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A fast and effective way to improve the merging accuracy of multi-view point cloud data

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Abstract—**In reverse engineering, in order to meet the requirements for model reconstruction, it is often necessary to locate and merge the different-view-measured cloud data in a global coordinate system. Many merging methods have been proposed, the method of three datum points is one of them and the registration precision of model data depends on the precision of three datum points which are selected. This paper introduces a new development of the "centroid of apexes" method instead of the former datum points to improve the three points positioning algorithm, the effectiveness of the methods is validated with experimental results and a revised algorithm is presented.**

Keywords-reverse engineering; points registration; coordinate transform; reference marker; 3-D pointsets registration

NOMENCLATURE

p q	Coordinate of feature points
V W	Vector between points
v w	Unit vector
$[v]$ $[w]$	Unit vector matrix
P	Coordinate of any point
R	Rotation matrix
T	Translation vector
ε	Absolute error of two edges
Δ	Relative error

I.   INTRODUCTION

The applications of three-dimensional (3D) shape measurement are widely used in the fields of industrial design and manufacturing, relic restoration, biomedicine and computer vision. There are various non-contact optical instruments involved in 3D surface measurement which are based on time-of-flight lasers [1], laser scanning [2], stereovision [3], and structured light [4]. These optical instruments can efficiently capture dense point clouds, which reveal the detail surface shape of the object being scanned. However, all of them can only obtain partial area of the object at one standpoint due to obstructions and the limited field of view of the sensor. In order to build a complete 3D model, it needs to collect point clouds acquired from different views. These multi-view scans are represented in their own local coordinate system, and geometrically aligning them to a global coordinate system is called the "registration problem".

Solutions that are commonly used in practice for registration of multi-view Point Cloud include using datum markers, exploiting mechanical devices like turntables [5] or multi-joint robotic arms [6]. The markers can be planar or solid and are usually adhered on or near the object to be scanned. While the measuring sensor is taking point clouds from a specific view, the 3D coordinates of the markers within the view are obtained at the same time. The relative position and orientation of two scans can be easily determined if only three or more pairs of markers are visible in both views. This registration method is usually fast and reliable. However, except for the preparation work before the measurement, the drawbacks of this strategy include that the areas covered by the markers cannot be digitized reliably. This problem is outstanding especially for objects with small size and abundant details. Moreover, adhering markers on the surface is obtrusive or even prohibited in some applications.

II.   REGISTRATION ALGORITHM BASED ON 3-D POINT SETS METHOD

Coordinate transformation of 3D graphics includes geometric transformations of translation, proportion, rotation and shear. The data alignments in this paper are only translation and rotation transformation. Since three points can express a complete coordinate, multi-view data transformation will be achieved simply with three different reference points. Besl and Mckay described manifold 3-D shape registration methods, including 3-D point sets, free-form curves and surfaces [7]. Among these methods, the 3-D point sets registration method is used in most places, especially in reverse engineering where the object shape is described as 3-D scan point sets. To carry out 3-D point sets registration, first construct least-square distance object function between the corresponding points, solve the object function based on the quaternions and the singular value decomposition (SVD) the rotation and the translation of the rigid movement [8-10].

Measurement data registration can be seen as a kind of rigid body movement, so a three-point alignment coordinate transformation method can be used to deal with data registration. Because three points can establish a coordinate, we can set up three datum points of the reference markers at a different view for the data alignment. The data registration of 3D measurement data will be achieved through the alignment of three datum reference marker points. In fact, the data alignment problem is converted to coordinate transformation.

The method of three-point alignment coordinate transformation: suppose datum feature points are p_1, p_2 and p_3. The coordinates of the three datum points in the second measurement turn into q_1, q_2 and q_3. Coordinate transformation can be achieved via three steps as derived by Mortenson and presented here for clarity [11]:

1. Transform p_1 to q_1;
2. Transform vector $(p_2 - p_1)$ to $(q_2 - q_1)$ (taking only the direction into consideration);
3. Transform the plane containing the three points p_1, p_2 and p_3 to the plane containing the three points q_1, q_2 and q_3. The algorithm is:

Step 1: Set up vector $(p_2 - p_1), (p_3 - p_1), (q_2 - q_1)$ and $(q_3 - q_1)$ (1)

