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3D reconstruction for prosthetic design

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Abstract — **This paper investigates the use of an inexpensive passive method involving 3D surface reconstruction from digital images taken at multiple views. The modification of existing model-based reconstruction, mainly on the deformation process of vertices is discussed and the results of different objects show a good possibility for using a passive method in orthotic and prosthetic devices. For a dummy limb, the fitting of the model with the data shows a satisfactory result. The results of 15 measurements of different length between both reconstructed and actual dummy limb show both the model and the actual limb data are highly correlated. The methodology developed is shown to be useful for prosthetic designers as an alternative to manual impression during the design.**

Keywords - 3D image processing; prosthetic design; model-based reconstruction.

I. INTRODUCTION

Three-dimensional (3D) digitalisation systems applied to the orthopaedic domain allow for the freeing from the necessity of making manual impressions of the socket during orthotic and prosthetic design. The work carried out in these fields aims to find the best fitting of the socket into the portion of the arm or leg remaining after an amputation (residual limb or stump), during the prosthetic design by using a multiview method. A prosthetic device is an artificial substitute for a missing body part such as an arm, leg, hand or foot, and is used for functional or cosmetic reasons, or both.

Most of the previous works on orthotic and prosthetic design are based on manual design and use Computer-Aided Design (CAD) systems [1, 2]. With a manual design, the most common way of defining the shape of a residual limb is to make a mould of the residual limb itself. A trained practitioner can then manipulate the mould in order to correctly spread out the pressure that the mould exerts on the patient. One of the advantages in CAD is the reduced need for cast modifications and is, thus, a time saver. However, computer-aided systems increase the initial cost and training that is needed to operate the system. This initial cost and training is decreased if there is a system that can capture the residual limb shapes and give the actual dimension of the limb for the design. This can be realised using a reconstructed image of the limb for orthotic and prosthetic design. The cost of training will be reduced as the image is analysed automatically. Using the reconstructed 3D image would also be more comfortable for the patient when compared to using a traditional fabrication, as the latter might cause more injury during the design.

In this paper, the shapes of objects which are similar to a limb are used as a starting point of this research. A cylinder, cone or a combination of these are suitably similar shapes to the limb. The scope of this paper is to provide a system which uses a 3D reconstruction technique that is capable of producing the measurement of the limb and creating a model of the limb in order to help the practitioner or prosthetist design the prosthetic device.

II. SURFACE RECONSTRUCTION FROM MULTIVIEWS

3D surface reconstruction from multiviews is the process of estimating the shape and position of 3D objects from different views. In general, techniques employed for 3D digitisation can be categorised under two groups: active and passive. Active methods make use of calibrated light sources such as lasers or coded light; the most typical example of which is the shape from the structured light method. Passive methods, on the other hand, rely solely on two-dimensional (2D) images of the scene to extract surface information. In this paper, the shape from silhouette [3, 4] method is used because it offers the use of low cost hardware (a camera and turntable) and the robustness for various environments and objects.

Typically, shape from silhouette techniques start with an acquisition step where images of the object are taken from different locations around it. For each of these images, the object silhouette is extracted using simple differencing or image segmentation techniques. The computed silhouettes for every image along with the centre of the corresponding camera are then used to define a volume, which if back-projected to 3D space can be assumed to bind the object. The intersection of these volumes associated with the set of acquired images yields a reasonable approximation of the real object. This intersection volume was named the 'visual hull' by [3] and described as the maximal object that gives the same silhouette with the real object from any possible viewpoint. The visual hull is reconstructed as the intersection of the regions calculated by silhouettes. The

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regions have the possibility of existence as a part of the object. In case where a small numbers of multi-cameras are used to capture the images, the visual hull includes additional regions, which do not represent parts of the object. Decreasing the additional regions means that the reconstructed shapes become more accurate. However, it is not realistic to install so many cameras around the object. The number of cameras is limited by the conditions on the physical size of the cameras, space for setting cameras and prices of cameras etc. To exceed the limitation, a shape reconstruction method that integrates silhouettes obtained in multiview frames has been proposed [5].

III. MODEL-BASED TECHNIQUE AND PRELIMINARY EXPERIMENT

A model-based 3D reconstruction technique [7] that can generate a patient-specific and detailed 3D surface model from multiviews images is introduced. Since the limb shape variances make it difficult to extract the feature and segment, a reference model provides important prior knowledge for reconstruction. The final model is obtained by deforming the reference model with constraints imposed by the shape from the silhouette result. There are two methods used for obtaining the reference model of the limb and others similar to the limb object. First, using the octree data from 3D reconstruction technique [5] and secondly, the data created by computer programming.

