Master's Thesis

Correct Projection Mapping on - and Interaction Techniques with - Cloth-based Deformable Surfaces

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Acknowledgements

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Abstract

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1 Introduction

Deformable displays allow new methods of interaction with virtual scenes, which simply are not possible on flat displays. These interactions are more immersive and feel more natural to the user as they touch, push, pull or pinch the deformable surface. The interaction with the scene can now be done in a 3D space, similarly to how we interact with objects on a daily basis, while also providing a degree of haptic feedback.

The first part of the master thesis project deals with the development of a deformable display prototype on which undistorted visuals can be projected. The distortion of visuals due to irregularities in the surface of an arbitrary-shaped object (the display surface) is the main problem that must be solved.

1.1 Problem Description

One of the main challenges when dealing with deformable surfaces, is correcting the distortions which arise from the user's interaction with the display. The image must be changed(the pixels must be shifted) so that the contents still appear as on a flat surface, even when the surface becomes an arbitrary 2.5D object.

If, for example, we are sculpting into or pulling out of a piece of cloth on which visuals are projected, some degree of distortion will appear on the final image. The image should be undistorted in the sense that, the visuals would still look like a fixed display (rather than being deformed with the display), after the previously mentioned pull or pinch gesture is performed. The solution will involve tracking of the cloth material and the modeling of a 3D representation of the material that is deformed based on depth sensor data.

In order to solve the problem we need to first setup a scenario where one can test how images are deformed when interacting with deformable displays. In order to do this we need: a surface that can be deformed by a user(e.g.: a cloth material) which serves as our display, a projector that is used to display contents to the end user and a depth camera that is used to track the display and surface and detect changes.

1.2 Hardware Setup

The deformable display prototype(see figure 1) consists of the following components:

- Cloth display (that can be deformed) + frame
- Projector that is used to display the visuals onto the cloth surface
- Depth camera that is used to retrieve the cloth displays depth information

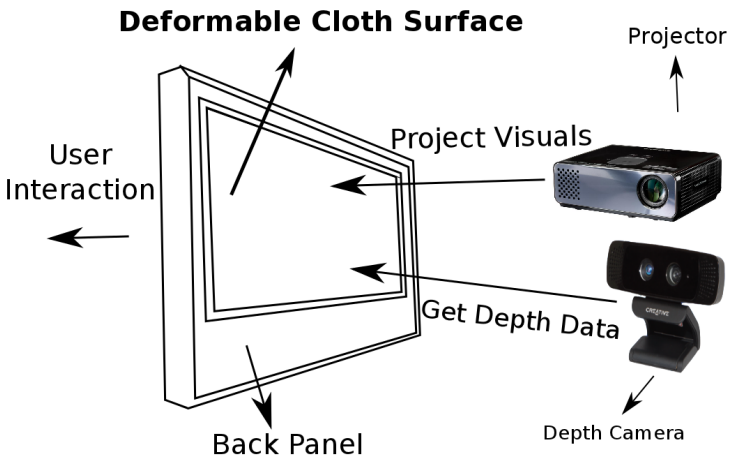


Figure 1: Physical setup of the prototype

2 Related Work

In this chapter, relevant research and related works are highlighted, mainly in relation to deformable user interfaces, tracking and projection techniques on deformable surfaces, interaction techniques with deformable displays, 3D projection and the design of affordances in order to convey information or suggest particular interaction methods. Investigating related research will help in finding solutions to projection issues with deformable surfaces. Moreover, this will also be useful in order to analyze, compare and contrast different approaches to tracking as well as correcting the projection distortion. Further, existing research on interaction techniques and affordances with deformable surfaces will provide a starting point to test, design and implement relevant interaction scenarios for the prototype. Finally, work related to stereoscopic and autostereoscopic projections will be consulted, in order to arrive at a sensible projection technique that can be used in the present case.

2.1 Tracking and Projection on Deformable Surfaces

In this section, literature related to projections on deformable surfaces as well as possible distortion correction and tracking techniques techniques will be presented.

As a starting point, it makes sense to consider existing approaches of projection onto complex or non-planar physical shapes. As discussed in [12], calibration is needed in order to correct distortions arising from a difference between the digital and the physical object. The study deals with projection on several

physical objects, including a complex, organic, non-planar shape, **Holger the Dane**, as shown in figure 2.

Figure 2: Projection on Holger the Dane. Courtesy of [12]

Further, it also proposes a few design themes for 3D projection on physical objects:

- New potentials for well-known 3D effects (lightning, particle systems, shadows, sound etc).
- Dynamics between the digital and physical world and switching between 2D and 3D projections allow to focus the projection on hotspots, while customizing properties allows outlines and switching material textures.
- Relations between object, content and context.

Although the information about the necessity of device calibration as well as the projection on a complex surface provide some insights into the projection distortion issue at hand, the study was only concerned with projection on static objects and thus, does not address problems arising from dynamic surface deformation, where the projection would need to be adapted in real-time according to the deformable surface's depth information.

FlexPad(figure 3) is a real-time interactive system with a highly deformable hand-held paper display. A projector is used to display the visuals, while tracking the display surface with a depth camera provides the required depth information for detecting changes in the surface. Further, as described in [38], any 2D image from Microsoft Windows can be projected and correctly warped unto the display.

Moreover, a deformation model(figure 4) is described, in their case using a 25 x 25 vertex plane at the size of the surface. The model can be represented by a 15 dimensional vector consisting of the angles of 8 basic deformations, a z

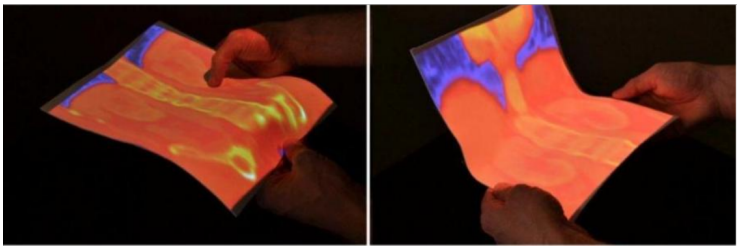


Figure 3: Interaction with Flexpad. Courtesy of [38]

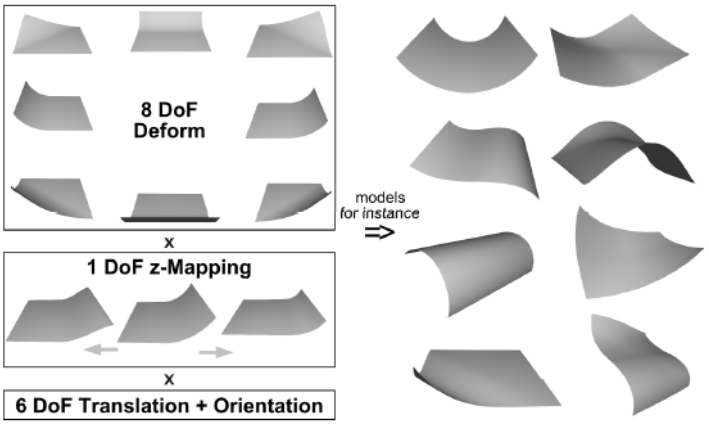


Figure 4: Deformation model of Flexpad(left) and deformations it can express(right). Courtesy of [38]

mapping parameter as well as 6 variables for DOF (degrees of freedom) required for affine 3D transformations.

After obtaining a deformation model, the tracking problem can be defined as finding parameters of the model such that, when synthesized as a depth image, they match the input depth image best(Analysis by Synthesis or AbS). This represents an optimization problem of finding the best parameter vector. The CMA-ES optimization scheme is used because it is a global optimization algorithm and it applies a smart distribution scheme, minimizing function evaluations needed to find an optimum. More information about these tracking methods will be presented below.

The primary limitations of the FlexPad come from those of the Kinect depth camera not being able to track very sharp bends, however these limitations could be overcome by installing several depth sensors or a more powerful sensor. The hand occlusion issue is not particularly relevant to the current project, since the depth camera will be installed in the back of the display, while interaction shall be from the front - thus completely removing this problem.

As discussed in [30], the deformation model can use NURBS surfaces, which can be easily handled via 3D control points, while being able to approximate every surface with arbitrary accuracy. These are widely used in computer graphics and can reduce the high dimensional space of all possible triangle mesh deformations.

The first step is to create an arbitrary NURBS surface using control points and knot vectors, using the algorithm discussed in [30]. Next, once we have a triangle mesh(which can be supplied from a modeling program or computed via OpenGL), we can approximate the mesh with a NURBS surface. The NURBS functions must be fitted to the mesh by minimizing the distance between the surface face function and the vertices of the mesh, or, in other words, finding control points for a given set of vertices, that minimize the sum over all squared distances. Mesh registration can then be performed by associating each 3D vertex coordinates to the previously generated NURBS surface. After this step, the mesh can be translated, rotated and deformed by displacing the control points of the NURBS surface function. Now we can apply an AbS method with a CMA-ES optimization scheme.

DeforMe is a projection-based mixed reality (MR) technique, which provides a method for augmenting deformable surfaces with deformation rendering graphics, as described in [4]. Projected graphics are realistically deformed to match the deformed surfaces. Mixed reality creates the illusion of a virtual modification of the physical surfaces. In this study, a flexible surface is used to allow the user to interact with the projected graphics while obtaining tactile feedback. Further, they present some drawbacks of existing tracking methods such as measuring surface deformation via a depth camera, which is not applicable to tangential deformations that can appear on a surface in a horizontal direction during interactions (e.g.: touching, pulling, etc.). To summarize, DeforMe is a projection-based MR system which allows projected graphics to be deformed to the deformation of the real object, while performing real-time es-

timations of the tangential deformation flows with a small number of feature points. Various deformable materials can be used without prior knowledge of their mechanical properties or deformation models. However, since depth information can be measured for a cloth-based deformable display (with the material properties being known), it is unclear if there is an immediate advantage of this method, for the current project, over the tracking techniques employed in the FlexPad system.

Another project that provides useful information on projecting onto irregular 3D surfaces, as well as tracking them using depth data, is **The Office of the Future**(see [21]). One of their objectives is to use real surfaces in the office, as spatially immersive display surfaces. High-resolution graphics is projected onto these surfaces(see figure 5).

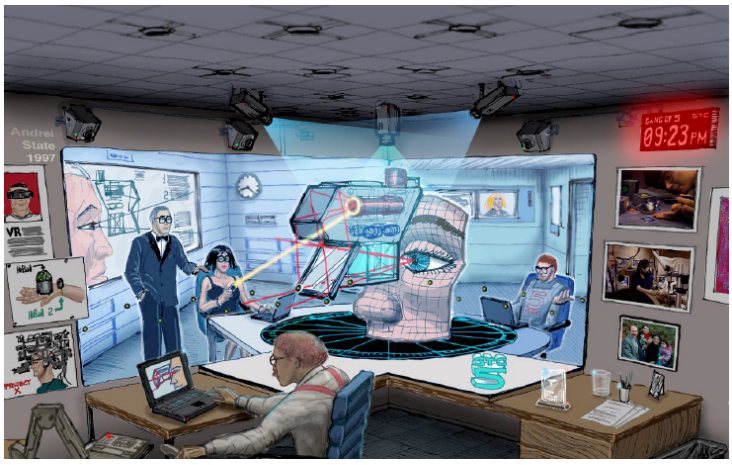


Figure 5: The Future Office. Courtesy of [21]

They extract depth using imperceptible structured light (projecting binary-coded patterns that are not detected by the visible eye and recording the images with video cameras) - this process can be replaced in the current project by the use of an off-the-shelf depth camera. Further, they describe how, by knowing the object's surface, the viewer's location, projector calibration parameters and the contents to be projected, they can render on irregular 3D surfaces by the use of conventional 3-D methods(e.g.: projective texture mapping), in real-time. Finally, they state that their system can be used to detect display surface changes at non-interactive rates. However, due to a large increase in computing power in recent years, and the possibility to write graphics programs that run directly on the hardware(e.g.: shader programs), similar techniques can be used today, to detect display surface changes in real-time.

