Lahden ammattikorkeakoulu
Lahti University of Applied Sciences

# From reality to 3D model

## Post production of photogrammetry based model

LAHTI UNIVERSITY OF APPLIED SCIENCES
Master's Degree Program in Information and Communications Technology
Master's Thesis
29.11.2016
Antti Laakso

Lahti University of Applied Sciences
Master’s Degree Program in Information and Communications Technology

LAAKSO, ANTTI:

From reality to 3D model

Post production of photogrammetry based model

108 pages, 26 pages of appendices

Autumn 2016

ABSTRACT

The aim of the thesis was to study the photo to 3D model process and determine aspects to be considered in the work process. The basis of the thesis was to gain knowledge of how the photogrammetric techniques can be used to generate photorealistic 3D models and how the models can be post processed to be suitable for different end uses. The thesis presents a workflow model for creating and post processing a photogrammetry based 3D model.

The thesis includes experiments of the use of modern photogrammetric applications and finally a case example project. The goal of the case example was to experiment how the developed workflow can be applied in a real life case. The successful project proved that the developed post processing workflow model can be applied in future projects The experiments with the generated 3D models proved that the photogrammetry based 3D models can be post processed for different end uses including real-time rendering environments.

Key words: 3D model, photogrammetry, photography, modeling, visualization

Lahden ammattikorkeakoulu
Master’s Degree Program in Information and Communications Technology

LAAKSO, ANTTI:

3D-mallinnus

Fotogrammetrian avulla toteutetun 3D-mallin jälkikäsittely

108 sivua, 26 liitesivua

Syksy 2016

TIIVISTELMÄ

Opinnäytetyön tavoitteena oli tutkia ja hyödyntää fotogrammetria tekniikkaa 3D-visualisoinneissa käytettävien 3D-mallien luomisessa. Työssä keskityttiin selvittämään aihepiiriin liittyvää teoriatietoa ja löytämään 3D-mallien totuttamisessa vaadittavan työprosessin keskeiset työvaiheet. Tavoitteena oli, että olemassa olevasta esineestä saadaan valokuvien ja fotogrammetria pohjaisien sovelluksien avulla toteutettua 3D-malli, joka soveltuu laaja-alaisesti erilaisiin käyttökohteisiin, kuten fotorealistisiin visualisointeihin, tietokonepeleihin ja tulostettavaksi.

Fotogrammetria tekniikkaan pohjautuvien sovellusten avulla tuotettujen mallien hyödyntämisessä on tärkeää huomioida erilaisien käyttötarkoituksien ja käyttöympäristöjen tuomat vaatimukset 3D-malleille. Tavoitteen mukaisen jälkikäsittelyn avulla 3D-mallin geometria voidaan kuitenkin muokata soveltuvaksi erilaisiin käyttötarkoituksiin. Opinnäytetyössä esitetään jälkikäsittelyn työprosessi, jonka avulla fotogrammetria pohjaiset 3D-mallit voidaan joustavasti muokata käyttötarkoituksen vaatimaan muotoon, säilyttäen kuitenkin mallien visuaalinen tarkkuus. Kehitetyn työprosessin soveltuvuutta käytäntöön arvioitiin erillisessä asiakasprojektissa, josta saatujen kokemuksien perusteella työprosessi arvioitiin hyödylliseksi.

Asiasanat: 3D-malli, fotogrammetria, valokuvaus, mallinnus, visualisointi

CONTENTS


1 INTRODUCTION 1
1.1 Aim of the study 2
1.2 Research questions 2
1.3 Research methodology 3

2 CLOSE-RANGE PHOTOGRAMMETRY 4
2.1 The photogrammetric process 4
2.2 Point cloud processing 6
2.3 Technical aspects of photography 7
2.3.1 Exposure 7
2.3.2 Depth of field 9
2.3.3 Lens diffraction 12
2.3.4 Optical distortion 16
2.3.5 Qualities of digital images 17
2.4 Acquiring suitable photographs 18
2.4.1 Environmental factors 19
2.4.2 Camera settings 20
2.4.3 Equipment 22
2.5 Technology limitations 23
2.6 Commercially available photogrammetry software 26
2.6.1 Autodesk ReCap 360 26
2.6.2 Autodesk ReMake 28

3 3D MODELING 30
3.1 The 3D production pipeline 30
3.2 3D model types 34
3.3 Creating 3D models 36
3.4 Quality of the mesh 42
3.4.1 Polygon count 42
3.4.2 Mesh topology 46
3.5 UV coordinates and texture maps 48
3.6 3D geometry file formats 49
3.6.1 Autodesk FBX 49
3.6.2 Object file 50
3.6.3 STL file 53

4 APPLIED PROJECT 56
4.1 Selected software tools 56
4.2 Photo to high definition 3D workflow model 58
4.2.1 The solution for the post processing of the model 61
4.3 Object reconstruction 67
4.3.1 Working with Autodesk ReCap 360 Pro 67
4.3.2 Working with Autodesk ReMake 71
4.4 Experimenting with the workflow 76
4.4.1 Photography and object reconstruction 77
4.4.2 Example of a game engine implementation 80
4.4.3 Case example: The Hunting Museum of Finland 85
4.4.4 Experimenting with 3D printing of photogrammetry model 93

5 CONCLUSIONS 99
5.1 Workflow of photo to 3D model 99
5.2 Knowledge and skill requirements 100
5.2.1 Photography skills 100
5.2.2 3D modeling skills 101
5.3 Photogrammetry based student projects 102
5.4 The future of photogrammetry software 102

REFERENCES 104

APPENDICES 108

# 1 INTRODUCTION

For most people a digital camera is a device for creating images for many different reasons such as for Facebook status updates or anything else from creative images to technical presentations. A camera is also a measuring instrument and three-dimensional information can be extracted from two-dimensional images. Images can be used to determine the shapes of the objects and with correct procedures, good quality software and algorithms, accurate models can be created. The process of taking measurements from two-dimensional images and transforming them to get three-dimensional coordinates from points on the objects is defined as photogrammetry. (Fryer 2007, 9.)

Photogrammetry can be defined as the art and science of obtaining precise mathematical measurements and three-dimensional data from two or more photographs. The capturing device can be a normal DSLR camera or a camera on an earth-orbiting satellite. The traditional use of photogrammetry is in the context of aerial photography. The evolution of digital cameras and increasing capabilities of computers and processing software has expanded the variety of applications of photogrammetry techniques. (Matthews 2008, 1.)

## 1.1 Aim of the study

The aim of the thesis is to focus on the photo to 3D model process and determine factors required to be considered in the work process. The thesis is based on a development project where main goal is to generate knowledge of the photogrammetry process by using modern technology and commercially available software. The main goal is to develop and test a workflow model for the process and finally evaluate and make conclusions of the suitability of the workflow model.

The Photogrammetric process can be applied in many different fields of science and for many different uses. In this study, the focus is to generate photorealistic 3D models that can be used for visual purposes. One example of an end use is using the 3D model in a game engine environment.

## 1.2 Research questions

This research aims to find out answers to the following questions:

1. What is the workflow of the photo to 3D model process and what needs to be considered in the process?

2. How must photogrammetry based 3D model must be post processed to obtain a model that can be used for different end, uses for example in a game engine?

3. What skills are required to create high-quality photogrammetry-based 3D models?

By answering to these questions, the thesis suggests a workflow model that can be applied when creating and post processing photogrammetry based 3D models. The selected software creates a basis for the model.

In addition, a subquestion for the research is to comment on based on the outcome of the study:

1. Which factors must be especially defined when planning photogrammetry related projects for students?

## 1.3 Research methodology

The overall pipeline of research methodology is shown in Figure 1. In this model, the research is divided to five separate phases. In the first phase, knowledge of the entire process is gathered and suitable software for the process is selected. In the second phase a workflow model for the entire process is developed. The goals of the third and fourth phases are to experiment and test the suitability of the workflow model. The third phase contains creating photogrammetry based models, which includes the photography and creating the 3D model with photogrammetry software. The fourth phase focuses on the post processing of the already generated 3D model. After these four phases, the results are examined and conclusions of the entire process are made.

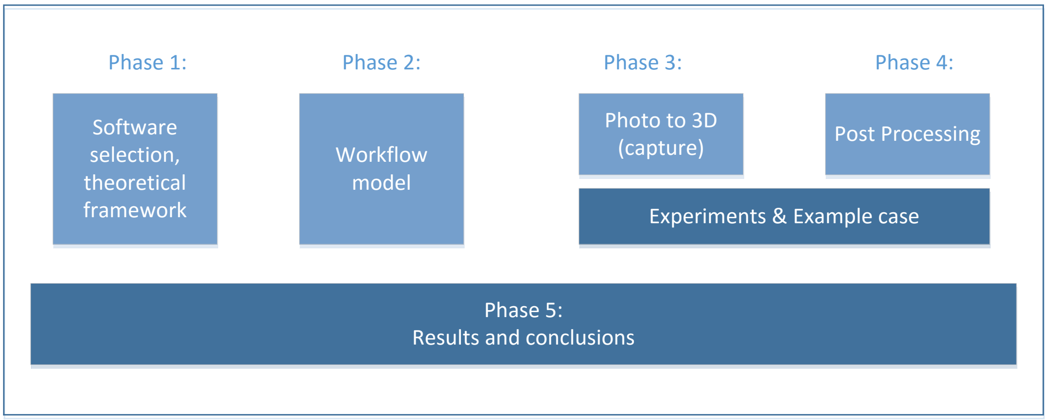



Figure 1. The pipeline of research methodology

# 2 CLOSE-RANGE PHOTOGRAMMETRY

## 2.1 The photogrammetric process

Figure 2 shows the photogrammetry process that includes the techniques of digital image processing in order to derive the shape of an object from one or more photographs of the object. The primary purpose of photogrammetric measurement is to reconstruct the object in three-dimensional form. At the basic level the photographic methods can be applied in a situation where the object to be reconstruct can be photographed. (Luhmann 2006, 2-3.)

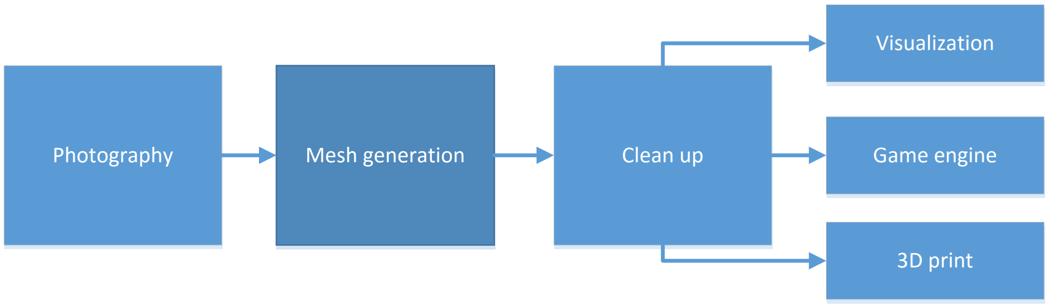



Figure 2. The photogrammetric process simplified

The resulting photographs of the object are in two-dimensional space whereas the real world is three-dimensional, which means a loss of information. Only the parts that can be seen on the two-dimensional images can be reconstructed. Figure 3 shows a comparison of two-dimensional and three-dimensional Cartesian coordinate systems. The position in space of each point on the two-dimensional image can be described with two coordinates X and Y, but to define the position on a three-dimensional object, also the third coordinate Z is required. (Luhmann 2006, 2-3.)

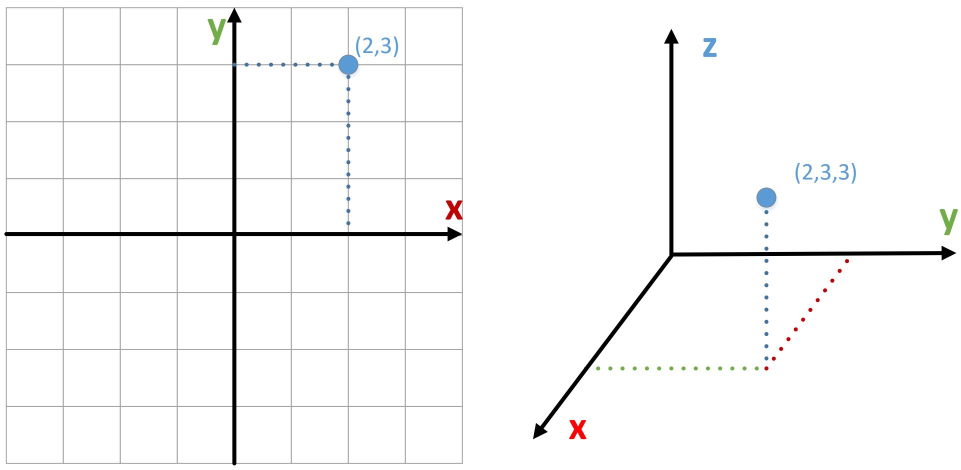



Figure 3. Bi-dimensional and three-dimensional Cartesian coordinate systems

To reconstruct a 3D-dimensional model of an object, different kinds of measurements and mathematical transformations between the image space and three-dimensional object space must be done. For example, the relative position of the camera and the object are calculated, the geometric changes of the object caused by the object shape, lens distortion and perspective must also be regarded in the calculation. In addition, the color changes (the radiometric changes) in the image must also be processed. Figure 4 summarizes the basic steps of the process, when reconstructing a real world object from two-dimensional images to a three-dimensional model. The figure shows the instrumentation used and the methods applied in the process. (Luhmann 2006, 2-3.)

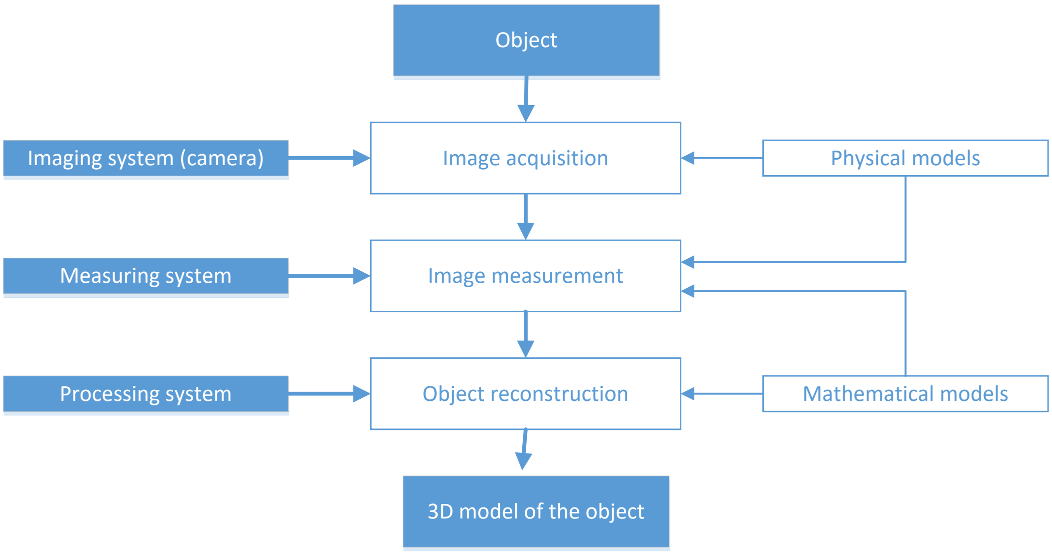



Figure 4. The photometric process (Luhmann 2006, 2-3)

Close range photogrammetry is based on fundamental sciences such as mathematics, physics, information sciences and biology. It has also close connections with other measurement techniques and significant connections with graphics and photographic science, computer graphics and machine vision, digital image processing, computer-aided design, GIS systems and cartography. (Luhmann 2006, 3.)

## 2.2 Point cloud processing

Laser scanning and photogrammetry are surveying methods that produce dense 3D point clouds. Point clouds can offer precise visualizations of an object but from the modeling point of view, they are often difficult to use (Raphaele 2014, 133). A 3D point cloud is a collection of points in three-dimensional space where X, Y and Z coordinates describe each point. A point cloud can also have color values attached to points. In a point cloud representation of survey data there is no relation between the points. The dense description that a point cloud creates of an object can be useful in some other usage than 3D modeling, for example for comparing the world and CAD designs. When creating a 3D model of an object, the processing of the point data continues by creating a mesh model of the object. (Raphaele 2014, 57.)

### 2.3 Technical aspects of photography

The chapter includes aspects of photography that are especially important when using the images for photogrammetry purposes.

#### 2.3.1 Exposure

A photograph's exposure is determined by three camera settings: aperture, shutter speed and ISO. Together, these three setting create an exposure triangle as seen in Figure 5. The same exposure of a photograph can be achieved with many different combinations of these three settings. The aperture controls the size of the area though which lights nters the camera, the shutter speed controls the duration of exposure and the ISO speed controls the sensitivity of the camera's sensor to the given amount of light. (McHugh 2016a.)

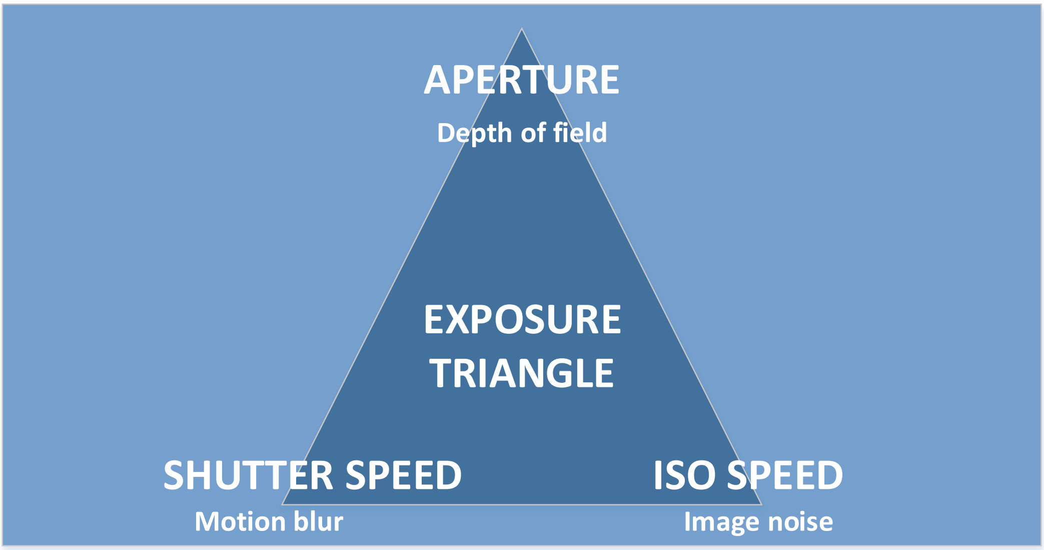



Figure 5. The exposure triangle (McHugh 2016a)

A fast shutter speed makes it possible to freeze the appearance of motion while a slow shutter speed can be used to get motion blur to images. A camera tripod or other stabilizing equipment is used to help achieve sharp focused images with slow shutter speeds. The aperture setting is specified in f-stop value. When the f-stop value increases, the area of the opening decreases and vice versa. When the f-stop value halves, the area collecting the light quadruples. For example, adjusting the f-stop value from f/22 to f/11 results in quadrupling the amount of light. This means that to archive the same exposure with the f/11 value the shutter speed can be four times faster compared to f/22. The aperture also has an impact on the depth of field: large f-stop results in large depth of field and low f-stop results in shallow depth of field. (McHugh 2016a.)

Different shutter speed and aperture settings can be used for different creative purposes. The third setting, the ISO speed, is usually always kept low if the appropriate exposure can be achieved by adjusting the aperture or shutter speed. The function of the ISO speed is to determine how sensitive the camera sensor is for light; with higher ISO speeds the exposure increases. The downside for ISO speed is that a high ISO setting increases the image noise. The image noise can be seen on the images as random speckles on otherwise smooth surfaces. These artifacts are generated by image noise in the digital images. The ISO setting amplifies the image signal in the camera and, as a result, the noise is amplified. High noise can significantly reduce the image quality. In addition, factors other than the ISO speed can increase the noise in the image; one typical such factor is long exposure time. (McHugh 2016a.)

### 2.3.2 Depth of field

The range of distance that appears sharp in the images is referred to as depth of field. The image is sharp in the focusing distance but immediately in front of or back of the focusing distance it begins to lose sharpness. The change from sharp to un-sharp occurs as a gradual transition. The camera sensor size, aperture and focusing distance have effect on the actual depth of field. The perception of depth of field is also influenced also by the actual size of the image and the viewing distance. (McHugh 2016b.)

McHugh (2016b) explains that because of the transition from sharp to un-sharp is gradual and there is no critical point, a term “circle of confusion” is defined. The circle of confusion defines how much a point needs to be blurred in order to be perceived as un-sharp. This means that a region is outside the depth of field when the circle of confusion becomes perceptible to human vison. For each print size and viewing distance combination, a different maximum circle of confusion can be defined. The suitable maximum value for appropriate allowable circle of confusion must also be defined in order to calculate the depth of field. The applied circle of confusion for a specific situation is based on both the camera’s sensor size and viewing distance and print size of the image. In order to calculate the depth of field, also the aperture and focal distance and focal length must also be known.

When taking photographs, the two main factors to control the depth of field are aperture and focusing distance. These factors determine how big the circle of confusion will be to the camera’s sensor. A large aperture and close focusing distance produce a shallow depth of field, Figure 6 shows an example of depth of field with different aperture settings. Figure shows four example images from the same focusing distance but with different apertures. Apertures are from left to right f/1.4, f/4, f/11 and f/22. The difference in depth of field can be seen when comparing the images. The image taken with the largest apeature, which means the smallest f-number, has the shallowest depth of field. (McHugh 2016b.)


Figure 6. Comparison of different apertures

Table 1 and

Table 2 show example depth of field values calculated with a depth of field calculator on McHugh’s Cambridge in Colour web site (McHugh 2016c). In Table 1 the aperture changes and in Table 2 the aperture remains the same but the focusing distance changes. Table 1 uses the constant focusing distance of one meter for all of the aperture values while Table 2 has several different focusing distances but the aperture remains as constant f/11. For both of the tables the other factors related with the camera and viewing remain the same. The values are counted for a digital SLR camera with CF of 1.6x and the used focal length is 50mm. Other factors that are connected with what is considered acceptably sharp are the viewing distance, print size and human eyesight. These example values are counted for small images with maximum print dimension of 15 cm and the images are viewed from close range. The viewing distance is 25 cm and the viewer has perfect vision. In most real-life situations, the viewer does not have perfect vision, which leads to larger depth of field.

Table 1. Example depth of fields calculated with a depth of field calculator, constant distance (McHugh 2016c)

| aperture | focusing distance | nearest acceptable sharpness | furthest acceptable sharpness | total depth of field |
|---|---|---|---|---|
| **f/1.4** | 1m | 0.99m | 1.01m | **0.01m** |
| **f/2.8** | 1m | 0.99m | 1.01m | **0.02m** |
| **f4** | 1m | 0.98m | 1.02m | **0.03m** |
| **f/5.6** | 1m | 0.98m | 1.02m | **0.05m** |
| **f/8** | 1m | 0.97m | 1.04m | **0.07m** |
| **f11** | 1m | 0.95m | 1.05m | **0.09m** |
| **f16** | 1m | 0.94m | 1.07m | **0.14m** |
| **f22** | 1m | 0.91m | 1.10m | **0.19m** |
| **f32** | 1m | 0.88m | 1.16m | **0.28m** |

Table 2. Example depth of fields calculated with a depth of field calculator, constant aperture (McHugh 2016c)

| distance | aperture | nearest acceptable sharpness | furthest acceptable sharpness | total depth of field |
|---|---|---|---|---|
| **1m** | f/11 | 0.95m | 1.05m | **0.09m** |
| **2m** | f/11 | 1.82m | 2.21m | **0.39m** |
| **3m** | f/11 | 2.62m | 3.51m | **0.90m** |
| **5m** | f/11 | 4.01m | 6.63m | **2.61m** |
| **10m** | f/11 | 6.69m | 19.75m | **13.06m** |
| **50m** | f/11 | 14.37m | ∞ (infinity) | **∞ (infinity)** |

McHugh (2016b) explains when using telephoto lens, the depth of field appears to be very shallow. This is because the telephoto lens magnifies the subject, not because the focal length has so much impact to the depth of field. The change in the focal length has negligible effect compared to both aperture and focusing distance.

McHugh (2016b) writes the visual feel of the image with a shallow depth of field can be different with same circle of confusion. This is because the circle of confusion sets the maximum value for the depth of field and does not describe what happens to the un-sharp regions. These out of focus regions are also called as bokeh. The lens used has impact on the look of the bokeh effect. Images with same depth of field may look totally different because of the bokeh effect.

### 2.3.3 Lens diffraction

No matter how many megapixels a modern digital camera may have, diffraction is an optical effect that limits the total resolution of the images. Figure 7 shows the single-slit diffraction phenomena that occur when light begins to disperse when passing through a small opening. Figure shows two examples of rays of light passing through a large aperture and a small aperture. When the aperture size decreases relative to the wavelength of light passing through the light rays begin to diverge and interfere more. In photography this issue can been noted when using a significantly small aperture. In most cases, other factors such as focus accuracy, motion blur and imperfect lenses are likely to have greater influence to image quality, even if the camera is near or past the diffraction limit. Knowing the diffraction limit of the used camera helps to maximize the sharpness of the images and avoid unnecessary long exposure times or high ISO setting. (McHugh 2016d.)

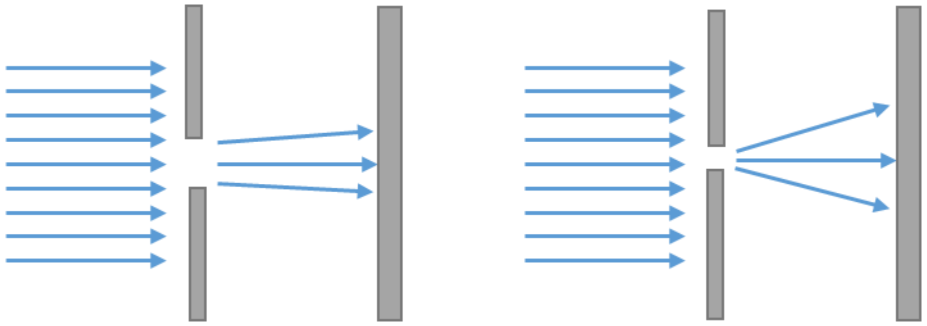


Figure 7. Single-slit diffraction (McHugh 2016d)

When rays of light are passing through a small aperture, they will begin to diverge and interfere with one another. The phenomena occur on some extent for any aperture but becomes more significant as the aperture decreases relative to the wavelength of the light passing through. Figure 8 shows the diffraction pattern produced by divergent rays of light. From the diffraction pattern can been seen the interference phenomena of light. After the edge of the opening, the rays of light are divergent, travelling different distances, part of rays of light move out of phase and begin to interfere with each other. The interference phenomena is the reason why the light intensity is not the same in each position. The peak intensities are where the amplitude of light wave add and the lower intensities are where the amplitude of light wave subtract as seen on Figure 8. (McHugh 2016d.)

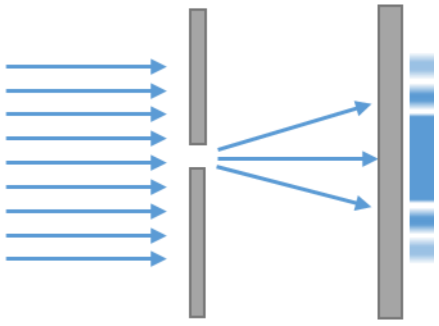


Figure 8. The single-slit diffraction pattern (McHugh 2016d)

The diffraction pattern of ideally focused spot of light created with a perfect lens with a circular aperture is called as Airy disk, after British astronomer George Biddell Airy. The diffraction pattern resulting from a uniformly illuminated circular aperture is shown on Figure 9. On optical system the smallest point to which a lens can focus a ray of light is the size of the Airy disk, which is the diameter of the first circle. (McHugh 2016d.)

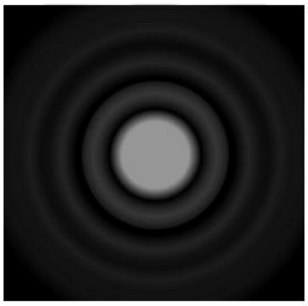


Figure 9. Graphic illustration of Airy Disc (Benson 1995, 786)

According to Rayleigh’s criterion two sources can just be resolved if the central maximum of one diffraction pattern coincides with the first minimum of the other. If the separation is reduced further between the sources they can no longer be resolved (Benson 1995, 786). When the aperture of the lens decreases, the diameter of the Airy disk’s central peak becomes large relative to the pixel size in the camera and this results to sharpness of the image (McHugh 2016d).

Photographs for photogrammetry should be as sharp as possible and have large depth of field (Matthews 2008, 38-39). This means that small aperture is essential to obtain enough depth of field. In this kind of scenario, the small aperture must be compensated with long exposure time or high ISO setting. The disadvantage of high ISO speed is that it generates noise. For the best image quality, high ISO speed should be avoided to compensate the shutter speed. This kind of exposure settings can lead to situation that the camera system passes the diffraction limit and therefore diffraction limits the total sharpness of the image.

McHugh (2016d) points out that on a real world scenario even if the camera system is past the diffraction limit other factors have more impact to image quality. In real-world the diffraction only limits the total sharpness of the image when the photograph is taken with tripod with high quality lens and also mirror lock-up mode is used in the camera. With the mirror lock-up mode the vibration of the camera is minimized.

According to McHugh (2016d) when taking photographs, it is good to be aware of the diffraction phenomena. When using sufficiently small apertures the diffraction limits the sharpness of the photograph independently from the number of megapixels in the camera. The light wavelength and aperture (the f-number) of lens sets this fundamental resolution limit for the images. The diffraction effect can be seen from normal real-world photographs or it can be calculated with various analytic models.

Table 3 shows example calculations of the Airy disk size for Canon 7D SLR camera, which have 1.6x crop factor sensor. Because of the camera’s sensor anti-aliasing filter and the Rayleigh’s criterion, an Airy disk can have a diameter of 2-3 pixels before diffraction limits the resolution. For example, Canon 7D camera with a pixel diameter of 6.9µm can be used with aperture of f/11 without the diffraction limits the sharpness of the image.

Table 3. Size of the Airy disk, example calculations (McHugh 2016d)

| Aperture | Diameter of Airy Disk | Aperture | Diameter of Airy Disk |
|---|---|---|---|
| **f/1.4** | 1.9 µm | **f/8** | 10.7 µm |
| **f/2.0** | 2.7 µm | **f/11** | 14.7 µm |
| **f/2.8** | 3.7 µm | **f/16** | 21.3 µm Diffraction Limited |
| **f/4.0** | 5.3 µm | **f/22** | 29.3 µm Diffraction Limited |
| **f/5.6** | 7.5 µm | **f/32** | 42.6 µm Diffraction Limited |

### 2.3.4 Optical distortion

Nassim Mansurov (2013) professional photographer, author and founder of Photography Life web publication explains that in photography, there are two types of distortions both results some kind of deformation to images. Optical distortion is caused by the optical design of the lens and perspective distortion is more related to how close subjects are with the camera. Typical situation when perspective distortion occurs is when the subject is too close to camera. Figure 10 shows examples of optical distortions that deforms and bends otherwise physically straight lines and makes them appear curvy. The barrel distortion makes the straight lines to curve inwards. The opposite of barrel distortion is pincushion distortion that makes the straight lines are curved outwards. More complex radial distortion is referred as wavy or moustache distortion. Because the wavy distortion is combination of barrel and pincushion distortion, it features different kind of distortion in the center of the frame and in the corners.

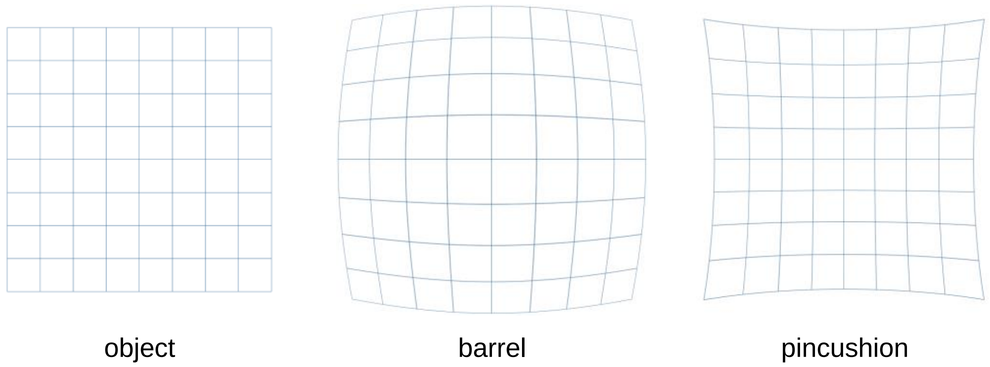



Figure 10. Examples of distortions

The curvature of the camera lens and the alignment of the lens with the sensor affects the camera lens system so that there is always some distortion. In the close-range photogrammetry, the optical distortion is important factor that has to be taken into account. (Raphaele 2014, 31-32.)

