Hybrid Technique For Three-Dimensional Modelling From Close Range Laser Scanner's Point Clouds

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Key words: Registration, ICP, Surface Reconstruction, Delaunay/Voronoi

SUMMARY

The modelling of the object in three dimension (3D) by using a laser scanner is an attractive research in geomatic and computer graphic community. Laser scanner scanned the object by generating the point clouds that approximated the original shape of the object. 3D model of the object can be obtained by computed the surface bounded by these point clouds. The Hybrid technique for generating the 3D model from laser scanner's point cloud is introduced. First, the multiview point clouds are registered by using the ICP algorithm. Then, the point clouds are represented as Adaptive Moving Least squares (AMLS) surface. The surface bounded by AMLS is reconstructed by using Delaunay/ Voronoi based algorithm. The results show the Hybrid technique had successfully reconstructed the smooth surface from point clouds scanned by using Vivid 910, NextEngine and Faro laser scanners. Difference of measurement values between real objects and 3D models from Hybrid technique are within 0.017cm cm to 0.040cm. The Hybrid technique evaluated the general framework on how to generate the 3D model from point clouds and very useful for design the new software system in 3D applications.

Hybrid Technique For Three-Dimensional Modelling From Close Range Laser Scanner's Point Clouds

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1. Introduction

The modelling of the object in three dimension(3D) by using close range laser scanner is an attractive research in geomatic and computer graphic community. Laser scanner scanned the object by generating the point clouds that approximated the original shape of the object. The 3D model of the object can be obtained by computed the surface bounded by these point clouds. The generated 3D models have many applications in various fields and area, for example, medical imaging (Setan *et al*, 2007), historical heritage documentation (Crespo *et al*, 2010; Kheder *et al*, 2009) and reverse engineering (Chen *et al*, 2012).

The generating of 3D model from point clouds in most cases cannot be finished in one step (Remondino, 2003). Multiview scanning point clouds must be merged or registered to get the whole shape of the object. Noise in point clouds must be removed or edited before the good 3D model can be generated. Several techniques had been introduced to generate the 3D model from point clouds in the research community (Armesto *et al*, 2010; Bosche, 2010; Pu and Vosselman, 2009). Since the full automation of 3D model generation from point clouds are still an open problem in the research area, the Hybrid technique which can be used to design the automated 3D modelling system for 3D applications are developed.

2. Iterative Closet Point (ICP) algorithm

In most cases, the laser scanner cannot scan the whole object in one view. The multiview scanning is needed to capture the whole shape of the object. Because each scan has its own local coordinate system, all the point clouds must be transformed into a common coordinate system before the 3D surface can be generated. This process is usually referred as registration. The well known solution for point clouds registration is Iterative Closet Point (or ICP) algorithm developed by Besl and McKay (1992) , Chen and Medioni (1992) and Zhang (1994). ICP algorithm searches the pairs of nearest points between two point clouds and estimates the rigid transformation which best aligned these point clouds. This algorithm assumes that one point set is a subset of the other. When this assumption is invalid, false matches are created (Gruen and Akca, 2005). Several solutions had been conducted to resolve this problem (Rusinkiewicz and Levoy, 2001; Greenspan and Godin, 2001; Sharp *et al* , 2002; Chetverikov *et al* , 2005).

The overlapping of point cloud is the key factor to be considered when applying the ICP algorithm in point cloud registration. To define the overlapping area between two point clouds, the corresponding points are selected. Corresponding points are the common points between two point clouds that share the common surface. To define the corresponding points, one "point" from first point clouds is selected, then using the K nearest neighbour method to define the closet point (K value selected here is 1000, which mean 1000 point that closet to selected point will be used as corresponding point). The same procedure will be applied on second point clouds (The selected point from first and second point clouds must be located at the overlapping surface). The rigid transformation parameter (rotation and translation vector) is computed from these corresponding points by using the least square adjustment method (Ghilani and Wolf, 2006). The computed rigid transformation parameter will applied on first and second point clouds. These two point clouds (point clouds x and y) will be used as initial surface for the ICP algorithm.

The simple modification had been applied into ICP algorithm. To register two point clouds (Figure 1, point clouds x and y), the Delaunay Triangulation of point clouds x is computed. Triangulation used to define the surface of point cloud y. The corresponding point for point clouds x is defined by using the K (where K=1000) nearest neighbour method (Greenspan and Godin, 2001) based on Triangulation x. There will be a number of pair corresponding points for each K value point. To reduce the time used by the ICP algorithm to register the point clouds, only corresponding point with Euclidean distance smaller than the tolerance distance will use to compute the rigid transformation (Rusinkiewicz and Levoy, 2001). The minimum value for tolerance distance is 3 as suggested by Rusinkiewicz and Levoy (2001). By applying this filtering, the iteration of ICP algorithm can be terminated by using the number of corresponding points on each iteration (Figure 1). Since not all corresponding point is used to compute the registration parameter, the modification ICP algorithm will be faster than original ICP algorithm.

