High Accuracy Silhouette Based Reconstruction with Conventional Optics

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***Abstract*—Silhouette based techniques have been used for 3D object reconstruction due to the simplicity of object segmentation they require. They are however prone to certain kinds of errors. In this paper, we present two major novelties, First, we describe a simplified method of camera calibration using a mesh-grid pattern that greatly simplifies subsequent computation in reconstruction. Our second contribution is a novel analytical iterative algorithm to correct the systematic error caused by perspective effects arising out of the finite focal length of the optical system. The algorithm allows us to achieve high dimensional accuracy without the use of expensive telecentric optics.**

***Index Terms*— silhouette, reconstruction, high accuracy, conventional optics.**

I. Introduction

A 3D virtual model of a real-world object essentially means the reconstruction of an object with respect to a 3D co-ordinate system. To reconstruct an object, it is vital to know two things. First, the set of 3D co-ordinates of the points those lie on the surface or in the volume of the object, with respect to fixed coordinate axes, for geometrical shape reconstruction. Secondly the texture or the color distribution present on the surface of the object to reconstruct the texture and external appearances.

II. Previous Work

A lot of work has been done on construction of 3D models of objects from multiple views. In [5], volume segment models are constructed using orthographic projections of silhouettes of an object. These volume segment models approximate the visual hull of the target object. This method is well known as volume intersection in computer vision literature. In [2], an octree model of an object is generated using its three standard orthographic projections. Further on, extensive research has been going in the direction of octree based models. In [1], a theoretical foundation for the geometric concept of visual hull was introduced. It also addresses the problem of finding which parts of a non-convex object are relevant for silhouette based image understanding. Visual hull reconstruction is performed using uncalibrated and unsynchronized video streams in [7]. In [8], a visual hull based algorithm is presented for objects with auxiliary components using multi axis object centered cylindrical system. In [9] an improved 3D reconstruction in silhouette based method that uses mesh grids was proposed. In this work various dimensional measurements of the reconstructed cylindrical object were calculated and also compared against real world measurements. Apart from silhouette and laser based reconstruction methods [8] also presents an algorithm for texture mapping using four texture images of an object, each taken after rotating the object by 90 degrees. In this paper, we have used the silhouette algorithms proposed in [9] and introduced a few improvements and new applications. Importantly, we propose an iterative algorithm for the correction of perspective error in the measurements of the silhouette caused by the use of conventional, non-telecentric optics.

There are an infinite number of points that make up the surface and volume of the object due to the continuous nature of space. But by considering a discrete 3D space that is sufficiently dense, and additionally making some physically acceptable choices relating to the resolution of the desired reconstruction, an adequate number of points can be known to reconstruct the object. This requires the sampling of the object surface in 3D space. This idea is closely related to the conventional notion of signal sampling in the time domain of a 1D signal. After 3D signal sampling, 3D geometric data needs to be acquired: this can be done through contact or non-contact scanning. Contact scanning involves the use of a scanner probe that determines the object surface through physical touch. It is used mostly in manufacturing and can be very precise. The disadvantage though, is that it requires contact with the object being scanned, so the possibility of object modification or damage exists; moreover, they are extremely slow compared to the other scanning methods. The principle behind non-contact scanning is acquisition of the necessary 3D data without disturbing the shape of the object, thus making it very useful for visual metrology. Where exact dimension measurement is required, it is extremely important to keep the shape of the object intact and undisturbed, which is possible with non-contact scanning. Non-contact scanning can be further classified into active and passive. Active scanners emit a particular radiation and detect its reflection to probe an object or an environment. On the other hand passive scanners instead of radiation emission, detect reflected or otherwise affected ambient radiation. Most scanners of this type detect visible light as it is readily available. Passive methods can be very cheap, because, in

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most cases they do not need particular hardware. The silhouette based scanner is a passive non-contact scanner which uses outlines created from a sequence of images around a three-dimensional object against a well contrasted background. These silhouettes are extruded and intersected to form the visual hull approximation of the object. However, with these kinds of techniques some kinds of concavities of an object (e.g. interior of a bowl) are not detected.