A digital camera is used in this paper because instead of the vast capability, it is widely used in computer graphics, a relatively small device and cheaper than contact methods or a laser scanner, easy to handle and has the freedom of movement to capture object images from multiviews. Since the involved data are two data sets (the reference model (model) and the target objects (data)), the data need to be registered in order to merge them into a complete set of points in single views before the deformation process can be done between both data sets. To achieve that, the iterative closest point (ICP) algorithm is used [6]. The point set of the data shape is rigidly moved (registered and positioned) to be in best alignment with the model shape.

After registration, pre-processing takes place to establish the correspondence between both registered data sets to find the feature points on the reference model (model) that correspond to the points on the target objects (data). Although the registration between two datasets produces good results, correspondence establishment is needed because ICP only does the rigid registration and there is no non-rigid movement or re-sampling of the vertices. A reference model point is the corresponding point of the data shape if both points are projected to the same location on the intermediate object. In the proposed algorithm, the cylinder with the unit radius is used as the intermediate object.

The most prominent points on the limbs (lower and upper) of the reference model and the data can be easily found, and these are used to define the cylinder's axis to ensure the relative position between the reference model and the cylinder is the same as the relative position between the data and the cylinder. Several points may be projected to the same location on the intermediate object, so that one-to-one correspondence cannot be established. To solve this problem, the distance between a point and the projection centre is used as the secondary parameter to identify the correspondence. Fig. 1 demonstrates this process: A is the projection centre — both points P_1 and P_2 are projected onto the same location C on the cylinder. The distances d_1 (between P_1 and A) and d_2 (between P_2 and A) are also used to identify their corresponding points. For some cases, the cone is suitable to use if the apex is obviously determined between both data sets.

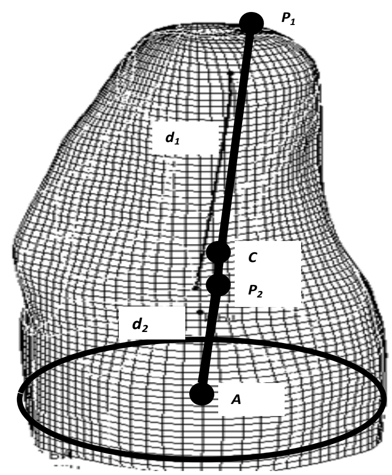

Figure 1. Using a cylinder axis as reference of lower limb.

After the correspondence between the reference model and data is established, the reference model is deformed to match the data.

IV. RESULTS AND DISCUSSIONS

The results are obtained by using Visual C++ (Ver. 6.0) with some OpenGL environment. The proposed method for the deformation process was applied to six different objects, which included the dummy lower and upper limbs. Table I summarised the percentage of non-matching vertices for these six objects after the deformation process. The table shows that for a large number of object vertices (candle) and the object which have lot of sharp corner (fruit), it is difficult to fit their model to the data. Both of these objects almost have a half percentage of non-matching vertices after the deformation process which are 50% for a candle and 47% for a fruit. The rest of the objects have below 30% of non-matching vertices and are considered low. However, there are plenty of opportunities to improve this percentage.

The experimented results show that the movement of model vertices to fit the data vertices depends on some of the cases below:

1) If a few vertices' locations are different, the method performs very well, where almost all the vertices can fit or move towards the data.
2) As the differences between the model and the data vertices increase, it becomes difficult for the model to fit to the data.
3) For a dummy limb, the fitting of the model with the data shows a satisfactory result. The results of 15 measurements show that both the upper and lower limbs have a correlation coefficient close to 1, i.e. both the model and the actual limb data are highly correlated.

TABLE I. THE PERCENTAGE OF NON-MATCHING VERTICES OF SIX OBJECTS

Objects	Non-matching vertices (approx.)	Total registered vertices (approx.)	Percentage of non-matching vertices (%)
Candle	47650	82156	58
Spherical candle	1363	4808	28
Box	900	4200	21
Fruit	3094	6584	47
Lower Limb	1720	6373	26
Upper Limb	1023	4265	24

In prosthetic design, it is necessary to perform quantitative analysis and measurements. The length, angle, area of region, 3D surface area and volume of the limb are measured. The analysis and measurements are employed to ensure that the 3D model created will fit the actual data. It is helpful for the designer to design an appropriate size of the model prosthetic limb, where it is subsequently modified during the design.

