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3D Surface Reconstruction for Lower Limb Prosthetic Model using Radon Transform

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Abstract. This paper describes the idea to realize three-dimensional surfaces of objects with cylinder-based shapes where the techniques adopted and the strategy developed for a non-rigid three-dimensional surface reconstruction of an object from uncalibrated two-dimensional image sequences using multiple-view digital camera and turntable setup. The surface of an object is reconstructed based on the concept of tomography with the aid of performing several digital image processing algorithms on the two-dimensional images captured by a digital camera in thirty-six different projections and the three-dimensional structure of the surface is analysed. Four different objects are used as experimental models in the reconstructions and each object is placed on a manually rotated turntable. The results shown that the proposed method has successfully reconstruct the three-dimensional surface of the objects and practicable. The shape and size of the reconstructed three-dimensional objects are recognizable and distinguishable. The reconstructions of objects involved in the test are strengthened with the analysis where the maximum percent error obtained from the computation is approximately 1.4 % for the height whilst 4.0%, 4.79% and 4.7% for the diameters at three specific heights of the objects.

Keywords. three-dimensional reconstruction, uncalibrated image, multiple views, tomography

1. Introduction

Modern computer technology has given a rise in the research on prosthetic design to overcome the limitations of the existing methods. The prostheses have to be designed and customized specific to one's anatomical shape. It cannot be simply designed or manufactured through mass production since it is specific for an individual. However, the demand on the prostheses has increased as the number of amputees are also increasing and it is necessary to realize ad-hoc with high precision design methodologies [1, 2]. In addition, optimal design of prosthesis is very important for every single amputee. This is to restore and encourages functional muscular activity, pressure-sensitive areas can be relieved, and proper attachment of the prosthesis during ambulation able to be maintained [3]. The data can be acquired in several forms, such as a set of image sequences or a video, views from multiple cameras set up, or multi-dimensional data from a scanner. It has been seen that the computer-aided design and computer-aided manufacturing (CAD/CAM) accompanied with medical imaging technology has been introduced in prosthetic practice [4] where the image of a certain part of a patient is captured using X-ray computed tomography scan (CT-scan), magnetic resonance imaging (MRI), or ultrasound imaging [5]. However, capturing images using such devices are very expensive and the processing task requirements are enormous. The medical device also required to be operated by an expertise in a specifically designated room. It is also bulky and taking up a large space to be assembled.

The basic flow of this research is referred to the software operational framework by [6] that used CT cross-sectional scanning for the data acquisition. Utilizing CT-scan is very advantageous to detailed reconstruction and accuracy which is hardly can be denied. However, it involves a very high operational cost that also requires help by an individual who is expert in radiology known as radiographer or radiologic technologist. Thus, in contrast to an expensive method this research use uncalibrated digital camera is used to capture images of a residual limb model in multiple views for the data acquisition. The outcome from this research is expected to be able to compute and overcome possible constraints in the design of prosthetic part for lower limb amputees fitting to their body size, where the input data is 2D image sequences of amputated lower limb model captured by multiple views camera and a turntable setup in specified projections as the first step in adapting the research field. The advantage of this research is that it can be done with simple experimental setup, as the devices used are usually owned by most people like phone camera and affordable. In addition, reconstruction of three-dimensional surface in this research neither involves expensive equipment nor require any service by an expert to handle sophisticated mechanical scanning.

2. Methodology

2.1. Data Acquisition

Data acquisition for this research involves a very simple setup that consists of a digital camera mounted on a mini tripod stand, and a simple turntable together with black or dark color background that provides better contrast between object and background in the image going to be shot. The material used must not be able to reflect light that save the time and trouble computing silhouette image. An object is placed on the center of a wooden turntable. The object is approximately 700*mm* away from the lens of the digital camera as described in figure 1. The object is static and will not easily move or overturn when turntable is rotated. A mini tripod stand keeps the digital camera static whilst capturing images of the object on its target. A piece of metal is attached under the round turntable, thus helping it to turn smoothly to any desired angle of rotation.