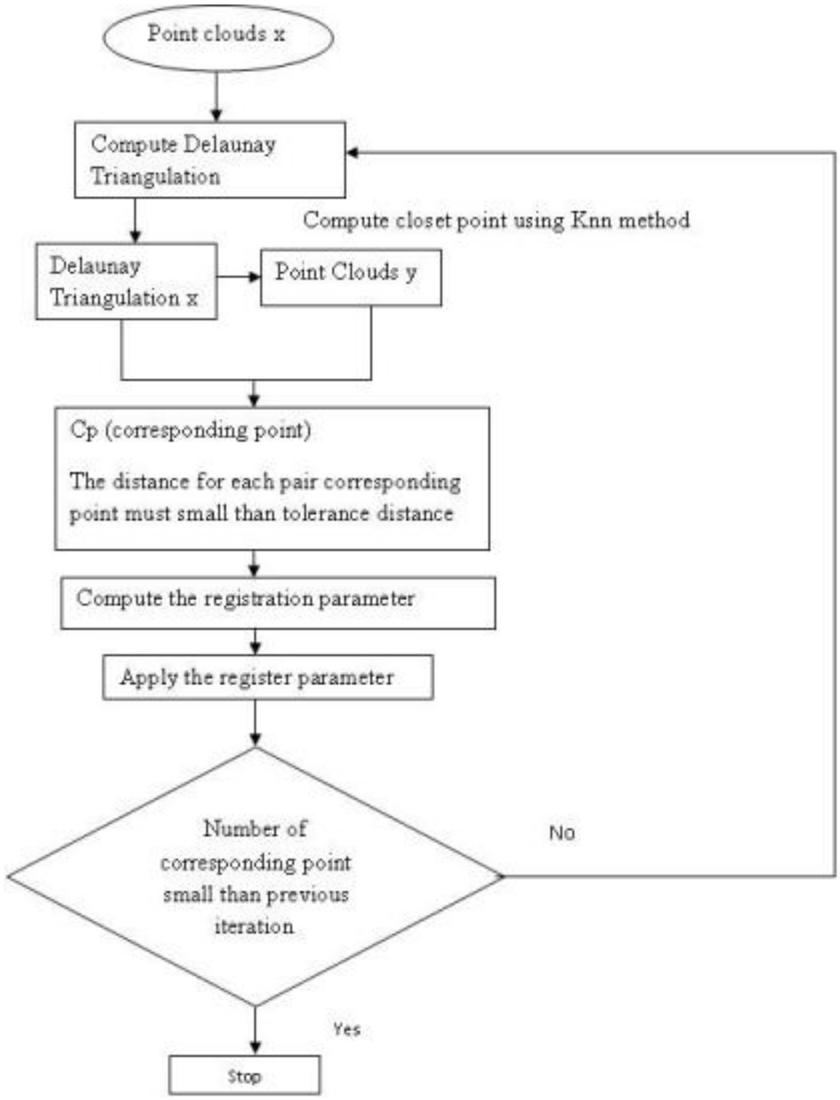


Figure 1 The modification of ICP algorithm in Hybrid technique

3. Adaptive Moving Least Square (AMLS) surface

Measurements always contain errors (Ghilani and Wolf, 2006). The same problem also happens for the point clouds captured by using laser scanner, for example, downsampling (the point clouds are not dense enough to describe the feature of the surface). When the point clouds contained the noise, the generated 3D model is not a smooth or topology surface is different with the scanned object.

One of the methods to remove the noise in the point cloud is to represent the point cloud as Moving Least Square(MLS) surface (Carr, 2001; Levin, 2001; Alexa *et al*, 2003, Dey and Sun, 2005a). The representation of point clouds as the MLS surface will allow the user to change the feature of 3D objects by changing the parameter of MLS function. This is very useful for adding or removing the sample points from point clouds when point clouds are downsampling (not dense enough) or upsampling (too dense). Dey and Sun (2005a) introduced the Adaptive Moving Least square (AMLS) surface that comes with theoretical guarantees. Compared with other existing algorithm, AMLS surface used local feature size to control the parameter of MLS function. This allowed the sampling surface directly control by using AMLS function.

The point clouds register by using the ICP algorithm is represented as Adaptive Moving Least square surface (AMLS). The representation of point clouds as AMLS surface can help to reduce the effect of noise on the surface. The smoothness of this surface can be controlled by changing the parameter in AMLS function.