A. Lower limb

In order to evaluate the result, the modified 3D model which has been created after the deformation process and the actual limb data are compared. The evaluation is done by comparing some selected points of the actual object with the size of the object created by the deformation process (the modified 3D data). In order to present the modified 3D model after the deformation process, *Matlab 7* is used. After the grid is manually drawn, as shown in Fig. 3, the actual limb is positioned to correspond to the modified 3D data in Fig. 2.

The measurement begins with measuring the diameter of the lower limb, as shown in Fig. 4. In this procedure, the new modified model is displayed with x and y axes so that the corresponding diameter of the actual limb can be easily determined. Both of the modified new 3D model and actual dummy limb measurements have been scaled and set to centimetre (cm) unit. The other measurements are the length of several cross-sections between the modified 3D model and the actual dummy limb. This extends to the measurement of a different 2D view, displayed in z and x axes in Figure 5, z and y axes in Figure 6 and the upper view in Figure 7.

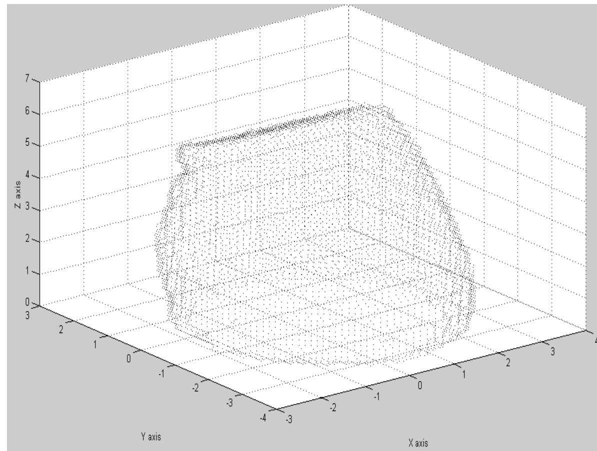

Figure 2. Modified 3D model of the dummy limb after deformation process

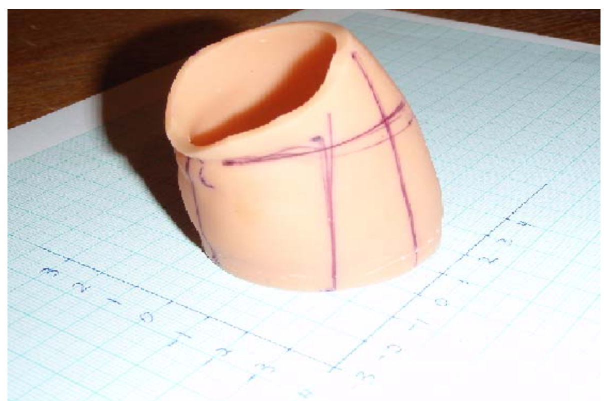

Figure 3. Measuring the approximate position of an actual dummy limb.

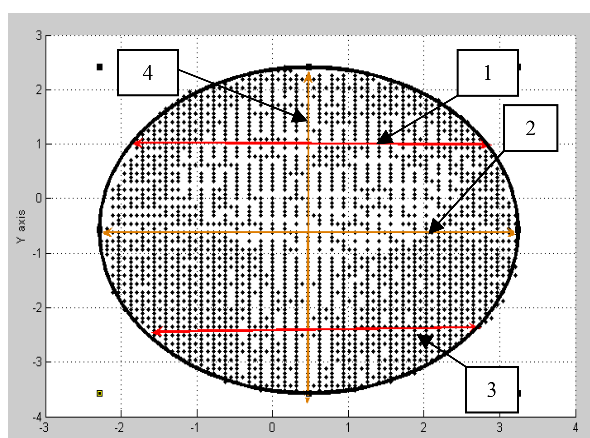

Figure 4. The cross-sections of the modified 3D model (x-y axis). Each labelled line represents the measurement of a length in Table II.

