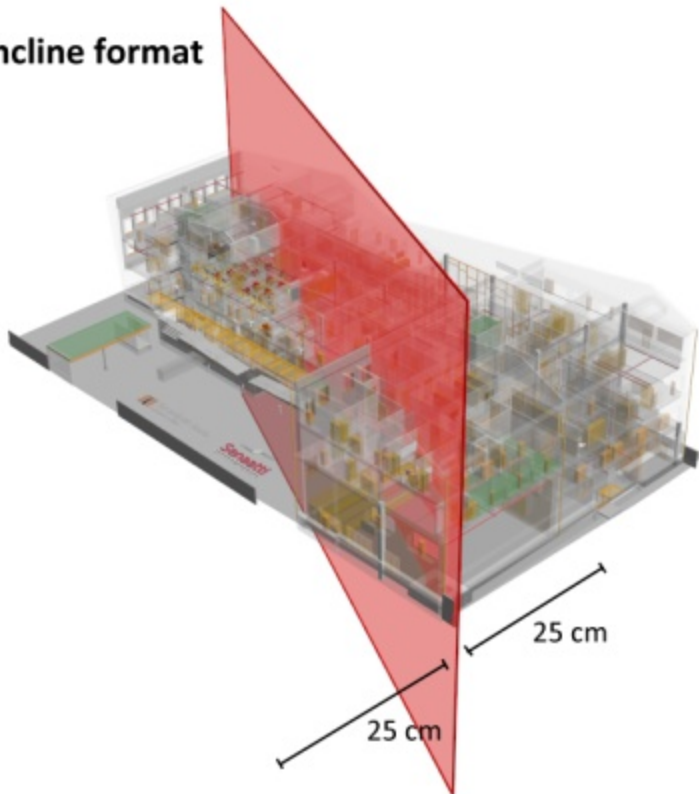


Appendix 2: Hogel plane orientation and depth of field

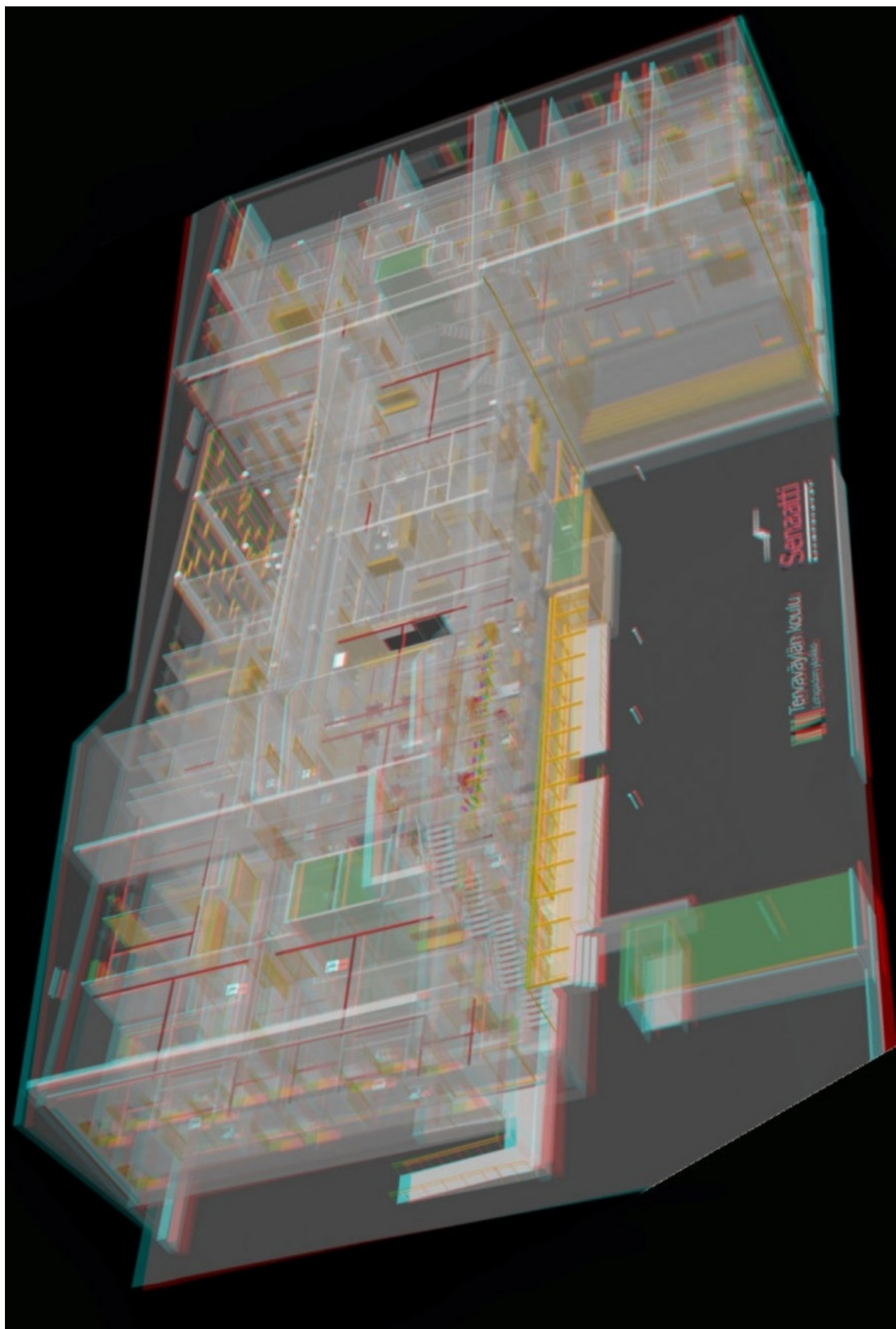