4. Delaunay/Voronoi based surface Reconstruction algorithm

The surface bounded by point clouds can be computed by using surface reconstruction algorithms. Voronoi Diagram and Delaunay Triangulation are well known structure that can be used for surface reconstruction algorithms. Given the sample point **S,** divided the sample point into regions, where each region contains the closet points to point **p** (**p** can be any point from **S**). The diagram that contains this entire region is Voronoi Diagram (see Figure 2). The Delaunay Triangulation **P** in a plane is a Triangulation **P** such that no point in P is inside the circumcircle of any triangle in **P**. Delaunay Triangulation of **P** is duality with the Voronoi diagram **P (**see Figure 2**,** red line).

The first surface reconstruction algorithm that comes with a theoretical guarantee was introduced by Amenta *et al* (1998) using Voronoi Diagram and Delaunay Triangulation. Their work estimates the density of sample point by using r – sampling. r is the minimum distance between medial axis to the object surface. When the r is small enough ($r \approx 0.001$), the Voronoi vertex, called as pole approximate the medial axis of the point clouds (see Figure 3). By computing the Voronoi diagram of the point clouds and filter the unwanted triangle by using a pole, the surface bounded by the point clouds can be computed.

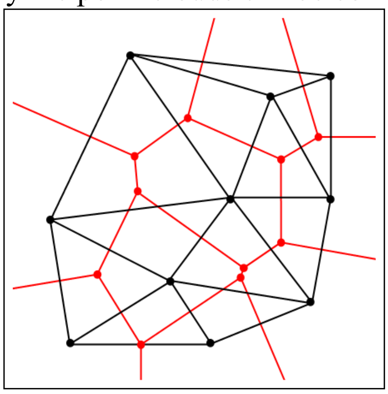


Figure 2 The Delaunay Triangulation (black line) and Voronoi Diagram (red line). Delaunay Triangulation is duality with Voronoi Diagram

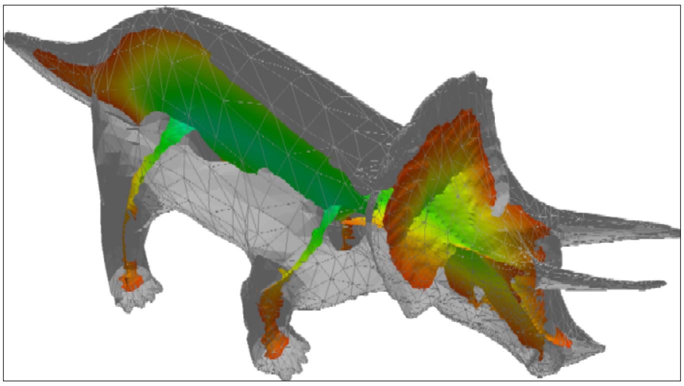


Figure 3 The medial axis of the 3D surface (the middle surface with colour). The medial axis of point clouds can be used to approximate the 3D surface of point clouds.

Based on the work by Amenta *et al* (1998), several extensions of Crust algorithms had been introduced. COCONE algorithm (Amenta *et al*, 2002) simplifies the complexity of the Crust algorithm by computed the collection of triangles (COCONE triangle) that will approximate the medial axis of the object. TightCocone (Dey and Goswami, 2003; Goswami and Dey, 2004) and PowerCrust (Amenta *et al*, 2001) labelled the computed triangle as IN or OUT. Then, the surface without hole is extracted as the boundary of IN or OUT triangle.

The 3D model generated from the point clouds contain hole when regions of surface cannot be accessed by the light of laser scanners. Commercial software, for example, RapidForm has provided the editing function to close the hole. For Hybrid technique, the surface reconstruction algorithm will automatically close the unwanted hole on 3D surface is used (Figure 4). First, the Delaunay Triangulation of the point cloud is computed. Then, compute the feature ball (refer to Dey and Goswami(2003) for definition of feature ball). Feature ball will be separated into Outer and Inner. Retain the point of Outer ball and final surface of point clouds will be computed from these points. As proven by Dey and Sun (2005), this algorithm can generate 3D surface without hole from noisy point clouds.

The implementation of surface reconstruction introduced in this paper had one difficulty: the computation of 3D Voronoi Diagram. The vertices of two-dimensional Voronoi Diagram approximated the medial axis of the object. But this does not happen on 3D Voronoi Diagram. According to the paper by Amenta *et al* (1998), in 3D space, the pole vector of Voronoi Diagram are approximated the medial axis of 3D objects. Hence, by computing all the pole vector in Voronoi Diagram, the shape that approximated the surface of the object can be generated. The algorithm proposed by Amenta *et al* (1998) is used to compute the medial axis of the point clouds.