Step 2: Define $V_1 = p_2 - p_1, W_1 = q_2 - q_1$ (2)

Step 3: Set up vector V_3 and W_3

$$\begin{cases} V_3 = V_1 \times (p_3 - p_1) \\ W_3 = W_1 \times (q_3 - q_1) \end{cases}$$ (3)

Step 4: Set up vector V_2 and W_2

$$\begin{cases} V_2 = V_3 \times V_1 \\ W_2 = W_3 \times W_1 \end{cases}$$ (4)

Obviously, the vector V_1, V_2 and V_3 constitute right-handed orthogonal lines, and the vector W_1, W_2 and W_3 also constitute right-handed orthogonal lines.

Step 5: Set up unit vector

$$\begin{cases} v_1 = \dfrac{V_1}{|V_1|}, v_2 = \dfrac{V_2}{|V_2|}, v_3 = \dfrac{V_3}{|V_3|} \\ w_1 = \dfrac{W_1}{|W_1|}, w_2 = \dfrac{W_2}{|W_2|}, w_3 = \dfrac{W_3}{|W_3|} \end{cases}$$ (5)

Step 6: Transform any point P_i in the system $[v]$ to the system $[w]$, with transformation formula:

$$P^*_i = P_i R + T ;$$ (6)

Step 7: As $[v]$ and $[w]$ are unit vector matrixes, $[w] = [v]R$, so the unknown rotation matrix about the $[w]$ system is

$$R = [v]^{-1}[w];$$ (7)

Step 8: Define $P'_1 = q_1$ and $P_1 = p_1$, put them into the equation, then the translation vector T is obtained:

$$T = q_1 - p_1[v]^{-1}[w];$$ (8)

Step 9: Equation is rewritten:

$$P^* = P[v]^{-1}[w] - p_1[v]^{-1}[w] + q_1 ;$$ (9)

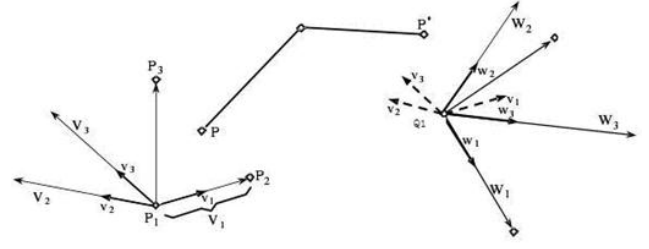Fig.1 shows a three-point coordinates transformation

Figure 1. Three points to three points transformation.

Using the above re-positioning algorithm and introducing the reference points in the process of measurement, there are at least three pairs of public feature points in the measurement process, the multi-view point cloud can be precisely registered. Through two coordinate transformations based on the positioning points, the registration of two point set can be achieved.

III. ACCURACY ANALYSIS OF THREE-POINT POSITIONING METHOD

From the above data transformation method it can be seen that the alignment accuracy of model data depends on the measurement accuracy of three selected reference point. In addition, in the same measurement error circumstances, selection of different reference points will also affect the alignment model data. However if the error is controlled within certain range, such data transformation is able to meet the requirements of modelling and assembly.

Tao [12] proposed multiple measurement of datum points method which used two datum points and centroid as the new triangle to reduce registration error. To analyze the error of two transform method, define the vector difference of the three reference points as:

$$a_1 = P_2 - P_1, b_1 = P_3 - P_2, c_1 = P_1 - P_3;$$
$$a_2 = q_2 - q_1, b_2 = q_3 - q_2, c_2 = q_1 - q_3$$

When measurement errors exist, because the three non-collinear points determine a triangle, if we take the conversion method based on the three reference points, in fact, it is to ensure the overlap of a point and an edge. Fig. 2 shows the situation that P_1 and q_1 points overlap, a_1 and a_2 edges overlap and we define $a_2 > a_1$, $c_1 > c_2$.
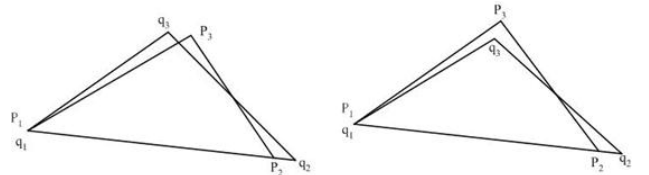

Figure 2. Three datum-points alignment model.