Horizontal format



Incline format



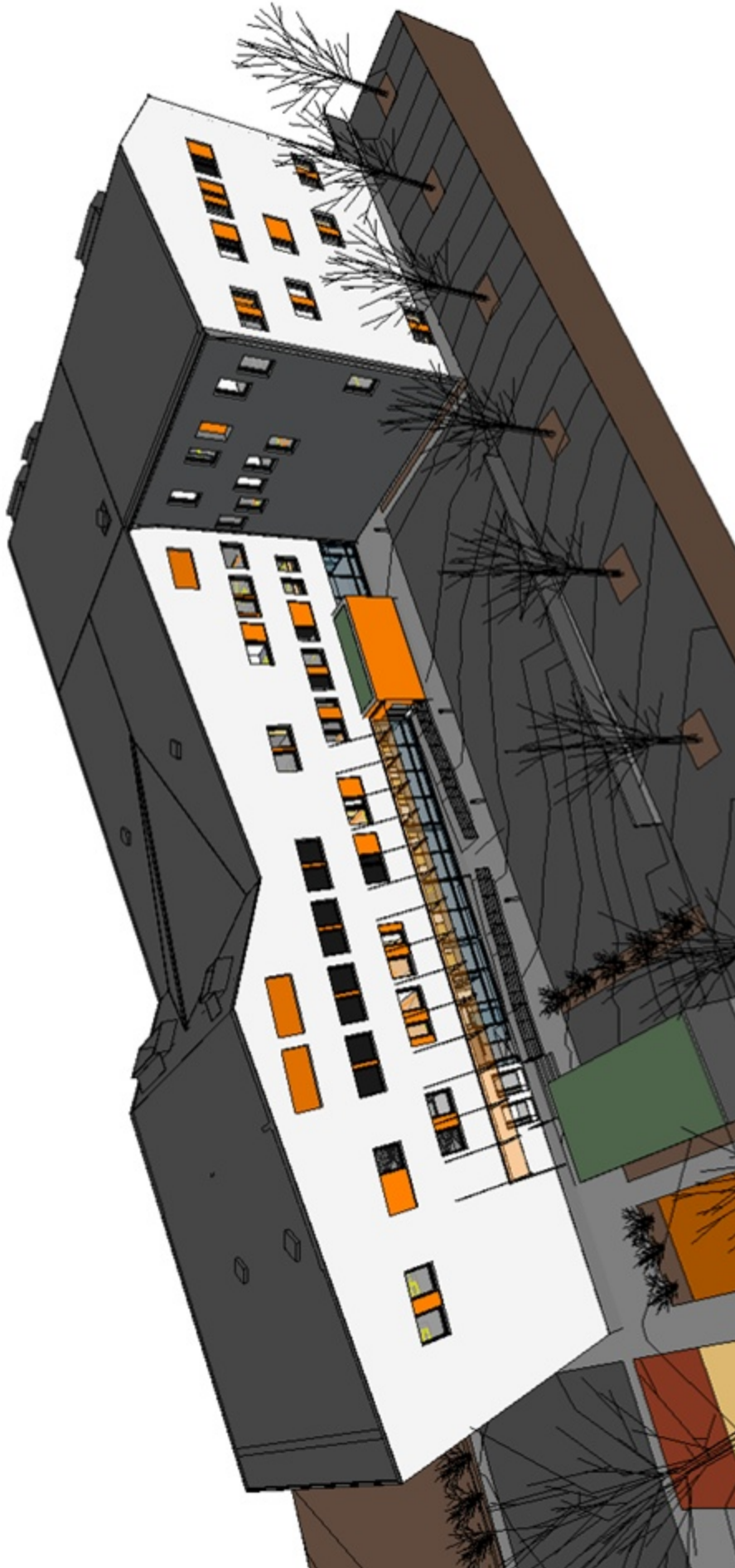
Appendix 3: Anaglyphic 3-D image of the school building