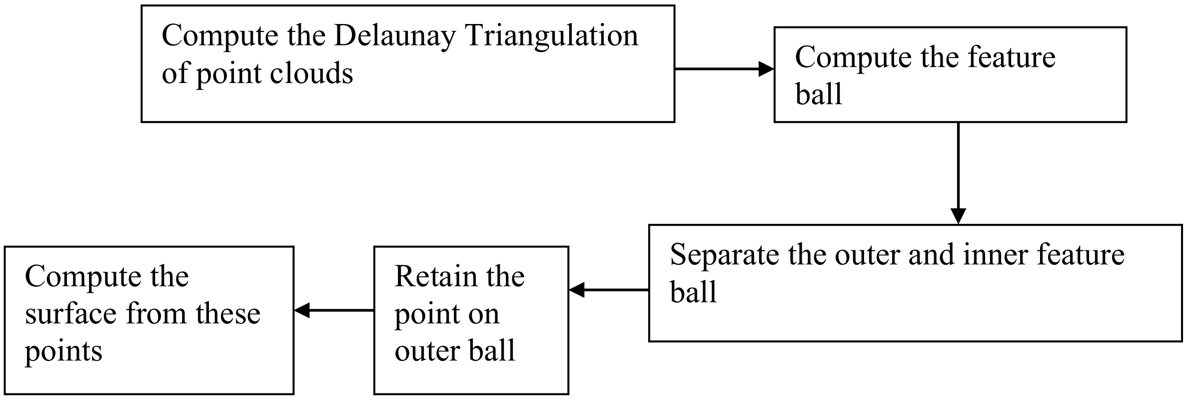


Figure 4 The surface reconstruction algorithm for Hybrid3D modeling technique.

5. The Hybrid Technique to Generate 3D model from Point Clouds

The Hybrid technique is the framework on how to generate the 3D model from point clouds. Figure 5 is the technique used by commercial software, RapidForm (RapidForm tutorial, 2004) to generate the 3D model from point clouds. First, register the multiview point clouds. Then, compute the triangulation of the point clouds. The triangulation surface is the 3D model of the point clouds. Since the point clouds always contain the noise, the surface editing step is needed to remove the hole on the 3D surface.

Compared with the technique shown in Figure 5, the Hybrid technique (Figure 6) introduced new flow in point clouds processing steps , that is represented the point clouds as Adaptive Moving least square or AMLS surface. AMLS surface can reduce the effect of noise in the point clouds. The smoothness of the AMLS surface is controllable by function parameter in AMLS function (Dey and Goswami, 2003).

The representation of point clouds as AMLS surface will make sure the Hybrid 3D modelling technique always created the surface that free from the noise effect. The Delaunay/Voronoi based algorithm is used to reconstruct the point clouds surface. Compared with other existing surface reconstruction algorithm, the Delaunay /Voronoi based algorithm in Hybrid technique always created the surface that free of hole. This type of surface reconstruction algorithm can handle a small amount of noise in point clouds and automatically close the hole on the surface. Hence, the surface editing task is not needed.

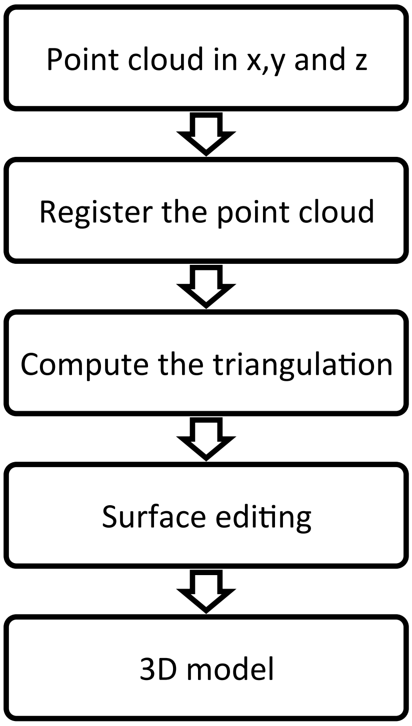


Figure 5 The technique used to generate the 3D model from point cloud by using Rapidform (RapidForm tutorial, 2004)

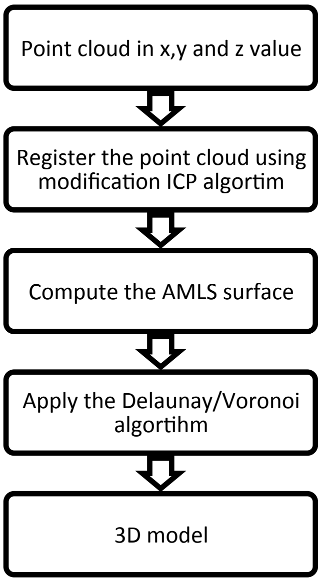


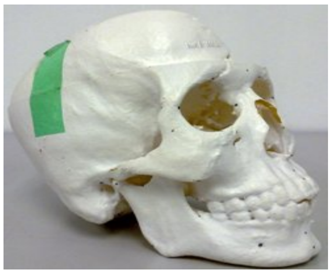
Figure 6 The Hybrid 3D modeling technique

6.Results and Analysis

The Hybrid 3D modeling technique is implemented on three objects (Figure 7) that captured by using Vivid910 and NextEngine. Table 1 shows the numbers of scans, the model of laser scanner used to generate the point clouds and number of total point clouds for models. The ICP algorithm, Delaunay/Voronoi based algorithm and Adaptive Moving Least square algorithm are implemented using MATLAB programming language. MATLAB programming language only supported around ~ 130,000 points. If the numbers of input point clouds are over this limit, the out of memory error will happen. To resolve this problem, the open source MeshLab(MeshLab) had been used to reduce the point clouds to around 130,000 numbers of points.