III. Basic Algorithm

A brief overview of the basic algorithm for silhouette based reconstruction using mesh grid for real world dimensional measurement of the reconstructed object presented by [9] is discussed in this section.

The camera is calibrated by placing the mesh-grid patterns in the Central Axis Normal Plane (CANP) shown in Fig. 2.1. A source of uniform luminous emittance is used for rear illumination to capture the silhouette image. The object is rotated by small angular increments until it is scanned completely. For every silhouette image, the background and foreground are separated using relatively straightforward image conditioning to get the clear edge of the silhouette. For all images, the width of the object at different heights is evaluated with the help of calibration images to obtain its horizontal cross-sections. Every cross section is reconstructed separately using the surface carving algorithm. Object registration is done according to acquired data.

We compute the coordinates of the object surface with respect to the real world using the calibration data. Fig. 2.2 shows the reconstructed object. The measurements of original object have been made using vernier caliper while that of the reconstructed object have been made using volume intersection computations. The height is measured by plotting the surface profile of any one view. For measurements of diameters, for each cross-section we take 20 pairs of diametrically opposite points and then calculate the distances between them.

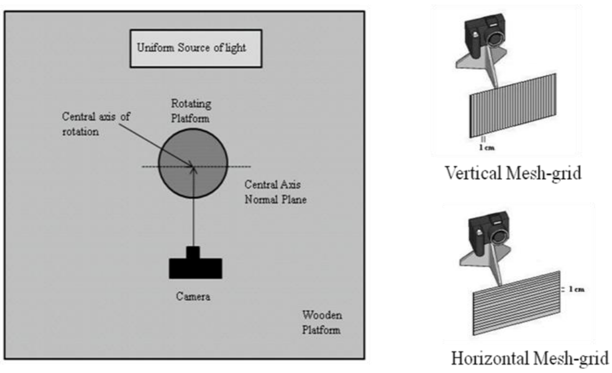
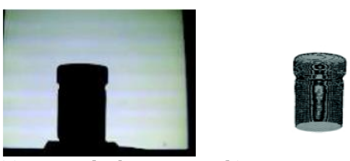


Figure 2.1: Mesh grids aligned with central axis normal plane



(a) Original Object (b) Reconstructed object

Figure 2.2: Reconstruction of an object

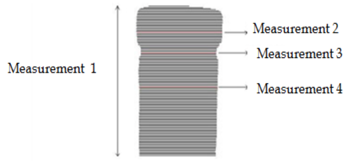


Figure 2.3: Measurement

The calculated diameters are averaged out. This process is repeated for each marked cross-section. The table taken from [9] (Table I) shows the measurements of the actual object and the reconstructed object. The deviations in the values of the measurements of the actual object and the reconstructed object are evident.

TABLE I. Comparison of the Measurement of Actual and Reconstructed Object

	Actual Object (cm)	Reconstructed Object (cm)	Percentage Error
Measurement 1	5.25	5.36	2.052
Measurement 2	3.67	3.88	5.414
Measurement 3	3.38	3.42	1.125
Measurement 4	3.54	3.56	0.561