### 2.3.5 Qualities of digital images

Digital image consists of pixels. On RGB image, each pixel’s color is created through combination of the three primary colors: red, green and blue. Each primary color can be referred as a color channel. Each color channel’s range of intensity values is specified by the channel’s bit depth. The bit depth quantifies how many unique values are available for the color channel. The sum of all three-color channels quantifies the bit depth of the image. The bit depth is the factor that eventually sets the limit for available maximum colors in the image. If each of the primary color channels is defined with 8-bits then each primary color channel can have 256 different intensity values. Image, which have three 8-bit primary color channels can have over 16 million different colors. (McHugh 2016e.)

## 2.4 Acquiring suitable photographs

Photography is an essential part on creating 3D models with photogrammetry technology. The photographed object can be virtually in any scale but the basic requirement of overlapping pair of photographs must be fulfilled. Suitable photograph for a successful close-range photogrammetric process is different that artistic photographs as seen in Figure 11. The image seen in figure has blurred background and partly unsharp main object. The artistic style has been achieved using large aperture, which leads to shallow depth of field. A suitable photograph in this context refers to sequence of images that have uniform exposure and high contrast. In addition, the photographed subject must fill the frame and the images must be sharp as seen on Figure 12. (Matthews 2008, 37-38.)

Figure 11. Example of artistic style image

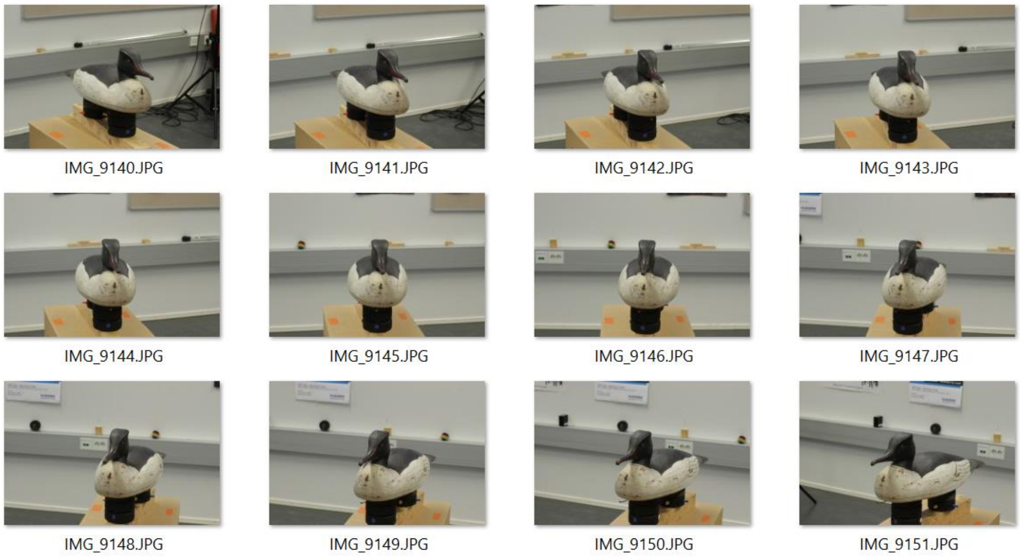



Figure 12. Example of image sequence for photogrammetry model

Matthews (2008, 37) writes to achieve the requirements of the photographs several aspects of photography must be noted. Successful result is combination of many factors like the experience of photographer, the quality of camera and other equipment and the suitability of the selected environment.

### 2.4.1 Environmental factors

To achieve matching images appropriate lightning set-up is critical. Objects for photogrammetry technology can be photographed outside or indoor. Nevertheless, requirements for suitable images are the same. To fulfill the requirements in each situation the lightning set-up, other environmental factors and the camera settings must be done so that every image is clear, properly exposed and have adequate overlap with adjacent image. (Matthews 2008, 37.)

Dzambazova explains (2014) the aim in creating the lightning set up is to get diffuse light. There should not be shadows on the images, especially from objects outside of the area of interest. This means that for example flash cannot be used, because it would create strong shadows on each picture. Also taking photographs with the help of spotlights and fluorescent lights should be avoided. Outdoors a cloudy weather is better for the process than sunny day, which usually creates strong shadows. In each occasion, the camera settings should be set up appropriate for the environment.

### 2.4.2 Camera settings

Matthews (2008, 37) points out the photogrammetry processing is based on suitable images and image sequences. Table 4 lists the most important features to be recognized to achieve suitable photographs. The camera should be adjusted in each situation so that is possible to achieve sharp, properly exposed images. To obtain high-quality results, the selected camera settings should not be changed during the image sequence.

Table 4. Camera settings to be noticed when taking photographs for the close-range photogrammetric process (Matthews 2008, 38-39)

| Camera setting | Reasons |
|---|---|
| Focal length | Zoom lens can be used but a fixed lens makes the process more efficient. With zoom lens, the focal length must be kept same for all of the images. |
| Focus weighting | Select appropriate method how focus is determined. Camera settings make usually possible take reading from center of field of view or average reading, or from selected location. |
| Aperture | To ensure proper depth of field select suitable aperture. Use manual or aperture priority setting to ensure the selected aperture. Suitable aperture may vary depending on case and equipment, tryout with f8 and if necessary increase the aperture for example to f11. Be aware of the cameras diffraction limit. |
| ISO sensitivity | In general, the ISO setting affects sensitivity of camera sensor. Increasing the ISO too high will affect graininess and other artifacts to the image. In low light situations, high aperture setting can be compensated with increased ISO setting, but the possible artifacts on the image are bad for the photogrammetry process. |
| Shutter speed | It is necessary to be aware that high aperture setting, which have not been compensated with ISO can require low shutter speed. Usually lower that 1/200 of a second shutter speed needs mounting the camera to a tripod. |
| File format | The image quality should be kept as good as possible. Usually this means RAW-images and good quality jpg-images for preview purposes. |
| Custom settings | Digital cameras may include specific setting for automatic sharpening, dust cleaning and image stabilization. Experiment the settings so see the effect on image quality and photogrammetric process. |
| Auto rotate | Auto rotate function should be kept off. |

### 2.4.3 Equipment

Dzambazova (2014) explains although images for photogrammetric process can be photographed with almost any camera, to ensure successful generation of the 3D model it is important to notice the suitable equipment for the project. The reason for the appropriate equipment is to ensure successful images for the process. Because the adjacent images should always overlap, it is important that all of the images are successful. Table 5 lists the equipment needed in the process.

Table 5. Equipment for the close-range photogrammetry (Dzambazova, 2014)

| Equipment | Reasons |
|---|---|
| **Camera body** | The lens is more important than the camera body. Typical Digital SLR has enough settings to be used in the photogrammetry process. |
| **Lens** | To avoid blurriness in the images good quality fixed lens is the best for the photogrammetry. Fixed lens makes possible to archive sharp images. No accidental focal length change. |
| **Polarizing lens filter** | Polarizing filters decrease reflection and increase color saturation. Especially reflections should be avoided in the photogrammetry process. |
| **Tripod or monopod** | Ideally, to avoid blurriness and un-sharp images a stable platform for the camera should be used. To get all the angles of objects a monopod or other stand can be used. |
| **Remote control** | Remote control makes possible to use low shutter speed when camera is mounted on a tripod without shaking the camera. |
| **Items for scale and color** | Ruler or other item with known size near the photographed object for size reference. Some colorful objects for color reference. (See Figure 67 on page 86) |

## 2.5 Technology limitations

Like many other technologies, also photogrammetry has limitations. The fundamental problem is related on real-world object’s surface and how the surface reflects light. Accurate 3D models cannot be processed from objects with transparent, glossy or reflective surface. Figure 13 shows an example of 3D model created from a glossy object. On the 3D model’s geometry, the reflection highlights can be seen as dents on the surface. One important benefit of photogrammetry is that the texture for the object can be automatically generated on the same time as the model itself. One solution for glossy object would be painting it over with a spray paint or appropriate powder. This might help to generate the 3D model but leads to situation that the texture map for object must be created with a different method. (Dzambazova, 2014.)

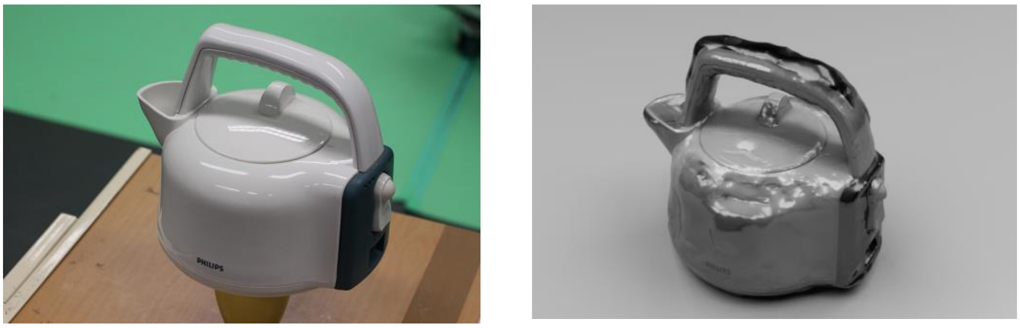


Figure 13. Example of unsuccessful 3D model

One other clear limitation is moving or deforming object. The object must be stable during the photography. In addition, objects like clothes which shape can easily vary during the photography should be avoided. In larger scale, also the environment should remain the same on all of the images. Object’s shape can be also a limiting factor when trying to achieve 3D models, which include all of the details of the real-world object. The details that are not seen on the images cannot be recreated to 3D models. (Dzambazova, 2014.)

The object’s own shape can occlude other parts of the same object or there might be that some parts of the object cannot be seen from the images. This is especially true in case of hollow object as seen on Figure 14. The photogrammetry based 3D shoe looks photorealistic from outside but view from different angle proves that there are problems on the inside surfaces. This is because the inside surfaces cannot be seen from the photographs, which are used to generate the model.

Figure 14. Photogrammetry based 3D model example

Figure 15 shows a similar example of small missing detail. On this case the surface is created to object but it lacks the possible details and also the authentic texture is missing. A small part of the object cannot be seen from the photographs and leads to a model with a missing detail.

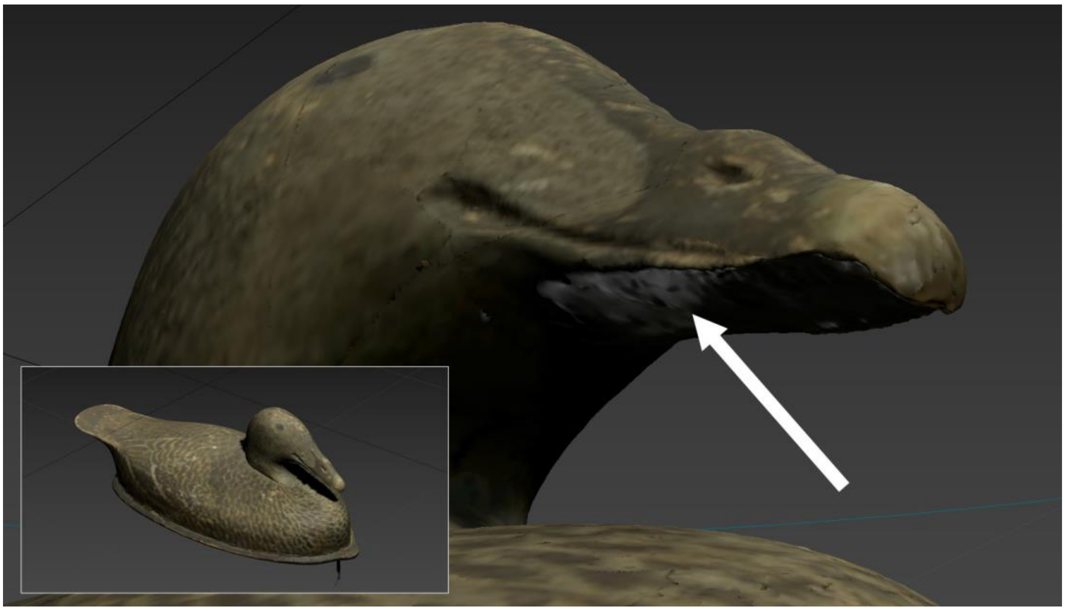


Figure 15. Example of a small missing detail in photogrammetry based model

## 2.6 Commercially available photogrammetry software

### 2.6.1 Autodesk ReCap 360

Recap 360 is Autodesk's reality capture and 3D scanning software family. Autodesk releases two versions of the software, ReCap 360 and ReCap 360 Pro. Figure 16 shows a screenshot image of ReCap 360. In the figure is a view of dense point cloud, which is created with laser scanner. ReCap 360 is a stand-alone software and it is available in most Autodesk suites. The main feature of ReCap 360 is the laser scanning point cloud viewing and editing. (Autodesk 2016a.)

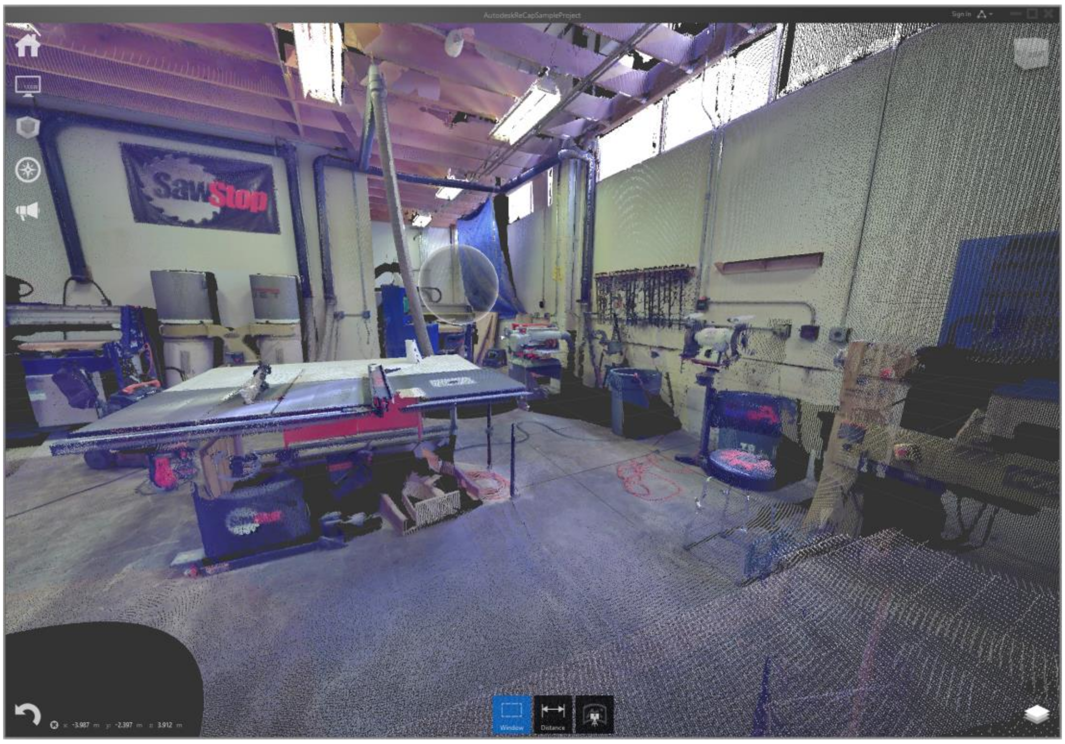



Figure 16. Screenshot of Autodesk ReCap 360 stand-alone software

Figure 17 shows Autodesk ReCap 360 Pro. The figure is a screenshot of Google Chrome browser with ReCap 360 Pro cloud service. ReCap 360 Pro cloud service can be subscribed from Autodesk. Recap 360 Pro can be used as a tool for laser scan data processing or photo to 3D processing as seen on the figure. Recap 360 Pro uses cloud computing in the processing of the data, user submits and uploads image files with a web browser for cloud based computing.

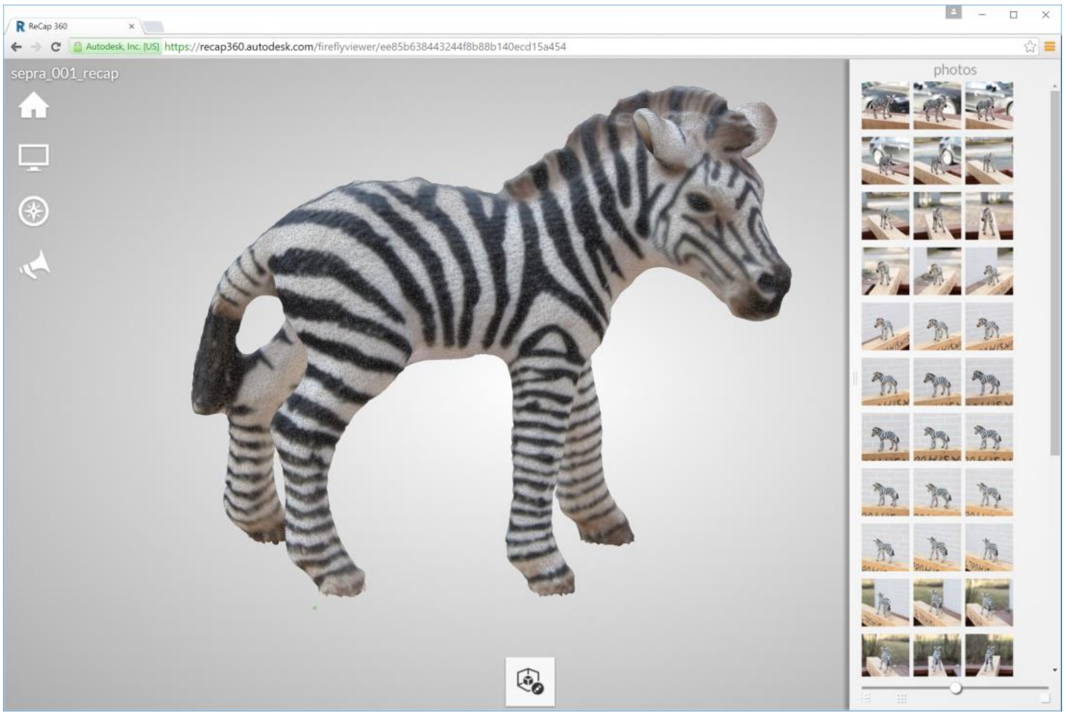



Figure 17. Screenshot of Autodesk ReCap 360 Pro

Autodesk ReCap 360 pro is available for subscription from Autodesk store. One-year subscription is around 400 € and monthly subscription around 50 € (Autodesk 2016b). Autodesk have developed a mobile version of Recap 360 service, under the name of Recap 360 Mobile. It can be used for viewing, annotating and sharing 3D laser scan projects created in Autodesk ReCap 360. The mobile version also includes iPad –enabled features. At time of writing ReCap 360 Mobile is in technology preview state and Autodesk Feedback community members can request participation to the development project and test the preview version of the software. (Autodesk 2016 Labs.)

### 2.6.2 Autodesk ReMake

ReMake is also part of Autodesk's reality computing portfolio as the ReCap products. It is an end-to-end solution for converting photos into high definition 3D meshes. ReMake is a stand-alone software but the models can be sent to cloud based processing. The main difference to ReCap 360 Pro is that ReMake supports the whole workflow from images to mesh including also tools for the optimizing of the mesh. On the ReMake there are tools for 3D mesh cleaning, fixing, sculpting and optimizing. ReMake offers more tools for post production of the mesh than the ReCap 360 Pro. (Autodesk 2016c.)

Figure 18 shows the user interface of Autodesk Memento, which was the beta version of the ReMake. At the beginning of May 2016 Autodesk released the first commercial version of Memento with the name of ReMake (Autodesk 2016d).

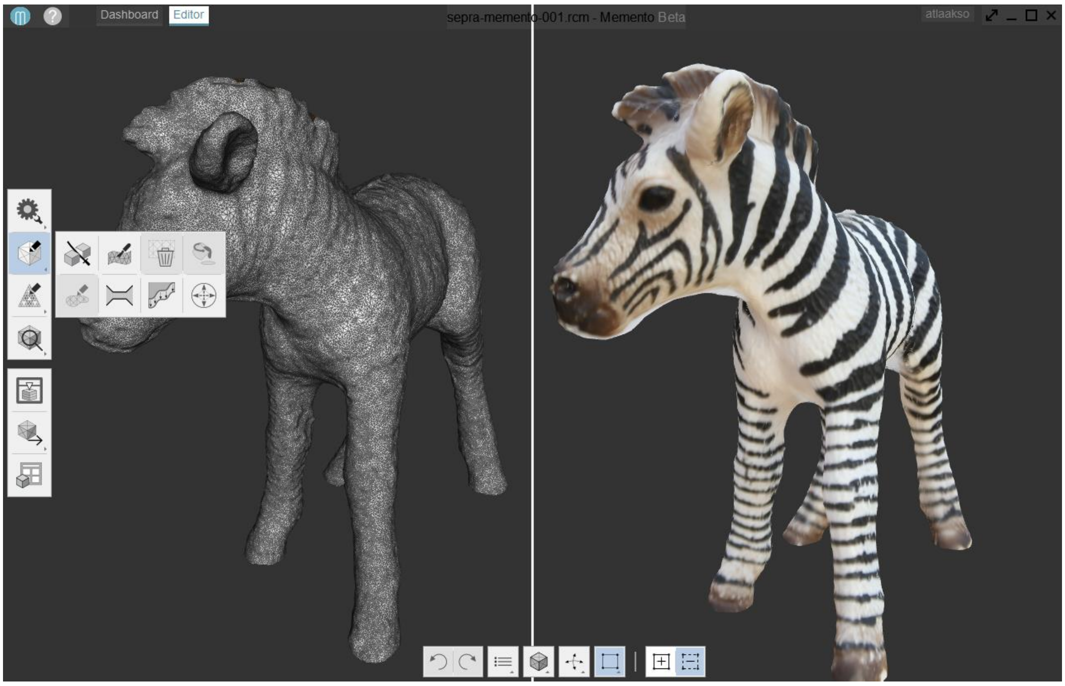



Figure 18. Screenshot of Autodesk Memento

Figure 19 shows example model created with Memento. This model includes all the surfaces for room and it has over 10 million polygons. The maximum image count, which is 240 images, is used to generate the model. On this study the photogrammetry applications are mainly used for digitalizing individual items. This example shows how the technology can used for digitalizing environments. The figure shows three different view modes to examine the scene. Each mode has its benefits when viewing the scene.

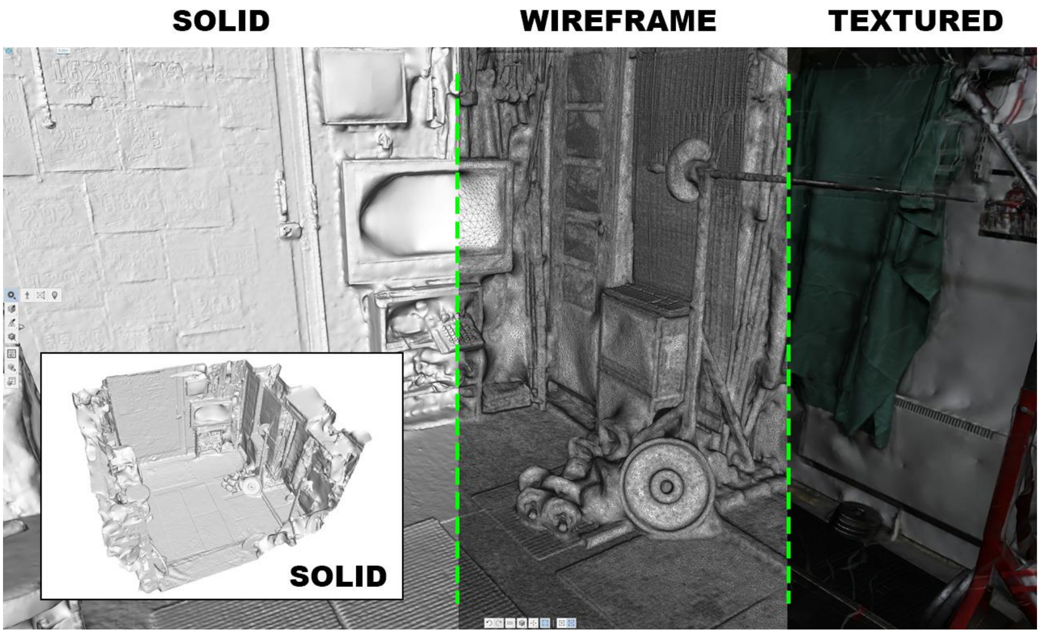



Figure 19. Example model created in Autodesk Memento

# 3 3D MODELING

The result of 3D graphics related project might be a simple product visualization, educational animation, a short movie or almost anything else. On a small production, one person may be responsible for all of the tasks included to project, as a bigger project may need collaboration with multiple people. In every case thinking ahead and planning the project is a good practice. In 3D production, the entire process including planning, scheduling and all of the production phases is usually referred as the production pipeline. Although different projects may need different steps in the production pipeline, the three basic stages can be found as seen on Figure 20. The figure presents the main stages of the production pipeline. (Vaughan 2012, 22-23.)


Figure 20. Digital modeling pipeline, the main stages of production (Vaughan 2012, 23)

## 3.1 The 3D production pipeline

All of the three main stages in 3D production pipeline, which are pre-production, production and post production can be broken to smaller work phases. Pre-production phase can hold for example the planning of visual look and story. It is the preparation of all of elements involved in the particular production. The pre-production stage is important because the foundations for project, no matter how small or a big are created in the stage. A successful project starts from overall properly carried out pre-production stage before continuing to next stage which is the production stage. (Vaughan 2012, 26.)

Vaughan (2012, 40-60) explains depending on the project outcome, the production stage may have different tasks included. Figure 21 represent several tasks included to the production stage. A simple product visualization may not need all of the tasks included. For example, the animation or rigging, which are usually related to character animation may not be included. In addition, the effects phase, which contains creating elements like water, fire and smoke is not necessary included in every project. The reason that effects can be broken to own separate phase is that these elements are usually created in a different way than the normal 3D models. Effects are concerned as non-model elements.

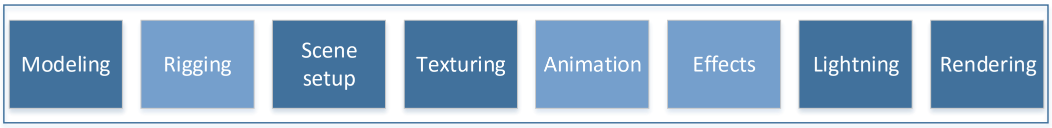



Figure 21. The production stage (Vaughan 2012 40-60)

Vaughan (2012, 40) writes the essential part of the production stage is the modeling phase, which involves generating the 3D models. The quality of the 3D model, which can also be referred as a mesh, or a mesh model have also other features beside the shape and look of the object. Different kind end use of the 3D model may have distinct requirements for the model. To achieve an appropriate 3D model the mesh topology, polygon count and texture coordinates must be noted when creating the object. For example, in case of character rigging, which means creating controllable rigs to control the animation of a character, the mesh topology is crucial for the clean deformation of the object.

When 3D model's geometry is finished, it needs to be brought to life with colors and textures as seen on Figure 22. Creating textures for the model includes generating the texture maps and utilizing material shaders to achieve the desired look. In modeling, a shader typically refers to algorithm that specifies how the object's surface responds to light.

Applying applicable shaders to the models helps to achieve realistic models that look like they are made from a specific material like wood, plastic or metal. Applying the texture maps to meshes always needs the generation UV coordinates to models. UV map or UVW map refers to texture coordinates which specifies how the texture map is projected to the object’s surface. (Autodesk 2016f.)

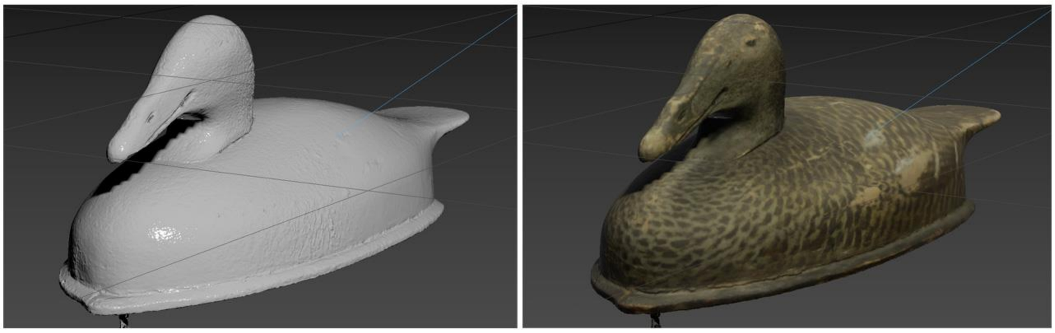


Figure 22. A model without texture and with texture.

On the scene setup phase, all of the created elements are placed in the final rendering environment. Various visual aspects are taken into account but also the total polygon count must be noted. If the polygon count grows too high additional problems might come up when working with the scene and rendering the scene. (Vaughan 2012, 45-47.)

The scene will be finished with creating light setup to environment. Using different kind of light setups diverse moods, colors and atmospheres can be created to scene. The final look of the rendered image is finished in the combination of light set up, rendering settings and the final composing of the elements. (Vaughan 2012, 56.)

The rendering phase is required to transfer the scene from the 3D software to 2D images. The render output is the scene’s geometry shaded using the selected light set up, materials attached to models and other environmental or rendering settings applied. (Autodesk 2016g.)

Figure 23 represents the final stage of the work, which is the post production. The post production includes the composing all of the elements together and enhancing each element and the final product. To achieve a high-quality results the post production is an essential work phase. The post production shows how well the whole project is planned because all of the elements should be finally fitted to together. On this phase the final product will be edited, the sound and audio are composed together and also the colors will be tweaked by color correction. (Vaughan 2012, 61-62.)

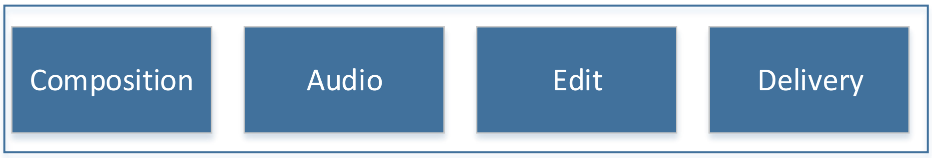



Figure 23. Post production stage (Vaughan 2012, 61-67)

Figure 24 is a simplified example of composing separate render elements together in the post production. In this example, a pre-rendered white shaded ambient occlusion layer is blended to rendered image to help to achieve a realistic shading of the 3D object.  The ambient occlusion layer emulates a true global illumination shader. Using a separate layer for the shadows gives an artistic freedom to work with the shadows on the post production stage. Adjusting the visibility or blending of the layers on the post production makes lighter or deeper shadows to final images.

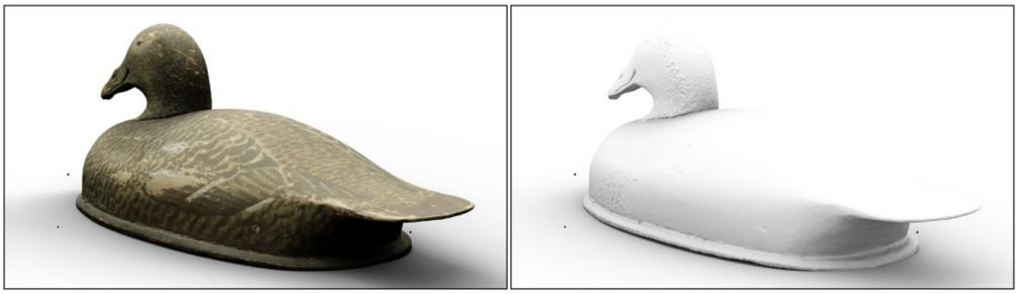


Figure 24. Example of render element composed together in post production

## 3.2 3D model types

3D model types can be divided in different ways depending on the point of the view. This chapter introduces two distinct methods, which are the type of the model created, or the selected technique used to create the model. One point of view is to think the tools and methods that are used to create the model. In the book Poly-Modeling with 3ds Max the author Todd Daniele (Daniele 2009, 5-29) defines spline-modeling, patch-modeling, box-modeling and poly-modeling as separate modeling types. The object’s geometry is the main thing to note when selecting a suitable modeling technique. As the title of the book pronounces this kind of division is typical for models created in Autodesk 3ds Max modeling software. These modeling types are issued in more detail in Table 6.