Appendix 4: Reference image of the school building



Appendix 5: Autodesk Revit image of the school building



Appendix 6: Cropped topography area

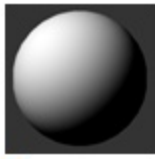
Inner area was used in the final scene. Outer area was cropped out.



Appendix 7: Materials used in the scene



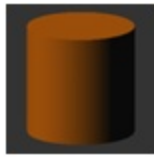
01
Default
Gray



02
Default
White



03
Default
Orange
Paint



04
Default
Orange
Metal



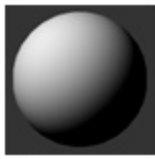
05
Default
Orange
Glass



06
Solid
Glass



07
Green
Grass



08
Ceramic



09
White
Wall
Paint



10
Metal



11
Free
Texture
Slot



12
Grey
Brick
Wall



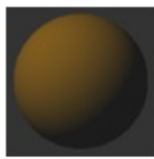
13
Roof



14
Floor



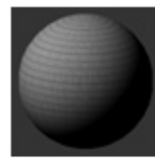
15
Ceiling



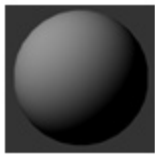
16
Doors



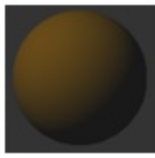
17
White
Wall
Paint



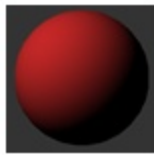
18
PoolTile



19
Opaque
Ramps



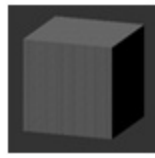
20
Furniture



21
Roof
Railings



22
Asphalt



23
White
Long
Tile



24
Pool
Water

Appendix 8: Structure of OBJ file format

```

# 3ds Max Wavefront OBJ Exporter v0.97b - (c)2007 guruware
mtllib Tervavayla.mtl
#
# object Specialty_Equipment__Kattokisko_i____Kattokisko_i_
#
# v means vector in the X, Y and Z space.
# vt means vertex texture in the UV mapping.
# g means group name for sub-object groups. f means face.
# The four numbers in f indicates which verticies was used to create the face.
v 24276.7031 -24741.0313 13580.0000
v 24276.7031 -24741.0313 13700.0000
...
v 24259.3809 -22941.0313 13562.6777
v 24259.3809 -22941.0313 13682.3223
# 16 vertices

vt 1.0000 0.1284 0.0000
vt 1.0000 1.0000 0.0000
vt 1.0000 0.0000 1.0000
vt 0.0000 0.0000 1.0000
# 20 texture coords

#
# object TervavaylanLogo
#
v 17433.2676 -44805.6797 7625.2920
v 17345.3809 -44805.6680 7625.2920
...
v 17437.9785 -45062.5039 7625.2920
v 17437.9785 -45062.5039 7659.2383
# 32 vertices

g TervavaylanLogo
usemtl wire_0000000000
f 1445 1446 1447 1448
...
f 1446 1449 1450 1447
# 18 polygons