The Deformable Workspace(see figure 6) is another approach to creating a deformable screen that acts as a boundary surface between the real and virtual

worlds and is presented in [5]. The workspace is set up in similar ways to other techniques by using an IR camera, IR projector and an LCD projector. Basically, the IR camera and projector could be replaced by a depth sensor such as the Kinect.

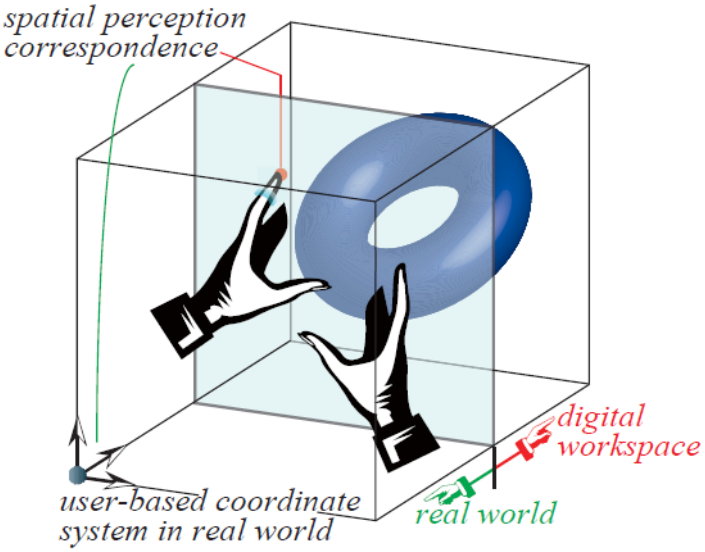


Figure 6: The Deformable Workspace Setup. Courtesy of [26]

Tracking is based on triangulation using structured light. A single snapshot of the illuminated surfaces is sufficient to grasp complete screen deformation - a high-speed camera acquires the image, and a dedicated co-processor for high-speed image processing calculates the coordinates of a 3D point for each spot of light in the pattern (real-time performance at 955fps with a latency of 4.5ms), as described in [25]. Although the frame rate achieved is incredibly high, this is a custom solution, that requires separate hardware. The previous method shall not be employed for this project as the deformable display can now be tracked with a standard depth camera(either a structured light or time-of-flight depth camera).

In [5] they also provide a method to compensate for projection distortion, given that both the calibration parameters and the shape of the deformed screen are known. An observation model in human vision is required to solve this issue, in this case, perspective projection. The technique involves pre-warping the image by shifting each projected point. Further, they claim that projective texture mapping can be used to calculate and render the warped image to be projected in real-time, efficiently and easily. A limitation of the previous approach is that an assumption has been made that the users eyes are fixed. However, a viewpoint-based projection should be employed to accommodate realistic scenarios - the virtual space must be rotated and transformed according

to the change of viewpoint.

As a final note, we can observe that the techniques used to project onto irregular objects and of correcting the visuals are similar in [26] and [21]: both extract depth information and form a polygonal model of the target object, they use the same rendering technique(projective texture mapping) and require the same calibration parameters.

2.2 Interaction Techniques with Deformable Surfaces

3 Prototype Design

Both the projector and the depth camera will be fixed in place relative to the deformable screen. Further, the projected visuals will be interactive applications that need to be rendered continuously. Finally, due to the fact that the projected image will be warped (distorted) according to the screen deformation, an algorithm is needed to shift the projected image pixels corresponding to the display surfaces depth data.

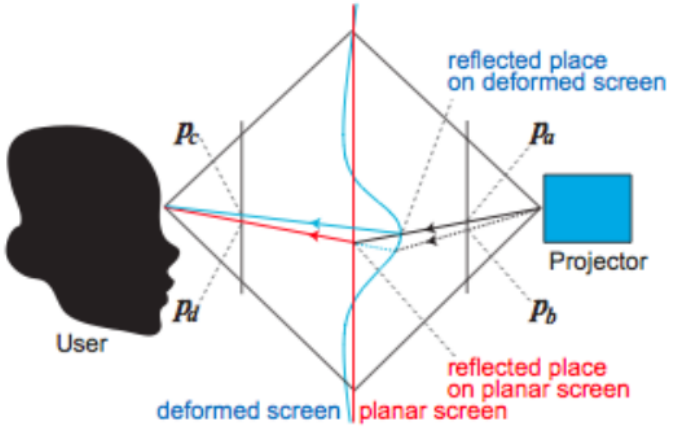


Figure 7: Compensation of image warp caused by screen deformation. Courtesy of [26]

In figure 7, p_d is the position where the ray is observed for a planar screen, while p_c is that of the deformed screen, if the projection is from p_a. To observe p_d for the deformed screen, projection must be from point p_b. Consequently, the image point needs to be translated to this position, in order to compensate for the distortion.

A possible approach to solving the distortion issue is discussed in [26], where

the authors state that in order to compensate for the distortions of the display one needs to know the shape of the deformed screen (depth data) and the projector calibration parameters.

Perhaps another solution would be to use some kind of spatial distortion, similar to the approach used for the **JellyLens** (see [19]). The focus + context lens(uses two levels of detail to connect a magnified region to the selected context) can dynamically adapt to the shape of the objects of interest. As we can see in figure 8, the object of interest adapts its shape(is magnified), while the context is preserved - surrounding objects are almost untouched by the applied distortion.

Figure 8: a) Only a portion of the object can be magnified with a small fisheye lens; b) A large fisheye magnifies almost the entire object, but at the cost of added distortion for sorrounding objects; c) JellyLens - adapting the relevant information of the object, while preserving the surrounding areas. Courtesy of [19]

The JellyLens can adapt to match the geometry in a three-step process:

- Obtaining information about the geometry of the objects (in our case, this can be accomplished by transforming our object depth data to 3D geometry)
- Computing the lens shape according to its position and visualization and to the geometry of the nearby objects of interest (in our case, the depth data can be used to determine how to shape the lens)
- Rendering of the region seen through the lens (in our case, we can apply a normal texture on the deformable mesh's geometry - that represents the contents, and distort it according to the lens shape obtained previously)

The authors of [19] also describe in detail how to model and adapt the lens using two techniques known as *AreaLens* and *PathLens*. For more detail about the process, please consult this reference.

For this project, a solution similar to that employed in [26] has been implemented. In order to get a better overview and understanding of the whole process required to correct the distortions, I have created a system pipeline(see

figure 9) that describes the whole process, at a high-level. Each part will be described individually in subsequent chapters.

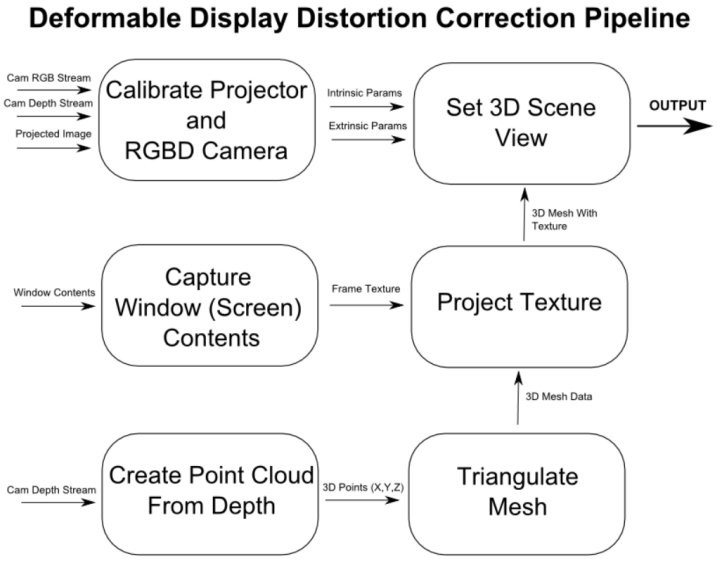


Figure 9: Distortion Correction Pipeline

4 Prototype Development

Considering our system pipeline, I will explain briefly, how the whole components work and why they are needed, in this section. The first process is calibration. Note that the order in which components are explained does not represent the flow in the pipeline, since it will be easier to see, for example, why calibration is needed once some of the other steps have been explained.

The idea followed in [26] consists of displaying the final application contents on a 3D model representation of the deformable surface. In order to obtain a relatively stable model, one can convert the depth data into a 3D mesh. An intermediary step required in order to do so, is to first create a point cloud from the depth data, or in other words, to use the depth value as the z-coordinate and create a cloud of points with coordinates (X, Y, Z) corresponding to the image pixels and depth.

Further, the application contents must be displayed in such a way that they distort with the object. Like with most problems in computer graphics, there is more than one solution. One could, for example, use raytracing to directly project rays of light on the object(also mentioned by the authors of [21]. However, this approach is known to be slow and may not run in real-time. Al-

ternatively, there exists a technique which has been tried and tested before, known in computer graphics, which projects a texture onto an object as from a slide projector. This technique can also be implemented in real-time on modern hardware, and, since the texture is projected from a virtual projector in the 3D scene, it will update with the distortions corresponding to the deformation on the object.

Finally, we need to make sure that our virtual camera corresponds, as closely as possible to the area we project onto with our physical display. Further, we also need to place our virtual projector, which also requires information about where the mesh(3D model) is placed, and how it is oriented. In addition to position and orientation we must also know the field of view(FOV), or the *"zoom level"* of our camera(as the other parameters depend on the FOV). In addition to the calibration required above, one also needs to manually(physically) align the projector so that if correctly fills the deformable display area. Furthermore, in case of manual calibration, the depth camera must also be placed as orthogonal as possible to the deformable surface area, so that it is easy to obtain acceptable parameters for the virtual camera and projector described above.

At this point, we basically have a solution to the distortion correction problem. The only remaining issue is to update the application contents dynamically, by capturing window/screen contents. This can be accomplished by using textures.

In the next sections, each of the above will be described in greater detail.

4.1 Calibration of the Projector and the Depth Camera

In order to properly display the contents on the deformable surface, three things must be ensured:

- The projector must be calibrated in order to find the intrinsic and extrinsic parameters that will be used to compute a transformation matrix that defines the world view of the 3D scene
- The physical projector must be aligned with the deformable screen area. Further, the depth stream must be adjusted manually so that the deformable display is almost perfectly in view, if the calibration is done manually, by trial and error;
- The projector and camera are static and must not be moved, otherwise the calibration process has to be repeated

The calibration problem is a projector-camera calibration problem, similar to the illustration shown in figure 10. The only difference being that, for this project, an RGBD camera(RGB stream + depth stream) is used. This means that there are two cameras: a normal RGB video camera, and a depth camera. If the calibration is done between the RGB camera and the projector, the RGB camera must then be correctly mapped to the depth camera or vice-versa.