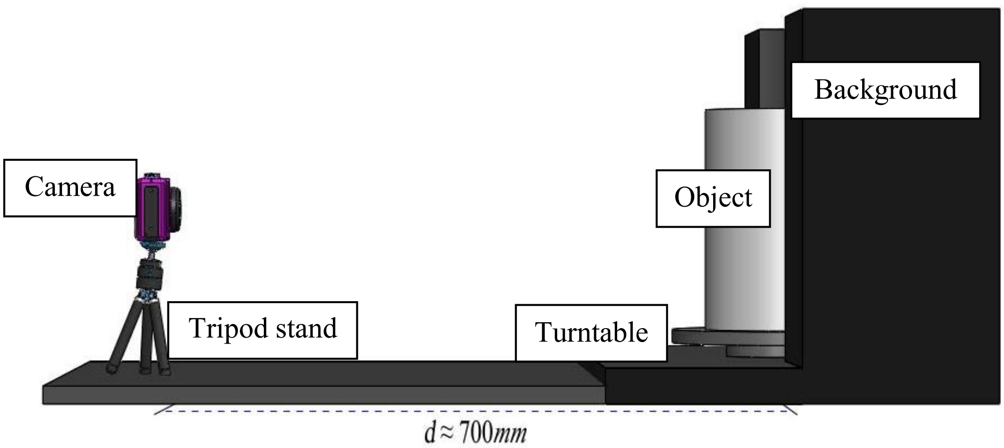

Figure 1. Illustration of the experimental setup at the side view.

It is important to know the field of view (*FOV*) of a camera in order to determine the optimal distance between camera and object to be placed in the scene. It is to make sure that the object is well-fitted into the image especially the height since the image is captured in landscape orientation of an image. For an example, figure 2 illustrates the relationship between the intrinsic parameters of a camera lens and the optimal distance. Hence, the field of view of a camera specifically for *y* direction, FOV_y, can be calculated by knowing the focal length of the camera lens, f, and the dimension of the sensor which either the height or the width, S_m, as expressed in (1).

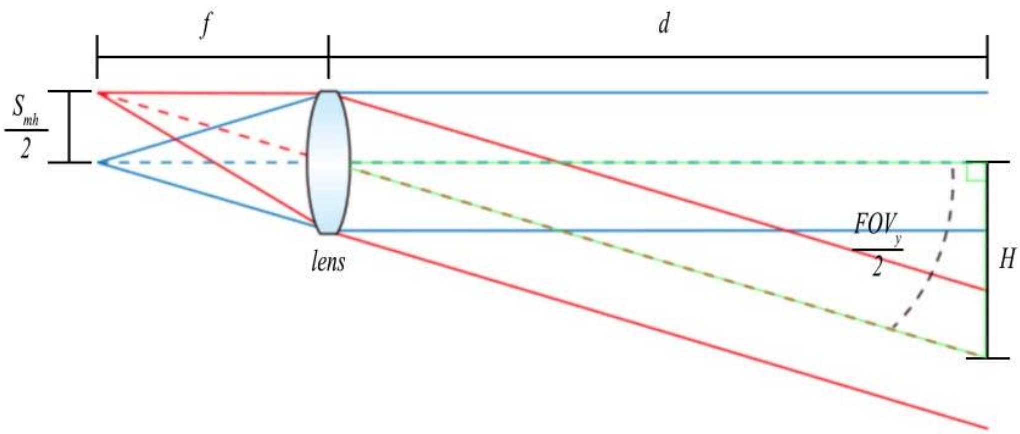

Figure 2. The relationship between the intrinsic parameters of a lens and the optimal distance.

$$FOV_y(°) = 2\tan^{-1}(\frac{S_{mh}}{2f}) \tag{1}$$

The turntable is rotated manually by hand in a fixed sequence which is practically challenging therefore it is limited to a total of thirty-six different views of the object with 10° of difference between each projection to keep the consistency of the input data. The turntable is rotated in a clockwise manner, pausing at every 10° to allow the digital camera to capture the image around the object on target at different projections to obtain thirty-six different views. The images of the object are then transferred to the computer as input for image processing tasks.