IV. Depth Related Issues

It is quite clear that the dimensional inaccuracy exists in the object reconstruction by silhouette based method using mesh grid. The reason for inaccurate measurements is the depth problem between CANP and camera optical centre. The initial assumption that the edges of the silhouettes lie in CANP is incorrect, as the surface contour on the object that actually yielded the observed silhouette might not lie in the CANP. So, the calibration with mesh-grids aligned to CANP cannot be used to measure the edges of the silhouettes that do not lie in CANP. This is clearly depicted in Fig. 3.1. The figure is shown as a top-view of the setup. The tangents *T1* and *T2* project the silhouette edges on the image plane. The points *P1* and *P2* where the tangents touch the object do not lie in the CANP but in a different plane which is closer to the camera optic center than the CANP. The actual points that lie on the CANP are *P3* and *P4*, where lines *T3* and *T4* cut the object. The actual width can be obtained by projecting *P3* and *P4* on the image plane given by which can be mapped onto CANP to get the real-world width. But in a silhouette measurement, edges are being formed by P1 and P2 so when we assume that *P1* and *P2* lie in the CANP then form the edges in the image plane giving the apparent width of the object. Since P1 and P2 are closer than P3 and P4, the apparent width we calculate is greater than the actual width. In fact, this exaggeration of all measurements made by the silhouette method is evident from Table I. The same problem also occurs during the calculation of height of the object (depicted in Fig. 3.2), but we do not address that here.

This distortion of object dimensions is clearly the result of the geometric limitations of the perspective imaging process implemented by a finite focal length lens. It is known, on the other hand, that telecentric lenses form an orthographic rather than perspective image of the scene. Hence, the image size remains almost unchanged when the object distance changes, so long as we ensure that the object to be inspected stays within the specified field depth/telecentric range of the lens. True horizontal and vertical cross-sections of the object are therefore directly available from the image, and the problem of incorrect (exaggerated) silhouette measurements will not arise. But telecentric lenses are extremely expensive.

V. Solution for Depth Issue Using Conventional Lenses

Since the telecentric lens is very expensive, it is not easily affordable to generate orthographic projections. We now present a novel approach to solve the depth caused inaccuracy issue that is purely analytical in nature.

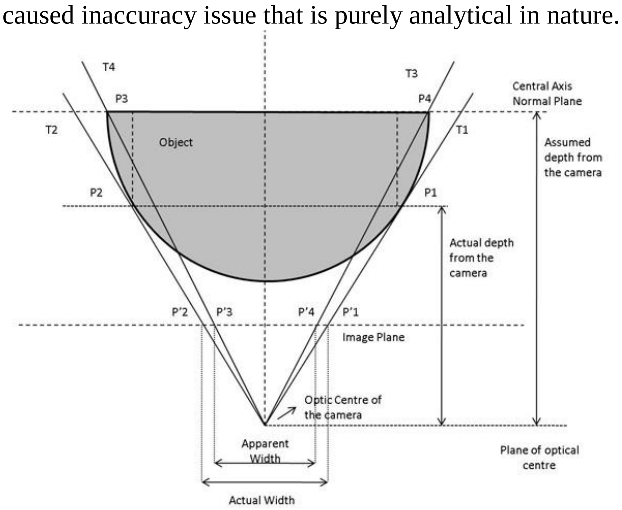


Figure 3.1: Depth issue in width

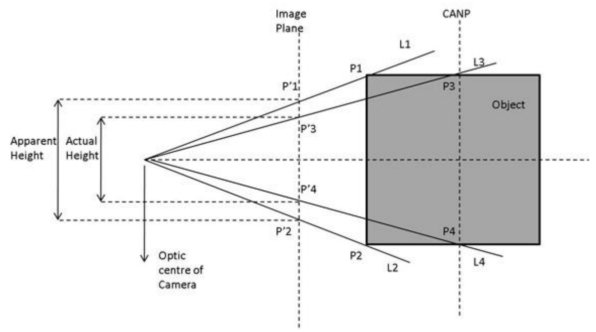


Figure 3.2: Depth issue in height

This approach operates on the initial edge data, generated using conventional, non telecentric optics, and only assumes that the distance between the CANP and camera image plane is known.