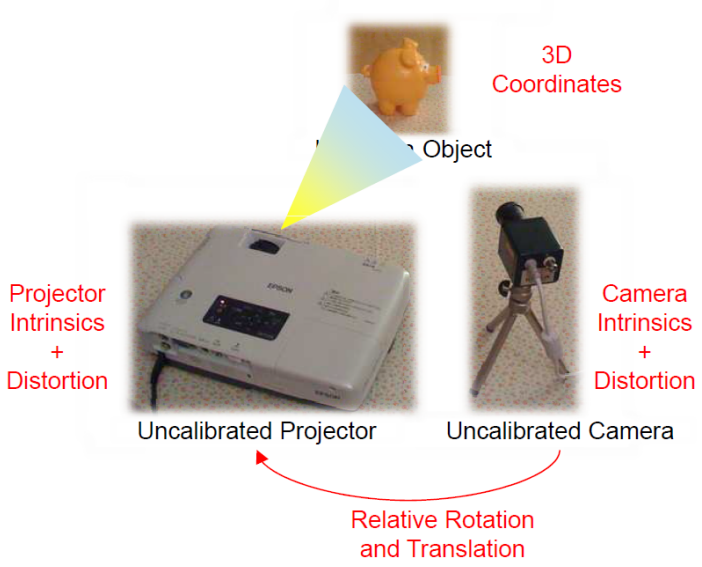


Figure 10: A setup that needs projector-camera calibration

In order to properly align the physical projector/camera with the virtual projector/camera we need to compute two matrices in a virtual world, based on parameters extracted from the calibration procedure. The first is the projection matrix, which can be represented as a frustum(see figure 11). We can define the projection matrix in OpenGL either by providing all the frustum parameters(the near and far parameters can be entered manually), or a field of view and aspect ratio, from which they can be computed.

It essentially defines the viewing volume of our 3D scene. In order to compute this matrix, one needs to know the intrinsic parameters of the physical projector. **Intrinsic parameters** refer to different aspects of a camera/projector such as focal length, scale parameters, a tilt compensation parameter and the image coordinates which define the image center or principal point. In addition, other parameters can be included to account for lens distortion. Lens distortion will not be addressed in the current project. The images projected with a modern device have low distortion.

Secondly, we need to compute the modelview matrix(see figure 12, for the structure of such a matrix). This matrix has information that relates to the position of the model(3D object space) as well as the camera(eye space). In this case, we essentially need to compute the view matrix from the extrinsic parameters, so that our virtual camera correctly points to the deformable display area on which our target contents are projected. **Extrinsic parameters** represent the **location** and the **orientation** of the projector/camera with respect to a

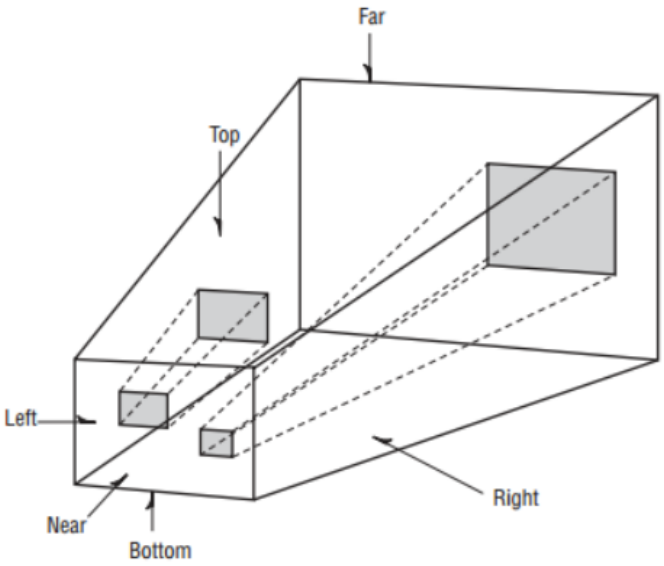


Figure 11: The projection frustum. Courtesy of [22]

world reference frame. For example, if we choose the world origin to be the position of the depth camera, then we can compute the rotation and translation of the projector with respect to the depth camera by finding the rotation matrix R and translation coefficients T. To obtain camera coordinates from world coordinates we simply need to multiply a position by R and add the translation T.

The pinhole camera model can be used to represent the projector, only the direction of the light rays are opposite, so the projector is in fact, an inverse camera model. The general pinhole camera model, where the center of projection does NOT have to be the world coordinate system is shown in figure 13.

4.1.1 Approaches to Calibration

- Structured Light Illumination Patterns

  The correspondences between 2D pixels and 3D world coordinates are found in both [20] and [27] by employing the structured lighting approach which involves projecting gray coded patterns that represent projector rows/columns onto the surface. This approach requires a camera to capture the projected patterns.

  An advantage of this approach is that it does not require any other physical items (such as printed checkerboard patterns), neither moving objects around, for calibration.

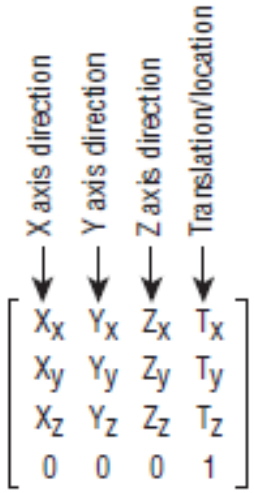


Figure 12: A 4x4 matrix that represents a position(column 4) and orientation(columns 1-3) in space. Courtesy of [22]

- Checkerboard Pattern

  Another approach for calibrating a projector-camera system is to use printed checkerboard patterns, extending from Zhang's method, as discussed in Chapter 3 of [14]. The known checkerboard patterns are projected onto a diffuse rigid object and their distorted appearance is photographed. Since a projector is the inverse of a camera, points on the image plane are mapped to outgoing light rays that pass through the center of projection. About 10-20 images with different positions and pose should be recorded.

  In [17] a plane-based calibration of a projector-camera system is described. It can be used to obtain the intrinsic and extrinsic parameters of both the camera and the projector. The steps involved are:

  - Calibrate the camera using Zhang's method
  - Recover calibration plane in camera coordinate system
  - Project a checkerboard on calibration board and detect corners
  - Apply ray-plane intersection to recover 3D position for each projected corner
  - Calibrate the projector using the correspondences between the 2D points of the image that is projected and the 3D projected points

The procamlib (https://code.google.com/p/procamcalib/) software package for Matlab can be used to calibrate the projector-camera system using this approach. The steps are explained in [17].

- Manual Adjustment

  It is also possible to adjust the physical projector and camera so that one can deduce the extrinsic parameters. The intrinsic parameters may also be obtained by looking into the respective product's datasheet and adjusting the value depending on distance, lens size etc. Otherwise, one must use a trial and error approach, and some tests need to be done to confirm that the accuracy is acceptable. Manual adjustment is likely to produce results of inferior quality, compared to the previous two methods.

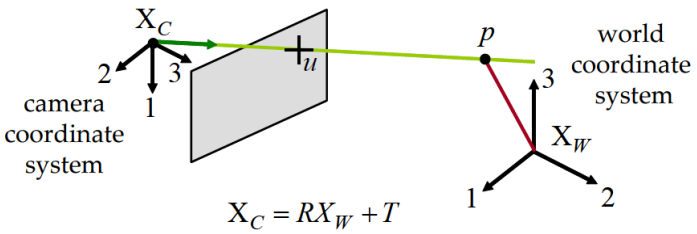


Figure 13: General Pinhole Camera Model

4.2 Creating a Point Cloud from the Depth Data

This step is an intermediary one towards creating a mesh structure on which textures can be projected. A 3D point cloud is a set of data points in the third dimension, usually defined by (X, Y, Z) coordinates.

The depth camera retrieves an image of 320x240 depth pixels. A point cloud can be created by using x, y values from 0 to the width and height of the depth image, respectively. The z value is simply equal to the depth, if the depth value is in a certain range(after it has been filtered). If the depth value is invalid, the current point is discarded and will not be rendered.

Further, the point cloud must be updated in real-time. Rendering is being done with OpenGL, and the previous can be accomplished by using simple hardware graphics shader programs and OpenGL's Vertex Buffer Objects(VBO). The OpenGL point cloud also has to be rotated, as it is upside down(unless the depth camera is positioned upside down).

In the following, I will include a subsection with information about the general rendering process, which is applied to render 3D objects with the programmable OpenGL pipeline. The process is similar, whether we wish to render a point cloud, or a 3D mesh, only the vertex attributes(position, color, texture

coordinates, normals etc.) which are stored in the VBOs and the programmable shaders will change.

4.2.1 Rendering

The transformation pipeline(see figure 14) describes how the vertex information is transformed from raw data, to window coordinates that can be viewed on a screen. The raw vertices are first multiplied by the modelview matrix, which yields the transformed eye(view) coordinates. Then, we multiply the result by the projection matrix and obtain clip coordinates. All data outside the clipping space(frustum) is removed. Then, coordinates are divided by the w value to yield normalized device coordinates in the +/-1.0 range, for all axes. Finally, OpenGL internally maps the scene to a 2D plane by the viewport transformation matrix, based on the viewport parameters provided.

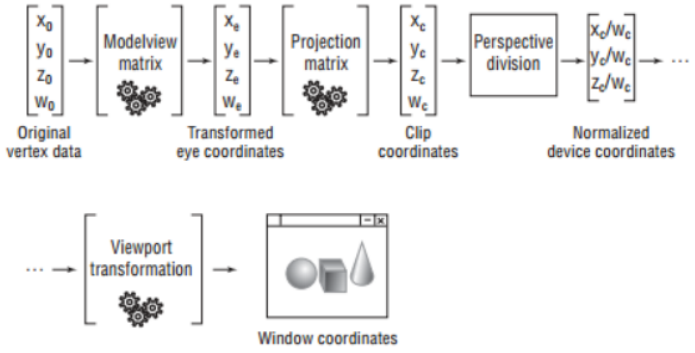
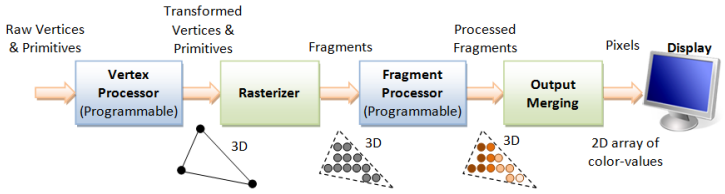


Figure 14: Vertex Transformation Pipeline. Courtesy of [22]

In the following, I will briefly describe the 3D graphics pipeline, shown in figure 15. It explains the stages required to process the vertices in order to obtain colored pixels and how vertex attributes can be programmed in the two shader stages(using the vertex and fragment processors).



3D Graphics Rendering Pipeline: Output of one stage is fed as input of the next stage. A vertex has attributes such as (x, y, z) position, color (RGB or RGBA), vertex-normal (n_x, n_y, n_z), and texture. A primitive is made up of one or more vertices. The rasterizer raster-scans each primitive to produce a set of grid-aligned fragments, by interpolating the vertices.

Figure 15: 3D Graphics Pipeline

As we can see from the pipeline, the raw vertices are processed by a vertex processor which manipulates vertex related attributes, most generally, position. For example, a vertex shader(a program that runs on this processor) can be used to apply the modelview matrix to an input vertex. Next, the data is rasterized into fragments.

A fragment contains the data necessary to generate a single pixel's worth of a drawing primitive in the frame buffer(the frame buffer is a portion of memory that contains a bitmap that will be sent to the video display - it represents a complete frame of data): raster position, depth and, after the fragment shader stage, it also contains interpolated attributes such as color and texture coordinates as well as a stencil value, an alpha value and the window ID. Note that a fragment only corresponds to a pixel if antialiasing is turned off, otherwise there will be K fragments for a pixel for Kx level antialiasing. As we can see from the above, the fragment shader receives fragments and processes them, computing color and texture coordinates. This shader can be programmed to color the geometry in any way desired. One can also apply textures and lighting at this stage. Finally, fragment shaders are also useful for visual debugging, as shader programs can usually not be debugged, since they run on the GPU hardware.