(a) Bowl

(a) Vase



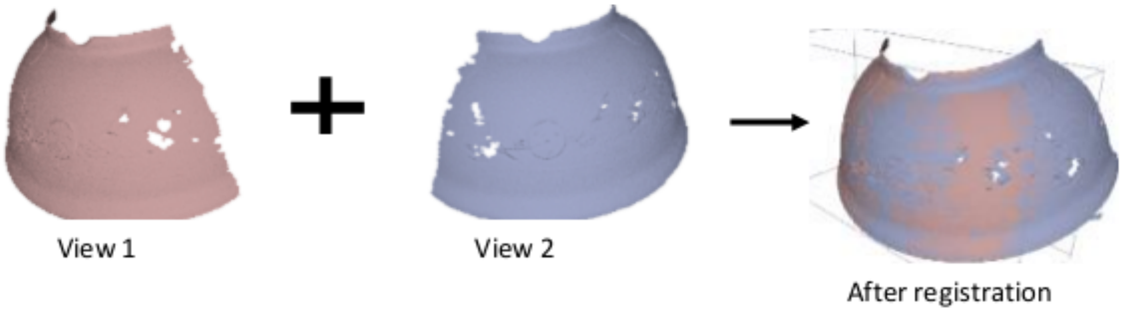
(c) Skull

Figure 7 Three objects used in this study as analysis purpose.

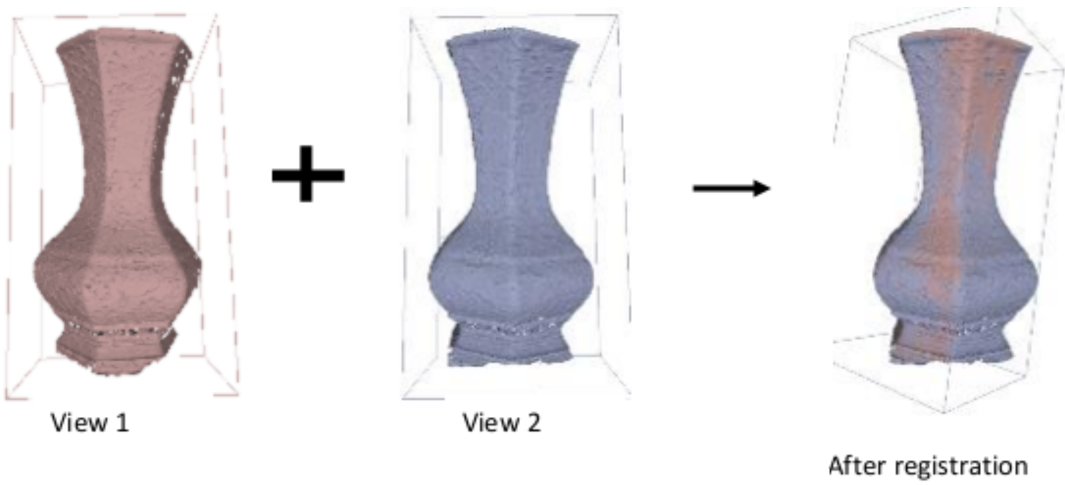
Object	Model of laser scanner used	Number of scans	Total number of point clouds
Bowl	NextEngine	9	126518
Vase	NextEngine	11	112788
Skull	Vivid 910	10	130542

Table 1 The model of laser scanner, the number of scan and the total number of point clouds for each model.

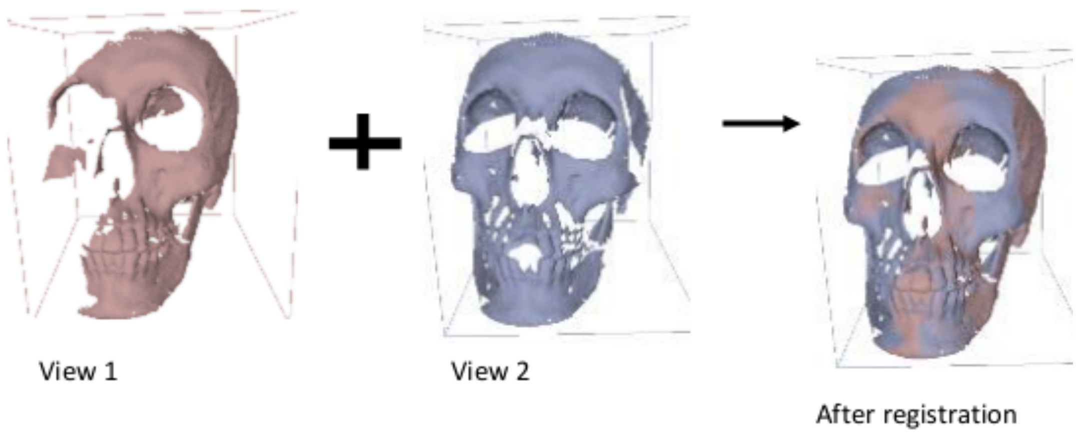
The multi view point clouds registration by using the ICP algorithm in this study is very simple. All the point clouds are registered pair (two point clouds as one pair) by pair until the complete shape of the object had been obtained. For the pair of point clouds there are partially overlapping, the MeshLab is used to compute the “Pre-register” surface. The registration results are shown in Figure 8.