Table 6. Different modeling types by Todd Daniele (Daniele 2009, 5-25)

| Modeling type | Typical features |
|---|---|
| **Spline-modeling** | 2D splines with surface modifier used to create models. Splines geometry controlled with parameters and Bezier handles. |
| **Patch-modeling** | 3ds Max patch object used to create models. Patch object differs from normal mesh object. Patch has some similar features as spline or NUBS-curves. |
| **Box-modeling** | General modeling technique that is applicable to most 3D applications. The modeling begins from the mass of the model, usually a box primitive and details are created along the modeling process. |
| **Poly-modeling** | The modeling begins from single polygon or group of polygons. The technique gives the modeler the ability to control the mesh structure and polygonal flow. |

Daniela (2009, 117 & 165) writes a common division is to divide objects to hard-edge objects and organic objects. A hard-edge object usually refers to a man-made object as organic object refers to characters, insects or creatures. Hard-edge or organic, which are also called as soft-edge model, needs to be issued with different approach.

In a book Digital Modeling by William Vaughan (Vaughan 2012, 102) the 3D models are divided into three different categories according to models technical type. These types are polygonal models, NURBS (Non-Uniform Rational B-Splines) surfaces and subdivision surfaces. In technical sense, there is a clear difference between polygonal model and NURBS surface but subdivision surface is more or less a polygonal model with a subdivision surface algorithm attached to it. The explanation of these model types is shown in Table 7.

Table 7. Different types of digital models (Vaughan 2012, 102)

| Model type | Typical features |
|---|---|
| **Polygonal models** | A mesh object made up of collection of points (vertices), edges and polygons (faces). |
| **NURBS surfaces** | A smooth surface calculated based on mathematical curves. NURBS stand for Non-Uniform Rational B-Splines. |
| **Subdivision surfaces** | Polygonal models which is divided to more faces with a subdivision surface algorithm while retaining the object's general shape. |

The task of subdivision surface algorithm is to divide the modeled mesh, which is referred as a base mesh, to more faces, but at the same time retain the object's general shape. More faces on a model means that more details or a smoother model can be created. The down side of using subdivision surface algorithm is that when the faces are divided the object's polygon count scales up. (Vaughan 2012, 196-197.)

## 3.3 Creating 3D models

There are many ways to create a 3D models. Model's geometry, modeler's skills and knowledge and modeler's way of solving the modeling problems has impact which kind of methods and tools are used to create the 3D model. In addition, different kind of reference material might require different approach.

To end up with a same looking geometry many different techniques can be applied. However, to create the same model with exactly the same polygonal flow is almost impossible. Everyone can try out to model the same object twice with different tools and compare the difference of the resulting models. Comparison of the wireframe structure of the models should show some differences in the polygonal flow of the object. Although the wireframe view can show some differences on the placing of the polygon edges or on the size of the polygons the rendered result can be almost identical.

Vaughan (2012, 138) outlines learning different methods to use in different cases and mixing the methods to solve problems in the modeling is an essential skill for a modeler. Figure 25 shows individual techniques, which can be used in the 3D modeling. The real-life modeling is more or less some kind of mix of these methods.

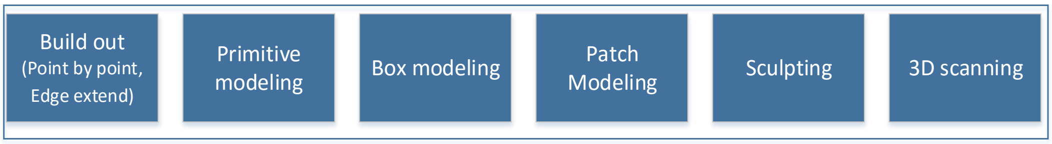



Figure 25. Different 3D modeling methods (Vaughan 2012, 121-133)

The build out method means approaching the modeling by creating one detail after another to complete the model. If using the point-by-point technique, the model is started from empty to create points (vertices) to define the shape of the object. After the shape is defined, a surface is created according to the points. The edge extend variation of the method starts with a flat polygon or group of flat polygons. Usually the starting polygon can be done with a primitive object. Like the method's name suggest the modeling continues by selecting edge and extending it to create a new polygons or set of polygons. On this method the modeler has total control over objects topology. The control over the topology is required for creating a clean mesh model and controlling the polygon count of the model. Figure 26 shows an example of the edge extend type of modeling. (Vaughan 2012, 122-123.)

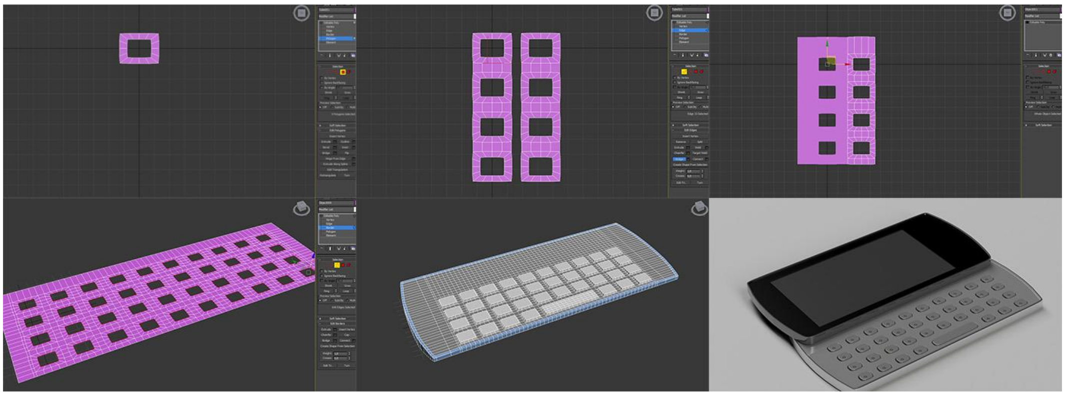


Figure 26. Example of edge extend type of modeling

All 3D software packages offer the creation of different primitive geometries like boxes, spheres, cones, cylinders and tubes as seen in Figure 27. Usually there are wide variety of other more complex primitives like a boxes with rounded edges, springs or capsules with hemispherical end caps. The shape and the topology of these primitive objects can be parametrically defined. From the modelers point of view, a desired final shape is not usually directly just one primitive. Multiple primitives can be combined together to achieve a desired result. Primitive objects are suitable to create a hard surface objects like bookshelves, tables or other man-made sharp edged objects. When primitives are manipulated with other tools on the 3D software, then endless possibilities are at hand to create various different geometries. With the help of other modeling tools, the shape of the primitive object can be modified with variety of ways. The modification of a primitive shape leads to the box modeling method. (Vaughan  2012, 124-125.)

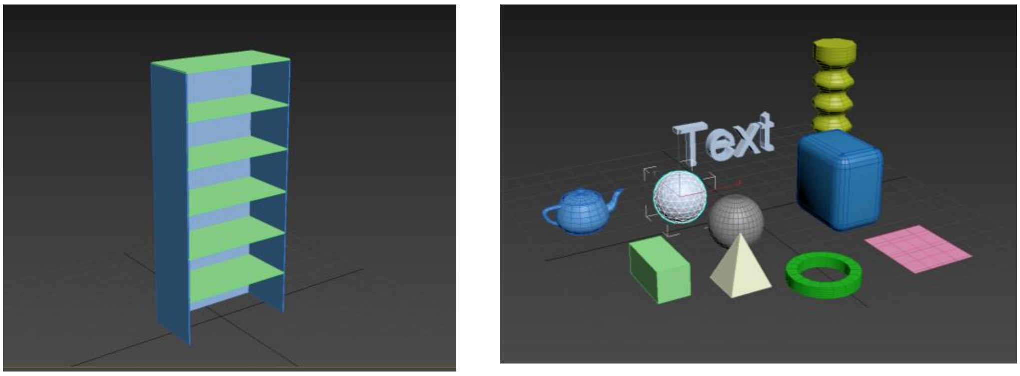



Figure 27. Bookshelf created from box primitives and sample of different primitive objects

In a first phase of the box modeling method a primitive object is created and after that the objects shape is modified to create more geometry. Different methods like extruding and dividing polygons are available to generate more geometry and add details (Vaughan  2012, 126.). A point to notice is that for example, a book shelve as seen on Figure 28 is created in box modeling by modifying a specific object’s shape and the final book shelve is created from only one object. If the same book shelve would be done only using primitive objects, then the result would consist of several objects.

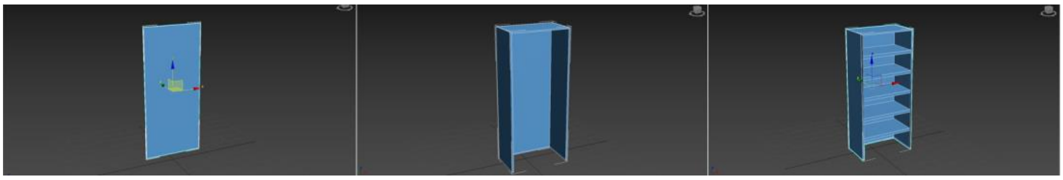


Figure 28. Bookshelf created with the box modeling method

Vaughan (2012, 127-128) explains the build out method and polygon modeling methods like primitive modeling and box modeling varies from patch modeling due the difference in the model’s technic. Patch model looks like a mesh surface but its curvature is controlled with splines or other curves like NURBS. Multiple curves are combined to create a surface between the curves. These surfaces are called as patches and they are controlled by the points that make up the curves. NURBS based patch modeling is more commonly used in computer-aided design (CAD) software. A patch surface can be converted as mesh model and after that modified as a normal polygon object.

One of the newest additions to modeling techniques is the digital sculpting. Digital sculpting gives the possibility to model objects with millions of polygons, this allows the creation of highly detailed objects. Sculpting starts from a base mesh which can be a standard primitive like a sphere. With the sculpting tools, the sphere can be modified as a game character, dragon or whatever the user desires. The interesting point in sculpting is that it gives an artistic freedom for the modeler to work with the model without paying attention to polygonal flow of the surface. When the geometry is finished the high polygon version of the model can be transformed to low polygon version without losing the details in the model. Tools and technics like retopology, normal maps and textures are used to create the low polygon version of the object. With these effective tools, the highly detailed original model with millions of polygons can be transformed to be used in a real-time game engine. (Vaughan 2012, 128-130.)

Figure 29 shows on example of Autodesk Mudbox sculpting software. Pixologic ZBrush and Autodesk Mudbox are examples of the sculpting applications (Vaughan 2012, 282). On this screen shot curves are drawn for a retopology process to generate a low polygon version of the model. With the retopology process the software generates a new mesh object with better polygon flow and user desired polygon count.

Figure 29. Screen shot of Autodesk Mudbox software

Generating a model from a real world object can be done beside image based photogrammetry technique with a 3D scanner. There are different scanner technologies but the main goal is to collect data from the objects surface whether the scanner is a noncontact scanner or contact based scanner. With noncontact scanners, there is a difficulty to scan surfaces, which are reflective or transparent. The scanning of an object produces a point cloud of the object, which can be converted as a mesh surface for further use. (Vaughan 2012, 131-133.)

## 3.4 Quality of the mesh

Vaughan (2012, 151-159) explains every 3D mesh object is not equal in a sense of the quality. Paying attention to models wireframe structure throughout modeling process is important. This is because the quality is related to the mesh topology of the object. Digital sculpting makes an exception to this, on other techniques, the models mesh structure or polygonal flow will be created among the modeling process. On sculpting, the clean model will be usually created with the retopology tools. A clean model is a model where the two core attributes of polygonal modeling have been taken account properly. The fundamental attributes are polygon count and mesh topology as seen on Figure 30. Paying attention to these core attributes helps to create mesh objects that deform well, are not too complex and are easy to modify.

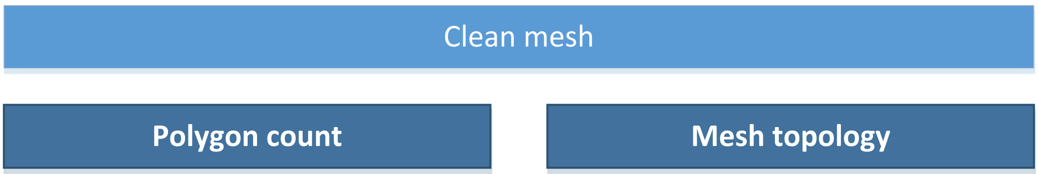



Figure 30. The fundamental attributes of clean mesh

### 3.4.1 Polygon count

Vaughan (2012, 148-149) writes usually is considered that high polygon count makes harder to work with 3D objects. This is because fever points or vertices keeps for example assigning vertex weight simpler than model with too many polygons. In addition, offline rendering and real-time rendering used in games works better with fever polygons. Offline rendering, means rendering scenes to image files and using the pre-rendered images later. On offline rendering lower polygon count makes possible to utilize higher-quality rendering setting. (Vaughan 2012, 148-149.)

When counting polygons, it is important to notice the true polygon count that in the end really matters. Usually preferred in a clean mesh model's topology are four-sided polygons called quads. The topology can hold also polygons with three sides and polygons with many sides, which are called as n-gons where n presents the number of sides. Although polygons can have different amount of vertices the true polygon count is counted in triangles or three-sided polygons, usually referred as tris. The reason for this is the rendering engines, both offline and real-time rendering engines convert the models to three-point polygons because the modern graphics cards work only with these simple triangles. Figure 31 shows examples of these different polygon types. All of the polygon types can be eventually divided to three-sided polygons. (Vaughan 2012, 149-150.)

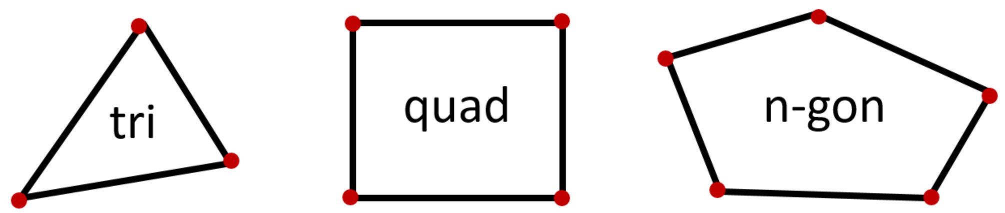



Figure 31. Polygons with different shapes

Figure 32 shows an example of converting the polygons to three sided. One reason why the topology should be based on quad sided polygons is that the conversion is easy to achieve. The n-gon of the example could be converted to five three sided polygons. Conversion of the many sided n-gons is not always this easy and can lead up to huge amount of three-sided polygons. This leads to higher polygon count because the true polygon count is counted by counting the triangulated mesh model. (Vaughan 2012, 149-150.)

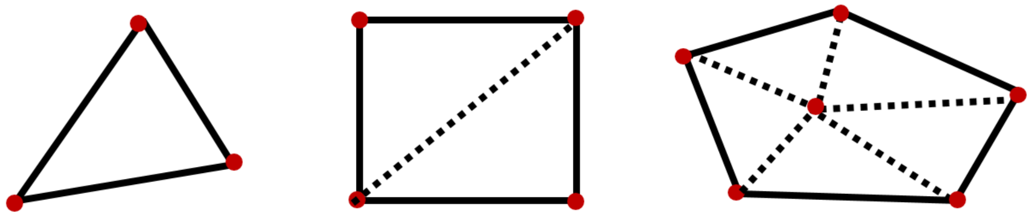


Figure 32. Polygons divided to three-sided polygons

Figure 33 shows an example of polygon count and mesh topology. The figure shows how photogrammetry based 3D model's original polygon count is reduced with retopology process. The original mesh has over 433 139 triangles and the optimized version has only 4155 quad sided polygons, which means 8310 triangles. Although the new model's polygon count is only about 2 percent of the original the resulting geometry looks the same. Close look of the surfaces would reveal small differences in the surface but the on many uses the details are not needed or can be produced with different method. The original model can be considered as high polygon count with complex mesh topology. The optimized version can be considered as a clean mesh model, although the topology of the optimized could be even better.

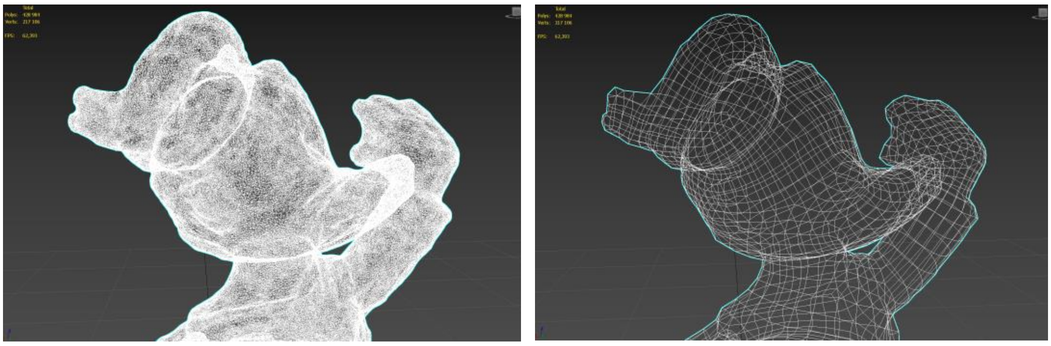


Figure 33. Digitalized Donald Duck figure with different topologies and polygon counts

The polygon count is especially important in real time rendering environments. On the game engine use, the number of polygons that can be onscreen at any given time depends on the platform that the game is targeted. For example, a game character in desktop platform the ideal range is about 1500 to 4000 polygons per mesh character. For mobile devices the ideal polygon count is lower and moves somewhere around 300 to 1500 polygons. For example, Valve's Half-Life 2 uses around 5000-7000 triangles per game character. (Unity Technologies 2016.)

### 3.4.2 Mesh topology

Another important thing in model's structure is the mesh topology also called as polygon flow. These terms refer how the 3D mesh is constructed. Figure 34 shows example topologies for simple 2D plane primitive object. The object's geometric shape can be the same although the wireframe structure differs. The second image in the figure shows that after simple extruding operation of the polygon the resulting geometry look different because the extruded polygons have different shapes.

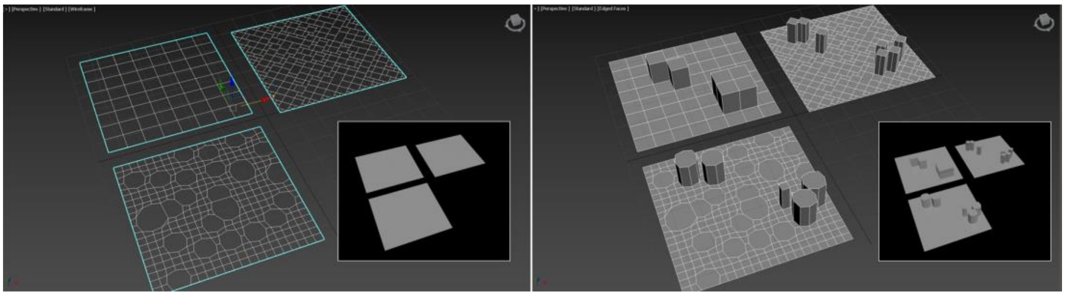


Figure 34. Simple plane object with three different topologies

Vaughan (2012, 153-154) explains using as few polygons as necessary is desired in sense of polygon count to make the model easy to work with. In addition, a suitable topology makes it easier to work with the object. The requirements for objects topology are related to the use of the object, a static model benefits from clean topology but in a model, which should deform the clean topology, is more crucial. On a static model, a problem in topology can produce unwanted dents and generating UV coordinates maps can be trickier. When creating a model that deforms the key point is to be able to predict how the surface will deform. Limiting the polygons to quad sided and placing the edges on the correct position where the model should deform ensures that there will not be surprises when animating the model's deformation.

Always when working with mesh models the direction of surfaces must be noted. Usually by default, the rendering engine renders surface visible only from one side, the visible side is the side where the surface normal vector points out. The normal vector is defined as a vector, which is perpendicular to the face and direction that the normal vector points is the outer surface of the object. (Autodesk 2016h.)

Errors in the normal directions can be caused by transferring meshes between different applications or by used modeling operations. These errors in the surfaces can be fixed with flipping the face normals. Figure 35 shows the surface normals and an example of correct and miss correctly flipped normal. The blue lines indicate the surface normal directions. On the second image the same geometry is rendered twice but other models faces are flipped so that the uncorrect side is visible. This leads to weird looking model. The reason for the weird look of the model is that the texture is now on the inside surface of the model and the outside surface can not be seen. (Autodesk 2016h.)

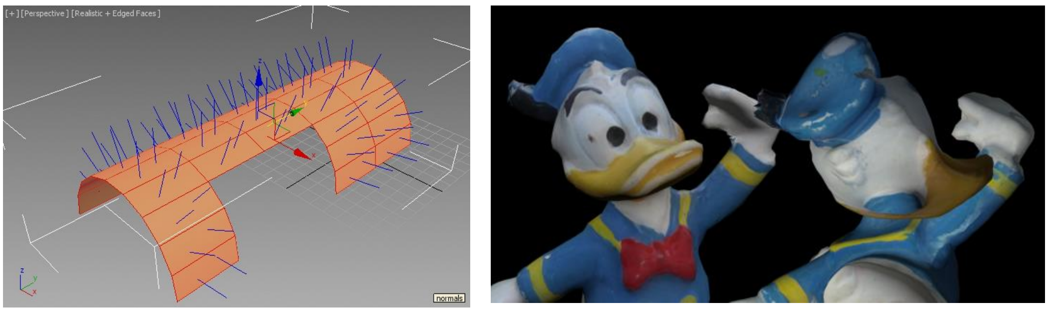



Figure 35. Surface normals

## 3.5 UV coordinates and texture maps

The UV mapping means creating the texture coordinates to the model. UV mapping creates a 2D layout of the models surface, this means setting up the relationship between the three dimensions of the model (X, Y, Z) and the two dimension of the image (U and V). The image space uses letters U and V to define the coordinates to avoid confusion in the object and texture coordinate spaces. If a model does not have UV coordinates, then a texture cannot appear on the surface of the object this is also true for other maps like normal maps or displacement maps. (Vaughan 2012, 314.)

Figure 36 shows three examples of UV map layouts. Applications have automatic features to unwrap models but to achieve a map, which does not limit the post processing of the map a manual approach is usually preferred. For example, drawing new details or trying to equalize the colors in post production to automatically generated texture map as seen on the figure would be difficult. The main for the problems is that the map is divided in small blocks.

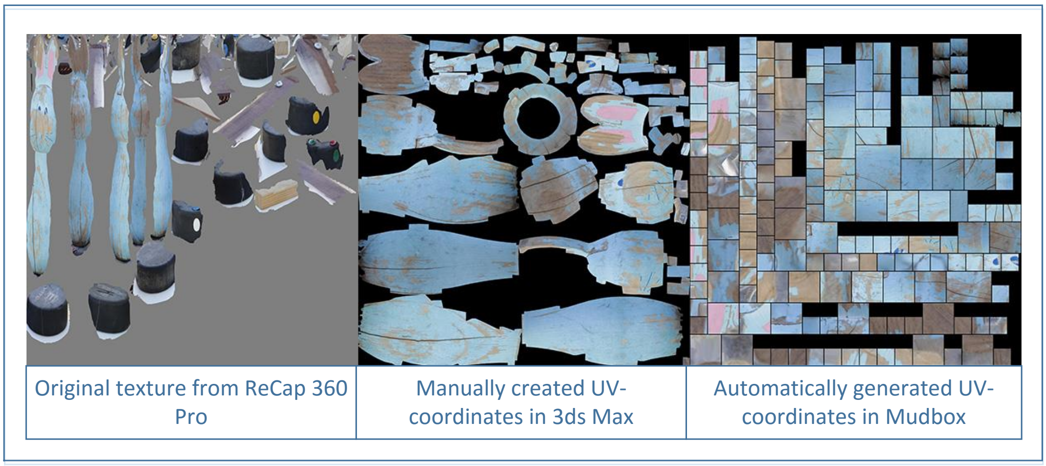



Figure 36. Three different texture maps for the same model with different style UV coordinates

On a normal map, the RGB values of the image correspond to the X, Y and Z coordinates of the object's surface normal. In practice, this means storing the details of the high polygon count model's surface to an image. The technic allows the small details of the model's surface to be generated for the model in a real time rendering environment. (Vaughan 2012, 318.)

## 3.6 3D geometry file formats

It is necessary to be able to transfer 3D models between different applications. 3D software may have own native file format but different neutral file formats provide interoperability between the applications. Some originally native file formats from different applications and developers are now open and adopted by other 3D applications. (Puhakka 2008, 430.)

### 3.6.1 Autodesk FBX

Regardless of the software vendor or computer platform the FBX file format (Filmbox) provides interoperability between most 3D software. Originally, FBX is native file format of Autodesk Motion Builder, a software for creating and editing key frame animation and motion capture based animation. FBX file contains data of model's geometry, textures, lighting and animation sequences. For example, Autodesk's 3ds Max, Mudbox, ReCap 360 Pro and ReMake supports the FBX format. Autodesk utilizes the FBX format as data exchange format between 3D animation software. The format makes possible the single step interoperability between the applications, which makes easy to exchange the digital assets from application to other. The FBX file format is also used for importing models for the game engines for example Unity supports the FBX format. (Autodesk 2016i.)

### 3.6.2 Object file

Object file (OBJ) is now a universally accepted format but originally it was developed by the Wavefront Technologies for the Advanced Visualizer software (FileFormat.Info, 2016). The Wavefront Technologies was renamed as Alias Systems Corporation in 2005 and became part of the Autodesk in 2006. The Alias Corporation's best-known product was the 3D modeling and animation package Maya that is now one of the Autodesk's 3D animation packages. (Autodesk 2016e)

The object file supports ASCII format or binary format. ASCII format object file must have the .obj extension in the file name. Binary data can also have a .mod extension. Figure 37 and Figure 38 are examples of ASCII based object files. Both of the examples contain one polygonal 3D object. The object described is a box primitive. The first example list only the corner points, faces, material library name and the name of used the material. In the file with the keyword "v" are described the corner points (vertices) and with the keyword "f" the polygons (faces). The second example is the complete object file which also describes the vertex normals (vn), texture coordinates (vt) and each face's smoothing groups (s). It is important to notice that even the complete object file listing does not contain any information of the units used. For this reason, the used application usually writes the units inside comments in the file. This means that the user must pay attention to the scale of the objects when transferring the objects between the applications. (FileFormat.Info 2016)

```
mtllib box-70x35x20-simple.mtl

v  -17.5000 0.0000 35.0000
v  -17.5000 0.0000 -35.0000
v  17.5000 0.0000 -35.0000
v  17.5000 0.0000 35.0000
v  -17.5000 20.0000 35.0000
v  17.5000 20.0000 35.0000
v  17.5000 20.0000 -35.0000
v  -17.5000 20.0000 -35.0000
# 8 vertices

g ExampleBox_Lengh70_Width35_Height20
usemtl Grey
f 1 2 3 4
f 5 6 7 8
f 1 4 6 5
f 4 3 7 6
f 3 2 8 7
f 2 1 5 8
# 6 polygons
```

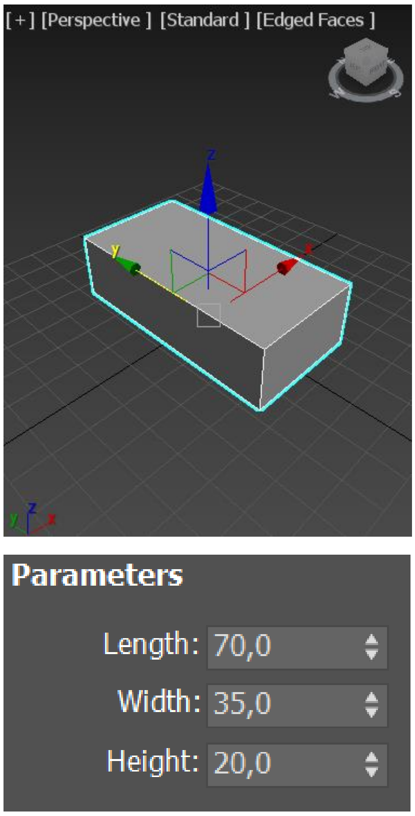



Figure 37. Basic example of the .obj file

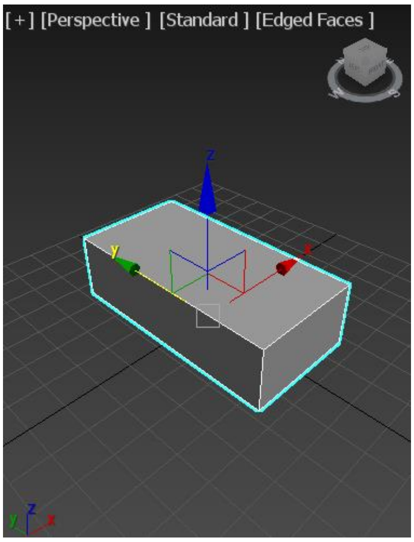
```
mtllib box-70x35x20-simple.mtl

v  -17.5000 0.0000 35.0000
v  -17.5000 0.0000 -35.0000
v  17.5000 0.0000 -35.0000
v  17.5000 0.0000 35.0000
v  -17.5000 20.0000 35.0000
v  17.5000 20.0000 35.0000
v  17.5000 20.0000 -35.0000
v  -17.5000 20.0000 -35.0000
# 8 vertices

vn 0.0000 -1.0000 -0.0000
vn 0.0000 1.0000 -0.0000
vn 0.0000 0.0000 1.0000
vn 1.0000 0.0000 -0.0000
vn 0.0000 0.0000 -1.0000
vn -1.0000 0.0000 -0.0000
# 6 vertex normals

vt 1.0000 0.0000 0.0000
vt 1.0000 1.0000 0.0000
vt 0.0000 1.0000 0.0000
vt 0.0000 0.0000 0.0000
# 4 texture coords

g ExampleBox_Lengh70_Width35_Height20
usemtl Grey
s 2
f 1/1/1 2/2/1 3/3/1 4/4/1
s 4
f 5/4/2 6/1/2 7/2/2 8/3/2
s 8
f 1/4/3 4/1/3 6/2/3 5/3/3
s 16
f 4/4/4 3/1/4 7/2/4 6/3/4
s 32
f 3/4/5 2/1/5 8/2/5 7/3/5
s 64
f 2/4/6 1/1/6 5/2/6 8/3/6
# 6 polygons
```



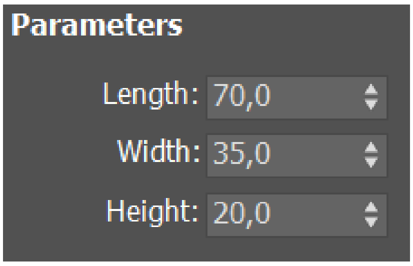




Figure 38. The complete object file for the box primitive

The material definitions related to the geometry are stored in a separate material library file with the extension of .mtl. The material library file contains each materials name, color, texture map, reflection map statements that describes the material (FileFormat.Info 2016). Figure 39 shows an example of the material library file. The left side of the figure describes a material with texture map. The right side explains the typical order of the statements related to file. The order of the statement can also be different but always starts with keyword newmtl. The material in the example file uses an external jpg image for the diffuse color but it does not have a reflection map attached.

```
newmtl Material_0

Ka 1.0000 1.0000 1.0000
Kd 1.0000 1.0000 1.0000
Ks 0.0000 0.0000 0.0000
d 1
Ns 0.0000
illum 1

map_Kd Museo-00101.jpg
```

```
newmtl my_materialName
 Material color
 & illumination
 statements

 texture map
 statements

 reflection map
 statement
```

Figure 39. Example of .mtl file

### 3.6.3 STL file

The STL (Stereo Lithography) file format can be considered as the de-facto standard data transmission format for the rapid prototyping industry. The company called as 3D Systems created the file format for the rapid prototyping purposes with stereo lithography technique. Almost all today's CAD systems support exporting data as STL format. STL file is also a polygon file format as the object file. If the original model is a CAD based solid model, then the surfaces are approximated to triangles. With few different parameters the resolution of the model can be modified, more triangles placed to the model's surface more accurate model can be produced. If model is created as surface model, the surfaces are only triangulated as seen on Figure 40. The STL format version is now created only with tree sided faces. (3D Systems Inc, 2015.)