2.2. *Image Processing*

Image-based 3D reconstruction is computationally intensive with a full 8-*bit* colour and high resolution image and with such amount of data in each image, it is impossible to do calculation manually without any computed program. The whole process of reconstructing 3D surface of an object involved at least thirty-six images to be manipulated sequentially, thus iterative and looping in the programming are necessary to simplify the computation and reduce time consumption.

With modern computers, it is possible to perform pixel-by-pixel image processing on the images but the task consumes longer time considering the huge amount of data involves in each image. In addition, RGB color might not works well with some of the image processing where any additional colors information is not helpful and working with grey-scale, the possibility to solve image segmentation problems is higher. The computation of converting the RGB image to grey-scale image is done based on the weighted average [7] as expressed in (2) with specific value of integer for red, green and blue colors respectively while figure 3 shows an example of the result obtained.

$$a = 0.299R + 0.587G + 0.114B \tag{2}$$

(a) (b)

Figure 3. Image of an object (a) before and (b) after grey-scaling.

Reconstructing 3D surface of an object involves thirty-six images and there are millions of data obligated to undergoes the serial computation in achieving a desired result. This number of data requires take a very long processing time, therefore it might not be an efficient system aiming for a fast computation. As an alternative, every single image is resized by reducing the resolution of the images using image resampling method [8]. All images of each object at 36 different projections are down-sampled from 5152×3864pixel by 0.16 scale factor to 309×232pixel.

Otsu thresholding eliminates the hue and saturation information of a color from the image while at the same time it retains the chromaticity or the quality of a color regardless of its luminance. This method works by selecting optimal local threshold value adapted to the image content which generate within satisfactory level results [9, 10]. An image $f(x, y)$ is defined by selecting a threshold value, T then the pixel within the range will be selected as the foreground, while the rest of the pixel will be rejected to the background forming binary image $g(x, y)$ [11, 12] and this can be summarized as in (3) followed with figure 4 displays the silhouette image obtained.

$$g(x, y) = \begin{cases} 1 & for \quad f(x, y) > T \\ 0 & for \quad f(x, y) \leq T \end{cases} \tag{3}$$

(a) (b)

Figure 4. Image of an object (a) before and (b) after Otsu thresholing.

The concept of Radon transform is used to compute multiple silhouette images, $g(x,y)$ to generate a sinogram where the silhouette images obtained are equivalent to indication of electron absorbed into the object as in x-ray procedure [13]. Based on the experimental set up explain in previous section, projection from different view angles, $\rho_\theta(s)$ can be obtained by rotating the object on the turntable at a constant rotation. The task is done based on the idea of following line expression (4) where s is the shortest distance to the origin and theta, θ is the angle of the projection.

$$s = x\cos\theta + y\sin\theta \tag{4}$$

2D cross-section of an object can be reconstruct with the knowledge of integrals computed along the straight line [14]. Radon Transform of an image represented by the function $R(s,\theta)$ such that perpendicular to s and it can be defined as a series of straight line integrals through $h(x,y)$ at different offsets from the origin which is parallel to y -axis with a projection line of $R(s,\theta)$, at angle θ, of an ideal situation [15] and it can be defined mathematically as in (5).

$$R(s,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h(x,y)\delta(s - x\cos\theta - y\sin\theta)dxdy \tag{5}$$

The sinogram, $R(s,\theta)$ is generated layer by layer corresponding to the number of rows equivalent to height of image $g(x,y)$. Inverse Radon transform reconstruct $h(x,y)$ at a specific layer utilizing. This is performed by projecting each of the layers and aligned the data to its actual rotation with back-projection, B that helps to form the cross-section of the object [16].