(a) Bowl model before and after registration



(b) Vase model before and after registration



(c) Skull model before and after registration

Figure 8 The registration of bowl, vase and skull model by using ICP algorithm

Figure 8 (a to c) shows the registration of point clouds view 1 (colour red) and view 2 (colour blue) for each model using the ICP algorithm. From Figure 9, the ICP algorithm proposed in this paper had successfully registered the true surface from the point clouds. Table 2 compared the iteration and RMS error for the ICP algorithm proposed in this paper with the classical ICP algorithm. The comparison had shown that the number of iterations of the ICP algorithm proposed in this paper is less than the number iteration of the classic ICP algorithm. The classical ICP algorithm used all the possible corresponding point to compute the registration parameter (Besl and McKay, 1992; Chen and Medioni, 1992). The ICP algorithm proposed in this paper only used the corresponding points with tolerance distance smaller than given value (in this paper, the value 3 is chosen) to compute the registration parameter. Hence, only few iterations are needed to minimize the mean square errors. The RMS errors computed from our ICP algorithm is similar to the RMS error computed from a classical ICP algorithm (see Table 2, column 2 and 4)

The time used by the ICP algorithm to register the point clouds based on number of points is shown in Figure 9. From the graph in Figure 9, the time used to register the point clouds had increased when the number of input point clouds are increasing. The time complexity to compute the Delaunay Triangulation or Voronoi Diagram is **O (n log n)** where n is the number of total point clouds. When the number of input point increase, the time used to compute the Delaunay Triangulation and Voronoi Diagram also increase. Since the ICP algorithm in this paper using Delaunay Triangulation to define the surface, the time used to register the point clouds also increased.

Model	**RMS error from classical ICP algorithm**	**Iteration of classical ICP algorithm**	**RMS error from ICP algorithm proposed in this paper**	**Iteration from ICP algorithm proposed in this paper**
Bowl	3.7133	25	3.714	14
Vase	0.2987	32	0.302	25
Skull	0.5333	27	0.529	14

Table 2 The comparison of iteration and RMS error for ICP algorithm. RMS error from classical ICP algorithm is similar with the RMS error of ICP algorithm proposed in this paper.