4.2.2 Limitations

Unfortunately, unless the point cloud is of sub-pixel density(which would also require a lot of processing power, due to the very large number of OpenGL primitives), it is easy to see that the target object is in fact made of discrete points(see figure 16). This breaks immersion, especially after applying a texture to the object. Due to this, we must then proceed to the following step, triangulation of the points into a 3D mesh.

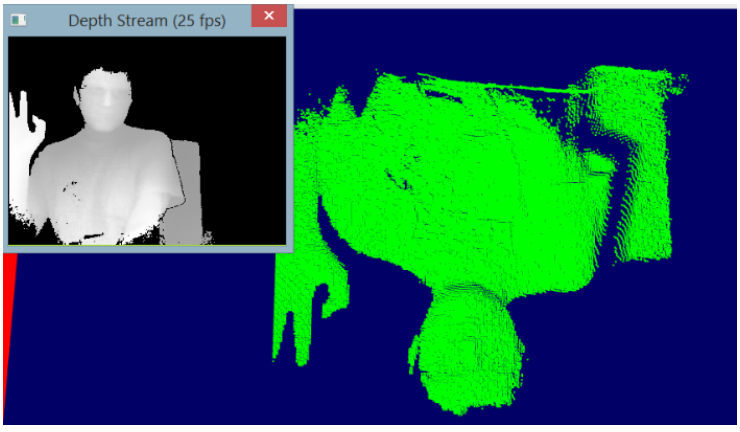


Figure 16: An example point cloud, corresponding to the depth stream, updated in real-time.

However, before we proceed, we must also unproject the points to world coordinates(we just had pixel positions and depth values, but we need to obtain the coordinates in regular metric space, so that the distances between the points are correct). This operation requires knowledge about intrinsic camera parameters, since we need to know the projection matrix, in order to unproject the points:

$$point => Viewport^{-1} => Projection^{-1} => ModelView^{-1} => PointInWorldSpace$$

The modelview matrix should be the identity matrix at this point, since we have not manipulated the points. More information about the unprojecting process is available in [18], although the authors unproject a 2D mesh with a set of sparse depth points. Nevertheless, the authors explain that unprojecting is the inverse process of how normal images are obtained, by projecting rays into a camera. In order to compute the rays, one needs to know the focal length and image center(intrinsic parameters), as well as the distance of the unprojection(ray length, which, in our case, corresponds to the depth for that pixel). They explain that the 3D position for a vertex $v(x, y)$ can be denoted by $p(v)$ and is determined as:

$$p(v) = t(v) * \vec{r}(v),$$

where $t(v)$ represents the ray length and $\vec{r}(v)$ represents the ray direction and is equal to

$$\vec{r}(v) = (\frac{x - x_c}{f}, \frac{y - y_c}{f}, 1)^T,$$

where (x_c, y_c) is the principal point or image center and f represents the focal distance.

However, the official library for the depth camera used in this project provides a very useful method that computes the unprojection given the array and number of points. So in the end, that is all we really need to know in order to un project the points, if we are using the *Creative Senz3D* depth camera.

4.3 Object Reconstruction by Mesh Triangulation

Before delving into the different methods of object reconstruction, it should be mentioned that there is an alternative to the full reconstruction approach. In [29], a method of tracking deformable objects using depth and color streams is described. The authors of this paper have used a NURBS(Non-uniform rational b-spline - common in computer graphics; can be used to approximate curved surfaces) based deformation function to decouple the geometrical object complexity from the complexity of the deformation. They deform the mesh using a number of control points(low dimensional space when compared to the number of vertices) on the NURBS surface to which the object is mapped. However, it is still needed to have an initial mesh and one way to obtain it is to define a 3D object from the initial frame of the video streams. The desired object can first be

segmented out of the frame, and then the 3D vertices can be unprojected to 3D space and connected according to their adjacencies in the depth image(actually, in section 4.3.1 a similar method is used, but it is running on the GPU and updates the mesh every frame). This mesh can be subsequently deformed using the control points, so that it matches the depth and/or color data. The mesh is also mapped to the color image to retrieve the colors of the vertices, but this is not needed for the deformable display, since a texture will be projected onto the mesh, completely replacing any color and lighting information.

Coming back to the general topic of object reconstruction, there are several techniques for reconstructing a 3D mesh from a point cloud. An important aspect for our deformable display is that we only need a 2.5D correct mesh, similar to a terrain(see figure 17) or heightmap.

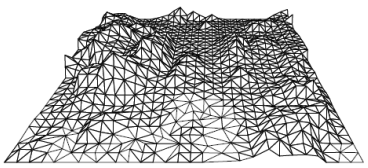


Figure 17: Perspective View of Some Terrain. Courtesy of [16, Chapter 9]

In order to obtain a full 3D model of an object, we would, anyway, need to rotate the depth camera around the object, or use multiple depth cameras, that look at the object from different angles. We always look from the front of the deformable display, as we would, down on a terrain, so such 3D detail is not needed. Therefore, the most straight-forward, naive approach, is to simply find any triangulation for the point cloud. In order to do this we can consider a grid of points, that can be connected either by using triangles or a triangle strip. The main idea of this method is also shown in figure 18, where a terrain is triangulated from some sample points.

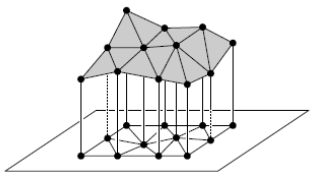


Figure 18: Polyhedral(solid object with flat surfaces) Terrain. Smoothness will depend on point density. Courtesy of [16, Chapter 9]

Although the naive approach has been implemented and used in this project, some more sophisticated alternatives will also be described and contrasted, as this approach was not the first one attempted.

4.3.1 Connect a Grid of Points with a Triangle Strip

Since the depth data captured via a depth camera is ordered, the easiest way is to consider the point cloud as a grid of points. Then, one can connect the vertices together using triangle strips. Triangle strip representation is a method of drawing triangles that can save some of the memory bandwidth, by connecting a new triangle to an existing strip with each new point. This means, that, for example, if we want to draw two triangles, we only use 4 points, instead of 6, which we would normally need. An important thing to keep in mind is triangle winding(the combination of order and direction in which the vertices are specified). By default, OpenGL considers counterclockwise winding to represent front faces, and clockwise winding to represent backfaces. This enables the use of back-face culling for optimisation(we do not need to render triangles which are not visible), and are also important for normal calculation, and thus lighting. Although we are not concerned with lightning in this project, it is always good practice to keep the winding consistent. For more information about triangle strips and other OpenGL methods of drawing primtives please consult [22, Chapter 3].

Coming back to the current problem, an internet article which explains how a triangle strip can be constructed from a grid of points is [13]. Figure 19 provides an overview, on how we can connect the vertices. Note that each point in the figure, numbered from 0-15 is a 3D vertex with coordinates (x, y, z).

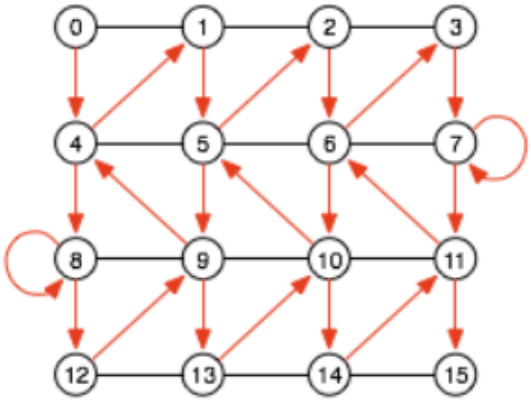


Figure 19: Ordering of vertices in a triangle strip for a grid. Courtesy of [13].

In this example, we can observe that on our path, we alternatively add 4 and subtract 3 for computing the next index, on the first row. On the next row, we still add 4, but subtract 5. The number 4 represents the number of vertices in the row or column, depending on how we advance($n + 1$ vertices, where n = number of divisions). The numbers 3 and 5, correspond to $m = (n + 1) + 1$ or $m = (n + 1) - 1$ and represent changes between adjacent columns. The number alternates, depending on the order of traversal on that particular row.

This approach provides a decent reconstruction, for a 2.5D object using data from a single depth camera. Normals can also be computed after we have the geometry(at an additional computational cost), however, there is no need for lighting in our 3D scene, since we will be applying textures(which represent the desired image contents) on the mesh before rendering. For improving the visual quality of the mesh, one could also look at more sophisticated methods of triangulation such as *Delaunay Triangulation*, or use standard 3D reconstruction techniques, like the *Marching Cubes* algorithm.

4.3.2 Other Methods for 2.5D Triangulation

The naive triangulation, by connecting the triangles without considering some measure of how natural it looks, may not provide the intuitively *best-looking* results. If the triangulation is not acceptable, it can be improved with a technique such as **Delaunay Triangulation**(explained in detail in [16, Chapter 9]), where triangulations are ranked by comparing their smallest angle(small angles, result in *skinniness*). The issue is shown in figure 20 where two triangulations of the same point set are shown. From the heights of the sample points, it seems as though the points were taken from a *mountain ridge*. If an edge is flipped to obtain very small angles for our triangles, we get what looks as a *narrow valley*(as you can see, the height value is now very small). The latter is a suboptimal triangulation and can be improved. Delaunay triangulation aims to find an optimal triangulation, given the fact that, for any set of points, there is a finite amount of possible triangulations.

However, for a dense set of points, such that obtained from the depth data, a naive triangle strip triangulation has provided adequate results - the deformation is clearly visible, both in the mesh and on the texture applied to the mesh. For this reason, Delaunay triangulation has not been attempted, although it may improve visual quality. It remains to be determined, as future work, if the computational cost involved is worth the possible increase in visual quality.

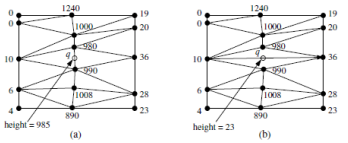


Figure 20: a)Mountain ridge; b) Narrow valley. Courtesy of [16, Chapter 9]

4.3.3 Marching Cubes on GPU

One of the classic computer algorithms for surface reconstruction is the *Marching Cubes* algorithm. An attempt was made to implement this algorithm. In order to run it on a GPU, one can use a *geometry shader* or *histogram pyramids* with a regular vertex and fragment shader. The attempt consisted of porting an existing implementation of the geometry shader for fixed-pipeline OpenGL to

modern OpenGL. Unfortunately, I did not get any geometry as output after running the algorithm, but there were also no errors. The problem is that I could not debug the shaders, since the tools I have tried did not work - some because of no support for modern OpenGL(3.0+) like *glslDevil*, and others did not work on my laptop because it uses the *nVidia Optimus* technology, as is the case for the *nVidia nSight* debugging tool for *Microsoft Visual Studio*. As this was taking too much time, I decided to go for a simpler approach, that should still prove appropriate for the real-time 3D reconstruction of the cloth, described in section 4.3.1. Nevertheless I will briefly describe the algorithm in the following section, as well as how it can be implemented on a GPU. This may be useful to look into, as an extension to the current project, if a higher quality mesh is desired(this method works well for 3D objects in general, and is not restricted to 2.5D, as is the case for the currently used method).

The Marching Cubes Algorithm

It was originally designed to create triangle models from 3D medical data - usually volumetric data, using voxels for representation(voxels are similar to pixels, only they exist in 3D space and can be represented as a cube). The algorithm also needs each vertex of the dataset to have a scalar value, that usually represents a property of the underlying data set. An example of such a voxel set is shown in figure 21. This value will be used to construct an isosurface, by comparing where vertices of the voxel edges intersect the surface(given a constant user-defined threshold or isovalue).