2.3. 3D Reconstruction

Edge detection is used for data extraction to find set of points in a digital image which represents an abrupt change of the image intensity [17, 18]. This method is applied on the images generated from inverse Radon transform to identify the contour of the cross-section (if present). The method for edge detection used in this computation is the Canny operator which is the optimal edge detector for image segmentation [19] and also extract border of a shape or an object which is less susceptible to the interference noise [20]. Figure 5 shows cross-section images of an object at a specific layer before and after Canny edge detection is applied. The extracted boundary of the cross-section is the key attribute in obtaining the *xy*-coordinates to reconstruct the surface of the object from the contour lines.

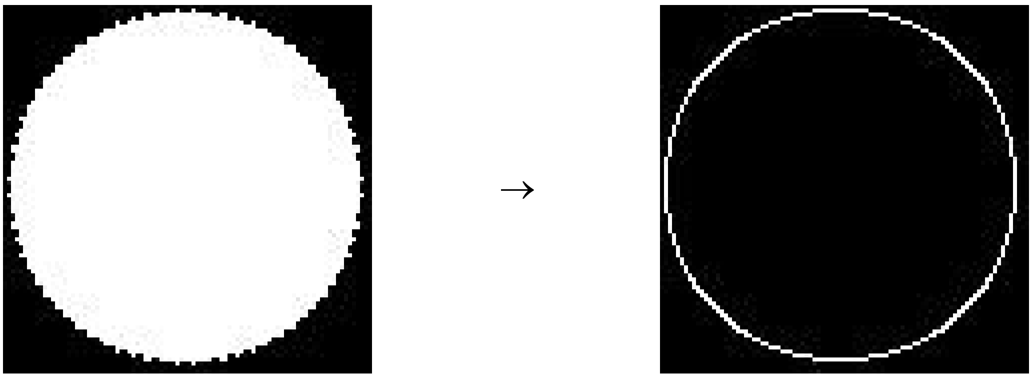

Figure 5. Canny edge detection on cross-section of an object.

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The point extracted from the layers of the cross-section images forms a point cloud where each point registered is comprises of *x*, *y*, and *z* coordinates information. Then, Delaunay triangulation is used for mapping and connect all the points to define 3D surface of the object where the result is shown in figure 6. Some parts at the side of the body of the 3D surfaces are reconstructed as a straight curve although the physical structure of the object is actually curvy. Delaunay triangulation provides sets of triangles to be used as polygons in the surface by creating meshes from the 3D point cloud. The meshes are refined to smooth up the surface and minimize distortion between a point and another neighboring point. Thus, the rough edge generated from the thresholding of the low-resolution images has caused the reconstructed 3D surface to be straight curve at the sides of the body of the object. But why Delaunay triangulation? This is because this method has several advantages where the triangles can construct stable structure and ensures that any point on the surface is as close as possible to a node [21-23].