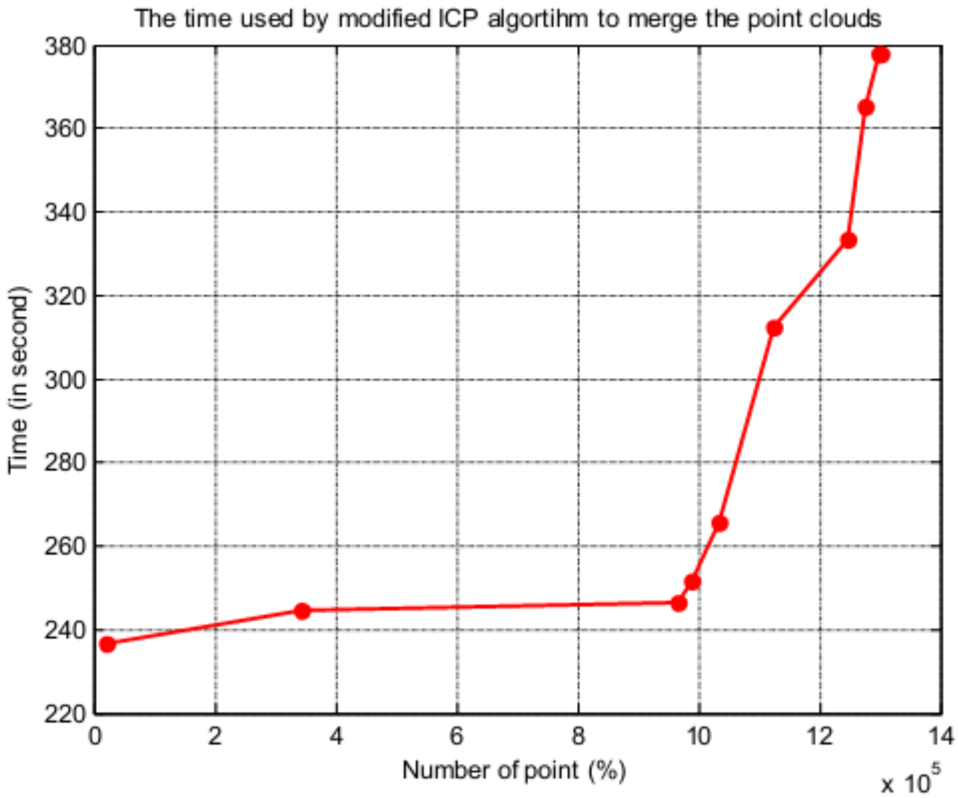
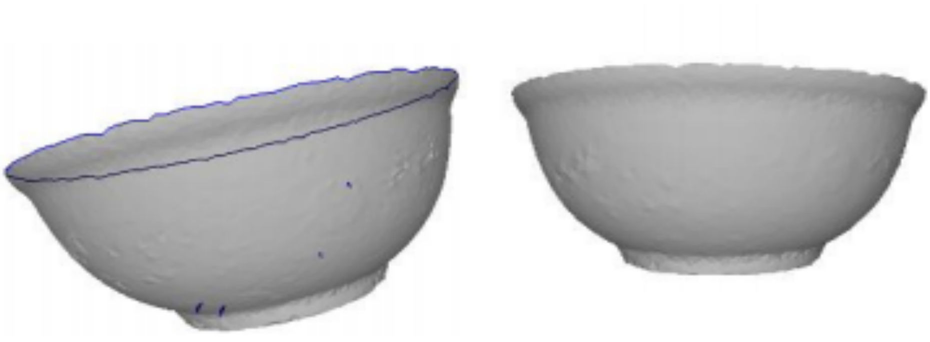
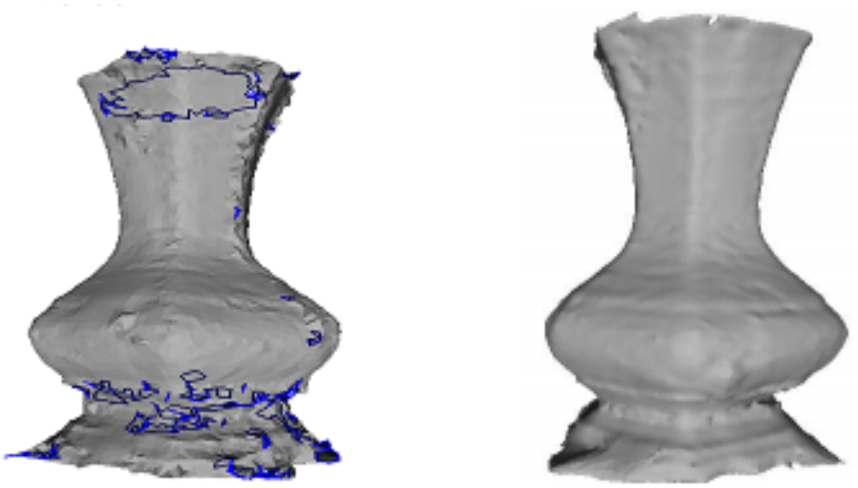


Figure 9 The graph show the time used by ICP algorithm proposed in this paper to register the point clouds when the number of point clouds are increased.

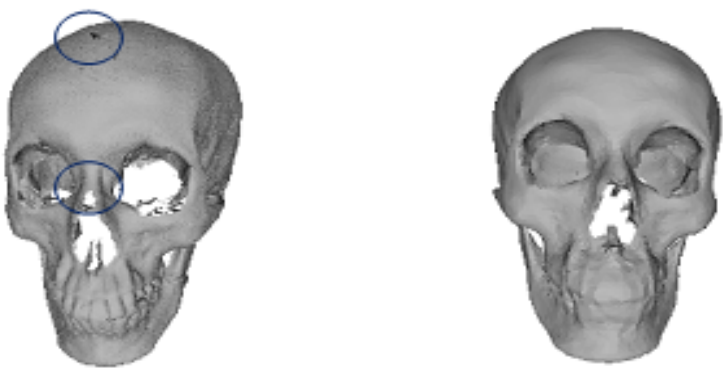
After the multi view point clouds are registered, the Hybrid technique computed the AMLS surface on the point clouds. The surface bounded by AMLS surface is reconstructed by using Delaunay/Voronoi based algorithm (see Figure 6). Compared with Hybrid technique, RapidForm computed the triangulation surface after the point clouds are registered. The surface editing tool is used to fill the hole in the triangulation surface if the point clouds have noise. Figure 10 shows the 3D model generated by RapidForm (without surface editing step) and 3D model generated by Hybrid technique. Figure 10 compared the 3D model generated by using RapidForm and 3D model generated from Hybrid technique. For a 3D model generated by using RapidForm, the hole on the surface can be closed by using surface editing tool. But for Hybrid technique, the hole on the surface is closed automatically (Figure 11b). To compare the final 3D model generated by using RapidForm and the 3D model generated from Hybrid technique, the hole on 3D surfaces (from RapidForm) is closed by using surface editing tool. After that, the 3D models (from RapidForm and Hybrid technique) are compared by using the surface deviation function that is provided in the RapidForm software.