A. Algorithm for Error Correction

This approach uses the initial edge data of the original object to obtain a more accurate reconstruction by an iterative procedure. The Fig. 3.9 is shown as a top view to the setup. In the figure, only one side projections has been shown for the purpose of simpler depiction of the algorithm. The outermost circle is the base reconstruction of the object using the basic silhouette method while the inner-most circle represents the original object to be reconstructed. The edge data of the outermost circle has been obtained by the projection T’ of tangent ray on to the image plane. What the conventional silhouette method thus takes as the object edge in the CANP is the point T on the CANP. This error repeats when other points of the object are reconstructed by projecting various such tangents to the CANP for corresponding silhouette images. It is clear that the cause for inaccuracy in the base reconstruction (outermost circle) dimension is the point E, or rather the assumption that E lies on the CANP. In truth, the tangents points such as E on the object do not lie in the CANP but in a considerably closer plane than the CANP. Since the problem is the location of the tangent points, edge data correction will be carried out upon these tangent points. The algorithm is explained in the following steps with the help of Fig. 4.1.

1) Calculate angle BTO, (i.e. P) using R and edge data BT.
2) Repeat step 1 for each captured silhouette image using corresponding edge data.
3) Find tangent line OT1 using base reconstructed edge data of the object.
4) Tangent line OT1 gives a tangential point r1 on the base reconstructed object.
5) Line segment Br1 provides the angle TBE1 i.e. Q and also it intersects OT at E1.
6) Calculate BE1 from triangle BTE1 and it is the corrected edge data in first iteration for tangent point edge data i.e. BE using the following equation 4.1

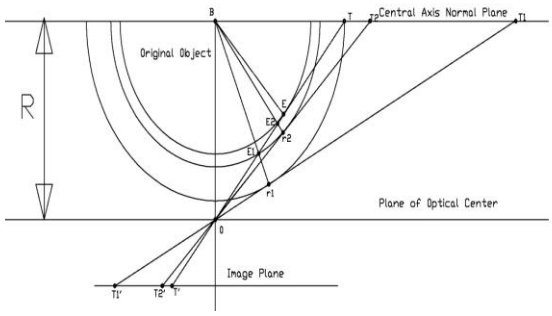


Figure 4.1: Figure to explain the error correction algorithm

$$BE1 = BT\cos\angle TBE1 + (BT\sin\angle TBE1)/(\tan\angle TE1B) \quad (4.1)$$

7) Correct the edge data of the base reconstruction model at tangent point by replacing edge data Br1 by BE1.
8) Repeat the steps 3 to 6 for all the captured silhouette images and this completes the first iteration in the error correction of the object data.
9) Repeat steps 3 to 7 until tangent OT is reached.
10) Once tangent OT is reached then edge data BE is the correct data i.e. in match with real coordinates.

B. Finding Tangent Line OT1

Considering the discrete nature of the proposed model, let W, X, Y and Z be the points on the base reconstructed edge data. In the simulated reconstruction good number of points are considered, which directly indicates number of silhouette images taken. The Fig. 4.2 shows the detailed process.

We have considered all the points on the surface of the object that lie in the first quadrant. Calculate projections of each considered edge data on to the line BO using the Equation (4.2) Let these projections be BW, BX, BY and BZ.

$$BW' = BW \times \cos(\theta_{\omega}) : \theta_{\omega} = \angle WBW' \qquad (4.2)$$

Similarly for all other points calculate projections. Also calculate perpendicular components of the edge data points WW, XX, YY and ZZ using Equation (4.3)

$$WW' = BW \times \sin(\theta_{\omega}) \qquad (4.3)$$

Calculate angle made by each of the line segments like OW, OX, OY and OZ at O using Equation (4.4).

$$\theta_{\omega'} = \arctan(BW' / (R - WW')) : \theta_{\omega'} = WOW' \qquad (4.4)$$

Find the largest angle in the above calculated angles. This largest angle gives the tangent point on the surface of the base reconstructed data and this tangent is similar to tangent OT1.