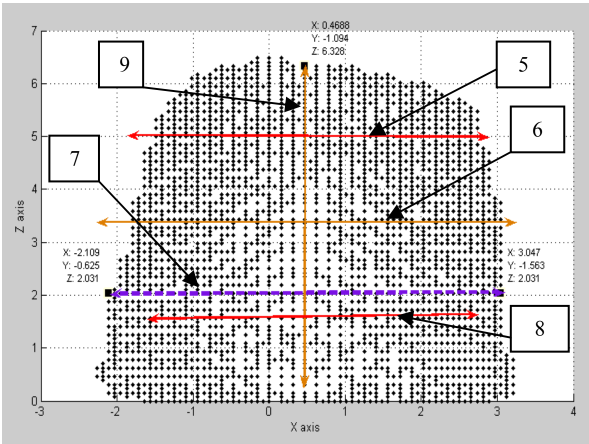

Figure 5. The cross-sections of the modified 3D model (z-x axis). Each labelled line represents the measurement of a length in Table II.

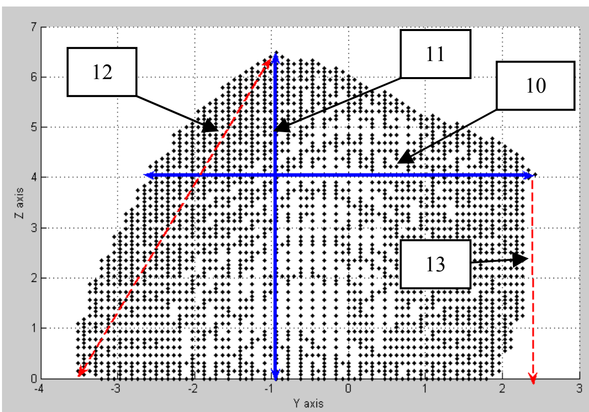

Figure 6. The cross-sections of the modified 3D model (z-y axis). Each labelled line represents the measurement of a length in Table II.

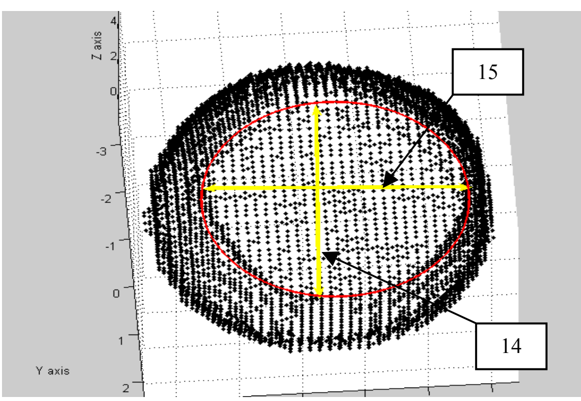

Figure 7. Upper view of the modified 3D model. The labelled lines represent the measurement of a length in Table 2.

Fifteen cross-sections were measured and compared between the modified 3D model and the actual limb data. These are shown in Table II. Table II shows that there are small differences for each measured length of both the modified 3D model and actual limb data. These differences show that the modified 3D model created after the deformation process is very similar to the actual limb. The small error between the 3D model and actual limb is dependent on several factors such as resolution and processing of the actual 3D image data, thickness and distance between vertices, the method of reconstruction (i.e., control parameters of the decimation algorithm or triangulation), and factors associated with marking the measurement points by a human.

TABLE II. DIFFERENCES BETWEEN THE MODIFIED 3D MODEL AND THE LOWER LIMB DATA

Length	Modified 3D model (cm)	Actual limb (cm) ± errors	Difference (cm) ± errors
1	4.8	4.8 ± 0.2	0.0 ± 0.2
2	5.5	5.4 ± 0.1	0.1 ± 0.1
3	4.1	4.1 ± 0.1	0.0 ± 0.1
4	5.8	5.9 ± 0.1	0.1 ± 0.1
5	4.4	4.4 ± 0.1	0.0 ± 0.1
6	4.8	4.7 ± 0.2	0.1 ± 0.2
7	5.3	5.3 ± 0.1	0.0 ± 0.1
8	4.0	4.0 ± 0.1	0.0 ± 0.1
9	6.3	6.2 ± 0.0	0.1 ± 0.0
10	5.1	5.0 ± 0.1	0.1 ± 0.1
11	6.5	6.4 ± 0.1	0.1 ± 0.1
12	7.2	7.3 ± 0.2	0.1 ± 0.2
13	4.0	4.0 ± 0.1	0.0 ± 0.1
14	4.1	4.0 ± 0.2	0.1 ± 0.2
15	4.0	4.0 ± 0.2	0.0 ± 0.2

B. Upper limb

For the upper limb, the same procedure of measuring the cross-sections and comparing those of the modified 3D model and actual limb is performed. The modified 3D data of the limb after the deformation process is shown in Fig. 8 and the corresponding actual limb is shown in Fig. 9.