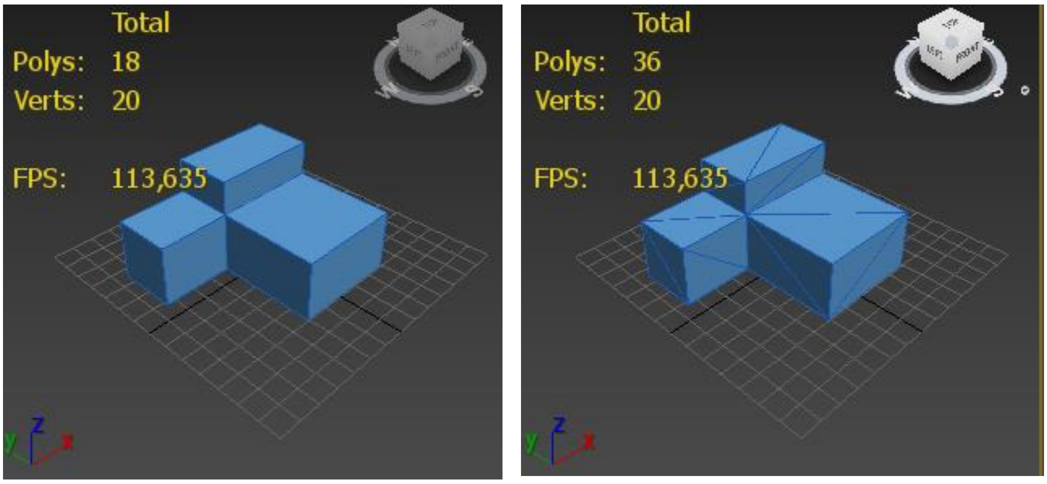



Figure 40. A quad faced polygon object and the same object transformed as STL file

When the model is used for 3D printing purposes the minimum feature thickness of the 3D printer is more limiting feature than the model resolution. The STL file can be saved as ASCII or binary file. Using the binary file option saves file size. The file size of the binary STL file is usually small, for a complex model the file sizes range between 1 to 5 MB has enough detail to produce parts with good quality. Model with a larger file size might have unnecessary details that the 3D printer is not capable to produce. (3D Systems Inc, 2015.)

The STL file describes the name of the triangulated surface, normal direction and vertices. The file looks different compared to .obj file because the vertices are described with floating-point numbers. Similarly, to .obj format the units are not defined. This must be noted when the format is used for 3D printing purposes. The noticeable difference to .obj format is that the standard STL file represent only the surface geometry. The file does not have any information on colors, textures or other attributes. Some software manufactures have created non-standard variation of the STL format and included color information. (Biehler 2014, 222-224)

Figure 41 shows an example of the STL file. The file listing shows only two triangles from the selected object, face normal directions and position of corner points. The entire object with 36 faces in Figure 40 is described with 254 lines. Because of the floating point values, the listing looks bit different than the listing for object file.

```
solid Example-STL-export-box

  facet normal 0.000000e+00 0.000000e+00 -1.000000e+00
    outer loop
      vertex -2.065649e+01 7.743902e+00 0.000000e+00
      vertex 2.837181e+01 7.743900e+00 0.000000e+00
      vertex 2.837181e+01 -3.965672e+01 0.000000e+00
    endloop
  endfacet

  facet normal 0.000000e+00 0.000000e+00 -1.000000e+00
    outer loop
      vertex 2.837181e+01 -3.965672e+01 0.000000e+00
      vertex -2.065649e+01 -3.965672e+01 0.000000e+00
      vertex -2.065649e+01 7.743902e+00 0.000000e+00
    endloop
  endfacet

...
...
...
```

```
endsolid Example-STL-export-box
```

Figure 41. Example of ASCII STL file

# 4 APPLIED PROJECT

The applied part of the thesis consists of developing and documenting a workflow model for creating photogrammetry based 3D models with the software commercially available. During the work process, several real-world items have been digitalized. The final experiment of the suitability of the workflow model is made in a customer-related case. The goal of the workflow is to ensure the quality of the photogrammetric models. The end use of the 3D model is not defined, which leads to the situation that the 3D model created with the help of the work phases should be able to work in different situations.

The first selected indicator for a successful workflow model is that it is suitable to be applied in cases which have different end uses for the 3D model. The second selected indicator for the process is that the 3D model’s topology is based on quad-sided polygons and the model can be referred to as a clean mesh model. The third and final selected indicator is that the polygon count of the object can be influenced clearly in the work process.

The correct shape of the 3D object is considered a self-evident factor. The quality requirements of the texture and the detail level of the model is left to be considered separately in each case.

The selected goals of the workflow are verified by creating high-resolution static renders of the digitalized items, embedding the digitalized items to a game engine and 3D printing the digitalized item.

## 4.1 Selected software tools

Generally, when working with 3D models and graphics there are multiple software tools needed in the different stages of the work process. The presented workflow is based on the commercially available applications. The workflow relies on the application capable of creating a mesh model from the images. The selected photo to 3D applications, Autodesk ReMake and the Autodesk ReCap 360 Pro are both suitable for the task.

Autodesk ReMake has more features to modify and post process the model compared to ReCap 360 Pro. For the post processing of the model, also other Autodesk's 3D applications are utilized. Table 8 lists the main applications required in the workflow. Alternative applications can be used if preferred, for example, Autodesk 3ds Max can be replaced with Autodesk Maya. The main reason for selecting the applications is that they are already available and the personal experience of using the applications.

At the beginning of the thesis process in autumn 2015 Autodesk had just released the beta version of Autodesk Memento and in the beginning of May 2016 Autodesk released the first commercial version of the same application with the name of Autodesk ReMake. The beta version was discontinued after the commercial version release.

Table 8. Main tools required for the project

| Software | Main use |
|---|---|
| **Adobe Lightroom** | Batch processing of the images and raw image file conversions (optional) |
| **Autodesk ReCap 360 Pro** | Photo to 3D processing |
| **Autodesk Memento (Beta)** | Photo to 3D processing (The software discontinued in the end of April 2016) |
| **Autodesk ReMake** | The commercial release of Autodesk Memento |
| **Autodesk 3ds Max** | 3D modeling, visualization and rendering |
| **Autodesk Mudbox** | 3D sculpting and painting tool used for retopology and texture extraction process |
| **Adobe Photoshop** | Texture cleaning and fixing. Post processing and composing of the final elements. (optional) |
| **Adobe After Effects** | Post processing and composing of elements (optional) |
| **Unity** | Game engine for dynamic presentation of the low polygon models (if selected end use) |

## 4.2 Photo to high definition 3D workflow model

The basic photogrammetric process consists of three steps: photography, mesh generation and the cleanup of the generated 3D model. In this context the cleanup means the necessary steps to clean the mesh. Necessary steps are for example deleting unnecessary surfaces of the model or making small adjustment to surfaces. For example, in many cases the elements from the environment where the object is photographed are created to the generated model. In this kind of case one of the cleanup tasks would be deleting the unnecessary surfaces. When comparing to post processing, the post processing stage could contain much more different processing procedures than the cleanup. The post processing can for example contain model optimizing or texture corrections. Figure 42 explains the photo to 3D workflow in Autodesk ReCap 360 Pro and in Autodesk Remake applications. The result of the workflow can be a photorealistic 3D model with high polygon count and complex mesh topology.

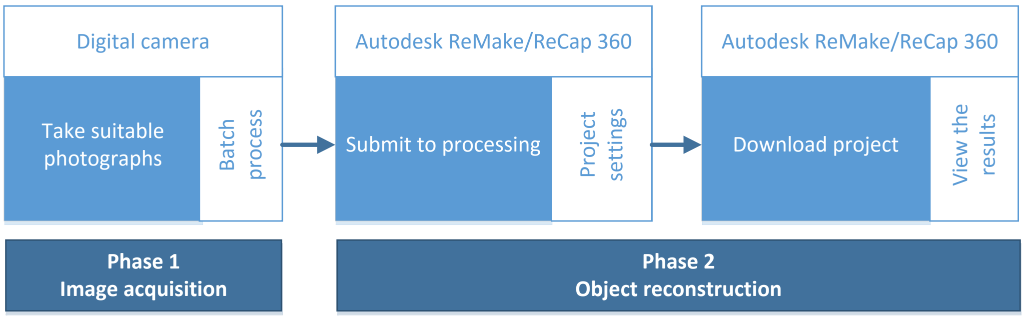



Figure 42. Photo to 3D workflow in Autodesk ReCap 360 Pro and in Autodesk Remake applications

The processing of the 3D model relies highly on the sequence of suitable photographs. The result can be a correctly shaped and highly detailed textured 3D model or it can be far from a perfect digital replication of the photographed item. One thing in common for the generated models is a complex mesh topology and high polygon count. The model's topology and polygon count can be a limiting factor in many end uses of the model. In addition, the post processing of the model can be difficult when dealing with the original high polygon mesh.

The mesh complexity does not mean that the model cannot be applied in visualizations but the high polygon count has its costs. The model can be used for static renderings. It is good to notice that rendering high polygon objects consumes an extensive amount of processing power. With the optimized version of the model, the same visual quality could be achieved with less processing power.

From the modeler's point of view, if the end result requires modifying the shape of the object, rigging or morph based animation, then the complex mesh with high polygon count sets obvious limitations. The complex mesh topology complicates the cleaning of the model. In this context, the cleaning of the model means making small corrections and modifications to the 3D model and the textures. One of the reasons that the model has something to be cleaned up is that the real-world items are difficult to be photographed from every angle. The missing information of the photographed subject leads to models which have holes somewhere in the surfaces. For example, the bottom of the item is not photographed with the result that a surface is not generated in the bottom of the model. If the model's mesh topology were transformed to obey the rules of a clean mesh, then the cleaning and the modification would be simpler compared with the original complex mesh topology.

If the model is required to be embedded in a game engine environment, then the limitations for mesh complexity are quite low. The high polygon count eventually prevents the use of the model in a real time rendering environment. In this case, the workflow is definitely required to contain the optimization of the generated mesh model. In Figure 43 the post processing of the model is included to the workflow. The post processing is divided in two parts, processing the 3D mesh, and correcting and optimizing the automatically generated textures.

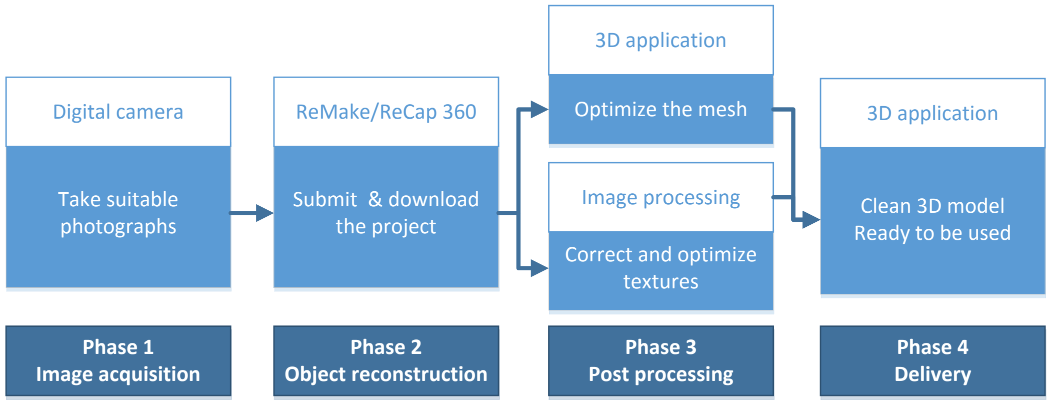



Figure 43. Workflow from images to optimized low polygon version

At the moment Autodesk ReCap 360 Pro does not provide tools for the post processing, it only allows the generated model to be post processed in a different application. Autodesk ReMake is clearly designed to be a more comprehensive application, which has a variety of features for fixing and exporting the model. The represented workflow is based on the concept that the generated mesh is processed externally from the photo to 3D application. In practice, this means utilizing normal 3D modeling and visualization applications in the post processing of the model. This does not mean that the tools provided with ReMake should not be used. ReMake has adapted similar features with the digital sculpting applications for fixing and smoothing the surface of the model. ReMake allows accomplishing all of the basic fixing procedures within the software. It also makes it possible to reduce the polygon count of the model. ReMake even has a simple feature for generating a quad based mesh. From my experience the feature does not work with good results. The same way as with the models generated with Autodesk ReCap, the model can be sent to an external application after the basic cleaning and fixing in ReMake.

### 4.2.1 The solution for the post processing of the model

The foundation for solving the problem with the complex mesh model is to adapt the capabilities of the sculpting applications. The mesh model created with ReMake or ReCap is similar to models created with a sculpting application. The polygon count of the high quality photogrammetric model can be somewhere around 200 000 to 600 000 polygons and it can be even higher. This is similar to a model created with sculpting software. During the sculpting process, the model can have millions of polygons (Vaughan 2012, 128). Even if the model has a million polygon during the sculpting process, the model can be processed to a low polygon version.

Vaughan (2012, 281-282) writes that one popular use of the sculpting applications is to sculpt characters for the game engine environments. This means that the sculpting applications have advanced processes to transform complex topology, even with millions of polygons, to a cleaner mesh with reduced polygon count. The process of creating a new mesh is called retopology. Both of the popular sculpting applications, Autodesk Mudbox and Pixologic ZBrush, have the retopology feature.

An example of the retopology process can be seen in Figure 44. The figure shows a detailed view of mesh topology before and after the retopology process. On the high polygon mesh the polygons are tris or n-gons. The re-created mesh is based on quads. The polygon count is reduced to the desired level which can be seen when comparing the sizes of the polygons.

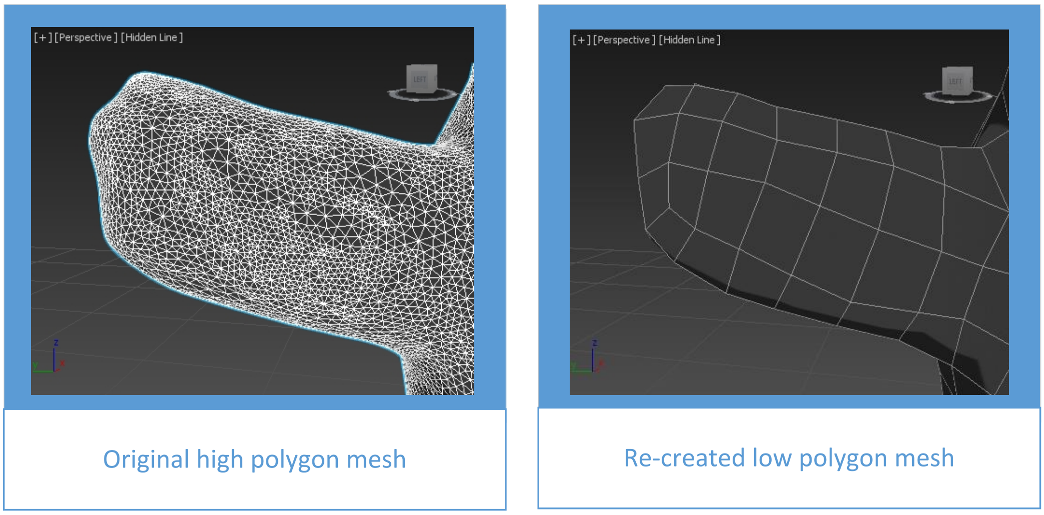



Figure 44. The retopology process

The essence of the retopology process is that the application creates a new mesh object by using the existing surface as a template to build on. The small details in the high-resolution models can be achieved in the new model with the use of a normal map. The retopology process deals with the reduction of the polygon count but it does not necessarily mean that the visual quality of the model degenerates. (Vaughan 2012, 282 & 318.)

Figure 45 shows a visual comparison of the original and the optimized model. The optimized model is created with the retopology tools of Mudbox. These two versions look similar to each other although the re-created model has only about one percent of the polygons of the original model.

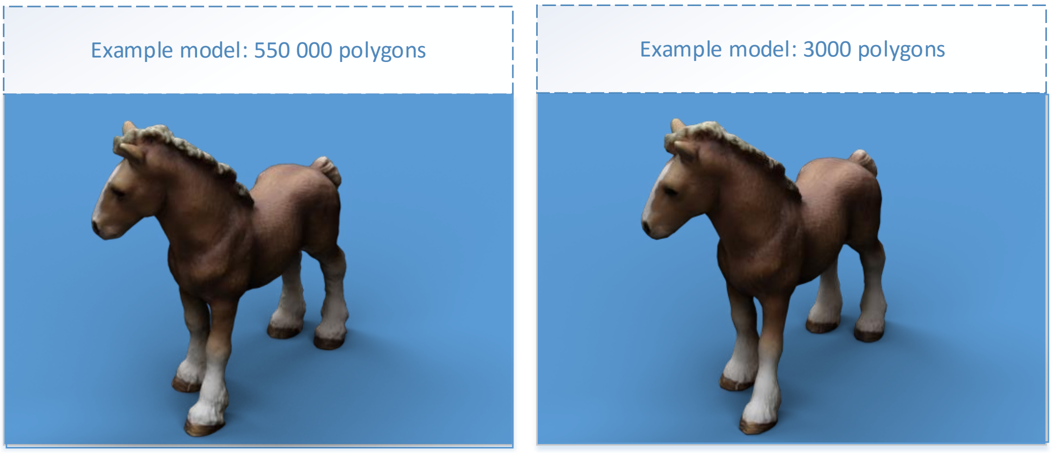



Figure 45. 3D model optimization example, rendered

Figure 46 shows the same retopology example but now the difference can be seen in the mesh topology. The high polygon mesh version has much smaller polygons and the shape of polygons is different. The low polygon version uses quad based polygons. The individual polygons of the high polygon mesh are so small that they are difficult to distinguish in the image.

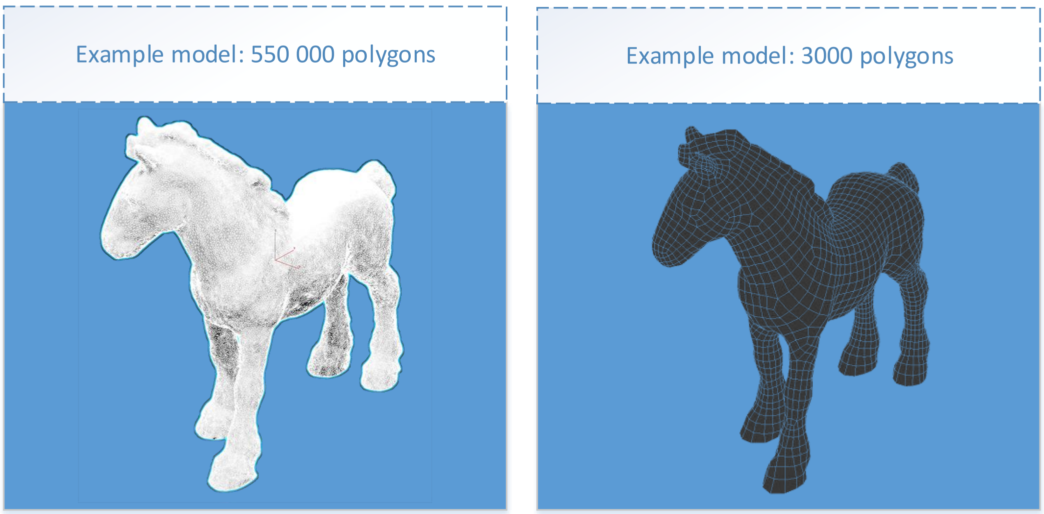



Figure 46. 3D model optimization example, topology

The benefit of the retopology process is that it simultaneously gives control over the mesh topology and the polygon count. With the retopology process, the polygon count can be brought to the desired level without losing all of the details in the model. In addition, the model can be re-created with quad based topology. (Vaughan 2012, 305-306.)

Figure 47 shows how Mudbox makes it possible to control the retopology process. The polygonal flow of the new model can be controlled with manually drawn curves and the desired polygon count can be selected among other parameters in the process. The green curves represent manually drawn curves to thr surface of the model. The topology of the new mesh is based on the user-defined curves.

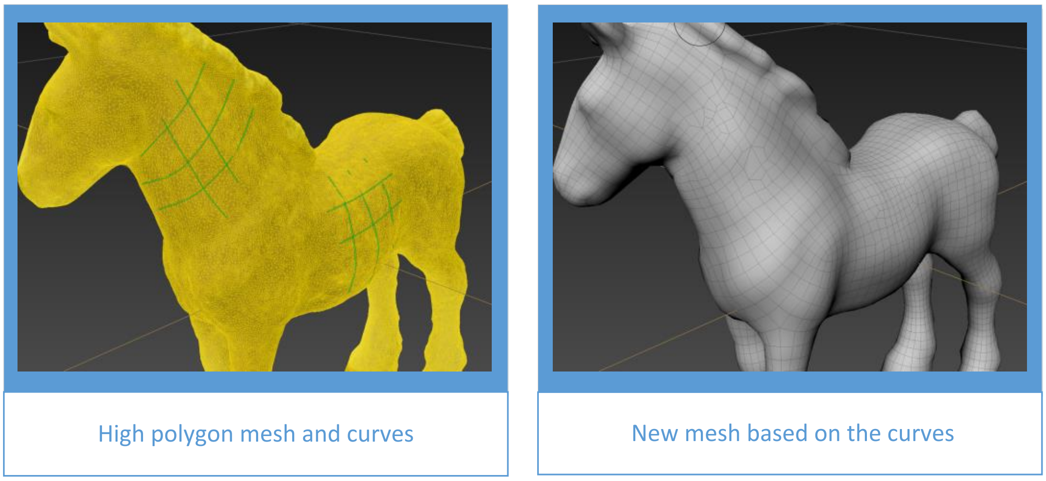



Figure 47. Controlling the retopology process

The photorealistic high polygon photogrammetric model has already a texture map attached to the surface (diffuse channel) and it has the automatically generated UV coordinates. In Mudbox the retopology process creates a new model which does not have UV coordinates. In practice, this means that the new mesh does not have any texture. This leads to a situation where the model's geometry is correct, the model does not look photorealistic any more. To solve the problem related to texture, a new work phase is required to transfer the original texture from the high polygon mesh to the new low polygon model. This work phase includes creating a UV coordinate layout for the retopology model. After the generation of the UV coordinates the texture can be transferred from the original mesh to the new mesh. In Mudbox the feature called as ”extract texture map” projects textures from one geometry to other. After successful texture extraction, the model can be transferred back to the preferred modeling and visualization environment.

Figure 48 summarizes the post processing workflow. The figure describes the post processing workflow model with Autodesk 3ds Max and Mudbox. With this workflow, the high polygon mesh model can be optimized to a clean mesh model with a desired polygon count. Transferring the texture to the optimized mesh is also taken into account. In the figure it can be seen that the model is transferred back and forth between different applications. In practice the back and forth sending of the model between the applications is not a problem. Autodesk’s application can manage the process internally: the model transfers between the applications in the FBX file format. This process is done so that the user does not have to care about saving the file between the transfers. If desired, one transfer between the applications can be left out. This is when the UV coordinates are generated with tools provided in Mudbox.

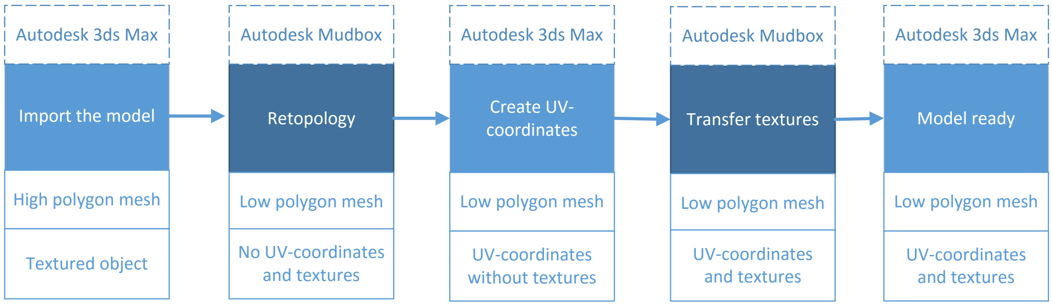



Figure 48. The post processing workflow model with Autodesk 3ds Max and the Mudbox

The previous figure did not include the entire workflow from images to a clean model. The entire process from a photogrammetry based model to a clean mesh with desired polygon count can be seen in Figure 49. With this kind of workflow, the resulting 3D object can be imported for example to the Unity game engine. The post processing is presented in this figure after the basic cleanup of the photogrammetric model.

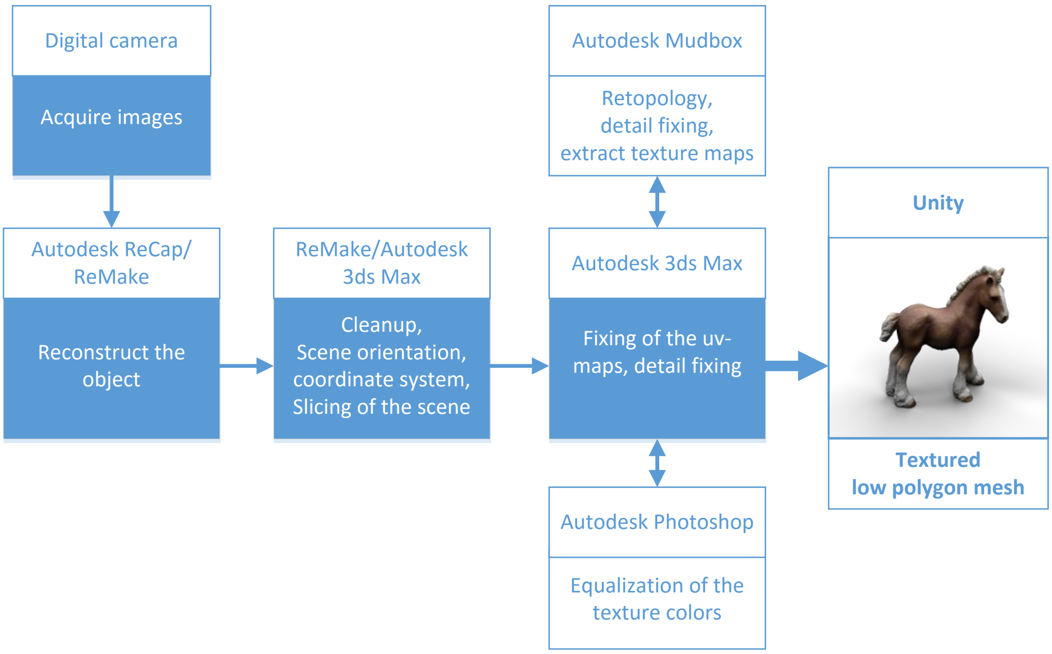



Figure 49. The entire photogrammetric workflow from images to clean mesh

## 4.3 Object reconstruction

The work process and the use of both of the applications ReCap and ReMake are easy to adopt. Although the applications are easy to work with, good results significantly rely on the photographs of the object to be reconstructed. With unsuitable photographs, the result is far from a perfect replication of the photographed item. The result should be carefully evaluated before continuing to post processing the model. In some case, the reconstruction might be required to be re-done with different settings or with new photographs. The quality requirements for suitable photographs and the technical limits of the photogrammetry have to be kept in mind when creating models.

### 4.3.1 Working with Autodesk ReCap 360 Pro

Recap is the simpler version of the applications. On ReCap the images are uploaded to an Autodesk server with a web browser based user interface as seen in Figure 50. The figure combines two screen shots of ReCap 360. After logging in to the service the user account’s main page shows all of the user’s previous projects. The submit image page can be seen on the second screenshot. This example screenshot shows the situation where 58 images from different angles are submitted to the server.

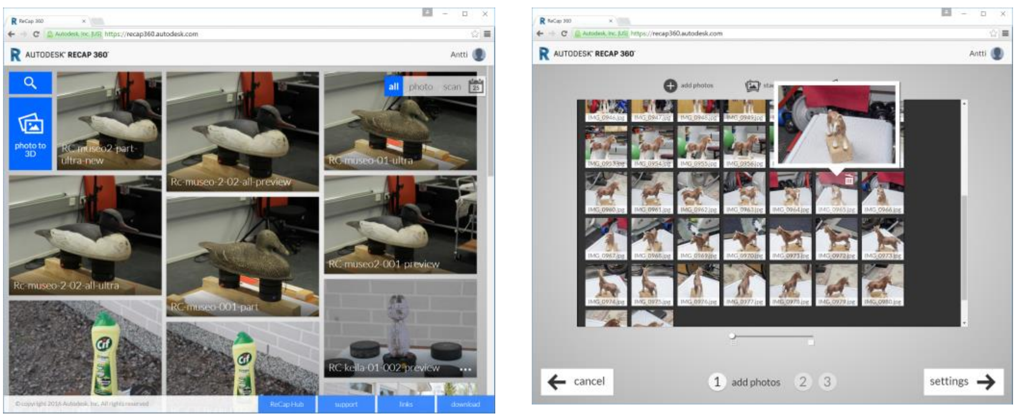



Figure 50. Screenshots of Autodesk ReCap 360, dashboard

After the configuration of the project settings and the scale of the model (dimensions), the images are sent to cloud based processing. Figure 51 shows the configuration of the settings and the upload screen. After the processing is ready the service sends an email notification to the user.

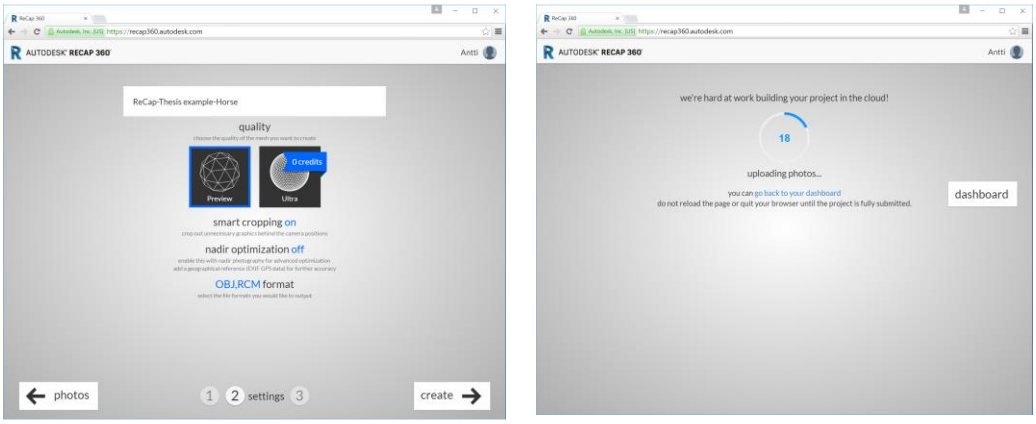



Figure 51. Screenshots of Autodesk ReCap 360, creating new model

After the file upload, the cloud based processing of the model starts immediately if there is not traffic on the cloud. From my experience, the image count and the project quality settings are related to the time it takes for the cloud to process the images. Usually the time has been from two to six hours. Creating models with the highest quality settings can consume even more time. Because the processing of the images consumes that much time it is recommended to apply the preview quality settings first. With the preview version of the model it is possible to see if there are any major problems before continuing to high quality.

When the processing is ready, the model can be viewed and inspected in a browser, as seen in Figure 52. The figure shows the initial result and version where other than the approbriate volume of the generated 3D model is deleted from the scene. After this basic cleanup the model can be downloaded in RCM or OBJ format. The download package also includes the texture for the object in jpg format. The deletion of the selected volume is the only possible cleanup procedure in ReCap 360 Pro. All the other desired post processing steps must be done in a separate application. For example, the downloaded model can be imported in OBJ format to Autodesk 3ds Max. With the help of RCM the processing can also continue in Autodesk ReMake.