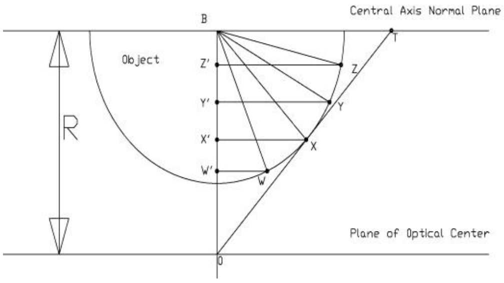


Figure 4.2: Finding tangent line OT1

C. Calculation of the Corrected Edge Data

After finding the tangent line a triangle can be drawn with its two angle and a side length BT. Corrected edge data in first iteration can be calculated from triangle BTE1 using the Equation 4.1

$$BE1 = BT \cos \angle TBE1 + (BT \sin \angle TBE1) / (\tan \angle TE1B)$$

The correction algorithm above described has been applied for a simple cylindrical object in our example. The fact that it indeed works for any other shape is demonstrated by the example images we have included. The Fig.4.3 shows the correction done to the object. In this plot edge data of the horizontal cross section of cylinder has been compared. From the figure it is observed that a significant amount of improvement in the dimensional accuracy of the object has been achieved.

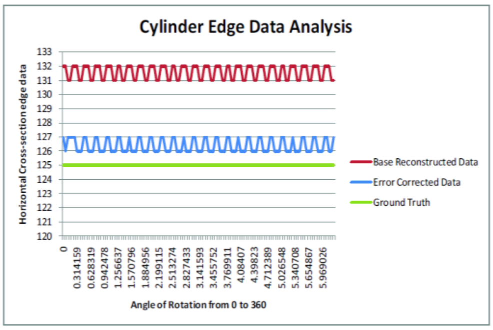


Figure 4.3: Cylinder performance analysis

D. Performance Analysis

To test the robustness of the proposed algorithm, it has been tested for different objects with convex protrusions using Open GL tool. Our algorithm has been applied on a cube of 2 units side length and a complex object. The complex object is created by embedding two 45 degree angle protrusions (beaks) separated by a 60 degree angle onto a cylinder where the radius of the cylinder is 1 unit. A cube has been chosen as it has multiple protrusions from the cylindrical, so this will give a better test for the proposed algorithm.

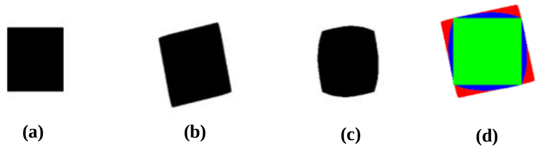


Figure 4.4: (a) Original Cube; (b) Cube without Correction; (c) Cube after Correction; (d) Merged Cube

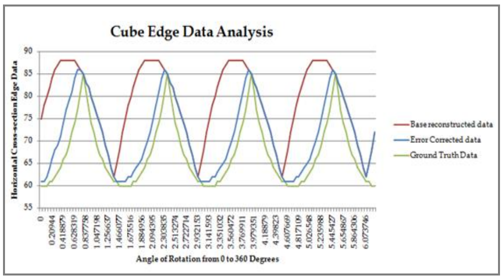


Figure 4.5: Cube Performance Analysis

Figure 4.6: (a) Original double beak (b) Double beak without correction (c) Double beak after correction (d) Merged double beak

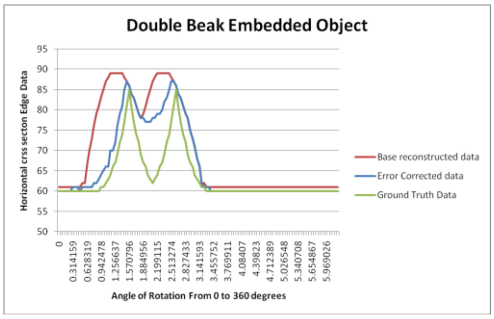


Figure 4.7: Double beak performance analysis

VI. Conclusion and Future Work

A novel method has been introduced for correcting the measurement inaccuracies caused by perspective effects in silhouette based volume intersection reconstruction. This method corrects the inaccuracy by a purely analytical process. The proposed algorithm significantly reduces the error caused by perspective effects. Thus this method makes the silhouette based reconstruction much more dimensionally accurate, obviating the use of expensive telecentric optics.

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