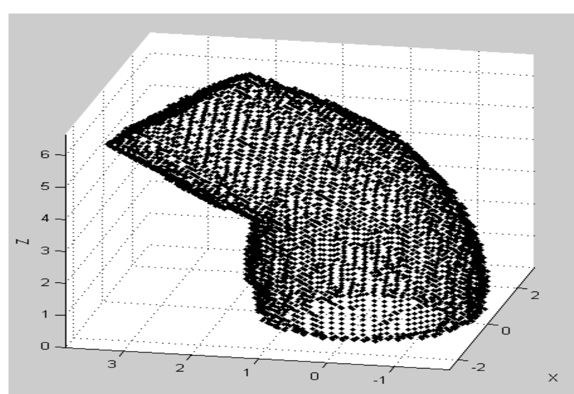

Figure 8. Modified 3D model of upper limb after deformation process.

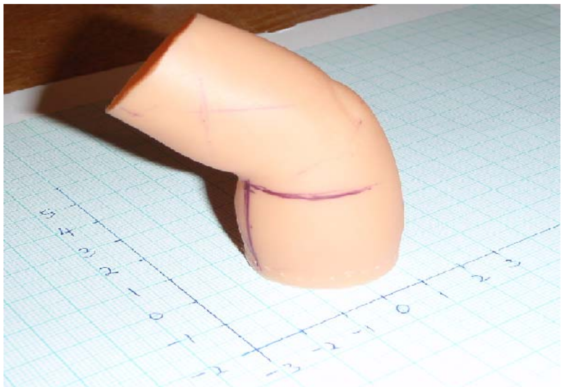

Figure 9. Measuring the approximate position of an actual dummy limb.

The fifteen measurements and comparisons between the modified 3D data and actual limb are shown in Table III.

TABLE III. DIFFERENCES BETWEEN THE MODIFIED 3D MODEL AND THE UPPER LIMB DATA

Length	3D new model (cm)	Actual limb (cm) ± errors	Difference (cm) ± errors
1	5.6	5.5 ± 0.2	0.1 ± 0.2
2	3.0	2.8 ± 0.1	0.2 ± 0.1
3	2.9	2.9 ± 0.2	0.0 ± 0.2
4	3.8	3.8 ± 0.1	0.0 ± 0.1
5	4.6	4.5 ± 0.3	0.1 ± 0.3
6	3.9	3.9 ± 0.2	0.0 ± 0.2
7	3.2	3.2 ± 0.1	0.0 ± 0.1
8	6.1	6.0 ± 0.1	0.1 ± 0.1
9	6.8	6.8 ± 0.1	0.0 ± 0.1
10	3.1	3.0 ± 0.2	0.1 ± 0.2
11	2.8	2.9 ± 0.1	0.1 ± 0.1
12	3.6	3.6 ± 0.1	0.0 ± 0.1
13	3.8	3.8 ± 0.2	0.0 ± 0.2
14	2.5	2.4 ± 0.0	0.1 ± 0.0
15	3.9	3.7 ± 0.2	0.2 ± 0.2

From Table III, the differences in length for several cross-sections of the modified 3D model and actual upper limb show a small difference, which means that the objective of fitting the model to the data during the deformation process has been adequately achieved. The correlation coefficient between 15 measurements of the modified 3D model and the actual limb is 0.99928. This shows that if prosthetic designers have chosen an appropriate design in order to fit the patient's residual limb, the proposed deformation process method could be used.

V. CONCLUSION AND FUTURE WORK

The results show how the modified method successfully handles the deformation process for different numbers of vertices. For a large number of vertices, the deformation process is possible, but not all vertices are deformed. Nevertheless, the objective of the deformation process for reshaping the model to fit with the data is achieved. The deformation process is successfully applied when the numbers of vertices are small. However, for a large number of vertices, the deformation still happened, but the results were not as good as when using a small amount of vertices. For real applications on limb data, if the residual limb of a patient is already obtained the designers can use their database of previous data of residual limbs and fit these with the current patient's limb data. If the starting model is already similar to the limb data, then the deformation process achieves better performance. This offers advantages to the designer to find a good fit to design the orthotic and prosthetic limb. Future research could consist of improving the approach and developing it further. One of the important considerations is to apply the technique on real human limbs instead of using the dummy limbs of this paper. The reconstruction from multiviews in this paper uses a turntable system, which in practice is difficult for obtaining 3D data of real human limbs. In this case, rotating the camera instead of the object is highly suggested.

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