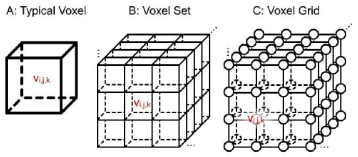


Figure 21: Voxel data representation. Courtesy of [34]

The authors of the original paper on the topic state in [32] that two primary steps were used in their approach:

- Locating the surface corresponding to a user-specified value(isolevel) and creating triangles.
- Calculating normals to the surface at each vertex of each triangle, in order to ensure a high quality image.

Since only the 3D mesh coordinates are required in order to capture the distortion of the cloth, the issue of calculating normals will not be described further, and we shall focus on the first part of the algorithm(although it should be mentioned that a fully shaded, reconstructed model could be useful for some

calibration approaches, since, at the time of this writing there are no reconstruction libraries for the depth camera used in this project).

The algorithm uses a divide-and-conquer approach by using logical cubes of eight pixels to locate the surface. How the surface intersects every such cube needs to be determined. In order to do this, a value of one is assigned to a cube's vertex, if the data value at that vertex exceeds the value of the surface we are constructing(if the scalar value is above a threshold called the isolevel). These vertices are inside the surface. Conversely, a zero value is assigned to values below, and thus outside, the surface. The surface intersects the cube edges where one vertex is inside and the other outside.

Moreover, there are eight vertices in each cube and two states(inside and outside) so we have a total of $2^8 = 256$ cases for intersection with such a cube. However, by eliminating symmetries, like complementary cases and rotational symmetry, the number of distinct cases of triangulation can be reduced to 14 patterns.

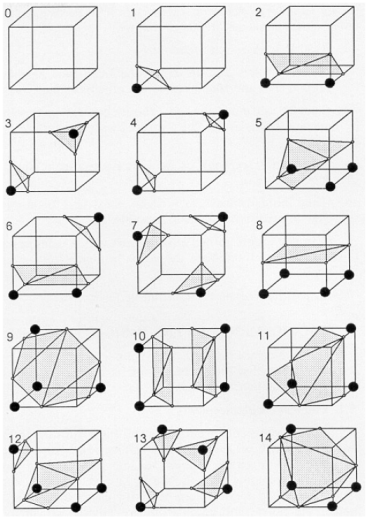


Figure 22: Marching Cubes - The 14 Patterns of Triangulated Cubes. Courtesy of [32]

As an example, the cube for pattern one in figure 22 contains one of the surface vertices(the lower-left vertex of the front face) and results in one triangle defined by three edge intersections. An eight bit index is created for each case, and it corresponds to the cube's vertex states(see figure 23). This index points to an edge tables that retrieves all of the edge intersections for the given cube configuration. The triangles are calculated using linear interpolation of the scalar values along the vertices of the respective edges(to determine the exact location of the triangle vertices on the cube edges). As described in [34], if $P1$ and $P2$ are the vertices of an intersected edge and $V1$ and $V2$ are the scalar

values of each vertex, the intersection point P is calculated as following:

$$P = P_1 + (isovalue - V_1)(P_2 - P_1)/(V_2 - V_1)$$

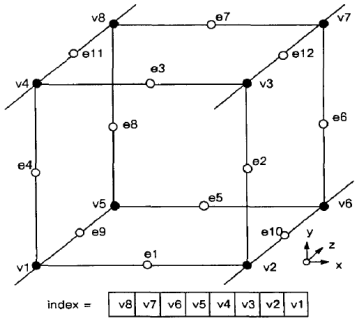


Figure 23: Marching Cubes - Cube Numbering. Courtesy of [32]

GPU Implementation

Geometry Shader

Many aspects from a classical implementation of marching cubes can also be used for a GPU implementation. This is the case with the basic look-up tables used to store edges and triangles. A version of these tables used in several implementations is available in an on-line article(see [10]), where the full source code is also available. Although, there is no version implemented in a programmable shader on the GPU available, an implementation using a geometry shader is described in another on-line article(see [11]). A geometry shader is simply a shader program that can be used to manipulate geometry directly - it allows the GPU to create geometry. This shader takes a single primitive as input(e.g.: a vertex) and outputs zero or more primitives(e.g.: zero or more triangles). This implementation is based on [10], with the main marching cubes logic inside the geometry shader. However, this implementation also uses deprecated OpenGL functionality. The main idea is that data can be stored inside 2D and 3D textures and can then be passed to the geometry shader as uniforms:

```
//Volume data field texture
uniform sampler3D dataFieldTex;
//Edge table texture
uniform isampler2D edgeTableTex;
//Triangles table texture
```

```
uniform isampler2D triTableTex;
//Global iso level
uniform float isolevel;
//Marching cubes vertices decal
uniform vec3 vertDecals[8];
```

In this code fragment the $dataFieldTex$ contains the 3D voxel scalar field data, the $edgeTableTex$ contains which edges intersect the current cube index, and the $triTableTex$ contains all the triangle indices needed, corresponding to each case. Next, the cube index is calculated by comparing the value in the grid(retrieved from $dataFieldTex$) with the $isolevel$ uniform. The position is retrieved by adding to the current vertex(to move the vertex at the appropriate position in the cube), the value in $vertDecals$. This adds the required offset in the x, y or z directions by an amount of $cubeStep$, which is defined initially. Having the cube vertex positions and scalar values, the interpolated values can now be calculated, for each edge. The final triangle vertices are retrieved by using the indices in $triTableTex$, for the previously computed interpolated values.

Histogram Pyramids

Another approach is to use histogram pyramids, as described in [15]. The authors state that their algorithm outperforms the known geometry shader approaches and it does not take much more effort to implement. The hierarchical data structured called the *HistoPyramid*, used for data expansion and compaction of 2D textures, is the focus of the previously mentioned paper. The term texel was used to denote single data elements, and the 3D array of voxels has been mapped to a 2D domain.

Implicit Surface Generation

As stated before, in order to use the marching cubes algorithm, one also needs to obtain a scalar value at each point in the data set, and, since we only have a point cloud, a function is needed to provide this - such a dataset is called an implicit surface. These functions were not a focus for this project, as the marching cubes algorithms was not successfully run on datasets that already represented implicit surfaces. However, in [34] the Hermite Radial Basis Function(HRBF) is mentioned as a workable method, please consult this resource for more information on the topic. Another function that can determine the scalar field is the Newtonian gravity field equation, please consult [37] for further information.

4.3.4 Greedy Triangulation

Another triangulation method that was briefly considered was the greedy projection algorithm described in [33]. As described in the previously mentioned source as well as in [34], the algorithm grows the mesh from a list of points, until

all points have been considered or there are no more valid triangles to be formed - in case of the latter, the algorithm is restarted somewhere in the unconnected area with vertices from a new *seed* triangle. The triangulation algorithm is of the greedy type(looks for simple solutions to a complex, multi-step problem by deciding which next step will provide the most obvious benefit) and incremental - it considers the neighborhood of the current point and projects it onto the plane that is tangential to the surface formed by the neighborhood. Next, points are pruned(removed if they do not meet certain criteria) by visibility and then, the remaining points are connected to the current point(and consecutive points) by edges, to form triangles. An implementation of the algorithm was readily available, and as such, the algorithm was not studied in detail, although the two previously mentioned sources can be consulted for more information.

An implementation is available in the PCL library, and a description on how to use it can be found in [36]. The algorithm has been tested on the bunny mesh that is mentioned in the PCL tutorial. The result was a triangulated mesh of the provided point cloud. The algorithm also computes the normals and a shaded model of the object is shown in figure 24. However, this was a static object and it was only comprised of about 400 vertices. When the test was run on the point cloud retrieved by the depth camera, the algorithm was running very slow, and it was clear it could not achieve an interactive framerate - it was taking seconds or even minutes per frame, before giving warnings/errors about the dataset; the size of the point cloud was of about 70000 vertices. Indeed, in [33] it is mentioned that the algorithm is (only) near real-time. Further, a performance analysis is provided, where a point cloud of comparable size was reconstructed in about 9 seconds. Some of the parameters of the algorithm could perhaps be changed in order to improve performance(and remove the warnings), although, it is unlikely that this method will reach an interactive frame rate of about 30 frames per second or more. This is an important aspect to consider, as the distortion of the cloth display needs to update reasonably fast(at interactive speeds) in order for the system to be usable. Due to the previous reason and time constraints, the alternative described in section 4.3.1 was employed.

Figure 24: Mesh from point cloud reconstruction of a bunny.

4.3.5 Kinect Fusion and Kinfu

4.4 Projective Texture Mapping

An article by NVIDIA which also references [24], describes projective texture mapping and how it can be implemented using OpenGL (see [28]). A short summary of this is presented below.

For projective texture mapping we need to use homogeneous texture coordinates. For example, for a projective 2D texture we have the coordinates (s,t,q) where the interpolated homogeneous coordinate is projected to a real 2D texture coordinate by dividing both s and t by q to obtain, (s/q, t/q). The homogeneous texture coordinates have to be assigned per-vertex. The final step implies a range mapping with [0,1] for each coordinate (using a scale and bias, so that the texture coordinates change from [-1,1] to [0,1]). In figure 25 the transforms that are applied to a vertex position in order to compute projective texture coordinates are displayed.

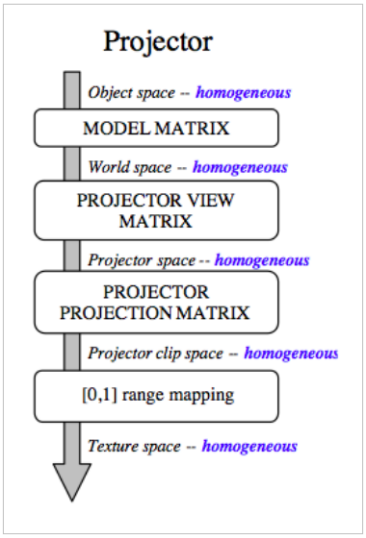


Figure 25: Virtual Projector Transformation Pipeline. Courtesy of [28]

The vertex position in object and eye space is used to generate the texture coordinate. In OpenGL this can be accomplished with the *texgen* facility (generates texture coordinates from vector attributes). In the *object* and *eye linear* modes, the texture coordinate is computed by solving a plane equation at the vertex position. Evaluating a plane equation is equivalent to a 4-component dot product, so the texgen planes form a 4x4 matrix, T:

where s, t, r, q are the texture coordinates, v are the vertices in *eye* or *object* space and T is the texgen matrix in eye or object space.

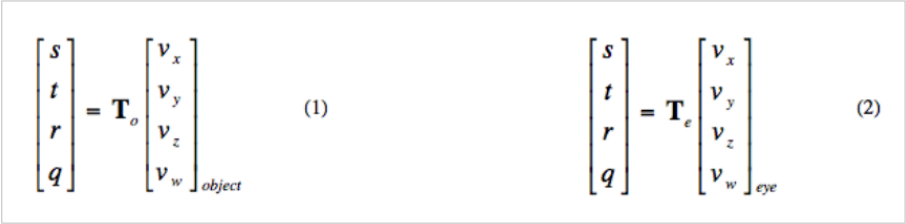


Figure 26: Projective Texture Coordinates from a 4x4 matrix and the vertices in object or eye space. Courtesy of [28]

4.4.1 Object Linear Texgen

The object linear texgen can be represented as shown in figure 27, where the first matrix is the scale-bias matrix, M is the model matrix (in our case this should be the model matrix of the deformable display), V_p is the view matrix for the projector and P_p is the projector's projection matrix.