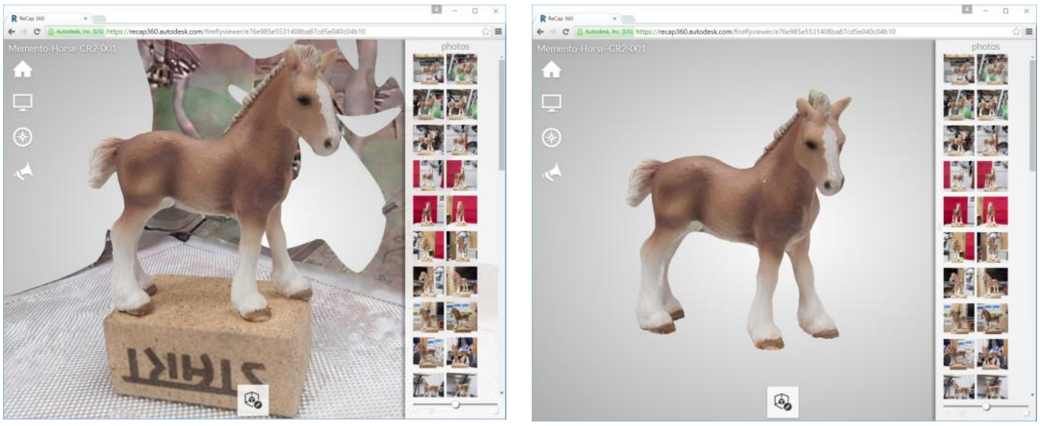


Figure 52. Screenshots of Autodesk ReCap 360, viewing of the model

Figure 53 shows an example of the texture generated by Recap 360. As seen on the image, the resolution is not efficiently used solely for the horse object. Without a high-resolution bitmap, the effective resolution of the texture of the selected object can be quite low. The texture also includes all surfaces that were deleted when the appropriate volume of the generated mesh was selected. In this example the pixels used for the selected surfaces are a small percentage of the whole resolution of the image. This can lead to a situation where the detail level in the texture is quite low.

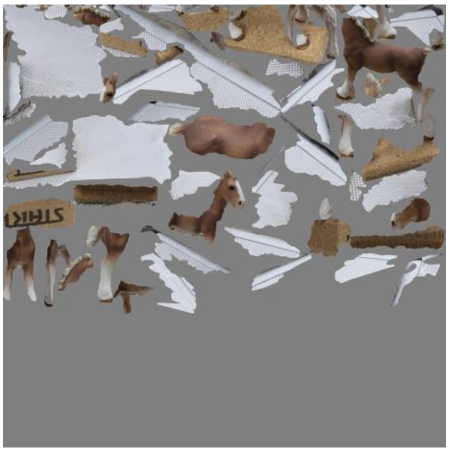


Figure 53. Example of texture generated by ReCap

Before exporting the model, the verifying of the result can be done with the help of different view modes. Figure 54 shows a comparison between the model and one of the original photographs. In the screen shot image a shaded wireframe version of the 3D model is projected on top of an original photograph. This view mode gives the user an easy way to visually verify the result.

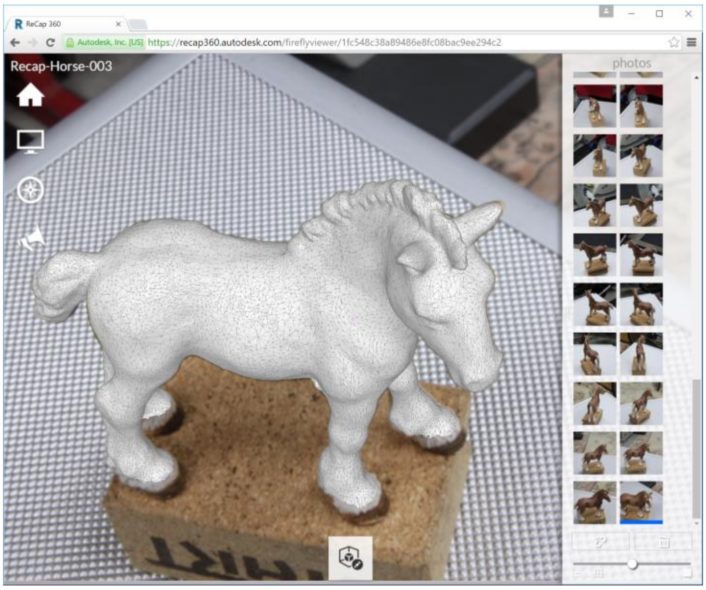



Figure 54. ReCap 360, verifying the result

### 4.3.2 Working with Autodesk ReMake

ReMake is Autodesk’s new tool for producing 3D meshes from photos or scans. It can also be used to clean and process models created with ReCap 360 Pro. Besides the same capabilities as ReCap, the application has features for cleaning, fixing, editing and optimizing the mesh. ReMake is stand-alone software but the models can be sent to cloud based processing. (Autodesk 2016c.)

Using the basic features of ReMake is intuitive and easy. The application makes it possible to use one’s own desktop computer to generate the model or the model can be generated with the Autodesk cloud service. The generation of a mesh object from a photographed sequence of images starts with selecting the images as seen in Figure 55. The process is similar to ReCap 360 Pro but ReMake is a stand-alone application with its own user interface. The selecting of images used for the model also works similar to ReCap. The maximum count for the images is 240.

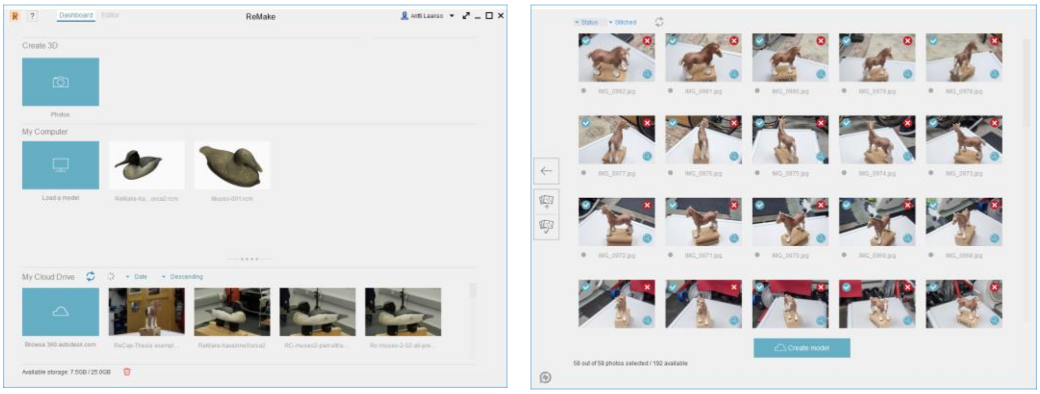



Figure 55. Autodesk Remake

Selecting the images used for model creation leads to the settings menu. The model quality can be set as standard or ultra. If the model is created on the cloud, then only the preview quality is free of charge. For the ultra-quality credits are required. Credits for ReMake can be bought from Autodesk. Figure 56 shows an example of the settings. The ultra-quality has sliders for the surface detail level but for the standard quality there are no settings.

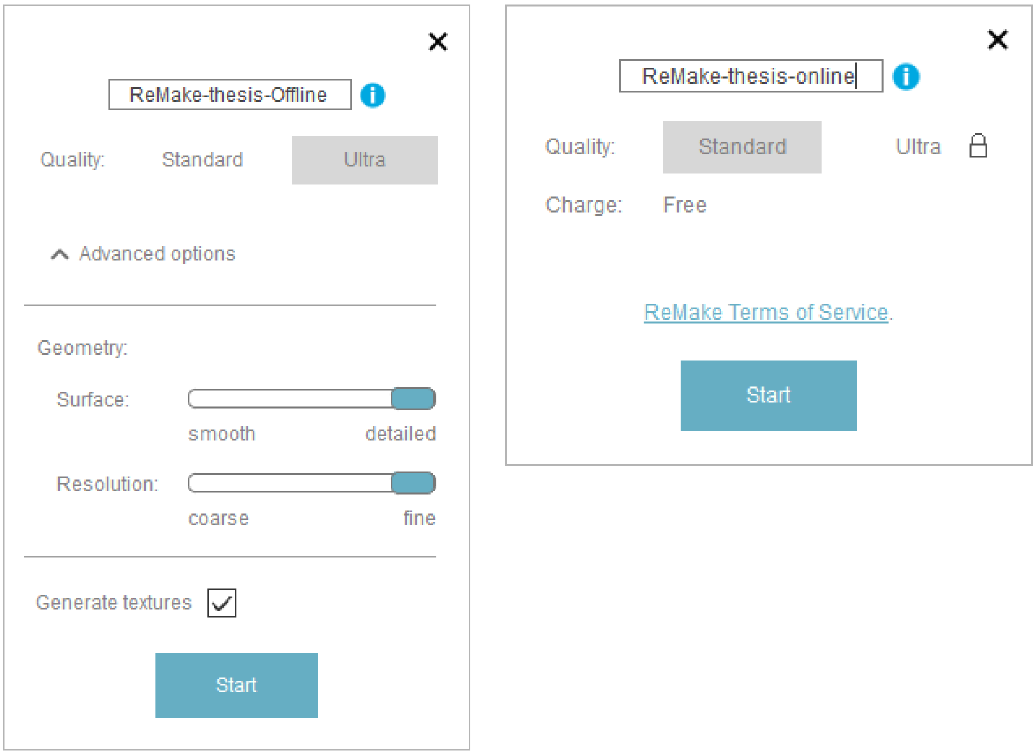



Figure 56. ReMake project settings

After the processing of the images, the generated model can be downloaded from the cloud. The downloaded file can be viewed with the stand-alone application. The quality of the model can be verified with the help of different viewing modes. Figure 57 shows examples of different viewing modes. Each mode has its benefits when viewing the model. The solid mode is useful for verifying the geometry of the model. The wireframe mode shows the mesh structure of the model and the textured mode shows the final result. The textured mode is the only mode which shows the possible problems in the texture.

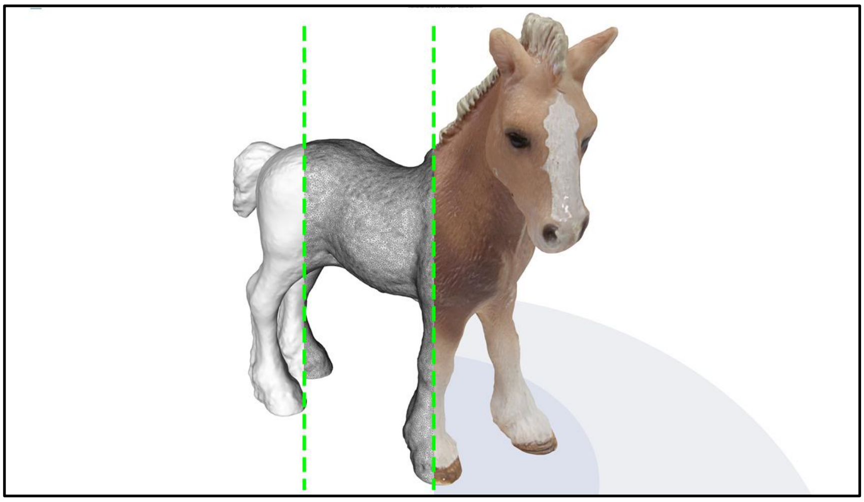


Figure 57. Example of different view modes

Figure 58 shows the generated 3D horse model. Besides the different viewing modes, the mesh report gives information of the model. This model has almost 300 000 faces.


Figure 58. The generated 3D horse model

While ReCap 360 Pro only offers a tool for selecting the appropriate mesh volume, ReMake includes many more tools to be used with the model. Before exporting the model from ReMake different kinds of tools can be used for cleaning and modifying the mesh. ReMake includes similar tools as sculpting applications to modify the mesh. Figure 59 shows an example of smoothing the model's surface. The smoothing tool makes it possible to smooth surfaces that have unnecessary details. ReMake also has tools for slicing of the model and filling of the holes.

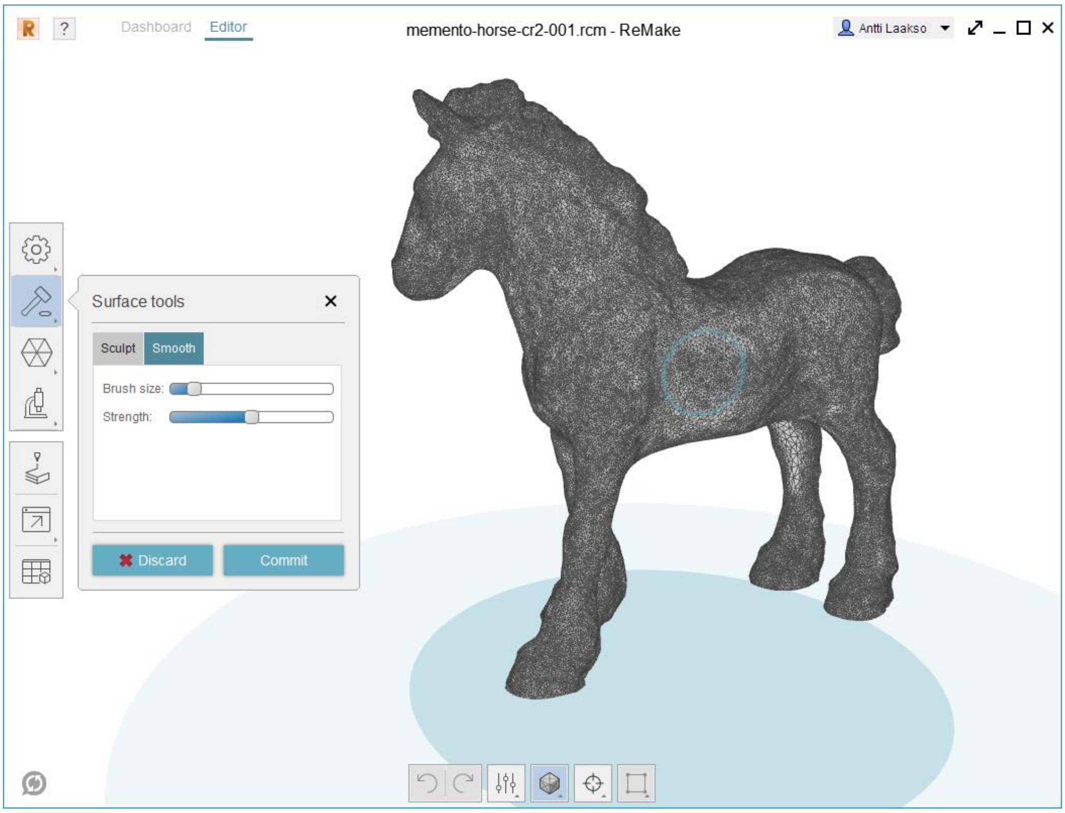



Figure 59. Example of the surface tools in ReMake

ReMake has considerable more possibilities to export the model than ReCap 360 Pro. For example, the polygon count, texture resolution and file format can be effected in the export phase. The model can be exported as OBJ, FBX, STL or PLY file formats. The texture map can be generated in 8K (8000x8000 pixels), 4K or lower resolutions. In addition, a normal map, displacement map and ambient occlusion map can be generated. Figure 60 shows an example of texture maps created with ReMake. The main improvement comparing to ReCap 360 is that the maps can be re-baked after the appropriate volume of the model is selected. This means that the application re-creates the texture map including only the necessary textures. In this example the textures that were part of the surrounding environment are not part of the re-baked texture file. This improves the effective texture resolution. In addition, ReMake can produce an ambient occlusion map and normal map for the model.

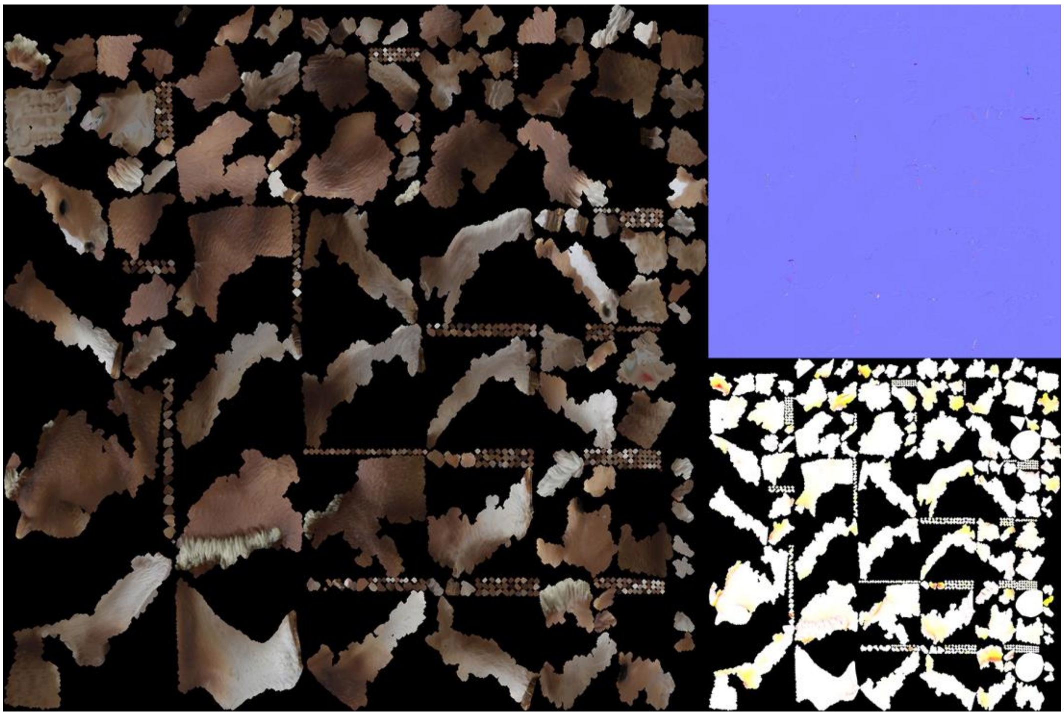


Figure 60. Example of texture maps created in Remake

## 4.4 Experimenting with the workflow

To acquire experience on the workflow and the selected software tools several real world objects have been digitalized, cleaned and post processed. Appendix 1 contains examples of the digitalized models. The examples show the high polygon version of each object. This original version of the model has been created from photographs with ReCap or ReMake. In addition, examples of the low polygon version of objects can be seen in the appendix. The previously described post processing workflow has been used to create a low polygon version of each object. The common goal for the post processing of the objects has been to process each model suitable for game engine use.

In addition to game engine use also other experiments and examples have been created. High quality pre-rendered still images and animations have been created to see how photo realistic the result is. The case example of the Hunting Museum of Finland is related to creating precise pre-rendered visualizations of photogrammetric models. Another end use of the model is related to manufacturing the photographed object with a 3D printer. One experiment represents the 3D printing of a photogrammetry based object.

The general suitability for game engine use has been tested by importing the models to a Unity based game environment. Figure 61 is a combination of four screen shot images of a Unity game engine. The figure is an illustration of a scene which has been populated with digitalized objects. Even with multiple photogrammetry based 3D objects the total polygon count of the scene stays low. The objects are not deforming like game characters but they have been given dynamic properties. In Unity all of the photogrammetry based models are rigid body objects, which means that they are under control of physics. In practice this means, for example, that the game character might be able to push objects to a different position or knock over objects.


Figure 61. Photogrammetric models in Unity game engine

### 4.4.1 Photography and object reconstruction

In the image acquisition phase all of the objects were carefully photographed. In the photography phase, it is especially important to follow the guides represented in chapter 2.4. The equipment used can be seen in

Table 9. From my experience, the location and lighting are extremely important for a successful image sequence. There should be enough room around the object to be digitalized and the surroundings of the objects must be suitable. It is easy to make a mistake and change something around the surroundings if there is not enough free space to move. Also, a vivid background for the images helps the automatic stitching of the images.

Table 9. The equipment used

| **Equipment** | |
|---|---|
| **Camera body** | Canon EOS 7D |
| **Lens** | Sigma 50 mm f/2.8 DG (f/11 & f/13 used)<br><br>(also with Canon EF 50 mm f/1.4 USM) |
| **Other equipment** | Tripod, tape measure, reflecting plates |

The object reconstruction phase is significantly based on the photographs. Both of the applications work only with jpg files and the original RAW images need to be converted without any additional image processing.

In the post processing phase the possible mesh problems of the generated model can cause harm. In the worst case, the mesh related problems could even prevent the whole post production of the model. The generated mesh model's topology can have mesh properties that are not supported by the other post processing applications. From my experience most of the mesh problems were generated when cleaning and processing the model with ReMake's surface tools. Appendix 2 lists some common mesh problems that can come up when transferring the model to Mudbox and suggests solutions for the problems.

### 4.4.2 Example of a game engine implementation

In this case example, a simple bowling game's 3D models have been replaced with photogrammetry-based models. The idea is to see how identical the digitalized pins are compared to real world pins. This simple example proves that that photorealistic 3D models can be used in a game engine environment when correctly post processed. Unity is the selected game engine environment in this example.

The reference photograph of the real world pins and a pre-rendered image of the 3D versions of the pins can be seen in Figure 62. The post processing steps and a link to an external post processing video can be found in appendix 3. These materials describe in more detail the steps included in the post processing workflow.

Figure 62. The reference photograph of the real world pins and an example of the pre-rendered low polygon pins

For the optimal performance of the models in a game engine environment, it is important to consider the polygon count of single object. A mesh with a high polygon count needs a lot of processing power from the computer. Without enough processing power, the frame rate of the game drops or the game might not work at all. The comparison between the polygon counts of the original and the post processed version of models can be seen in Table 10. Comparison of the polygon countsThe original version of the models has been created with Autodesk ReCap 360 Pro. When comparing the original polygon counts the quality settings used in ReCap 360 Pro have to be taken into accont. In this example one object makes an exception to the used settings, and it  uses the high quality setting in ReCap. All other models are generated with the preview quality settings. The preview quality produces a lower polygon count compared to high quality settings. The objects in this example do not have so many geometric details, which leads to a situation where the preview quality processing produces enough details for the models.

The result in the reducing of the polygon count is significant. To form a complete view of the quality of the low polygon objects, also a visual comparison between the original and the optimized model has to be made. The comparison between the high polygon versions and low polygon versions of the objects can be seen in Figure 63. The geometry of the low polygon object is not so rounded as in the original and some small details may be missing. The similar texture in the low polygon object is essential to keep the look of the object realistic.

One of the benefits of photogrammetry is the ability to create realistic textures and with appropriate post processing work flow the realistic texture can be transferred to the low polygon version of the model.

Table 10. Comparison of the polygon counts

| | images | original polygon count (triangles) | optimized polygon count | percent of the original |
|---|---|---|---|---|
| **red chicken** | 67 | ~58 000 (high quality) | 446 | ~0.8 |
| **grey bunny** | 42 | ~18 000 (preview quality) | 414 | ~2.3 |
| **green cow** | 42 | ~26 000 (preview quality) | 414 | ~1.6 |
| **blue bunny** | 46 | ~17 000 (preview quality) | 292 | ~1.7 |
| **black pin** | 53 | ~22 000 (preview quality) | 235 | ~1.1 |
| **broken cow** | 46 | ~31 000 (preview quality) | 478 | ~1.5 |
| **TOTAL** | 296 | ~172 000 | ~2 279 | ~1.3 |

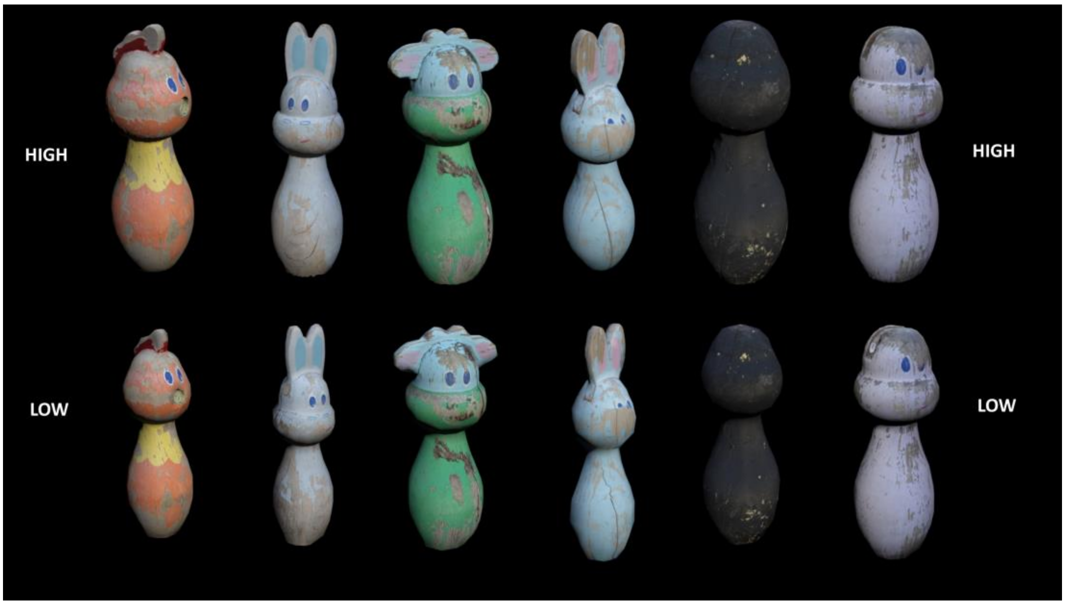



Figure 63. Comparison of the high polygon versions and low polygon versions

After suitable low polygon objects are created the models can be imported to a Unity game engine in FBX file format. In the exporting phase in the 3D modeling software different settings can be used to obtain desired properties for the models and also pre-created animation can be attached to FBX file. The image files that contain the texture maps can be imported to game engine as separate files.

Before importing the textures to a game engine, the texture resolution must be considered. The polygon count of the object is essential for how much processing power the model needs from the computer in a real-time rendering environment but also the texture resolution and the used material shader have an impact on the processing power demand. An example of a Unity project can be seen in Figure 64. The screen shot image shows the project and the graphic elements included in the scene. The pins are rigid body elements and therefore under the control of physics. This screen shot shows the development view of the project. The Figure 65 shows screen shot images of the game play view. The used material shaders, lights and effects are also connected to the quality of game play graphics.

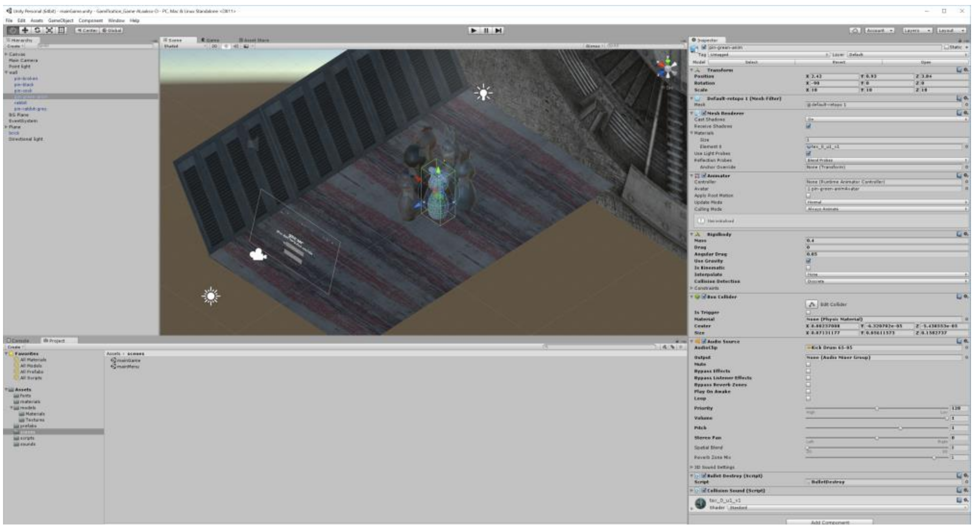


Figure 64. The 3D models imported to the Unity game engine

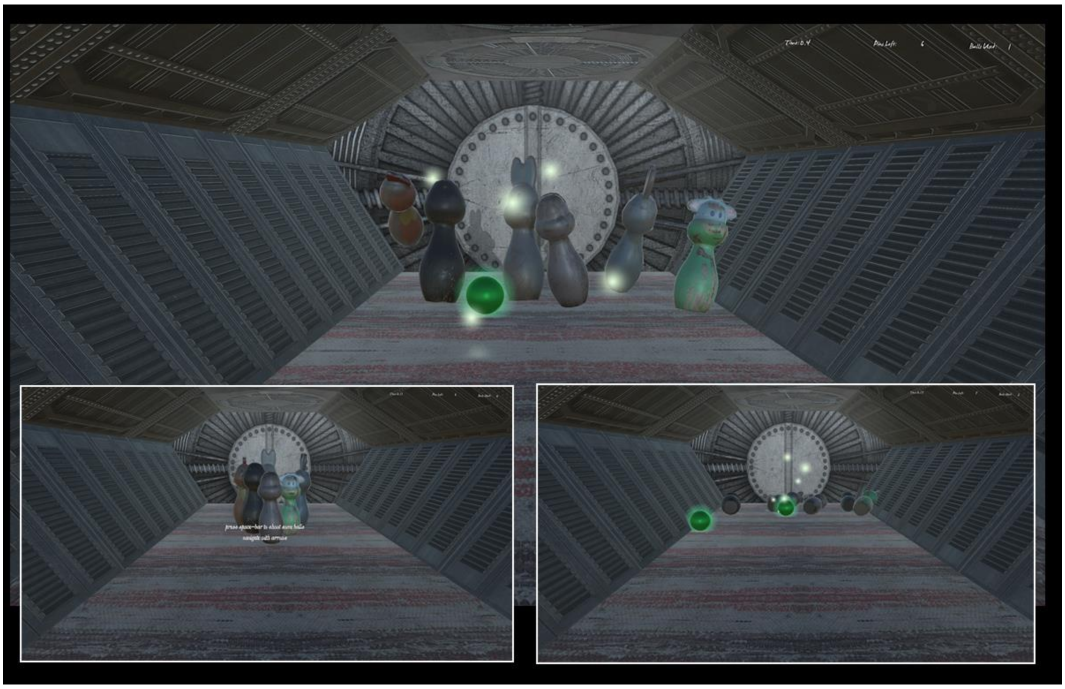


Figure 65. Screen shot images of the simple bowling game with photogrammetry modeled pins

### 4.4.3 Case example: The Hunting Museum of Finland

For Häme University of Applied Sciences on, one suitable partner for projects involving photogrammetry based 3D modeling could be the Hunting Museum of Finland, which is located in Riihimäki. Museums and archeologists have been using photogrammetry-based technologies for a long time. The development of digital cameras and increasing capabilities of computers and analytical software have brought the opportunity to apply photogrammetry even without special tools. The images can be captured with a standard DSLR camera, and commercial software available for anyone can be used to process the data. Museums have huge numbers of items, which could be somehow digitalized. Some of the items may have properties that make them unsuitable to be digitalized with photogrammetry. In this project two old wooden items, which are related to an upcoming exhibition, are selected to be digitalized. The items selected to be digitalized can be seen in Figure 66. The digitalized 3D versions of the objects should be compared to the original items or these reference photographs.

Figure 66. Reference photographs of the items to be digitalized

For example, the Smithsonian museums has an extensive exhibit of digitalized models in their web pages. One of the technologies used to digitalize objects by the Smithsonian Museum Conservation Institute is photogrammetry. With the help of the Smithsonian X 3D (beta version release) web platform, an extensive collection of 3D models can be viewed with a web browser. The Smithsonian Museum advertises that viewing and navigation with 3D models breaks the normal rule that the museum objects cannot be touched. With the help of the virtual platform, the models can be rotated and looked at from different angles as seen in Figure 67. (Smithsonian Museum 2016.)

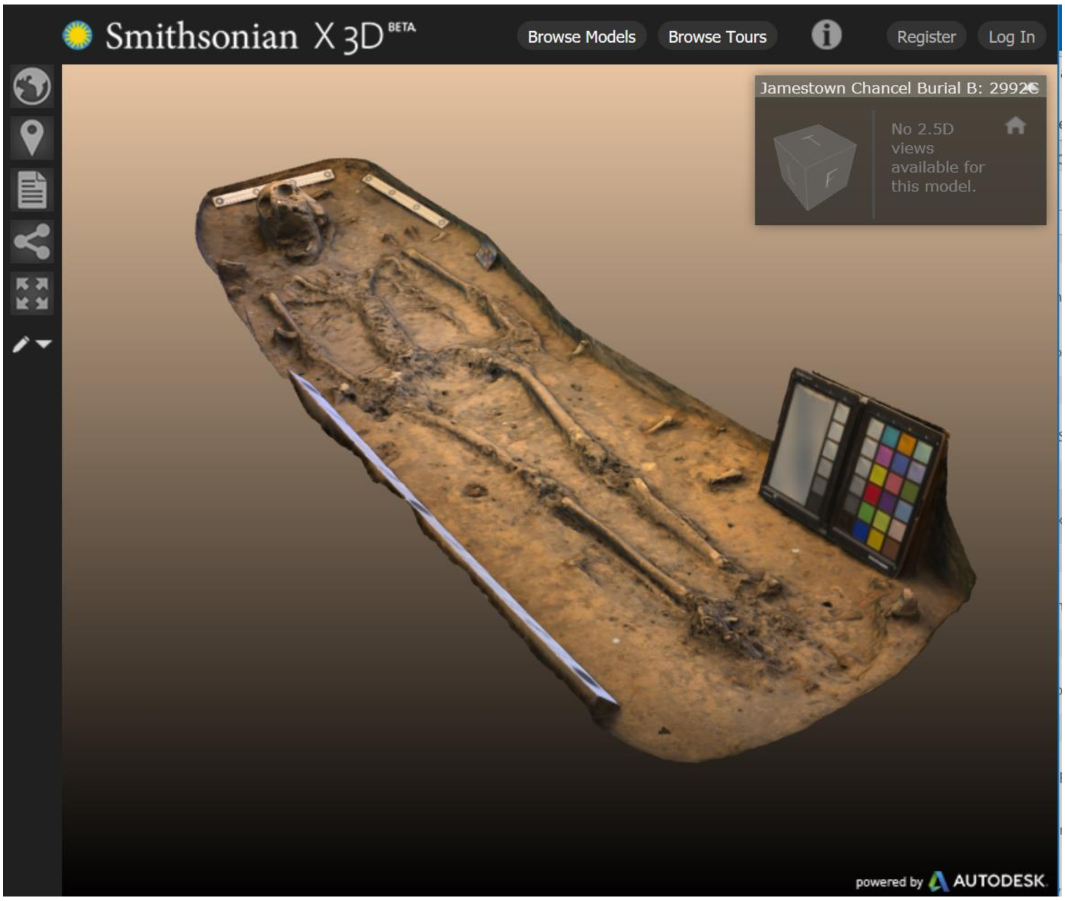



Figure 67. Screen shot image from the Smithsonian X 3D beta platform (Smithsonian Museum 2016.)