```

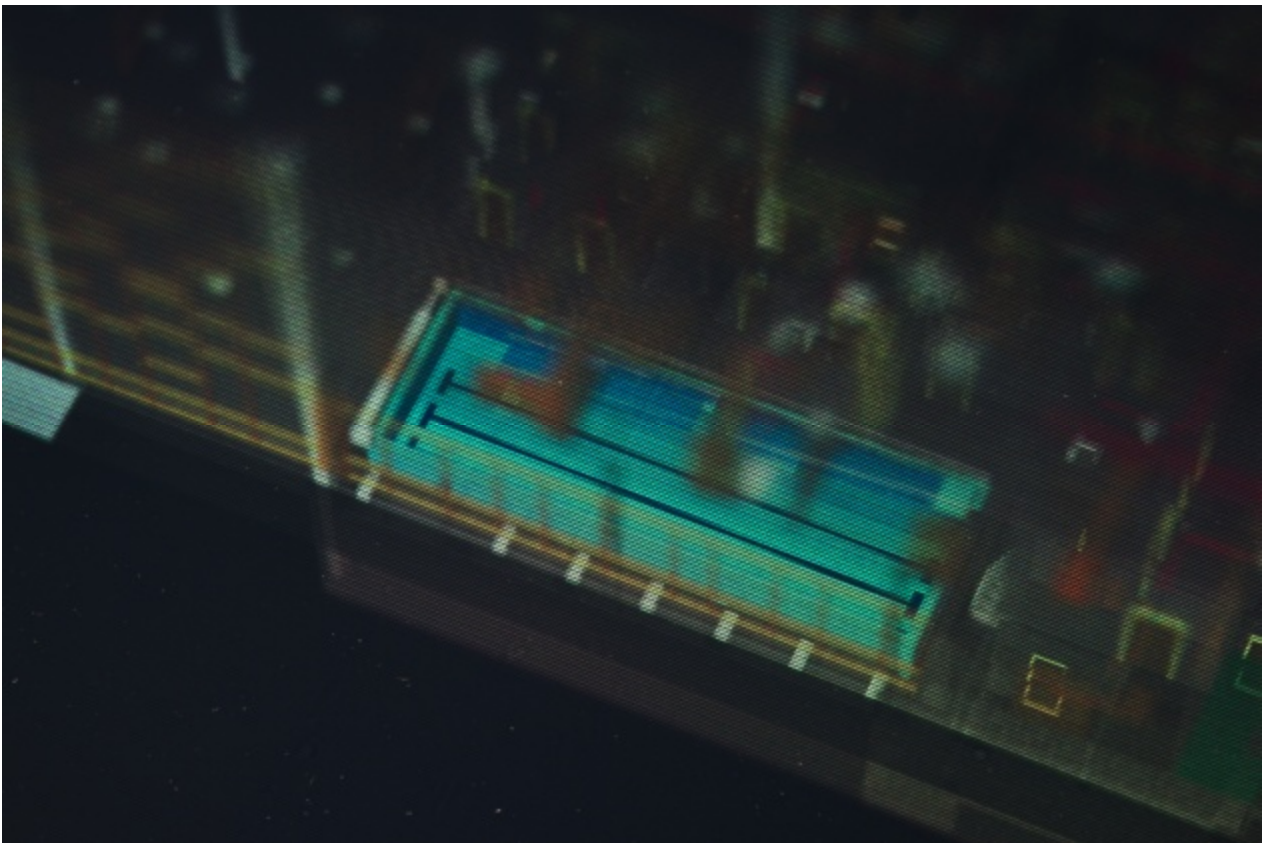
Appendix 9: Structure of MTL file format

```
# 3ds Max Wavefront OBJ Exporter v0.97b - (c)2007 guruware
newmtl 17___White_Wall_Outdoor
    Ns 10.0000                # shininess
    Ni 1.5000                 # refraction index
    d 0.1000                  # dissolve factor
    Tr 0.9000                 # transparency
    Tf 0.1000 0.1000 0.1000  # transmission filter
    illum 2                   # illumination number
    Ka 0.0000 0.0000 0.0000  # ambient color
    Kd 1.0000 1.0000 1.0000  # diffuse color
    Ks 0.0000 0.0000 0.0000  # specular color

newmtl 12___Grey_Brick_Wall
    Ns 10.0000
    Ni 1.5000
    d 0.5000
    Tr 0.5000
    Tf 0.5000 0.5000 0.5000
    illum 2
    Ka 0.0000 0.0000 0.0000
    Kd 0.1059 0.1059 0.1059
    Ks 0.0000 0.0000 0.0000
    map_Ka -s 6.0000 4.0000 1.0000 Brick_Non_Uniform.png
    map_Kd -s 6.0000 4.0000 1.0000 Brick_Non_Uniform.png

newmtl wire_000000000
    Ns 32
    d 1
    Tr 0
    Tf 1 1 1
    illum 2
    Ka 0.0000 0.0000 0.0000
    Kd 0.0000 0.0000 0.3255
    Ks 0.3500 0.3500 0.3500
```

Appendix 10: Hologram under wrong type of halogen light



Appendix 11: Hologram under LED lighting



Appendix 12: Hologram under strong ambient lighting