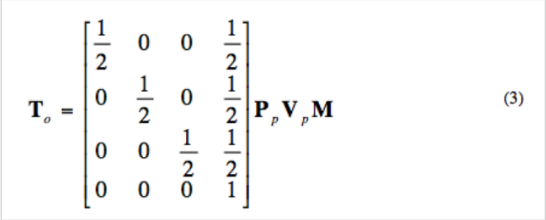


Figure 27: Object Linear Texgen. Courtesy of [28]

4.4.2 Eye Linear Texgen

The eye linear texgen can be represented as shown in figure 28, where the same notations are used as in the previous section, but instead of multiplying with the model matrix M in the end, we multiply with V_e^{-1} which is the inverse of the eye(or camera) view matrix.

4.5 Capturing Dynamic Contents

5 Prototype Implementation

5.1 Tools and Technologies Used

The prototype has been implemented in C++ using *OpenGL v3.3*, which uses the programmable OpenGL pipeline(the vertex and fragment shaders must be programmed to suit the problem's specific needs). This means that shaders must be used to render graphics on the screen. This choice was made because

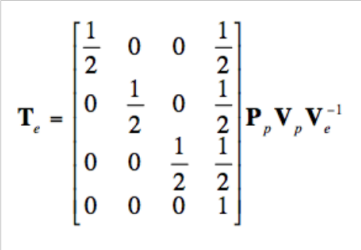


Figure 28: Eye Linear Texgen. Courtesy of [28]

of performance improvements over the OpenGL immediate mode, as well as allowing the code to take advantage of the latest OpenGL features, in possible future extensions.

The development environment used was the *Microsoft Visual Studio IDE*. Initially, development started on the 2013 version of the IDE, but due to incompatibilities with some of libraries used, the toolchain was switched to that of *Visual Studio 2012* (while still using the 2013 IDE - in order to do this, both versions need to be installed). Note that the professional edition of *Visual Studio* is needed in order to be able to install the plug-in for syntax highlighting of shader files.

Further, several libraries were used to create a simple graphics engine that can be used to render objects, import meshes, move around a virtual world etc. The *GLEW* (see [2]) library was used for importing the OpenGL functions and extensions into the project, while the *GLFW* (available at [3]) library was used for managing the window context, as well as for managing keyboard and mouse input.

Another useful feature is to be able to import textures and apply them to objects in the 3D world. The *FreeImage* library(available at [6]) has been used for reading in images and checking if the format is correct. Further, objects can be imported from standard graphics programs through ASSIMP(details at [1]), using well-known file formats like *WaveFront OBJ* and *Autodesk 3DS*. This feature was useful when debugging different aspects of the graphics engine and it was also used to test projective texture mapping on a physical ball, by using an imported mesh of the interior half of a sphere.

Another important library is *GLM* (available at [4]), which contains very useful math functions, like the ability to work with matrices and vectors, calculating the inverse of a matrix etc. In addition, this library uses the same syntax as that of GLSL(OpenGL Shading Language), which means that there is more consistency in the code and there is no need to learn a third-party syntax.

Further, the *Point Cloud Library*(PCL, available at [8]) was used for trying out some reconstructions techniques, like the greedy projection triangulation. However, this library has not been used in the final implementation, as the mesh was triangulated by connecting a triangle strip, using the fact that the point cloud was ordered, to connect adjacent points.

Finally, the only other library used was the *Intel Perceptual Computing SDK* (details at [5]) which can be used to retrieve the depth and color streams, and do some basic processing on the respective stream. For this project, only the depth stream was used. The data was quite noisy, so in order to reduce noise, some depth smoothing functions were applied. These will be described in one of the future sections. Otherwise, the library allows one to easily convert the data from the depth camera to a point cloud, as well as to unproject it to 3D space, as described in the following sections.

5.2 Virtual World Setup

The process to set up the virtual world will not be described in detail here. The structure of the code was inspired by the OpenGL tutorials available at [7], as well as several other on-line articles/tutorials describing OpenGL functionality. Basic functionality is contained in a class, or cpp file - for example, all texture related processing is the responsibility of the *Texture* class, shader programs are compiled and linked by the *LoadShader* method defined in *loadShader*.h/.cpp, etc. Next, the 3D world is created as a scene(indeed, several such scenes were creating during development, for testing purposes). Each scene must implement three different methods, inheriting from a *SimpleScene* class:

- $initScene(GLFWwindow * window)$ - used to initialize everything that is needed before rendering, for example, the compilation and linking of shader programs is done at this stage
- $renderScene(GLFWwindow * window)$ - this method loops continuously; it is called every frame, and it is responsible for the actual rendering that can be observed on the screen
- $releaseScene()$ - this is mainly used for memory deallocation and is called before the application exits

This template can be used to create new scenes, and all basic functionality such as texture and object importing, camera movement, shader compilation and linking, shaded/unshaded rendering by using different vertex and fragment shader programs, are already available and can be easily reused.

5.3 Point Cloud Generation

The *RawDepthPipeline* class is responsible for retrieving video frames from the depth stream. A method has been added, $renderFrame(..)$ that simply acquires the current frame so that the data can be converted to a point cloud, and subsequently a mesh. If the frame data is valid, a call is made to $createPointCloudMappedToWorld$ which is the function responsible for converting the raw data into a 3D point cloud, in world coordinates.

An array is needed to store the point cloud:

```
pcPos = (PXCPoint3DF32*)new PXCPoint3DF32[nPoints].
```

The data type is from the Intel Perceptual Computing library and represents 3D points with x, y, z coordinates and floating point values. Further, the number of points, namely `nPoints`, is set tot the maximum number of elements we could have in the cloud, which is equal to `depthCamWidth*depthCamHeight`, where the previous two variables represent the width and height of the depth frame, respectively. Then, we just need to iterate over all the depth values and retrieve the depth value:

```
pxcU16 depthValue = ((pxcU16*)ddepth.planes[0])[y * depthStride + x],
```

where `ddepth.planes[0]` is an array containing the depth data, and `x` and `y` represent the current index on the height, and width of the image, respectively. The `depthStride` is used to properly access a two-dimensional array using one index, and it represents the width of the row. Finally, we check if the depth value is in a certain range, and, if so, it is stored in our `pcPos` array:

```
if (depthValue > 10 && depthValue < 2000)
{
pcPos[n].x = (pxcF32)x;
pcPos[n].y = (pxcF32)y;
pcPos[n].z = (pxcF32)depthValue;
}
n++;
```

The elements in the array for which we do not have valid depth values remain uninitialized(n is incremented irrespective of the depth value). This is required, because when we send the array later to an *OpenGL VBO(Vertex Buffer Object)*, all valid elements are rendered. This means that initializing the values with, for example `(0, 0 ,0)`, would mean that a lot of points would be connected to the origin point `(0, 0 ,0)`, which is not desired.

The last thing that needs to be done at this stage is to unproject the points to 3D space. In order to do this, one needs to know the depth camera's intrinsic calibration parameters(these parameters relate to the field of view of the camera, distortion coefficients, principal point etc.). However, the Intel Perceptual Computing SDK provides a very handy method that does the necessary computation for us:

```
projection->ProjectImageToRealWorld(nPoints, &pcPos[0], worldPos.data()).
```

The *worldPos* vector array will contain the final points that will be rendered on screen. If we were to render the image now, we would get a 3D point cloud representation of our depth stream. Therefore, the final issue which remains is to connect the points in order to form a mesh, so that the texture will be projected on a polygonal surface. This process will be described in he following section.

5.4 Mesh Rendering

5.4.1 Rendering Process

In order to render a mesh that changes every frame at an acceptable speed, the use of OpenGL VBOs has been employed. This object is nothing more than a contiguous untyped block of memory(untyped means it does not have a particular structure; the structure is defined by the user as we shall see shortly), which can be used to store several vertex arrays and upload them to the GPU. A vertex array is usually used to store a specific vertex property, such as position, color etc. For an example of an interleaved vertex array with two attributes(position and color), please consult figure 29. Note that we are only interested in position for our mesh, since we will only use one full color of the mesh for debugging purposes and, the user will only see the color of the texture.

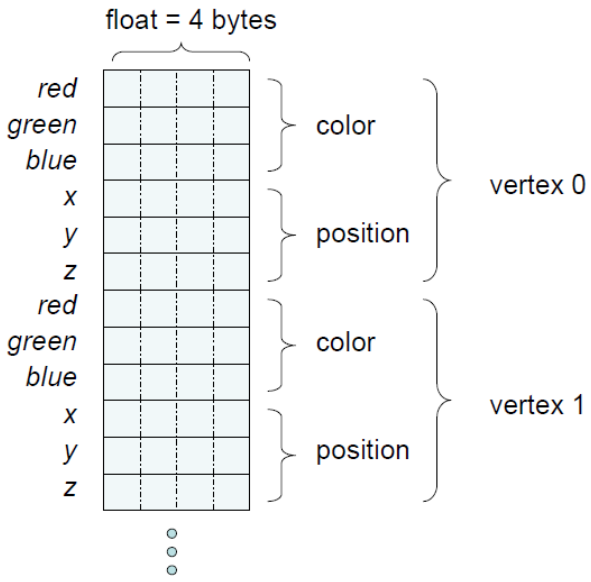


Figure 29: Vertex array layout with two vertex attributes. Courtesy of [31]

A good resource that explains how to properly use VBOs in OpenGL and why they are needed is [31]. The author explains that the GPU doesn't have arbitrary access to conventional system memory(so called client memory). With VBOs one can point the GPU at the vertex arrays and let it read the vertex attributes from the arrays contained inside it(the arrays are stored in spatially negotiated regions of memory, maintained as buffer objects, that both the application and the OpenGL implementation can access). An example of how the VBO data is transferred to the GPU via DMA(direct memory access) transfers is shown in figure 30. As you can see from the figure, there is no communication between the data and the CPU, all transfers are made using DMA transfers

directly to the GPU. This means that the performance can be greatly improved by avoiding unnecessary communication with the CPU. This is in stark contrast with the OpenGL immediate mode, where each call to `glBegin()` and `glEnd()` had to be sent first to the CPU, in addition to a full list of commands for drawing(now we just draw the VBO with one call to `glDrawArrays` or `glDrawElements`).

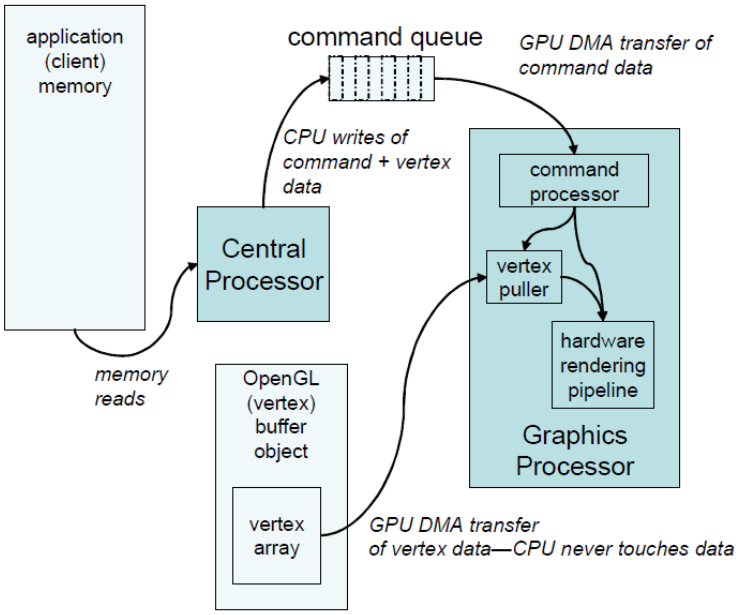


Figure 30: Transfers of vertex array object data using DMA.