There have been three separate goals in this particular case. The main purpose has been to create an example of how an item from a museum's collections can be reconstructed as a 3D model with the tools available. the same time this has been a good opportunity to test the entire At workflow from images to a 3D model. The third goal has been to show the client what can be achieved and, as well as the quality of the created models.

The entire workflow a from photo to 3D presented in the previous chapters has been successfully applied in the case. In the first phase both objects have been separately photographed. Figure 68 shows an example of the camera positions for the photographs. In this case the item has been captured with two rounds of photographs from different heights.

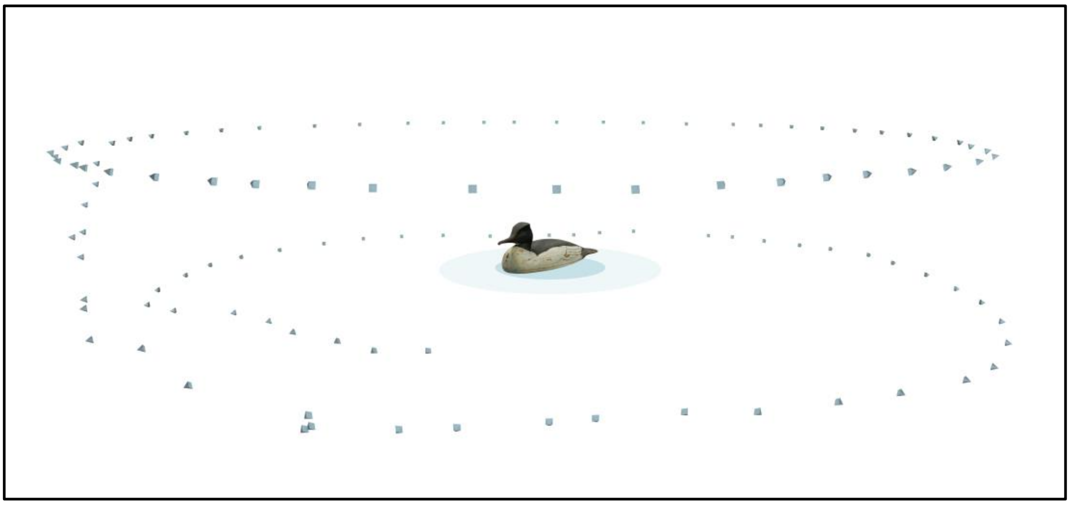


Figure 68. Camera positions

After the photography phase the images have been sent to both Autodesk ReCap 360 and Autodesk ReMake applications to produce the models. Several different settings have been experimented with to achieve the best possible results. Both applications have settings for model quality but also generating the models without all of the images were tested. Sometimes one unsuccessful image or a series of somehow unsuccessful images produce undesired artifacts to the model as seen in Figure 69. This screen shot shows an example of an almost perfect model. A closer examination reveals an undesired dent in the head.


Figure 69. Screen shot image from Autodesk ReCap 360

A successful version created in Autodesk ReMake can be seen in Figure 70. Visually the created 3D model looks authentic compared to original item, but from the technical side the fact that the model has over 46 000 polygons limits the possibilities to use and modify the model. A closer inspection to the model’s mesh structure can be seen in Figure 71. This figure reveals the problematic nature of the model. This kind of mesh topology makes all mesh level modifications to the model difficult. The dense triangle based structure makes it hard to make even small adjustments or surface correction to the model.

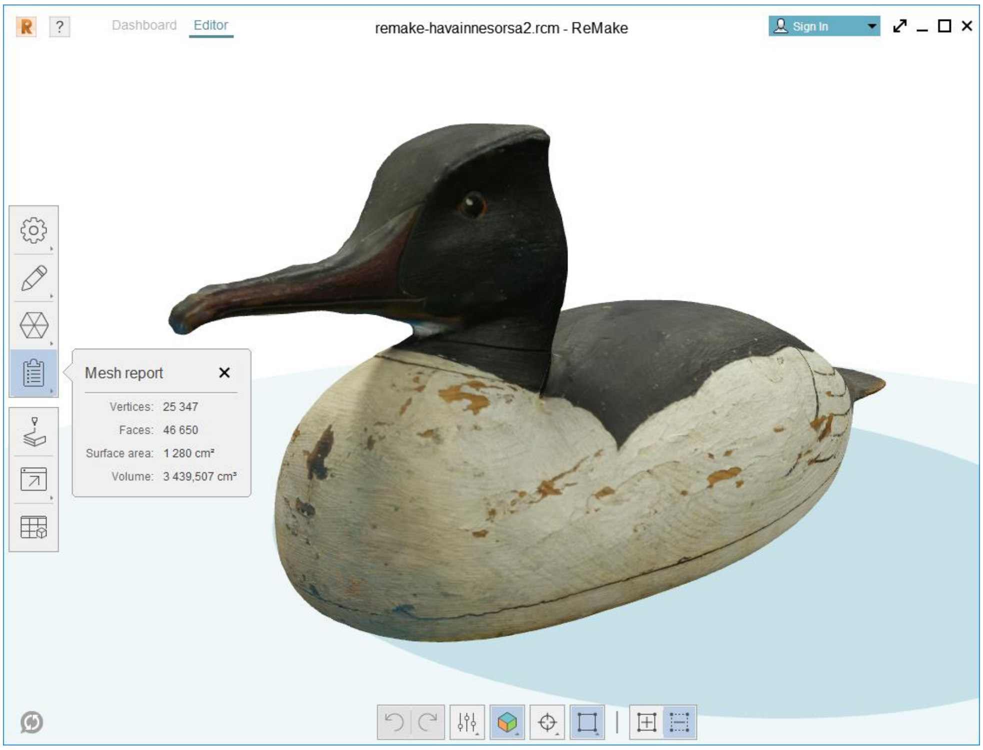



Figure 70. The model created with Autodesk ReMake

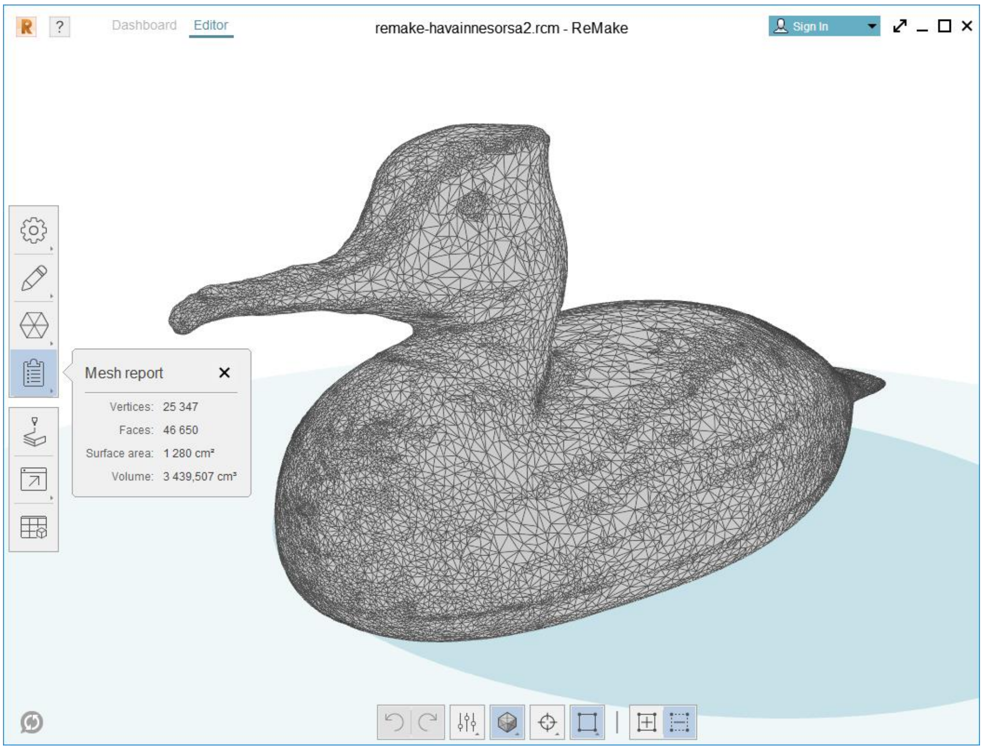



Figure 71. The mesh structure of the model

After the high polygon mesh version has been created with photogrammetry tools the model must be post processed as a low polygon model. Also the post processing part of the workflow has been done following the procedures explained in the previous chapters. The main goal of the post processing has been to create a textured clean mesh version of the model. This also includes correcting the possible artifacts in the model and texture. Figure 72 shows the clean mesh version of the model without the texture. Figure 73 shows the same model with the texture. This model has been created with the help of the retopology process. At this point the polygon count has been reduced to less than 15 percent compared to the original model. The resulting model is created with 2769 quad base polygons with the result that the total polygon count in the triangles is 5538. The final adjustments and the rendering of the model can be done with this quad based mesh. Also the possible problems in the texture can still be fixed.

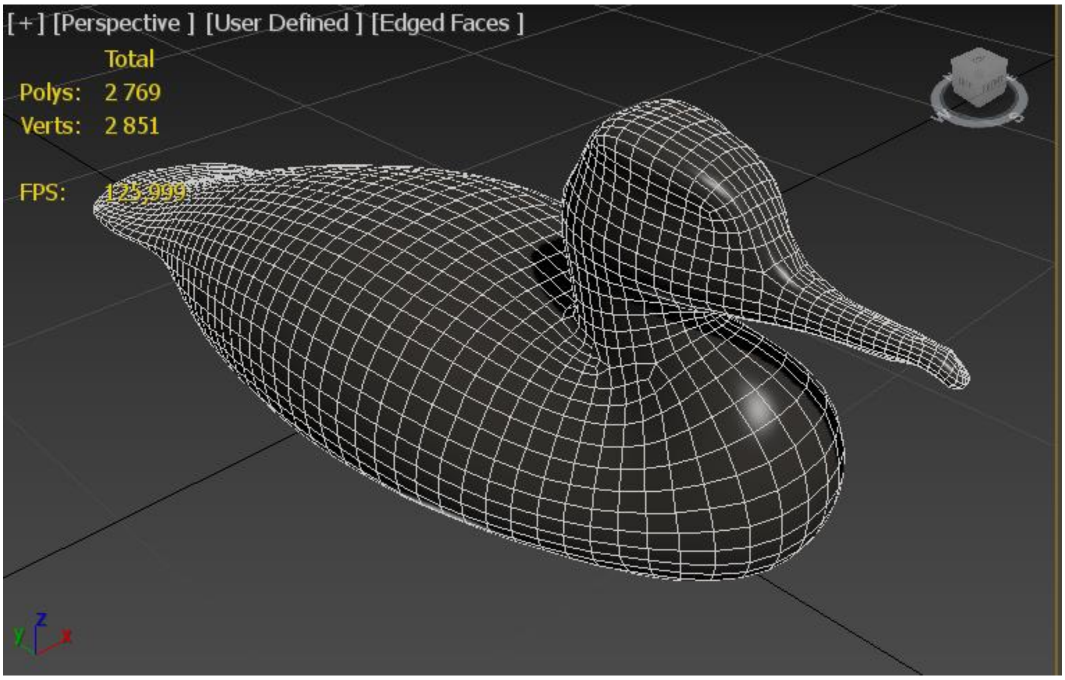



Figure 72. The quad based low polygon version of the model

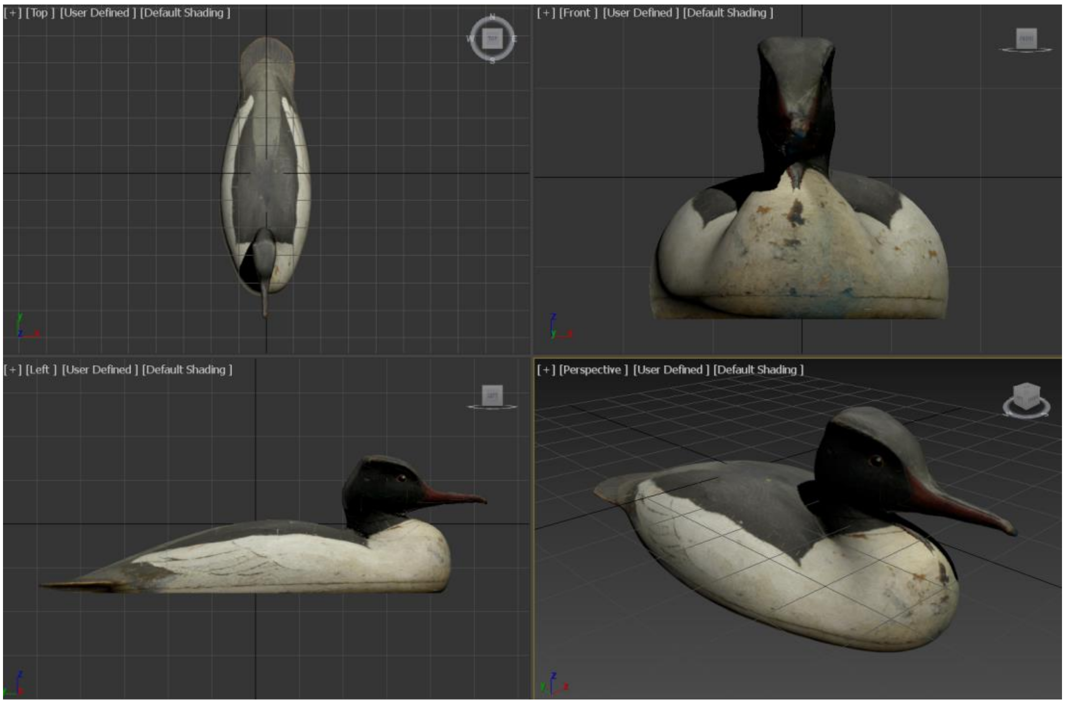



Figure 73. The quad based low polygon version of the model with a diffuse texture

After the post production of the digitalized models have been completed the final videos and still-images have been created. At this stage of work, virtual lights have been used to light up the environment. In addition, the suitable rendering settings have been defined. After the desired images have been rendered from appropriate camera angles the final still images have been composed and fixed in Adobe Photoshop. In this case, the final images are composed from two separate elements. A separate layer called ambient occlusion layer is rendered to achieve high quality. With the help of the ambient occlusion layer more artistic freedom has been gained to compose the final image. This is because more control over the shadows is available in the composition phase when using a separate render pass for shadows. Figure 74 is an example of this simple composition method. On the left side of the image is the normal rendering. On the center of the image is the ambient occlusion layer blended to normal rendering by multiplying each pixel’s color values. On the right side, only can be seen the ambient occlusion layer.

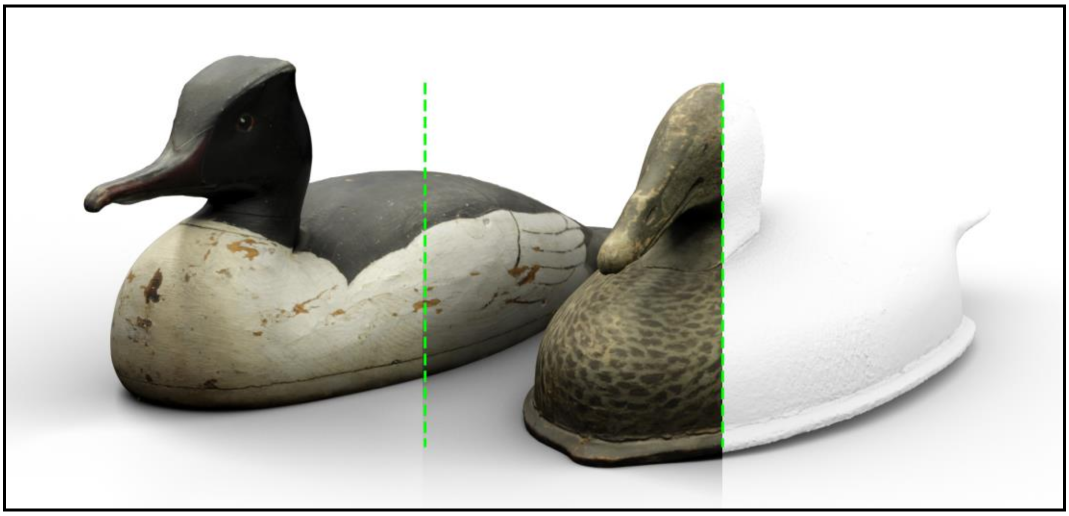


Figure 74. Example of a simple composition method

Figure 75 presentd the final composed images. For the client the final material has been created in full HD resolution. The same kind of image composition has been done for the animation sequences but in Adobe After Effects.

Figure 75. Examples of the final still images

### 4.4.4 Experimenting with 3D printing of photogrammetry model

In this case example, a photogrammetry based model is reproduced with a 3D printer. The main purpose is to experiment how well the post-processing model of the photogrammetry based object is suitable for creating a model for 3D printing purpose.

3D printing is a form of rapid prototyping that makes physical objects from 3D model data. Unlike to traditional machining, 3D printing uses the additive manufacturing method. This means building the model from multiple thin layers. One layer is created at a time and on top of each layer the next layer is created. The entire physical object has been created when all of the layers are finished. (Vaughan 2012, 322.)

Different kinds of 3D printer technologies are available for printing a physical object. These involve methods where liquid material is hardened one layer at a time or material is melted to produce the layer. In the ink jet sytem printing powder is hardened with a binding agent to create the layers. (Vaughan 2012, 322.)

The same workflow has been used for the post processing of the model as for the models in the other case examples. In this case, the polygon count of the model has been left higher to better maintain the geometric details of the model. Because the model is printed without colors only the shape of the object is important. The printer used for the case is 3D System’s ZPrinter 450. The printer is an ink jet printer which creates the model from powder with the help of the binding agent.

In this case one additional task in the post processing of the model is to ensure that the model is a solid. This means that the entire model has to be airtight and there cannot be any holes in the surface. Figure 76 shows how the bottom of the model has been modified to achieve an airtight model.

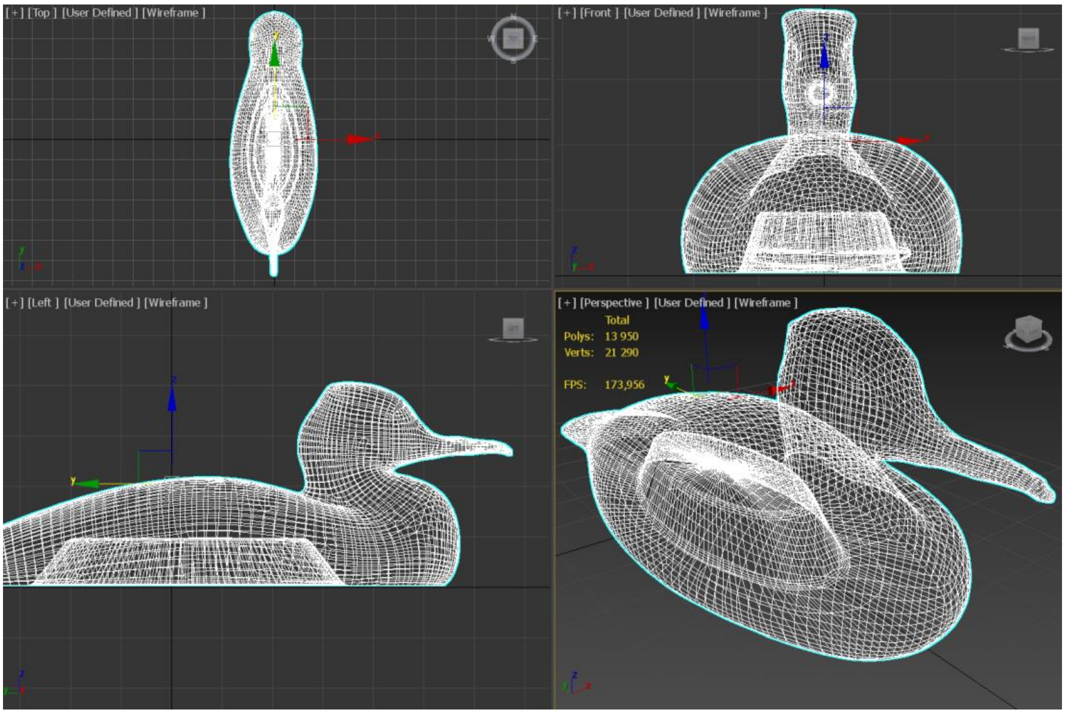



Figure 76. Solid version of the model

For the software that drives the 3D printer the model must be converted to STL file. Before exporting the model to STL format, possible mesh errors can be checked automatically. Some of the possible errors in the model's surface can be hard to see and the automatic check feature seen in Figure 77 can be used to avoid problems when creating the conversion. This tool gives user feedback on the features of the model that should be repaired before printing the model. These features can include for example open edges, holes and overlapping surfaces.

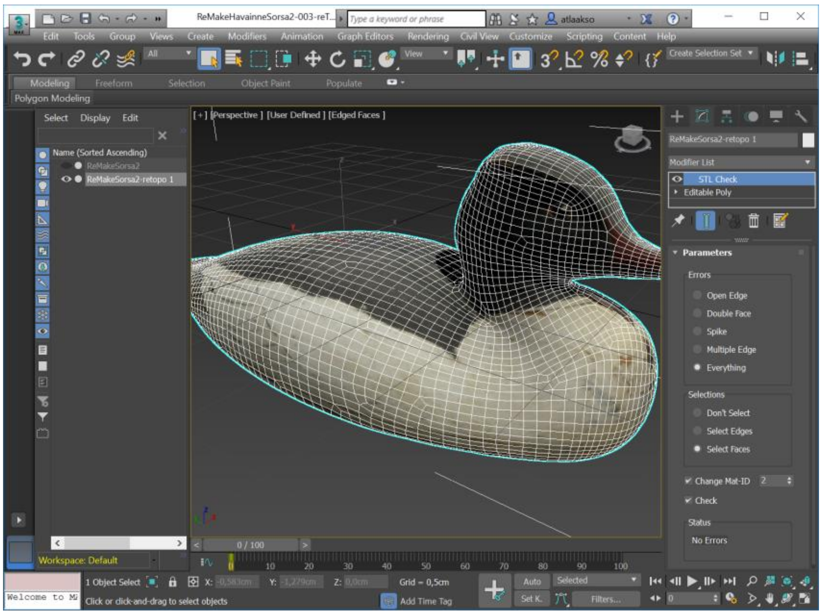



Figure 77. STL error check

The conversion of the model to STL format re-triangulates the polygons. The resulting polygons are three sided as seen in Figure 78. Because of the limitations of the standard STL format the colors and texture are not defined in the file.

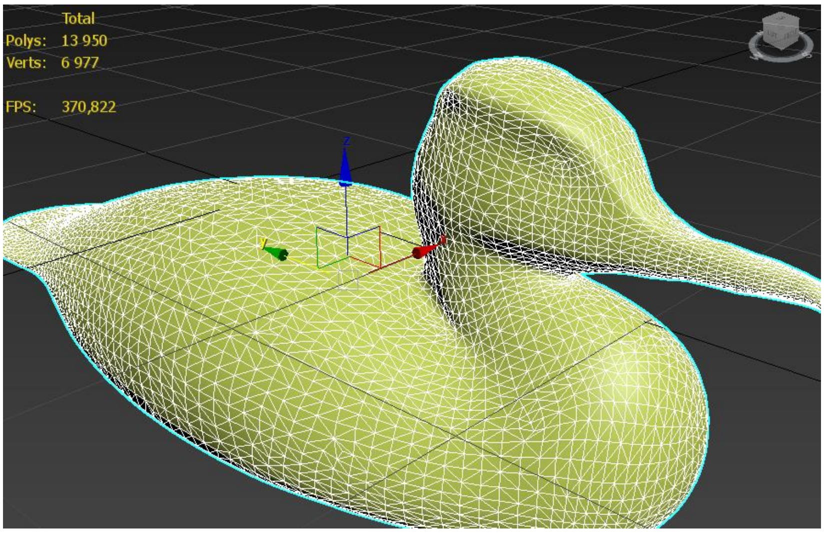



Figure 78. 3D model converted to STL format

Before printing the object with a 3D printer, the correct size for the object must be considered. Because the STL format does not support units the correct size of the object must be checked manually before printing object. Figure 79 is a screen shot from the 3D printer driver software. In the screen shot two copies of the model can be seen, set inside the printing volume. The position and the orientation of the model is important because the physical object will be created from narrow slices.

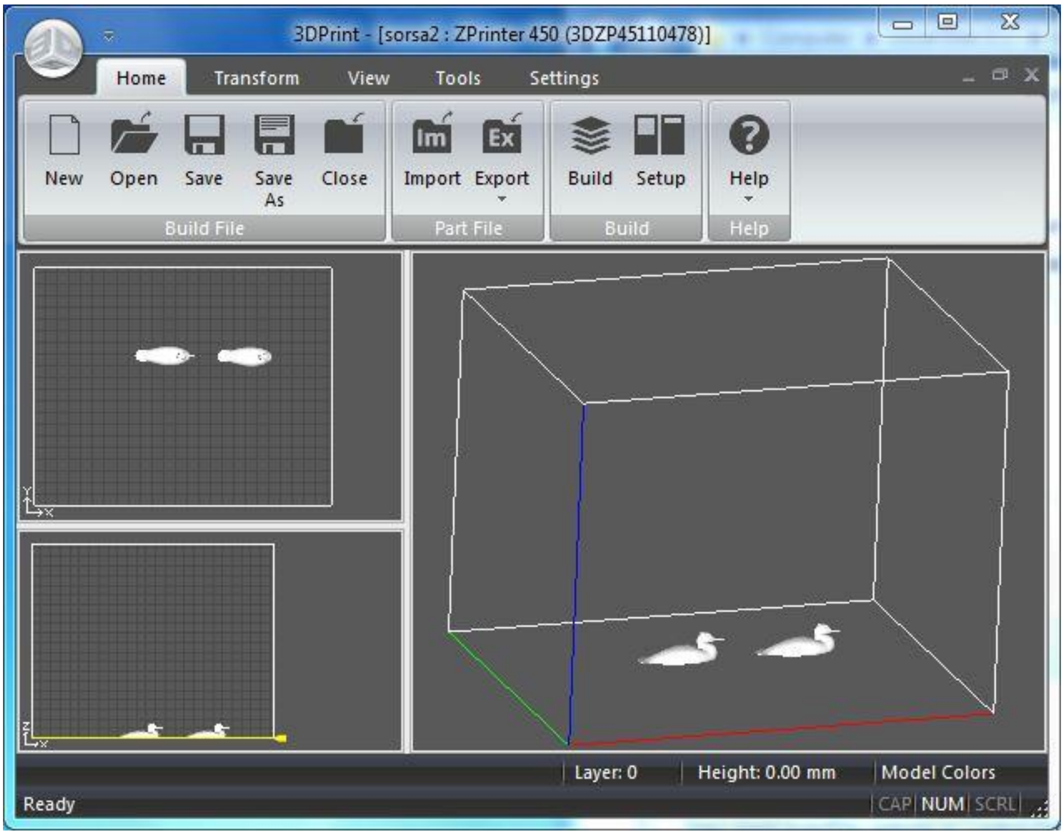



Figure 79. 3D printer driver software

Figure 80 shows the physical objects printed with 3D System's ZPrinter 450 printer. The 3D printer used 156 layers to create these small scale objects (17mm x 51mm x 16mm). The printing of the models took 41 minutes.

The objects are very fragile before they are hardened with chemicals. Figure 81 shows 3D System’s ZPrinter 450 printer and the chemicals for the hardening of the object’s surface. In this case, the printed objects are left without surface colors. The ZPrinter 450 would also  be capable of coating the surface of the model with colors as seen in the Figure 82.

Figure 80. The physical objects

Figure 81. 3D System’s own resin and hardener and 3D system’s ZPrinter 450

Figure 82. Two examples of 3D prints with color

# 5 CONCLUSIONS

## 5.1 Workflow of photo to 3D model

The first research question that the study aimed to answer concerned the workflow of the photo to 3D model process and factors required to be considered in the process. The study defines the work phases required to create models with photogrammetry. These work phases include image acquisition, object reconstruction, cleanup and the post production of the model. In addition, the study introduced the theoretical background for each of the phases. The entire workflow has an effect on the quality of the models. This means that it is essential to understand the theoretical background of all of the phases to obtain the best possible results. For example, it is important not to forget the technology limitations when selecting objects to be digitalized.

The examples created during the study prove that with the help of the modern software like Autodesk ReMake or Autodesk ReCap 360 visually high quality 3D models can be created from photographs. However, if the quality of a 3D model is defined based on also other properties than only the visual look of the model, then the situation can be different. If mesh topology and polygon count are included in the definition of high quality model, then the situation is not so clear any more. This leads to the second research question of the study, which aimed to find the answer to how a photogrammetry based 3D model must be post processed to obtain a model that can be used in different end uses.

Models generated with photogrammetry are likely to have complex mesh topology and high polygon count. In addition, in many typical uses of 3D elements, models with this kind of topology should be avoided. The mesh topology and the polygon count reduction are the main aspects to concern when defining a suitable post processing workflow.

The study presents a workflow which can be used to post process photogrammetry based models. The goal of the post processing is to maintain the original geometry of the model as closely as possible and at the same time re-create the model with better mesh topology. This means creating 3D models that follow the rules of clean mesh. The study defines a workflow that relies on the retopology process. The retopology process has been selected because it is capable to re-create the mesh object with new topology. The end result of retopology is a model that follows the rules of clean mesh. In addition, retopology has important benefits. The most significant benefit is that the polygon count of the object can be set to the user-desired level. This is an essential feature and makes it possible to use the same workflow for models with different end uses. For example, models for game engines and models for 3D printing purposes. The workflow presented in the study relies on the selected applications, but the basic idea of the workflow can be transferred to different applications with similar features.

## 5.2 Knowledge and skill requirements

The third research question of the study aimed to find an answer to the question: What skills are required to create high quality photogrammetry based 3D models? The knowledge and skill requirements for the process can be divided in two categories. The first are requirements related to capturing and processing photographs. The second category is the required 3D modeling skills.

### 5.2.1 Photography skills

The aim of photography is to create a sequence of photographs with uniform exposure. In practice, for the best possible result, this means a solid understanding of the exposure triangle and skills to use the selected camera. A theoretical background of knowing the requirements for the images, camera, lens and environment is essential so that mistakes can be avoided. Individual mistakes in photography do not necessarily mean that a model cannot be processed from the photographs but following the rules as closely as possible makes failure more unlikely. In photogrammetry, photography can be approached in a more technical sense than in artistic photography. In practice this means following the rules of photography when using it for photogrammetry.

### 5.2.2 3D modeling skills

The requirements for the 3D modeling skills are related to how much post processing of the model is required. Autodesk ReMake has already now some features that make it possible to make some modification to a model without a deep knowledge of 3D modeling. The sculpting based features makes it possible to modify the geometry without a knowledge of polygons, edges or mesh topology. However, if the generated 3D model needs to be modified in a standard modeling application like Autodesk 3ds Max then the requirements for modeling skills are much higher. There can be various reasons why the model should be modified in a modeling application.