Define:

$$\varepsilon_1 = |a_1 - a_2|, \varepsilon_2 = |b_1 - b_2|, \varepsilon_3 = |c_1 - c_2|$$ (10)

Then the relative error can be expressed as:

$$\Delta_1 = \frac{|a_1 - a_2|}{|a_1|}, \Delta_2 = \frac{|b_1 - b_2|}{|b_1|}, \Delta3 = \frac{|c_1 - c_2|}{|c_1|} \quad (11)$$

From equation (11), we can draw the following two conclusions:

(1) When the measurement error is constant, the bigger area of the triangle formed by the three points, then the smaller the relative error, that means the greater distance of reference points, the smaller impact of measuring errors on data alignment;

(2) In the case of normal distribution of measurement errors, the errors of three sides tend to be the same. The relative error should tend to be equal for the same impact of the various points. That is, the selection of reference point should be as close to an equilateral triangle.

IV. METHODS AND EXPERIMENT RESULTS

Since the error of each reference point can be seen as equal weight value, the relocation errors can be seen as average distributed errors. If we take a feature point of reference marker as the calibration reference point every time, the possibility of occurrence of human errors and accidental errors will increase greatly. Therefore, we can calculate the centroid of the vertices of reference marker and then use the centroid as the reference point to reduce registration errors. Specific methods are as follows:

Take equilateral triangle markers as artificial reference markers, there are three vertices of each reference point, shown in Fig. 3(a) and (b).
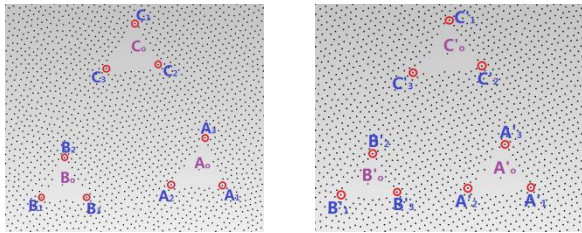
(a) The first measurement   (b) The second measurement

Figure 3. Three points alignment based on triangle reference markers.

First, take three vertices of reference markers A_1, B_1, C_1 as benchmark reference points, the corresponding vertices are A'_1, B'_1, C'_1. The coordinates of each vertex is shown in Table 1:

TABLE I.   VERTEX COORDINATES OF THE SELECTED REFERENCE MARKERS

Unit:mm	X Coordinate	Y Coordinate	Z Coordinate
A_1	63.751	52.445	925.525
B_1	26.602	-77.182	937.412
C_1	121.803	-56.026	958.979
A'_1	82.544	47.635	930.928
B'_1	60.090	-85.418	947.497
C'_1	152.957	-52.739	966.540

We can easily get the lengths of three sides of $\triangle A_1 B_1 C_1$ and $\triangle A'_1 B'_1 C'_1$ respectively, from equation (11), the relative errors can be expressed as:

$$\Delta_1 = \frac{\||B_1 C_1| - |B'_1 C'_1|\|}{|B_1 C_1|} = 0.0041, \ \Delta_2 = 0.0014,$$

$\Delta_3 = 0.0043$.

Then calculate the centroid coordinates of each vertex of triangle reference markers and use centroids as the new benchmark reference point, vertex coordinates and centroid coordinates are shown in Table 2.

TABLE II.   THE COORDINATES OF THE VERTICES OF REFERENCE MARKERS AND THE CENTROIDS

Unit: mm	X Coordinate	Y Coordinate	Z Coordinate
A_1	63.751	52.445	925.525
A_2	62.908	45.588	926.450
A_3	68.714	48.663	927.720
A_O	65.125	48.899	926.565
B_1	26.602	-77.182	937.412
B_2	32.108	-75.148	938.562
B_3	27.180	-71.638	936.488
B_O	28.630	-74.656	937.487
C_1	121.803	-56.026	958.979
C_2	116.215	-52.159	956.649
C_3	115.439	-58.752	957.885
C_O	117.819	-55.646	957.838
A'_1	82.544	47.635	930.928
A'_2	82.639	41.045	932.060
A'_3	88.507	44.432	933.298
A'_O	84.563	44.370	932.096
B'_1	60.070	-85.418	947.497
B'_2	65.673	-82.440	948.553
B'_3	59.994	-79.176	946.404
B'_O	61.912	-82.345	947.485
C'_1	152.957	-52.739	966.540
C'_2	146.920	-49.158	964.127
C'_3	146.520	-56.128	965.577
C'_O	148.799	-52.675	956.415