We need to define the type of data and how much of it needs to be stored in a VBO. In order to do this we use a vertex attribute pointer:

```
// vertex positions start at index 0
// the distance between two consecutive vertices is
// sizeof whole vertex data
glEnableVertexAttribArray(0);
glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, sizeof(PXCPoint3DF32), 0);
```

The signature of the vertex attribute pointer method is as follows:

```
void glVertexAttribPointer(GLuint index, GLint size, GLenum type,
 GLboolean normalized, GLsizei stride, const GLvoid * pointer)
```

In the previous code we enable the vertex array with index 0. The *glVertexAttribPointer* is also set to index 0(first parameter), since it is the one and only attribute(for example, we could interleave data, if we also had texture coordinates; then the index would be 1 since 0 would have already been used by the

position attribute). In it we can store data with 3 components: x, y, z and we specify the size of $PXCPoint3DF32$. The size will be used as an offset to store the next vertex(stride). We only store the point cloud elements in this VBO and, therefore, we can just set the pointer to 0, as there is no other data stored in the VBO.

Before a VBO has to be used, it must be bound, so that it is made the active VBO. The custom class *VertexBufferObject* provides methods so that we can easily create and bind VBOs, like so:

```
// create and bind VBO
vboSceneObjects.createVBO();
vboSceneObjects.bindVBO();
```

Now that our VBO is bound, we need to add the actual data:

```
glBufferData(GL_ARRAY_BUFFER, rdp->nPoints * sizeof(PXCPoint3DF32),
NULL, GL_STREAM_DRAW);
```

This line stores an array buffer of n points of the Intel Perceptual Computing type. Further, the hint `GL_STREAM_DRAW` indicates that our data will be constantly updating(every frame). This makes OpenGL optimize the VBO for dynamic contents. Another flag, `GL_DYNAMIC_DRAW` is available, but this is actually for dynamic data that does not change every frame, only at specific moments. So, in this case, the first flag is the appropriate one, since the mesh will be updated every frame.

OpenGL also has another data type, namely the VAO(Vertex Array Object) which can store multiple VBOs. These VAOs are mainly used to avoid setting the vertex attribute pointers each time we bind the VBO. We just bind the VAO, and we do not have to do anything else. Now, if we were to render our memory contents now, using *glDrawArrays* we would need to draw the type `GL_POINTS`. This is because we have not triangulated the point cloud yet.

5.4.2 Triangulation

As described in section 4.3.1 a triangle strip has been used to triangulate the point cloud. In order to do so, an *IBO(Index Buffer Object)* has been used to store a `GL_ELEMENT_ARRAY_BUFFER`. This object is very similar to a VBO, the only difference is that we do not store vertex attributes in the element array, but actual element indices. In other words, we need to compute an array of indices, that defines how the triangle strip should be connected, and then just simply bind the data to the IBO:

```
ibo.addData(&(rdp->indices[0]), rdp->indices.size() * sizeof(unsigned int));
ibo.uploadDataToGPU(GL_STATIC_DRAW);
```

We add an array of `int`s into the buffer object of the size of the depth camera's resolution, in pixels(`width*height`). Note that the index computation can only be done once! We always have the same indices, for the same grid,

since the x and y values are fixed for a vertex - the indices are computed for all points, even for invalid ones, this means we do not have to recompute the indices if the state of the points changes(since the VBO data for those invalid points is not initialized, they will not be drawn). This means the flag for data optimization has been set to `GL_STATIC_DRAW`. Further, the `uploadDataToGPU` method internally calls `glBufferData` with the previously added element array data. Finally, the IBO is bound and setup similarly to a VBO.

The drawing command in order to render a mesh from the indices(connected using a triangle strip), is:

```
glDrawElements(
GL_TRIANGLE_STRIP,      // mode
rdp->indices.size(),    // count
GL_UNSIGNED_INT,   // type
(void*)0           // element array buffer offset
);
```

The parameters are briefly explained in the comments, but to detail briefly:

- the first parameter is the type of primitive OpenGL will use for rendering
- the second parameter represents the number of elements required to draw the mesh
- the third parameter defines the type of the elements
- finally, the last parameter is simply a pointer that defines an offset, but since we only have the mesh data to render with indices, this can be set to 0

The only thing left to be is explained is how the index array has been populated. In order to understand how the code works, it is useful to review figure 19. The logic is contained in the `addIndexData` method from the *RawDepthPipeline* class. We traverse the two-dimesional grid with one index(in the same manner as we have traversed the depth frame before):

```
t = c + r * colSteps,
```

where `t` will represent our current position in the grid. As we can see from the previously mentioned figure, the indices are connected by using elements from adjacent rows, alternatively.We can then simply check if this position is divisble by 2 or not, so we know if we need to move to the other row. We first push index 0, and then we need to add the width of the grid to our current index(since it is divisble by 2):

```
if (t % 2 == 0) {
n += width;
}
```

In the next iteration, we go in the `else` loop and check if the index of the row is divisible by 2. This is required, since we traverse the grid from both directions and we need to subtract `width-1` or `width+1`, in order to traverse up with one row, depending on whether we are traversing the current row from left to right, or right to left, respectively:

```
(r % 2 == 0) ? n -= (width - 1) : n -= (width + 1);
```

Then, the process is simply repeated. Note that, since we pass through two rows in one direction, `colSteps` is set to `width * 2`(for example, the last element in the second row in the figure is 7, which is element number 4*2 = 8, since our width is 4 in that example). Further, we stop one row before the last, since we traverse through the last one, when we start on the one right before it, so `rowSteps = height - 1`.

Finally, we need to remember to add the degenerate triangle by adding the last index twice(once as shown below, and again at the start of the next loop, as `r` is incremented):

```
if (c == colSteps - 1) {
indices.push_back(n);
}
```

At the end of this process, the `indices` vector will contain all of the triangle strip indices and in the right order. Therefore, it can be added to the index buffer object, so that the data is available for rendering later(degenerate triangles will simply be discarded by the GPU, they will not introduce artifacts).

5.5 Depth Smoothing

The depth data is quite noisy and, due to this, the final textured image is shimmering(vertices are moving around between frames, which creates a distracting effect). The effect is similar to aliasing(the "staircase effect").

In order to reduce this noise, smoothing of the depth data can be applied. A whitepaper from Canesta(see [23]) discusses aliasing issues, as well as artefacts for time-of-flight cameras. The authors describe how the noise can be reduced through *spatial* and *temporal averaging*.

Further, they suggest the use of a median filter for improving resolution, as a solution for spatial averaging. They applied a 5×5 median filter and noticed a two-fold increase in resolution.

Next, they present a case where 10 frames were averaged over time. Their results indicate that this technique of temporal averaging made the image much clearer and considerably increased the resolution.

In the following sections the implementations for spatial and temporal averaging employed in this project will be described.

5.5.1 Spatial Averaging

A median filter is used as a means for spatial averaging. The basic idea is to form a window of size $N \times N$, where N is an odd number(greater than 1,

otherwise we would have just one element in the window). Typical values for N are 3, 5 or 7. We traverse with such a window through the whole image, with the current pixel(or vertex) being in the center of the window, and the other elements being the immediate neighbors. Further, we need to obtain the `median` of the window. The median is the center element of a sorted array. Therefore, we also need to apply a sorting algorithm. Insertion sort is typically used for median filter implementations, since it is efficient for small data sets.

The median filter can bet turned off and on by the press of a key, using a boolean variable. The size of the window must be specified before, since it is represented as a constant. The *medianFilter* method in the *RawDepthPipeline* computes the result for every frame, based on the specified `windowSize`. In order to do this, the fact that both index digits of the center element in the window are: `midIndex = (size - 1) / 2` is used(here `size` is equal to the `N` mentioned above). To compute the window elements, we traverse it using `for` loops and then assign the values like so:

```
window[index] = pcPos[(y - midIndex + i) * depthCamWidth
  + (x - midIndex + j)].z;
index++;
```

We simply need to subtract `midIndex` from the current position, in order to get the neighbor elements. For example, `midIndex` would be equal to 1, for a 3×3 window. Then `window[0] = pcPos[(y-1)* depthCamWidth  + (x-1)]`, ..., `window[8] = pcPos[(y+1)* depthCamWidth  +(x+1)]` .

Once we have the elements, we need to sort them, in order to find the median. Insertion sort was used to accomplish this: `insertionSort(window)`. Now we simply need to assign the median as the new depth value for the current point, and continue to iterate through the rest of the points.

Additionally, we must only apply the algorithm if all the neighbors of the current point have valid depth values(since certain areas of the image do not contain depth information), so this must also be checked.

The sorting method works by iterating through each element of the array, storing it(`temp = window[i]`) and then comparing it against the size of all elements to the left of `temp`. The left side represents the sorted part of the array(we start with the left-most element). If the current element is less than another one from the left of the list, the larger element is shifted one place to the right.

```
for (j = i - 1; j >= 0 && temp < window[j]; j--){
window[j + 1] = window[j];
}
window[j + 1] = temp;
```

The last line places the current element in its proper place. If it is the largest element in the left side of the list, `j` will not be decremented and it remains on its current position. Otherwise, it is moved to the left, depending on how many elements are less than the current value.

5.5.2 Temporal Averaging

A WMA(Weighted Moving Average) algorithm has been used for temporal averaging. The main purpose of this is to average the depth information over the last N frames. We assign weights or priorities to the frames, with the last frame having the highest priority when averaging.

The frame data is stored in a list from which we can push and pop elements(individual frame data arrays):

```
// push array to the back of the list
averageList.push_back(pcPos);
```

Once we push a new frame in the list, we also need to check if the size of the list is greater than the number of frames we need to average over(we call *checkForDequeue*). If so, we remove the extra frames from the list.

```
if (averageList.size() > averageFrameCount)
{
delete[] averageList.front();
averageList.pop_front();
checkForDequeue();
}
```

Next, we iterate through all of the arrays in the list, and compute the sum of the depth data for each element, with a weight that is 1 for the oldest frame, and N(currently 10) for the newest:

```
// count denotes the weight
sumDepthArray[index] += (pxcF32)item[index].z * count;
```

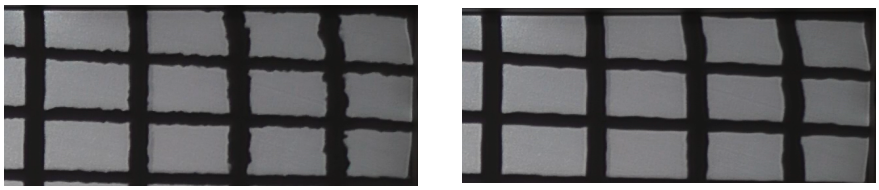
Further, we also store a denominator we will use to compute the average: `denominator += count`(we count how many times in total we add depth values from frames). Note that we need to finish this pass through all frames, in order to obtain all the sum values and the denominator.

Finally, we must iterate through the sum values and compute the average:

```
averagedDepthArray[index].z =
(pxcF32)(sumDepthArray[index] / denominator);
```

In order to speed up the process, we can use a `parallel_for` loop, so that the rows are processed in parallel. This is possible because the calculations are independent.

```
// Process each row in parallel
Concurrency::parallel_for(0, depthCamHeight,
[&](int depthArrayRowIndex)
{
...
}
```



(a) Grid Before Averaging (b) Grid With Both Averaging Techniques

Figure 31: A grid texture whch shows the noise reduction obtained by averaging.