A basic knowledge of 3D modeling is required to understand the concept of a clean mesh model. This gives the basic requirements how the automatically generated mesh model with high polygon count must be processed. Typically, the development of the 3D modeling skills starts from working with primitive objects, which leads to modifying objects in a box modeling way. Finally, the skills develop to the polygon modeling level, which gives the modeler the ability to control the mesh surface in various ways. The challenge is that if something goes wrong in the generation of the 3D model, then a wide knowledge of the polygon modeling tools is required to fix the model.

Besides working with a standard 3D modeling suite like Autodesk 3ds Max also at least basic skills to use a sculpting application like Autodesk Mudbox is required. The workflow model is dependent on the retopology process, which is a typical feature of sculpting applications. In addition, also a knowledge of other 3D modeling skills is required to embed the models in high quality to visualizations or to game engines. These skills include working with UV coordinates, materials, textures and normal maps.

## 5.3 Photogrammetry based student projects

The subquestion for the study aimed to define which aspects are important when planning a suitable case. The skill requirements for photogrammetry based projects are related to subjects that are taught in the Faculty of Information Technology in the HÄME University of Applied Sciences. This leads to a situation where the related knowledge for this kind of projects is not a problem. The practical skills can be learnt during the projects if the basic knowledge and understanding of the subject is already adopted. The quality requirements for the photogrammetry based models must be defined based on the student’s level of skills. In practice this kind of projects are opportunities for students to develop their skills but the fact that learning takes time must be taken into account. High quality results require time and effort and immediate high quality results cannot be expected.

The success of the projects is also dependent on correctly chosen items to be digitalized. The selected items cannot overcome the limitations of the technology. The task of choosing items is more difficult that it sounds. Although the limitations of photogrammetry can be defined clearly, applying them to reality is a different task. For example, shiny reflecting objects should be avoided, but in reality, it requires experiments to know when the surface of the item is too shiny to be digitalized. It is good to be aware that photogrammetry is only one possible approach to digitalize items. In some cases, a different approach to digitalizing the object might be preferable.

## 5.4 The future of photogrammetry software

The results in the applied projects show that photogrammetry based applications can already create good results. It is likely that in the future also the post processing of the models to clean mesh versions develops. This means that models can be used more easily for different end uses. Autodesk released the first commercial version of ReMake in May 2016. The applications already brought lots of good features to the photogrammetry process comparing to the features of Autodesk ReCap 360 Pro. The future shows what kind of features will be included in upcoming releases. At this point it feels that ReMake has potential to simplify the process in the future.

# REFERENCES

Printed sources and e-books:

Benson, H. 1995. University Physics Rev. ed. John Wiley & Sons, Inc.

Biehler, J., Fane B. 2014. 3D Printing with Autodesk. Que Publishing.

Daniele, T. 2009. Poly-modeling with 3ds Max: Thinking outside of the box. Oxford, USA: Focal Press.

Fryer, J., Mitchell, H. & Chandler, J. 2007. Applications of 3D Measurement from Images. Whittles Publishing.

Luhmann, T., Robson, S., Kyle S. & Harley, I. 2006. Close Range Photogrammetry: Principles, Techniques and Applications. Whittles Publishing.

Matthews, N. A. 2008. Aerial and Close-Range Photogrammetric Technology: Providing Resource Documentation, Interpretation, and Preservation. Technical Note 428. U.S. Department of the Interior, Bureau of Land Management, National Operations Center, Denver, Colorado.

Puhakka, A. 2008. 3D-grafiika. Helsinki, Finland: Talentum.

Raphaele, H., Laure, C. 2014. FOCUS: 3D Modeling of Buildings: Outstanding Sites. Wiley-ISTE.

Vaughan, W. 2012. Digital Modeling. Berkeley, USA: New Riders.

Digital sources:

3D Systems, Inc. 2015. What is an STL File. 3D Systems, Inc. [accessed 22 June 2016]. Available in: http://www.3dsystems.com/quickparts/learning-center/what-is-stl-file

Autodesk 2016a. Autodesk Recap 360. Autodesk Inc. [accessed 25 April 2016]. Available in: http://www.autodesk.com/products/recap-360

Autodesk 2016b. Autodesk Store. Autodesk Inc. [accessed 25 April 2016]. Available in: http://www.autodesk.eu/store/

Autodesk 2016c. Autodesk ReMake. Autodesk Inc. [accessed 24 August 2016]. Available in: https://remake.autodesk.com/about

Autodesk 2015d. Autodesk Memento. Autodesk Inc. [accessed 25 April 2016]. Available in: https://memento.autodesk.com/

Autodesk 2016e. Autodesk & Alias. Autodesk Inc. [accessed 15 April 2016]. Available in: http://usa.autodesk.com/adsk/servlet/index?id=5970886&siteID=123112

Autodesk 2016f. Autodesk 3ds Max 2017 Help, UVW Map Modifier. Autodesk Knowledge Network [accessed 21 June 2016]. Available in: http://help.autodesk.com/view/3DSMAX/2017/ENU/

Autodesk 2016g. Autodesk 3ds Max 2017 Help, Rendering. Autodesk Knowledge Network [accessed 21 June 2016]. Available in: http://help.autodesk.com/view/3DSMAX/2017/ENU/

Autodesk 2016h. Autodesk 3ds Max 2017 Help, Normal. Autodesk Knowledge Network [accessed 21 June 2016]. Available in: http://help.autodesk.com/view/3DSMAX/2017/ENU/

Autodesk 2016i. Autodesk 3ds Max 2017 Help, Autodesk FBX Files. Autodesk Knowledge Network [accessed 21 June 2016]. Available in: http://help.autodesk.com/view/3DSMAX/2017/ENU/

Autodesk 2016 Labs. Autodesk Labs: ReCap 360 Mobile. Autodesk Feedback Community [accessed 23 May 2016]. Available in: https://beta.autodesk.com/

Dzambazova, T. 2014. Autodesk webinar video presentation - Project Memento, It's all in the photos Best practices for taking the photos for best 3D reconstructions [accessed 15 April 2016]. Available in: https://memento.autodesk.com/resources

FileFormat.Info. 2016. Wavefront OBJ File Format Summary. Murray, J. D., Van Ryper, W [accessed 21 June 2016]. Available in: http://www.fileformat.info/format/wavefrontobj/egff.htm

Mansurov, N. 2013. What is distortion. Photographylife [accessed 12 November 2016]. Available in: https://photographylife.com/what-is-distortion

McHugh, S. 2016e. Bit depth tutorial [accessed 15 August 2016]. Available in: http://www.cambridgeincolour.com/tutorials/bit-depth.htm

McHugh, S. 2016a. Camera exposure [accessed 15 August 2016]. Available in: http://www.cambridgeincolour.com/tutorials/camera-exposure.htm

McHugh, S. 2016c. Depth of field calculator [accessed 15 August 2016]. Available in: http://www.cambridgeincolour.com/tutorials/dof-calculator.htm

McHugh, S. 2016d. Lens diffraction & photography [accessed 13 June 2016]. Available in: http://www.cambridgeincolour.com/tutorials/diffraction-photography.htm

McHugh, S. 2016b. Tutorials: Depth of field [accessed 15 August 2016]. Available in: http://www.cambridgeincolour.com/tutorials/depth-of-field.htm

Smithsonian Museum. 2016. MCI Imaging Studio [accessed 11 August 2016]. Available in: http://si.edu/MCIImagingStudio

Unity Technologies. 2016. Unity Documentation. Unity Technologies [accessed 24 May 2016]. Available in: http://docs.unity3d.com/Manual/ModelingOptimizedCharacters.html

# APPENDICES

Appendix 1 - Experimenting the workflow: examples, 20 pages

Appendix 2 – Fixing the mesh problems, 1 page

Appendix 3 – Post processing of a low polygon pin, 4 pages

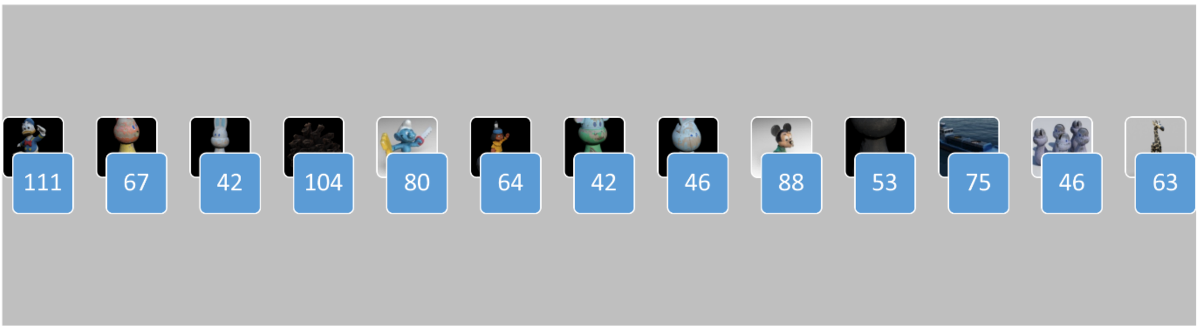
# APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES

## Experimenting the work flow


**The test objects**

1

## Items and image count




2

APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES

**Small Toy, Donald Duck Figure**

111 images
425 000 polygons

Recap 360

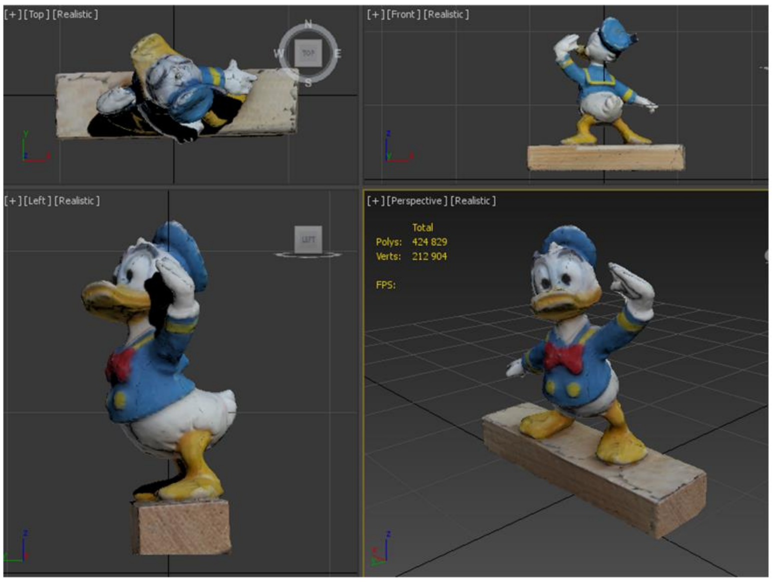
Notes:
Height of the object 7cm

**Low Polygon version**

4155 polygons

**HIGH POLYGON VERSION**

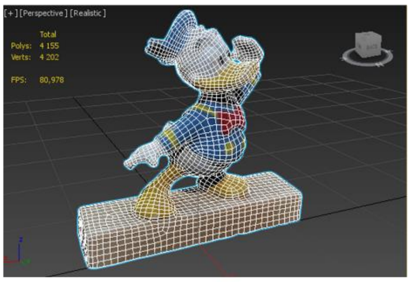
3




**HIGH POLYGON VERSION**

4

# APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES





**LOW POLYGON VERSION**

5

**Small Toy, Mickey Mouse Figure**

88 images
515 000 polygons

Recap 360

Notes:
Canon 50mm macro objective used

Notes:
Height of the object 6cm

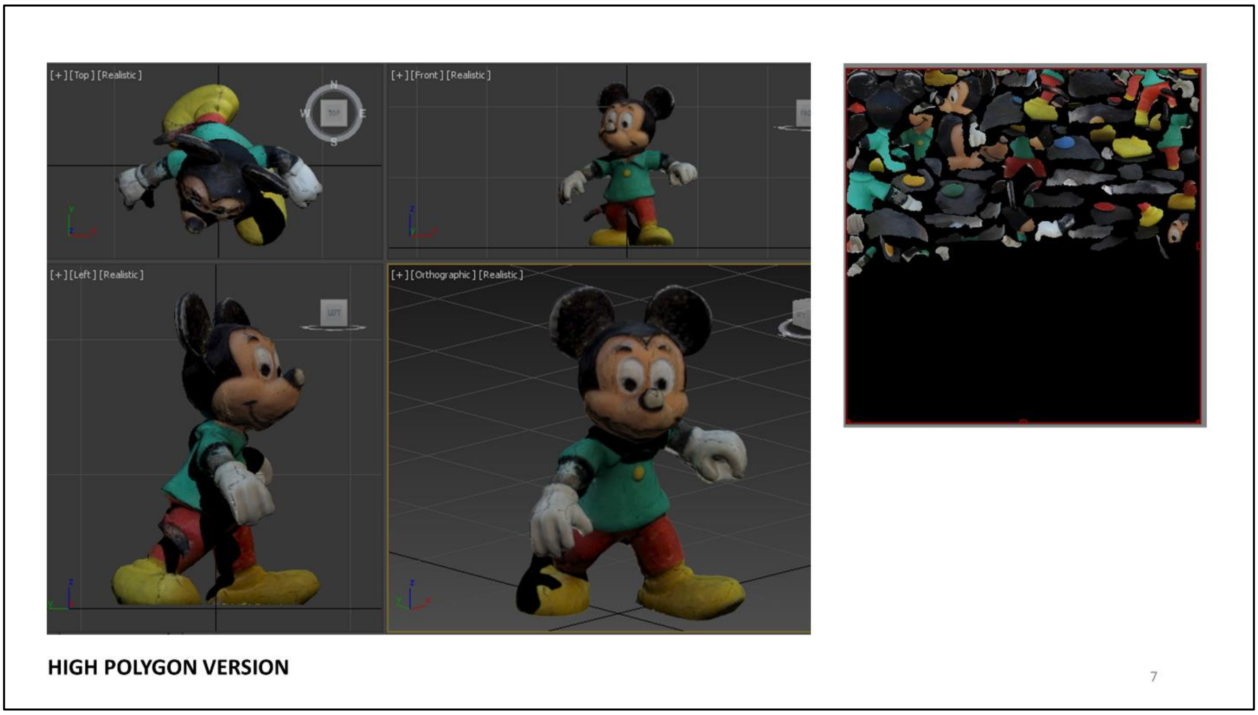
**Low Polygon version**

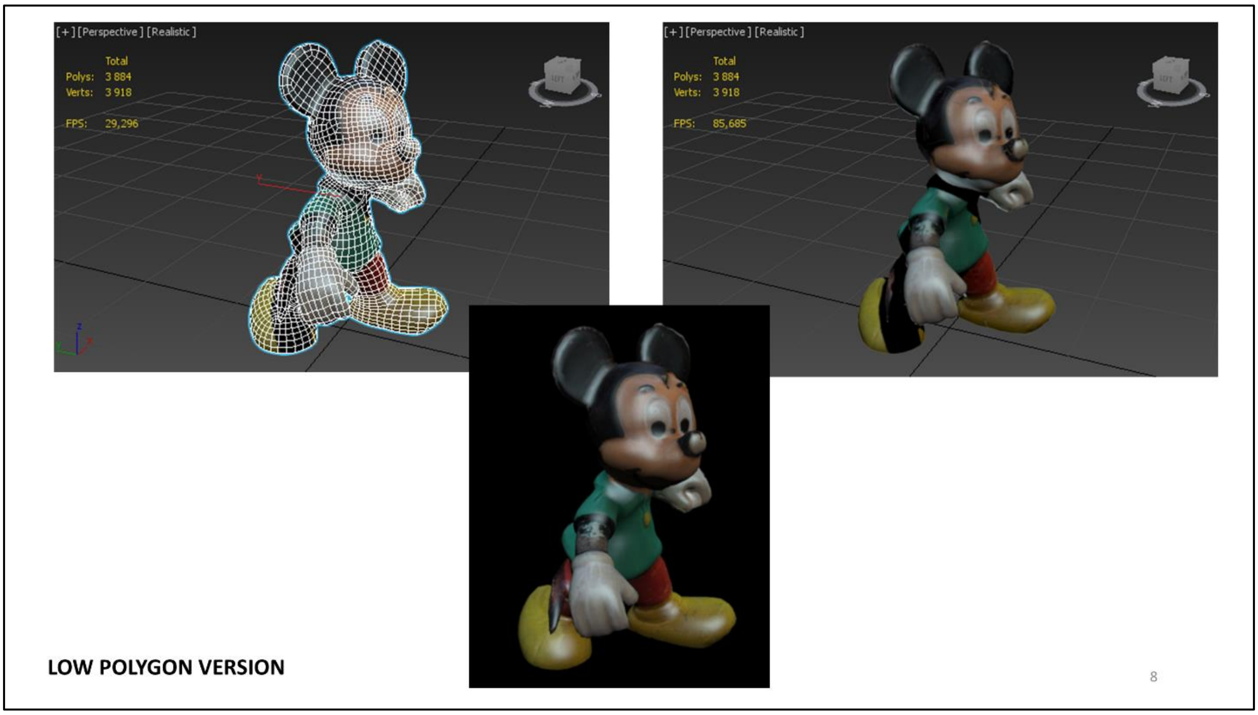
3884 polygons

**HIGH POLYGON VERSION**

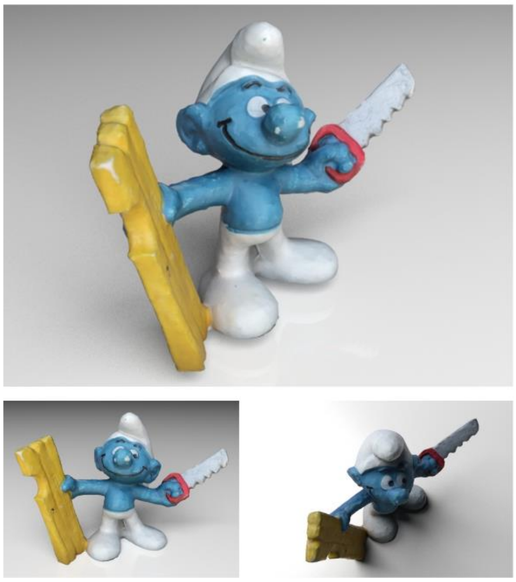
6

APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES



# APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES



**Small Toy, Smurf Figure**

80 images
338 000 polygons

Recap 360

Notes:
Height of the object 5.5cm

**Low Polygon version**

2815 polygons

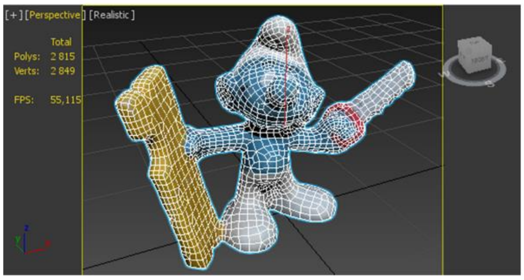
**HIGH POLYGON VERSION**

9


**HIGH POLYGON VERSION**

10

APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES


**LOW POLYGON VERSION**

11

**Small Toy, Indian Figure**

64 images
541 000 polygons

Recap 360

Notes:
Height of the object 6.7cm

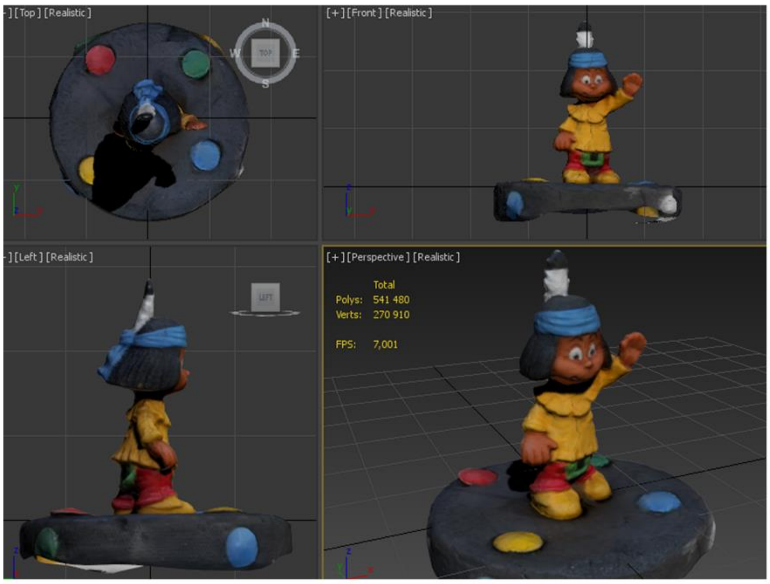
**Low Polygon version**

2599 polygons

**HIGH POLYGON VERSION**

12

## APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES

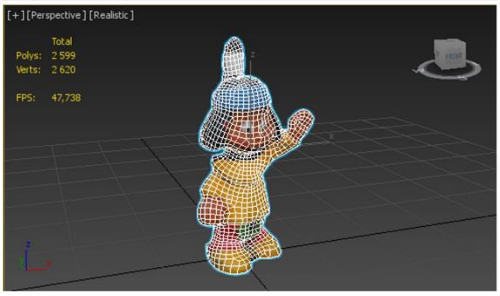



**HIGH POLYGON VERSION**

13

**HIGH POLYGON VERSION**

14


**LOW POLYGON VERSION**

15

**Real Pine Cone**

104 images
685 000 polygons

Recap 360

Notes:
Height of the object 5.3cm

**Low Polygon**

3366 polygons

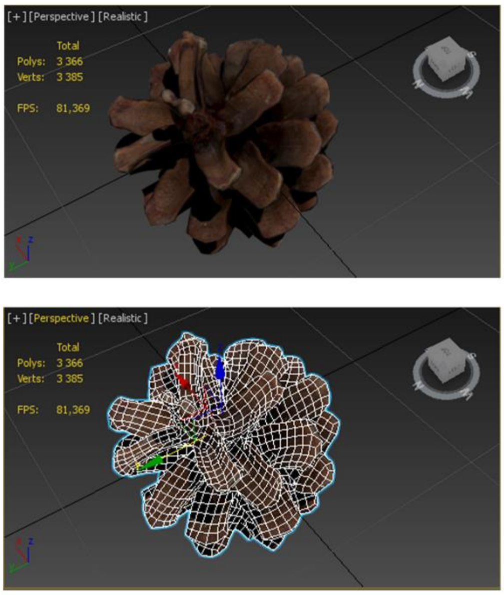
**HIGH POLYGON VERSION**

16

APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES


**HIGH POLYGON VERSION**

17




**LOW POLYGON VERSION**

18

**Wooden Toy Pin (Blue Cow)**

46 images
31 000 polygons (preview quality)

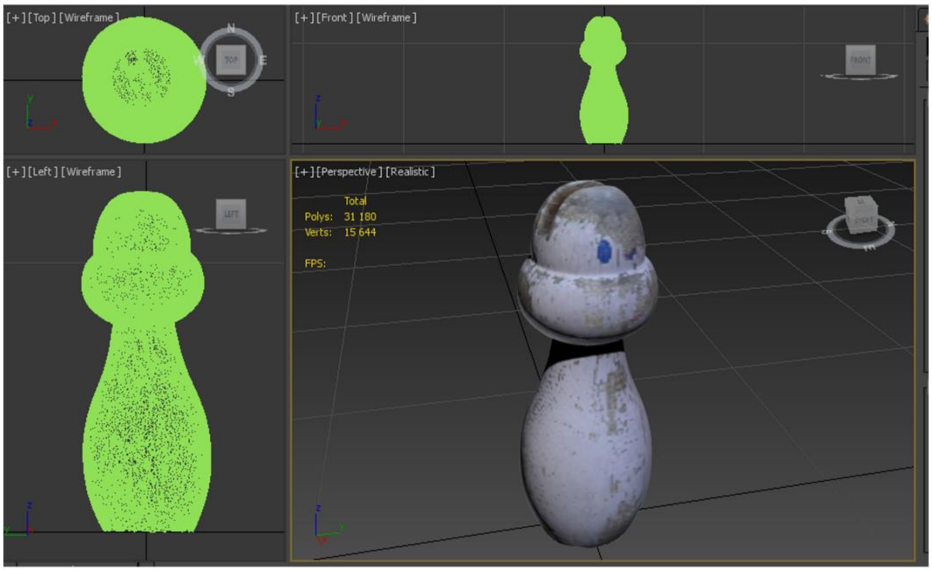
Recap 360

**Low Polygon version**

478 polygons

**HIGH POLYGON VERSION**

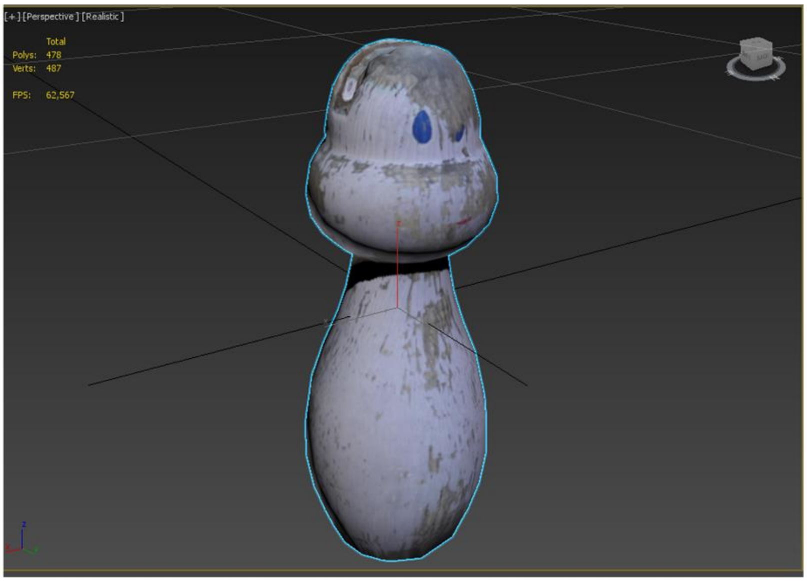
19




**HIGH POLYGON VERSION**

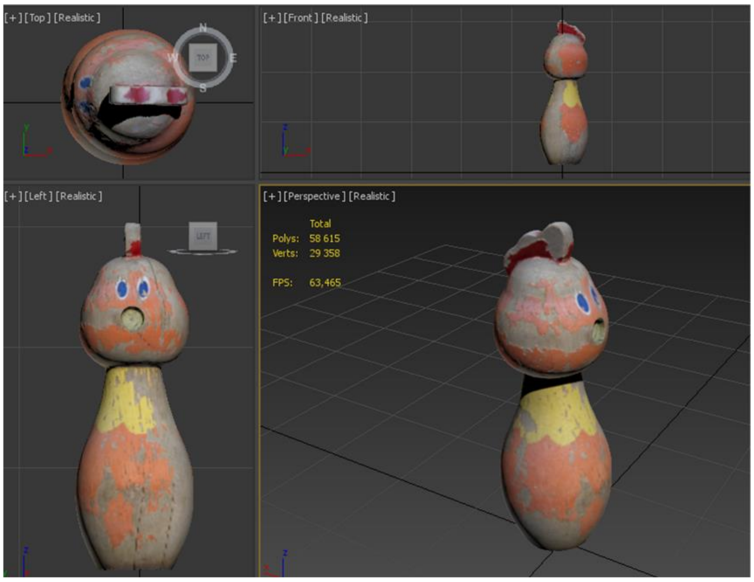
20

# APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES




**LOW POLYGON VERSION**

21




**Wooden Toy Pin (Red Rooster)**

67 images
58 000 polygons (preview quality)

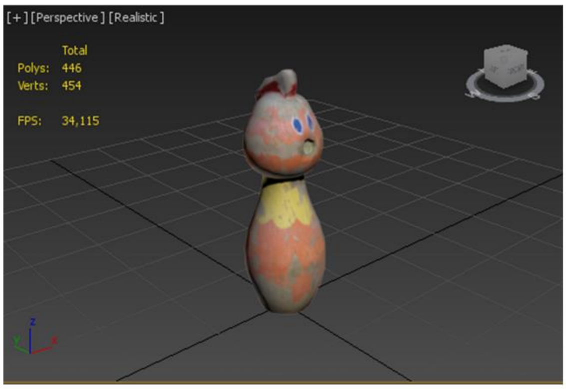
Recap 360

**Low Polygon version**

446 polygons

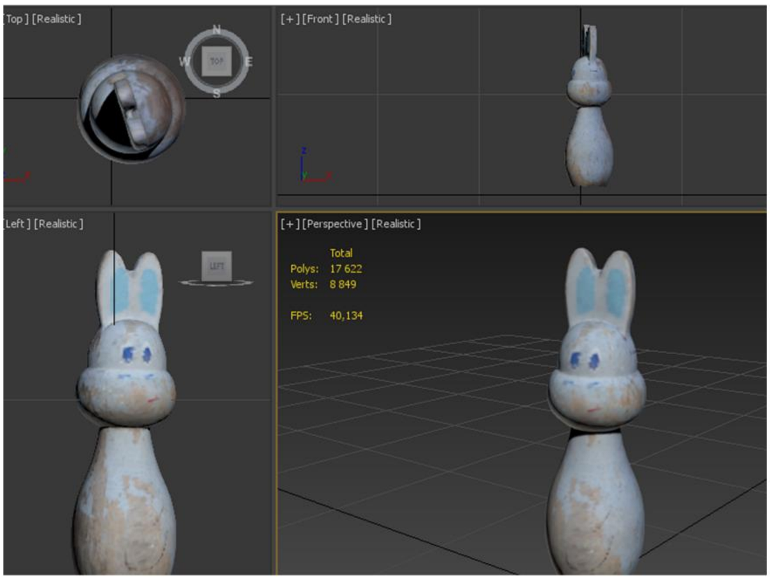
**HIGH POLYGON VERSION**

22




**LOW POLYGON VERSION**

23




**Wooden Toy Pin (Blue Rappit)**

42 images
18 000 polygons (preview quality)

Recap 360

**Low Polygon version**

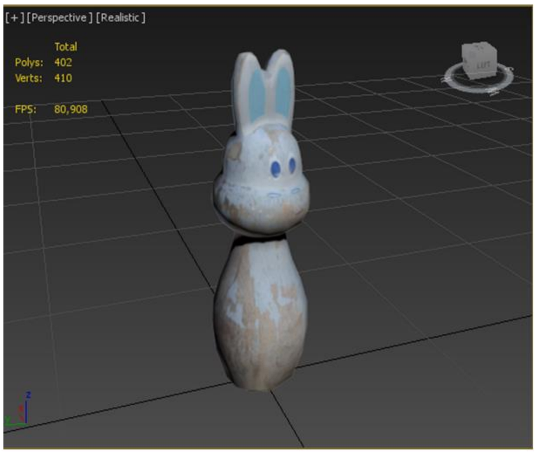
414 polygons

Jagged edge warning!
(bottom edge straightenet)

**HIGH POLYGON VERSION**

24

APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES




**LOW POLYGON VERSION**

25


**Wooden Toy Pin (Green Cow)**

42 images
26 000 polygons (preview quality)

Recap 360

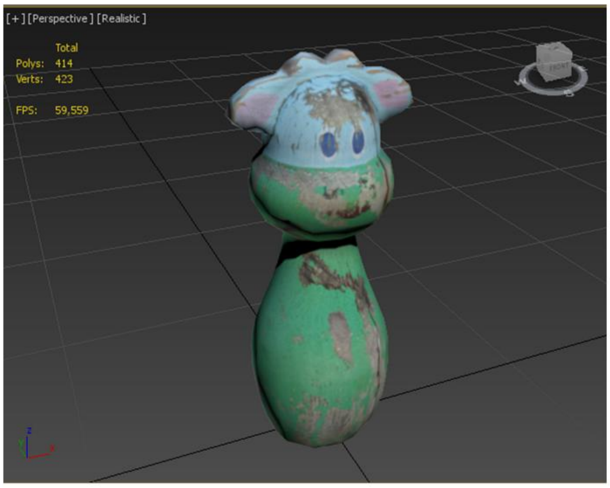
**Low Polygon version**

414 polygons

**HIGH POLYGON VERSION**

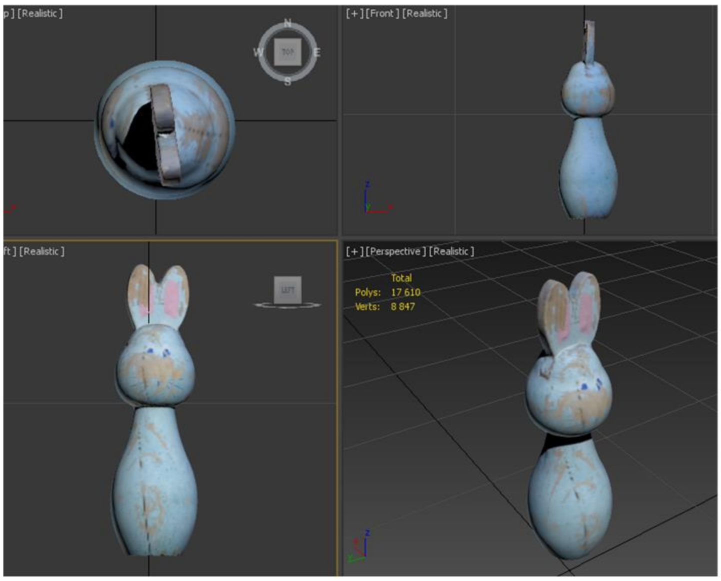
26

## APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES




**LOW POLYGON VERSION**

27




**Wooden Toy Pin (Blue Rappit)**

46 images
17 000 polygons (preview quality)