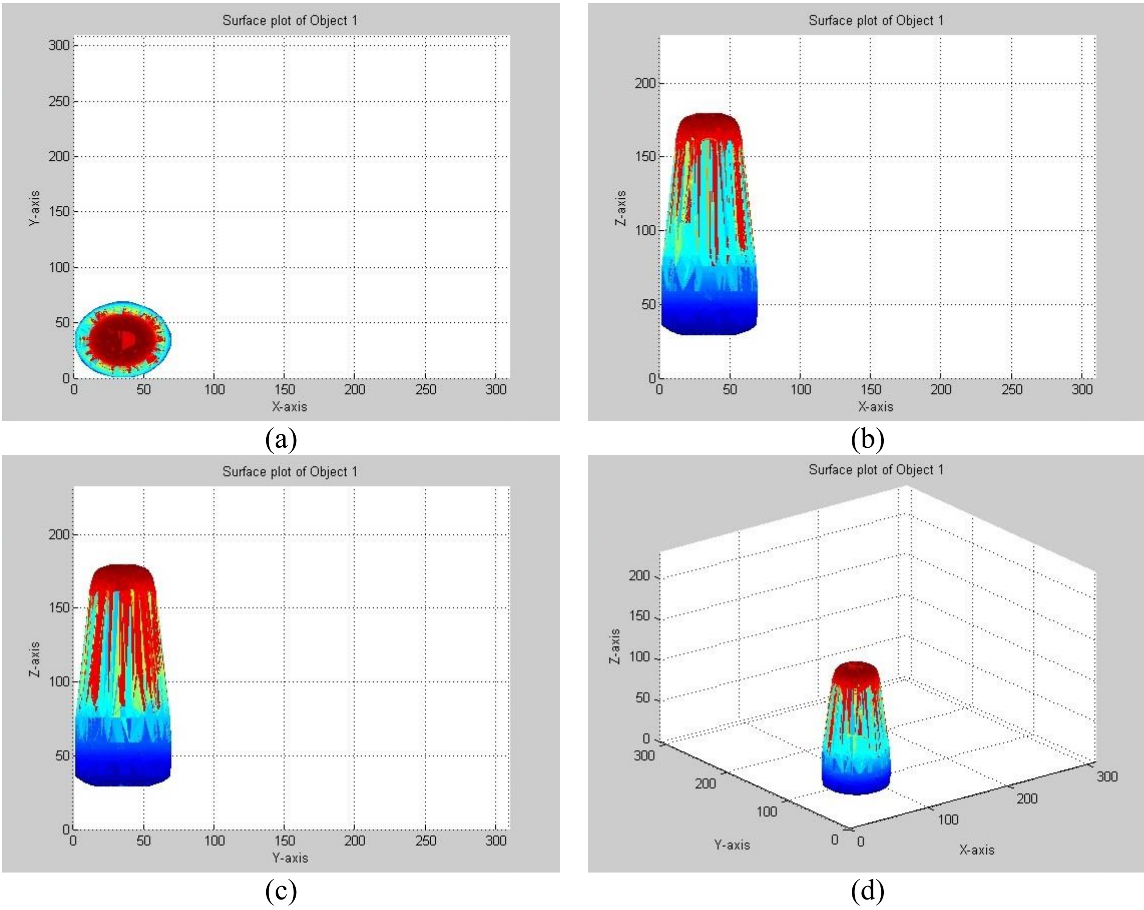

Figure 6. Image of Object 1 at (a) xy-view, (b) xz-view, (c) yz-view, and (d) 3D-view.

3. Analysis and Discussions

The proposed method has been evaluated on four different objects which are models of amputated lower limbs at the knee with average height of 400*mm* and 200*mm* diameter. Four different objects used are labelled with number one to four. The objects are placed upside down where the flat part is at the bottom serving as the base of the object while the amputated part is at the top. Height for the reconstructed 3D surface of the object is calculated and labelled as Position 1, *P1*. The diameter is also measured at three different height of the object which are the Position 2, *P2* is the diameter at the base, Position 3, *P3* Position 4, *P4* are the diameters at the one-third and two-third of the total height of the object respectively as shown in figure 7.

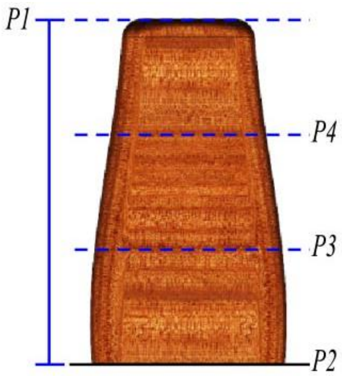

Figure 7. Position measured for model involved in the experiment.

A laptop with is used to provide visual display and also for the computation of the 3D reconstruction process including the error analysis which computes the percent error for experimental measurement over the actual measurement as summarized in figure 8. Reconstruction of 3D surface is highly dependent to the acquired images. High contrast 2D images contribute to higher accuracy of the reconstruction. Overall, the height measurements have better accuracy then the diameters of the objects because the reconstruction is done layer-by-layer by referring to the silhouette generated. The side curve of the object appears rough in the silhouette images, thus affect the accuracy of the diameters. It can be concluded from the analysis that the maximum percent error of the computation is approximate 1.4% for the height and also approximate 4.0%, 4.7%, and 4.7% for the diameters at three specific heights of the objects.