Averaging	Frame Rate
None	[55 - 60]
Temporal	[50 - 57]
Both(3x3 MF)	[30 - 40]
Both(5x5 MF)	[12 - 21]

Table 1: Frame Rate Comparison When Using Noise Reduction Techniques

5.5.3 Results

The averaging techniques have been tested on the deformable display, by judging the quality of a texture with a grid on it. This makes it easier to notice noise around the grid's lines. In figure 31, the difference between the grid texture with no averaging applied, and with both averaging techniques applied, is shown(the image is zoomed in so that the differences are easier to spot).

Note that it is easier to see the differences in the thesis' video, although it is still possible to see a significant difference in the figures. A downside of averaging is the reduction of frame rate. A 3×3 median filter was used in the final implementation, and a 10 frame moving weighted average was used as a temporal averaging technique. In table 1 some data about the frame rate is presented, when turning on and off different averaging techniques. The frame rate was printed out for a certain number of frames, every second. The tests were also repeated 2-3 times and the results seemed consistent. We can see that the temporal averaging technique only slightly reduced the frame rate, while the median filter drastically reduced it, almost halving it when a 3x3 filter was applied, and almost halving it again, when a 5×5 filter was applied.

In order to improve the performance, the median filter could be applied on the GPU, by using shaders. One such method is described in [35]. They only briefly describe the method, but provide source code and a reference where the full algorithm is explain.

Finally, all averaging techniques can also reduce detail, for example, they could make the distortion correction less pronounced. This issue has not been thoroughly tested, and needs to be determined as future work. In order to properly analyze the previous issue, the calibration of the system should also be corrected, because then it would be easier to compare with the expected result.

A further issue may be that the system was not calibrated, so the distance and field of view of the virtual camera were set by trial and error. This is important because distance affects both the noise amount, as well as the degree to which the distortion correction can be seen(it needs to be `just right`, and the correct parameters can only be obtained through calibration).

5.6 Projective Texture Mapping

In order to get a final image rendered with the distortion compensation, by using a mesh of the deformable surface, one can apply projective texture mapping(**PTM**), as described in section 4.4. This method was implemented using GLSL shaders.

5.6.1 Setting Uniforms and Computing the Texture Coordinates in the Vertex Shader

Since the programmable OpenGL pipeline was used, there is no predefined `Texgen` matrix. Instead, we can just use any 4×4 matrix. This matrix is defined as a uniform in the vertex shader(OpenGL server side code):

```
uniform mat4 TexGenMat;
uniform mat4 InvViewMat;
```

The matrices are set from the OpenGL client code(the actual C++ application). The inverse view matrix is needed in order to convert from eye to world coordinates. In addition to these PTM specific matrices, we also need the usual projection and modelview matrix, as well as the position of the vertices:

```
uniform mat4 P;
uniform mat4 MV;
layout (location = 0) in vec3 inPosition;
```

We need to compute the texture coordinates for the projected texture and pass them to the fragment shader:

```
out vec4 projCoords;
vec4 posEye    = MV * vec4(inPosition, 1.0);
vec4 posWorld  = InvViewMat * posEye;
projCoords     = TexGenMat * posWorld;
```

The `TexGenMat` has been constructed as described in section 4.4, in the object linear texgen equation, except the final multiplication with `M`:

```
texGenMatrix = biasMatrix * projectorP * projectorV;
invViewMatrix = glm::inverse(mModelView);
```

Actually, by the time we compute the inverse, in the second line of the code above, `mModelView` only contains the view matrix. The modelview matrix uniform is instead stored from another variable, called `mCurrent`:

```
glUniformMatrix4fv(iPTMModelViewLoc, 1, GL_FALSE, glm::value_ptr(mCurrent));
```

The `glUniformMatrix4fv` method binds the given matrix to the location of the modelview matrix in the shader. The 4 in the name, means OpenGL is expecting a 4×4 matrix, and the v at the end denotes a vector or pointer array, which we will need to pass in as the data - in this case, `glm::value_ptr(mCurrent)`. The proper location can be retrieved from the shader program ID and a string which corresponds to the name of the variable:

```
int iPTMModelViewLoc = glGetUniformLocation(programID, "MV")
```

The other uniforms are set in a similar way(if we just need to bind an integer we use `glUniform1i`):

```
glUniformMatrix4fv(iPTMProjectionLoc, 1, GL_FALSE,
    glm::value_ptr(*pipeline->getProjectionMatrix()));
glUniformMatrix4fv(iTexGenMatLoc, 1, GL_FALSE,
    glm::value_ptr(texGenMatrix));
glUniformMatrix4fv(iInvViewMatrix, 1, GL_FALSE,
    glm::value_ptr(invViewMatrix));
glUniform1i(iSamplerPTMLoc, 0);
glUniform1i(iProjSamplerLoc, 1);
//black
glUniform4fv(iColorLoc, 1, glm::value_ptr(glm::vec4(0.0f, 0.0f, 0.0f, 1.0f)));
// update debug state
glUniform1i(iDebugLoc, bFragmentShaderDebug);
```

We set the projection matrix, the texgen matrix, the inverse view matrix, and finally sampler locations, color locations and a debug uniform. The samplers, colors and debug uniforms are only used in the fragment shader, while the others are needed in the vertex shader.

Finally we need to apply the model matrix, in order to get world coordinates. First, the eye coordinates are computed(multiplying with the modelview matrix). Then, in order to get the world coordinates, we need to remove the effect of the view matrix. We can do this by multiplying with its inverse(this is equivalent of just multiplying with `M`, but in order to be consistent with other shaders, the modelview matrix is passed as one matrix, denoted `MV`):

```
vec4 posEye    = MV * vec4(inPosition, 1.0);
vec4 posWorld  = InvViewMat * posEye;
projCoords     = TexGenMat * posWorld;
```

Finally, the position is computed as usual, by applying the Model View Projection(MVP) matrix to the input vertex:

```
gl_Position = P * MV * vec4(inPosition, 1.0);
```

5.6.2 Applying the Texture in the Fragment Shader

Next, the fragment shader computes the final texture coordinates for the vertex and extracts the color from the sampler:

```
vec2 finalCoords = projCoords.st / projCoords.q;
vec4 vProjTexColor  = texture(projMap, finalCoords);
```

Samplers are used to access the texture data. In this case, we have two `sampler2D` types, since the object may have its own texture, on which we may then apply the projected texture:

```
uniform sampler2D projMap;
uniform sampler2D gSampler;
```

However, for the deformable cloth mesh we do not need to use an additional texture. A constant color value was used for the mesh, in the areas in which it is not covered by the virtual texture projector. Therefore, if the texture coordinates are valid and we do not have a reverse projection the output color is set to the one retrieved from the texture, otherwise it is set to an input color:

```
// supress the reverse projection
if (projCoords.q > 0.0)
{
    // CLAMP PROJECTIVE TEXTURE (for some reason gl_clamp did not work...)
    if(projCoords.s > 0 && projCoords.t > 0 &&
    finalCoords.s < 1 && finalCoords.t < 1)
    {
    outputColor = vProjTexColor;
    }
    else
        outputColor = vColor;
}
else
    outputColor = vColor;
```

The texture was clamped in the shader, so that it does not repeat. This was needed, due to the fact that the normal texture parameters(that can be used to specify the `GL_CLAMP` flag for a particular coordinate) did not work:

```
glTexParameteri( GL_TEXTURE_2D,
GL_TEXTURE_WRAP_S, GL_CLAMP );
```

Finally, as mentioned in [28], one of the problems of projective texture mapping is that it also produces a reverse projection when the sign of `q` becomes negative(see figure 32). However, it is easy to correct this in the shader by just checking that `q` is positive, as we have seen in the code snippet above.

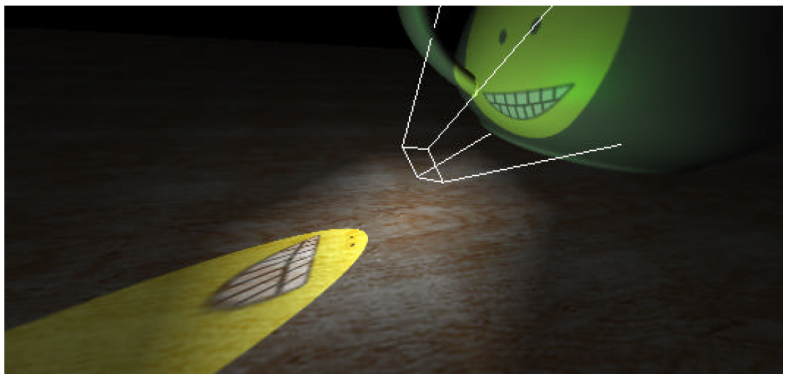


Figure 32: Reverse projection after applying PTM. Courtesy of [28]

5.6.3 Results

In addition to what has been described, a frustum has also been created for debugging purposes, so that we can see the virtual projector in the scene. The full code of the projective texture mapping shaders(for shaded scenes), is available in a *stackoverflow* discussion(available at [9]). I originally started it, while I was stuck on this problem. The previous resource may also describe some aspects in greater detail. The algorithm has been applied on several objects in figure 33. Further, in the accompanying thesis video, there is another example of the projected texture being moved, by transforming the virtual slide projector.

Further, the `debug` flag was used later on in order to change the color of the vertices, if they are within a certain depth range. More on this, in the following sections.

5.7 Manual Hardware Alignment (Calibration Not Used)

6 Empirical Study

Despite the fact that the system was not calibrated, it did seem to correct the distortions in certain areas or for certain cases. However, this correction is not perfect, and to find out how well it performs a user study has been run. Further, the users were also asked if they prefer the correcting method over a normal image projection.

7 Conclusions

8 Future Work

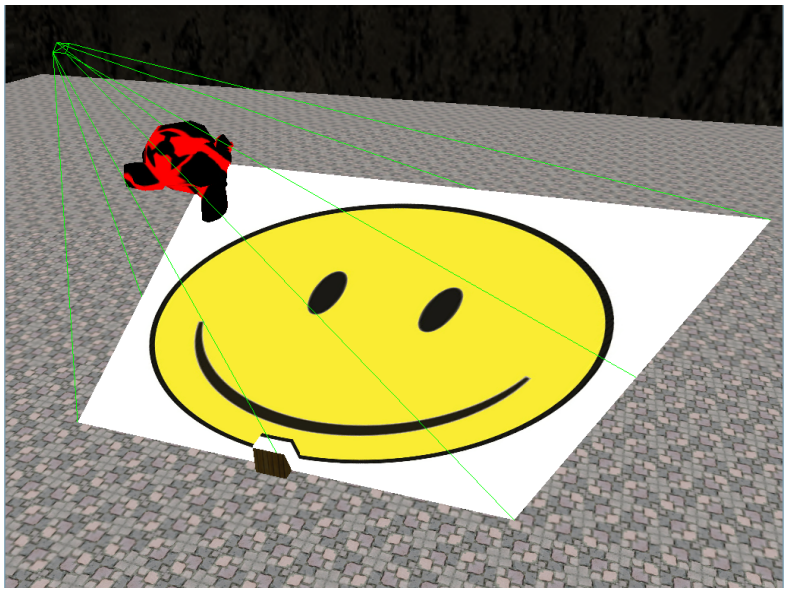


Figure 33: PTM applied on a Suzanne monkey head from Blender, and on a floor with a small cube. The frustum represents the virtual projector.

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