Recap 360

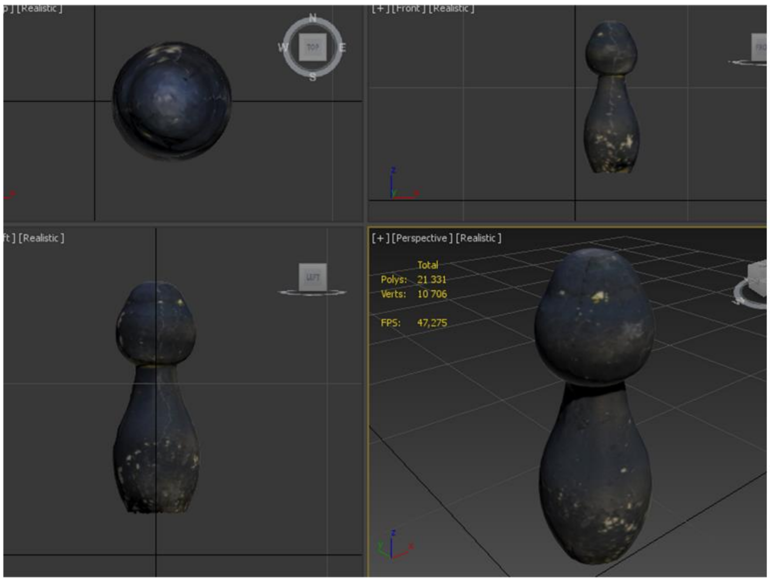
**Low Polygon version**

3542 polygons
292 polygons

**HIGH POLYGON VERSION**

28

# APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES




**Wooden Toy Pin (Matt Black)**

53 images
21 000 polygons (preview quality)

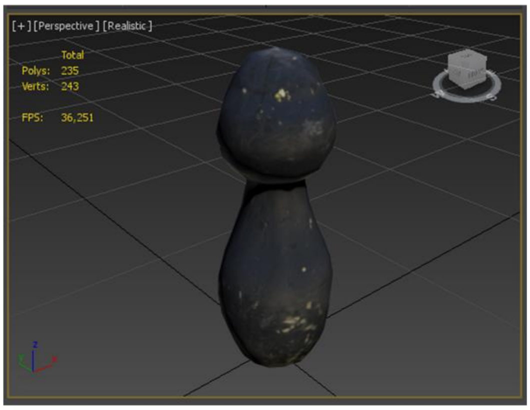
Recap 360

**Low Polygon version**

235 polygons

**HIGH POLYGON VERSION**

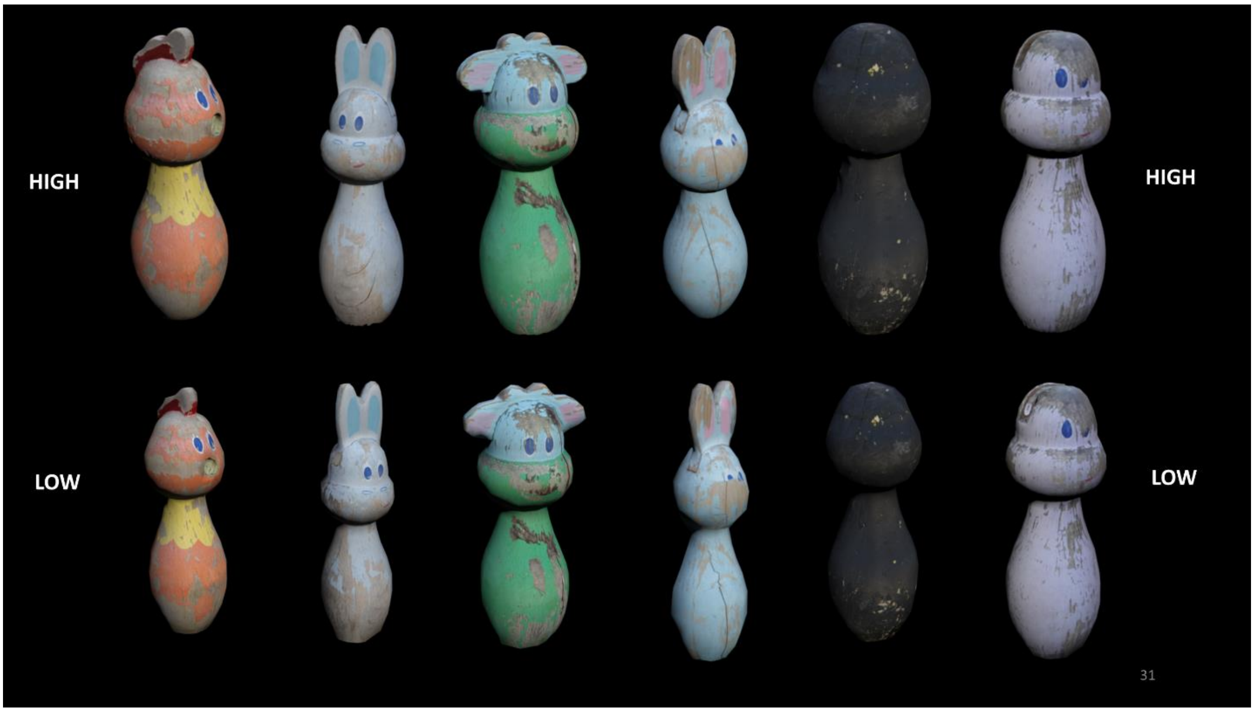
29

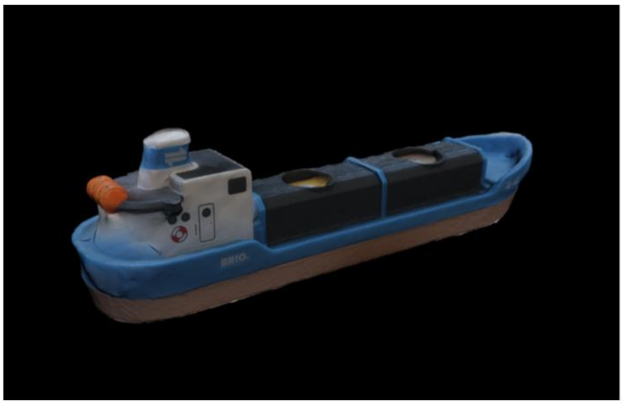



**LOW POLYGON VERSION**

30

APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES



**Brio Toy Boat**

75 images
816 000 polygons

Recap 360

Note: Canon 50mm macro objective used

Note:
Bit shiny surface, sharp corners
Length of the object 23cm

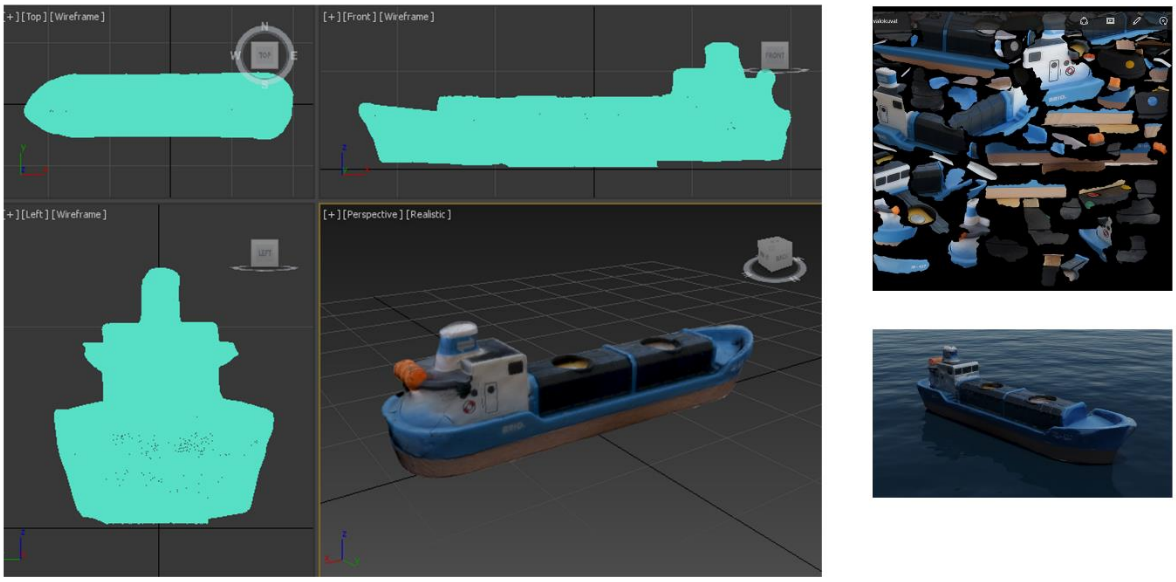
**Low Polygon version**

3765 polygons

**HIGH POLYGON VERSION**

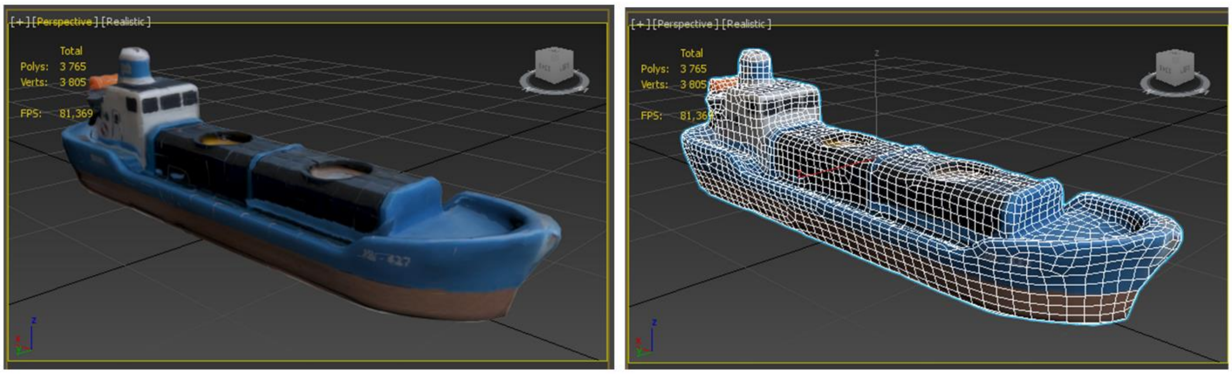
32

APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES




**HIGH POLYGON VERSION**

33




**LOW POLYGON VERSION**

34

APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES

**LOW POLYGON VERSION**

35

**Wooden Cirafe**

About 41 images
38 000 polygons (preview quality)

Recap 360

Notes:
Height of the object 50cm

**Low Polygon version**

2809 polygons

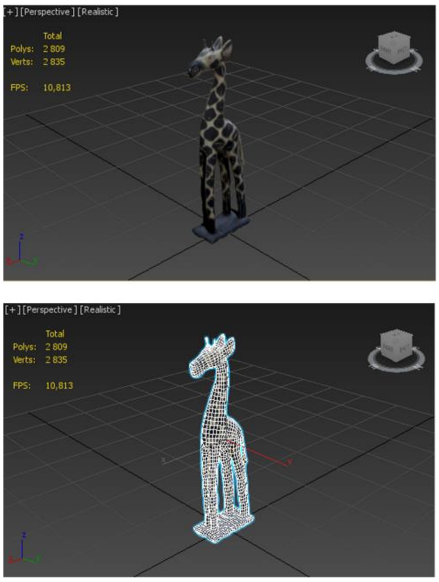
**HIGH POLYGON VERSION**

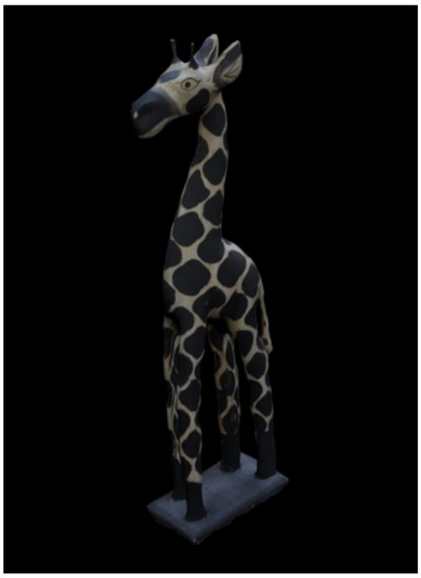
36

# APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES


**HIGH POLYGON VERSION**

37



**LOW POLYGON VERSION**

38

APPENDIX 1 - EXPERIMENTING THE WORKFLOW: EXAMPLES

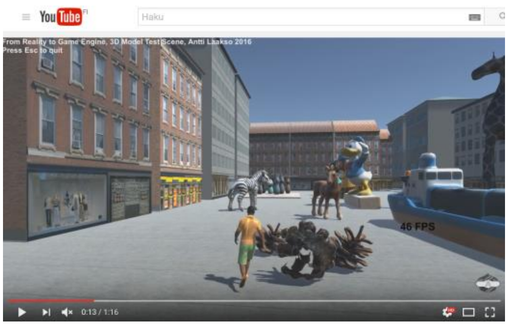
**Links to external material:**

Example models in YouTube:

- Cone, https://youtu.be/dtbNHf4mJ-M
- Donald Duck figure, https://youtu.be/UZv-eP57AjE
- Indian figure, https://youtu.be/6FI-a8R2KG4
- Mickey Mouse figure, https://youtu.be/AUZgKuRTjb0
- Smurf figure, https://youtu.be/bNmPfULmDOI
- Wooden pins, https://youtu.be/4Pj2Xk53BrU
- Wooden carafe, https://youtu.be/de3XT7nNqkE
- Zebra (polygons) https://www.youtube.com/watch?v=n1ZXLdq7MeI
- Zebra (textured) https://www.youtube.com/watch?v=cCurY6Y9MAY
- Wooden drum https://www.youtube.com/watch?v=-B7_d22-F2M
- Schleich toy horse (hidden line) https://www.youtube.com/watch?v=b2FrGT6Sf_k
- Schleich toy horse (textured) https://www.youtube.com/watch?v=O__NLkvkcc4

Game play example in YouTube:

- Unity scene with photogrammetry based models https://youtu.be/u9JaQC6pHtQ



## APPENDIX 2- FIXING THE MESH PROBLEMS

**Usual mesh problems when processing photogrammetry based models with Autodesk Mudbox and 3ds Max.**

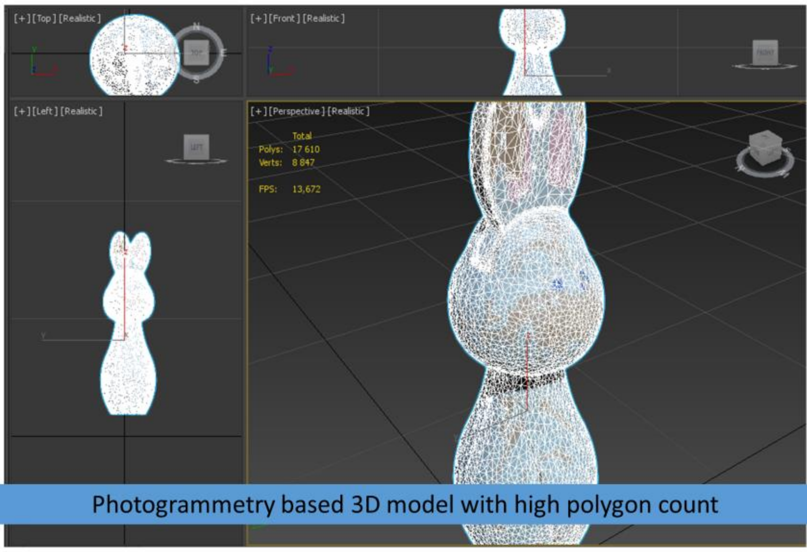
| Error message | Reasons | Possible solution |
|---|---|---|
| **Incomplete UV Set**<br><br>**Partial UV's for object** | Fixing holes with new surfaces<br><br>Creating new surfaces | Re-create the missing UV's<br><br>Can be fixed with normal UV tools in 3ds Max. Mudbox can create automatic UV's.<br><br>Must be fixed to get texture extraction working. |
| **Degenerated Face**<br><br>**Mesh has faces where corners lie on the same line or location on space** | The generation of the photogrammetric model<br><br>Manual aligning of the edges of the model | Find out the problematic faces in the Mudbox. Try to find the same faces also in the 3ds Max. Fix or delete faces. Scale object for example to 100 times larger.<br><br>Note: Fixing many problems takes more time than re-doing the whole process.<br><br>Can cause retopology to fail or produce bad topology.<br><br>Might work without fixing. Tryout before doing many fixes. |
| **High-valence vertex**<br><br>**One vertex has more than 16 adjacent edges** | The generation of the photogrammetric model | If possible, delete part of the surface and re-create with appropriate polygons.<br><br>Might work without fixing but can cause the map extraction to fail.<br><br>Tryout before doing many fixes. |
| **Jagged edge** | The generation of the photogrammetric model<br><br>(For example, the bottom of the object. The edge where the surface ends.) | Carefully align edge with normal tools. Do not overlap the edges and create degenerated face.<br><br>Usually works without fixing but makes bad retopology near edges of the surface. |

# APPENDIX 3 - POST PROCESSING OF A LOW POLYGON PIN

## Photogrammetry models

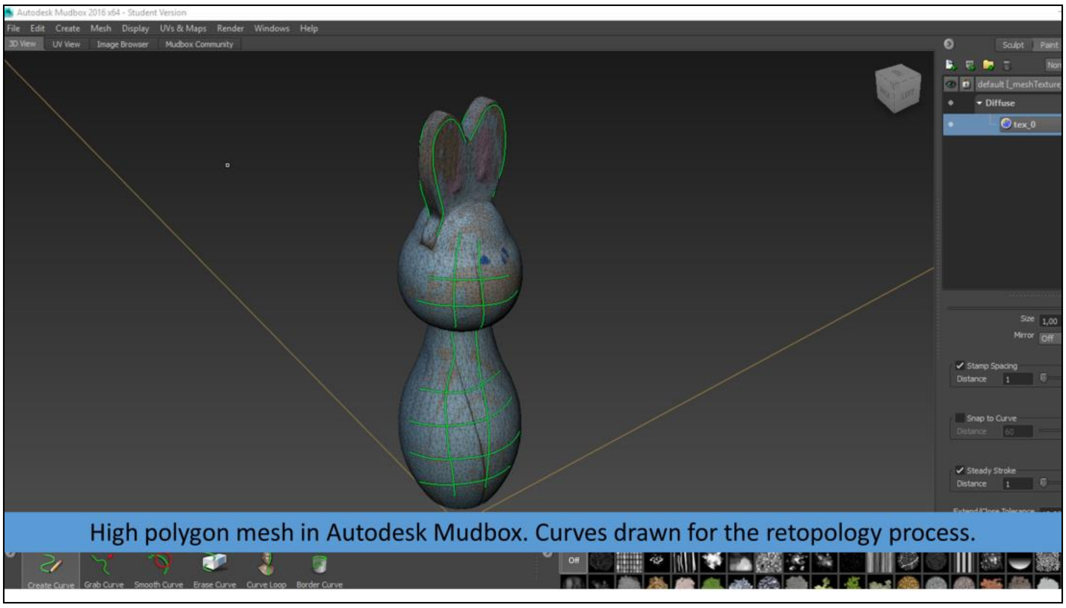
**Retopology & Map Extraction**

Antti Laakso

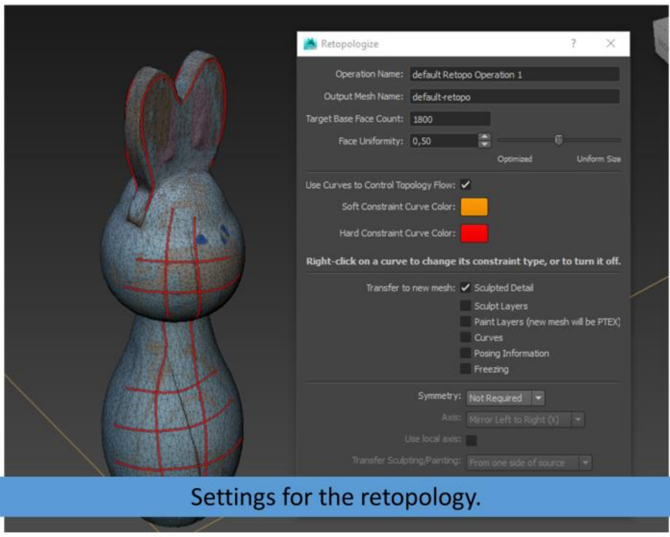



Photogrammetry based 3D model with high polygon count

APPENDIX 3 - POST PROCESSING OF A LOW POLYGON PIN

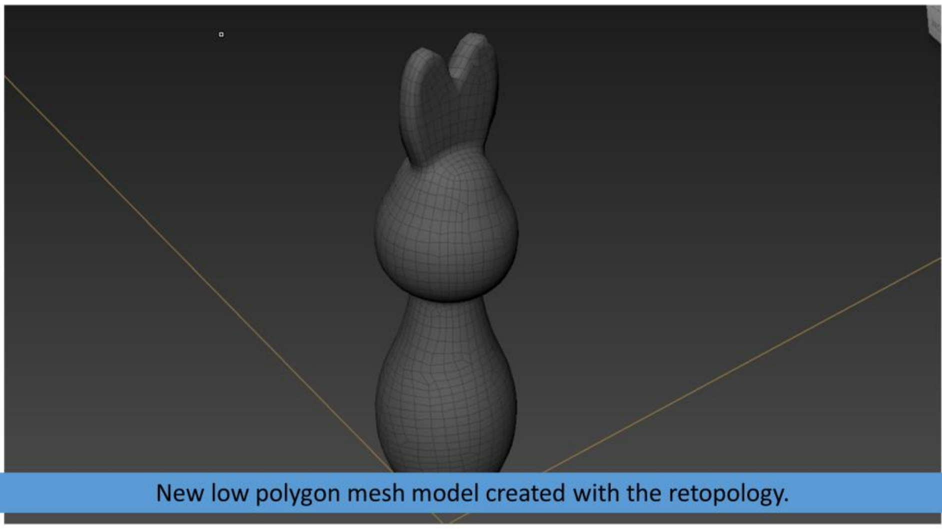


High polygon mesh in Autodesk Mudbox. Curves drawn for the retopology process.

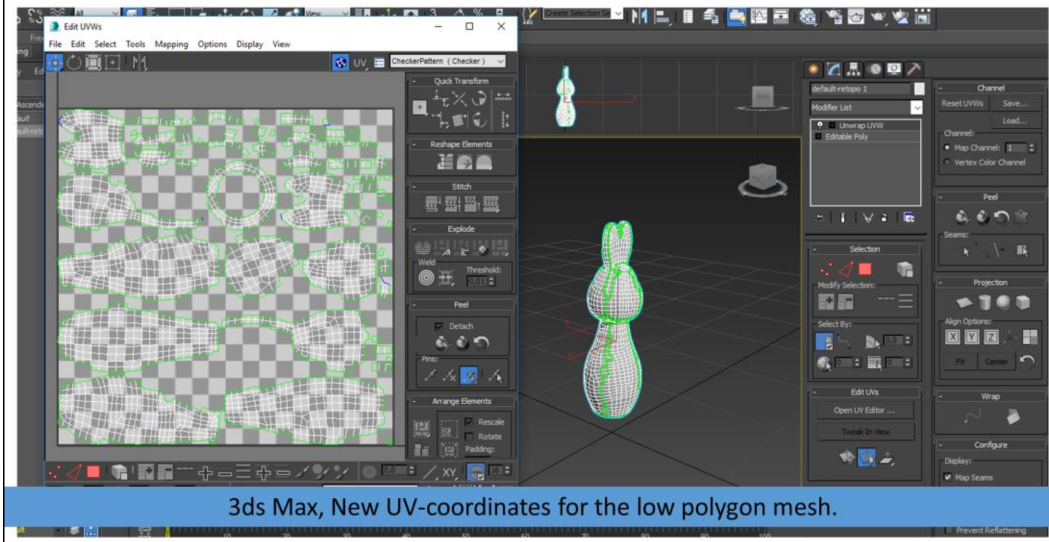


Settings for the retopology.

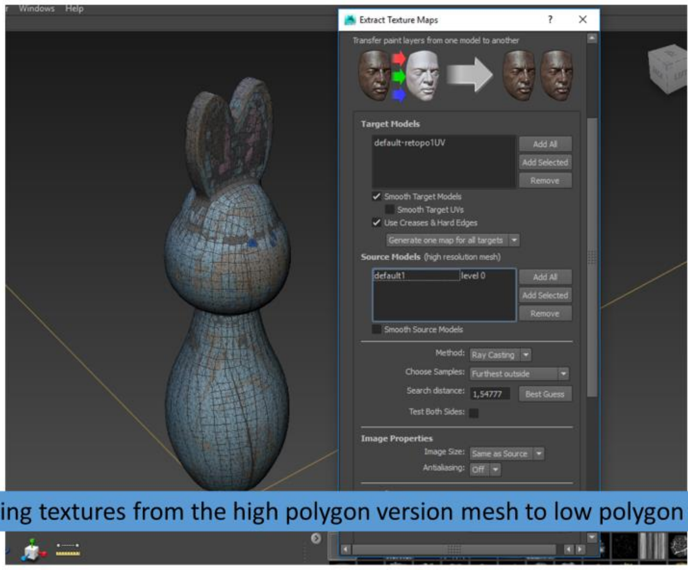
APPENDIX 3 - POST PROCESSING OF A LOW POLYGON PIN



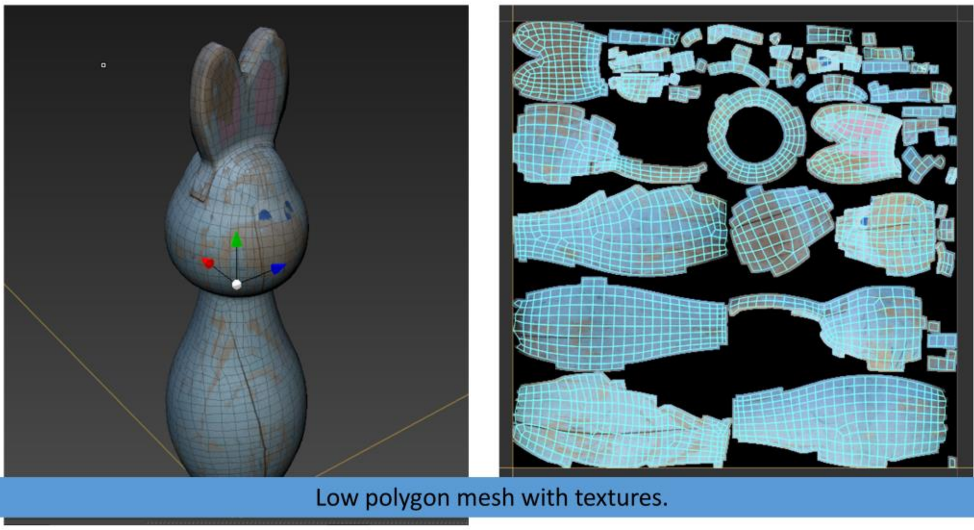
New low polygon mesh model created with the retopology.



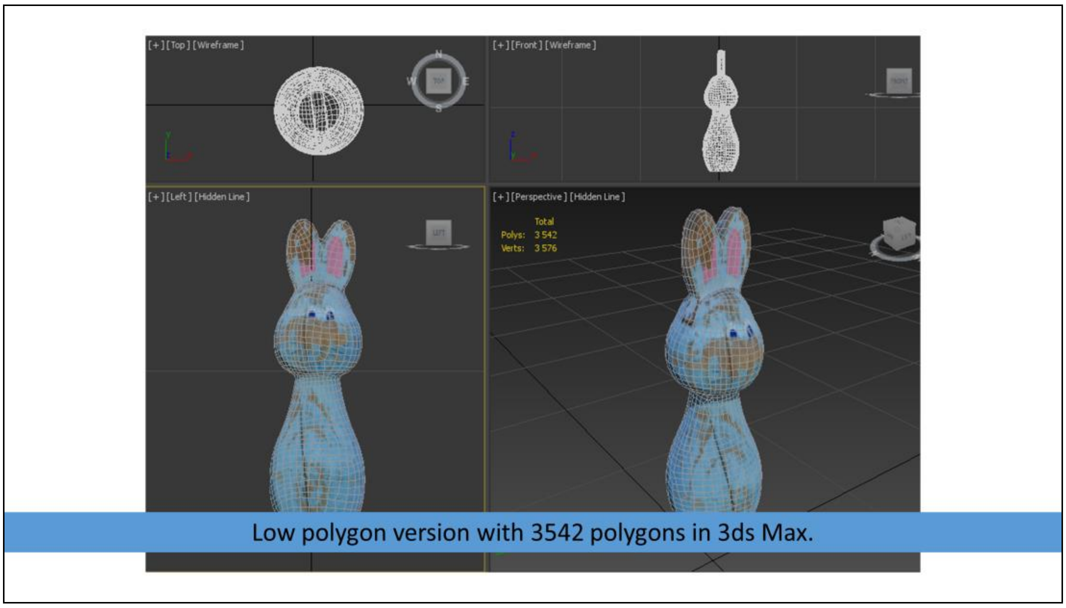

3ds Max, New UV-coordinates for the low polygon mesh.

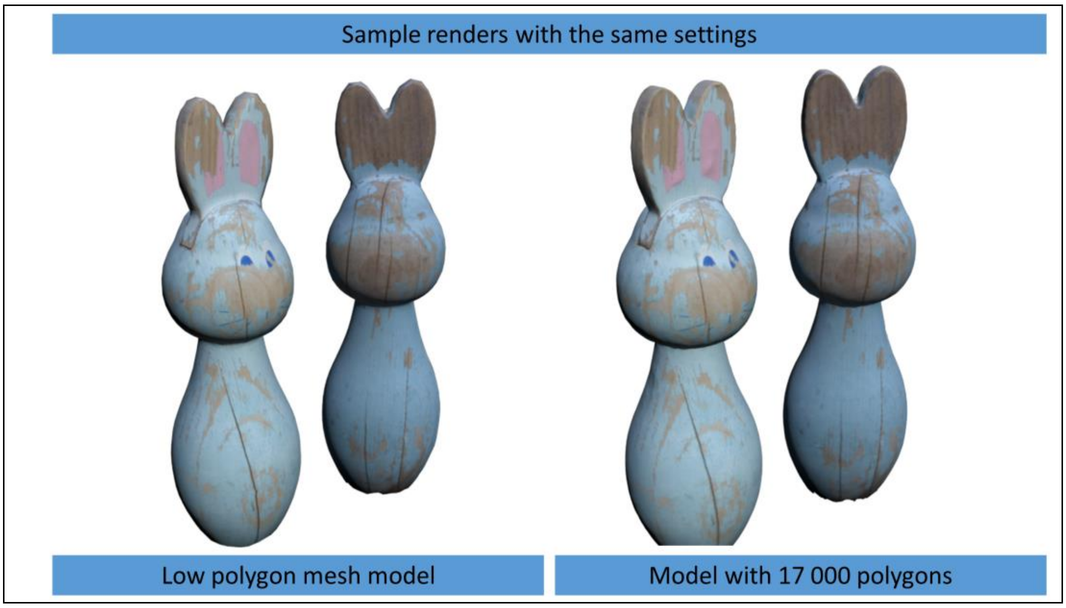



Transferring textures from the high polygon version mesh to low polygon version.



Low polygon mesh with textures.




**Links to external material:**

Post Production of Photogrammetry Model 2016 – 22min workflow video

https://www.youtube.com/watch?v=rvCG5ZHH7SM