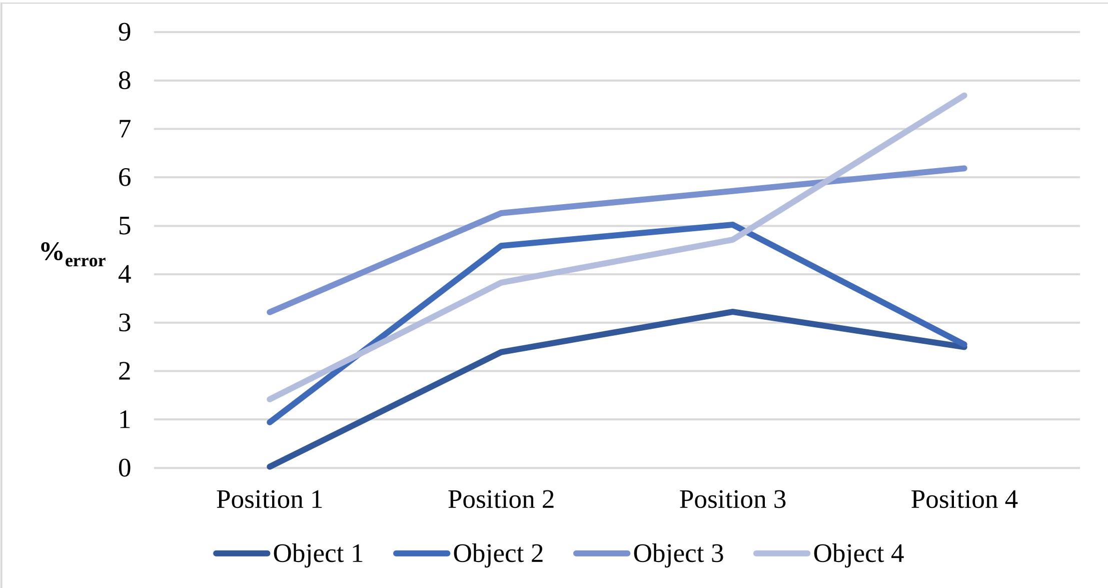

Figure 8. Percent error of four different position measured for four objects.

Shape-from-silhouette method is particularly sensitive to either the errors from silhouette extraction, or noise. Consequently, even small errors in extracted silhouette contributes large effects on the accuracy of a reconstruction, especially down-sampled image because the outline of the object probably only a few pixels wide in the original image with larger dimension has been compressed thus it also causes the errors in the measurement of the objects.

4. Conclusion

The main purpose of this research is to develop 3D surface from uncalibrated 2D image sequences of an object acquired from multiple views imaging system with digital camera as data acquisition device. The advantage of this research is that it can be done with simple experimental setup. The devices used are usually owned by most people and affordable. Therefore, digital camera with detailed specification is used but it does not require any sophisticated mechanical scanning system or expensive devices. However, the results do not support the idea that the study is practicable for the prosthetic design which demand high accuracy in the measurement. Future works should find a better solution to overcome the limitations and weaknesses of the developed method in order to obtain more accurate result and measurement as it is vital for prosthetic design especially at the irregular side curve shape of the model towards the top. This is because the 2D image sequences used are resampled to low resolution to simplify and reduce the time consumption for the whole processing. Low resolution image provides less information on the curve of the object which means this is one of the reason for the slight errors in the measurements of the reconstructed 3D surface that causes the inconsistent and the precision of the height and width of the objects. However, the images are resampled in order for a low specification laptop is able to reconstruct 3D image without any problem in computing all the data involve. Furthermore, it is possible to improve the accuracy by using an automatic image acquisition system to avoid any unintended movement on the object or the camera while capturing the images that will cause inaccuracy of the input data and it can also simplify the entire process.

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