(a) (b)



(a) (b)



(a) (b)

Figure 10 The comparison of 3D models from software RapidForm(a) and Hybrid technique (b). The line with colour blue on figure (a) is the unwanted hole on 3D surface. All these holes are automatically closed by Hybrid technique (figure (b)).

The comparison of measurement for real objects to measurement of 3D models generated from point clouds is shown in Table 3. The measurements of 3D models are obtained by using RapidForm and the real objects are measured by a ruler. Unit measurement for these objects and 3D models are in centimetre (cm). Table 3 shows the measurement of 3D model generated from Hybrid technique are similar to the real measurement of scanned objects. Maximum and minimum difference value for measurements real object and the 3D model are -0.04cm (bowl model) and 0.07cm (Vase model). These values are very small and can be ignored. To obtain higher accuracy 3D model, the calibration or correction on these 3D surfaces must be applied. The explanation about calibration technique of 3D surface is beyond the scope of this paper.

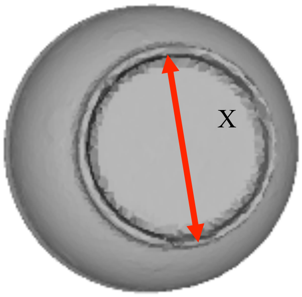
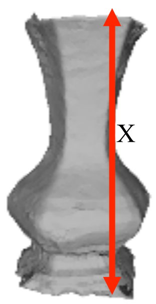
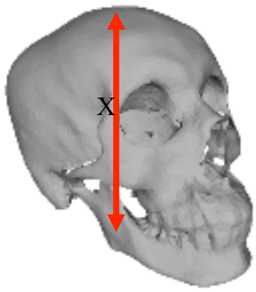
3D model	**Measurement for real object (cm)**	**Measurement from 3D model(cm)**	**dX=measurement real object - measurement 3D model (cm)**
	X=7.50	X=7.46	dX=0.04
	X=25.00	X=24.88(0.12)	dX=0.12
	X=17.00	X=16.83	dX=0.17

Table 3 The comparison of measurement for real object and 3D model generated from point clouds.

7. Conclusions

The Hybrid technique for generating the 3D model from point clouds captured by using Close Range laser scanner is developed. First, the multi view point clouds are registered by using well known ICP algorithm. After that, the Adaptive Moving Least square (AMLS) is computed. The surface bounded by AMLS is reconstructed by using Delaunay/Voronoi based algorithm. Compared with other existing ICP algorithm, our ICP algorithm defines the point clouds as a Delaunay Triangulation. The corresponding points are computed by using K nearest Neighbour method. The tolerance distance is used to control the number of corresponding points in ICP algorithm. Hence, the number of iterations of ICP algorithm can be reduced.

The Delaunay/Voronoi based surface reconstruction algorithm is based on PowerCrust concept, where the union of inner (outer) polar ball is the boundary of 3D surfaces. The polar ball in the point clouds can be estimated by using pole of Voronoi Diagram. The noise in the point clouds will cause the pole estimated the wrong medial axis. Hence, in this study, the big Delaunay ball (or feature ball) is used to estimate the medial axis of the point clouds. The surface computed by Hybrid technique is AMLS surface. AMLS surface is insensitive towards noise and always produce smooth surface. Comparison with the 3D model of commercial software (RapidForm) had shown the 3D model generated by Hybrid technique is similar to the 3D model generated from RapidForm.

8. Limitation of algorithm and Future Study

The ICP algorithm that introduced in this paper is a simple variation of ICP algorithm. Even from our results, this algorithm is able to register the true surface from the point clouds. This type of algorithm fails to register true surface when the noise in point clouds is beyond the limit allowed by the algorithm (Bae and Lichti, 2008). In other words, this ICP algorithm is sensitive towards the noise in the point clouds. The development of registration algorithm that robust towards the noise is a well studied problem in research community.

The generation of 3D model from point clouds automatically is still an open problem in research community nowadays. In fact there is lack of any formal definition about the noise in the point clouds and standard strategic to remove the noise from point clouds. In real time scanning, it is not easy to get the point clouds that free of noise. Even some author has introduced the automatic reconstruction 3D surface from range image (Bernardini *et al*, 1999), but we assume they work partially automatically since the manual remove of noise is still needed. Our future work to find the solution for automatically reconstructed the 3D surface from point clouds, start from registration to the texture mapping procedure.

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