It is easy to get the lengths of $|A_O B_O|$, $|B_O C_O|$, $|C_O A_O|$ and $|A'_O B'_O|$, $|B'_O C'_O|$, $|C'_O A'_O|$, calculate their relative errors:

$$\Delta'_1 = \frac{\||B_O C_O| - |B'_O C'_O|\|}{|B_O C_O|} = 0.0027,$$

$\Delta'_2 = 0.0010, \quad \Delta'_3 = 0.0012$.

Compare of the relative errors of two measurements, as shown in Table 3:

TABLE III.   THE RELATIVE ERRORS OF TWO MEASUREMENTS

The first measurement		The second measurement	
Δ_1	0.0041	Δ'_1	0.0027
Δ_2	0.0014	Δ'_2	0.0010
Δ_3	0.0043	Δ'_3	0.0012

It can be seen that $\Delta'_1 > \Delta_1$, $\Delta'_2 > \Delta_2$, $\Delta'_3 > \Delta_3$, the precision increase greatly after we used the new triangle formed by centroids to substitute the original triangle and then the centroids can be used as reference

points for registration. Therefore, the three points coordinate transformation method can be improved to:

Step 1: Calculate the vertex coordinates of each reference triangle (polygon) markers;

Step 2: Calculate of the centroid coordinates of triangle (polygon) reference markers;

Step 3: Use centroids to form a new of triangle;

Step 4: Turn to the front algorithm step 1, replace the three measurement benchmark points by the new triangle centroids.

We apply the method to register scan data and reconstruct the electric vehicle shape plastic parts model from clay model in reverse engineering. Fig. 4 shows the electric vehicle front panel reconstruction model.

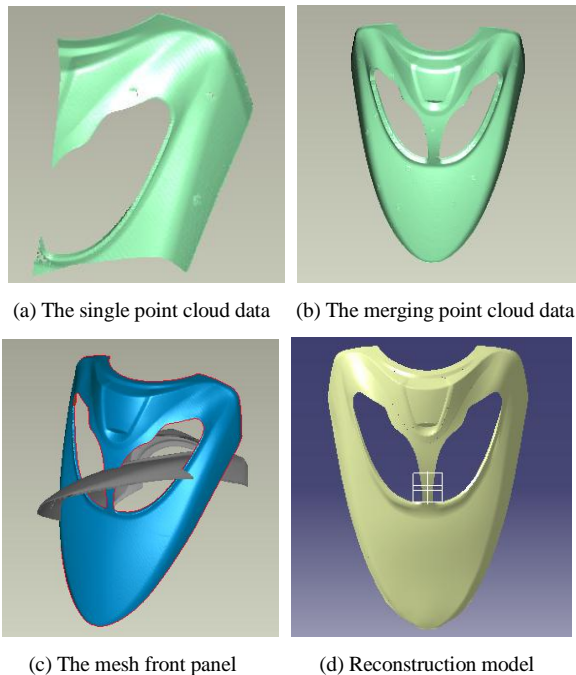The first scanning data is chose as the stationary part, the other panel data is transformed to it.

| (a) The single point cloud data | (b) The merging point cloud data |

| (c) The mesh front panel | (d) Reconstruction model |

Figure 4. Electric vehicle front panel reconstruction model.

V. CONCLUSION

Multi-view data alignment and the relocation is one of fundamental data processing problem in reverse engineering, a variety of methods has been proposed and 3-D point sets positioning method is a simple and practical one among them. In this paper, we use the centroids instead of original vertices of reference markers to register points cloud data and apply the method to make scan data registration. Compare to other implementations the "centroid of apexes" method is more practical and time-saving. In many case, we can also use feature points on the surface of object directly instead of references markers. Experiment results show that the new method can quickly and effectively improve registration accuracy as well as being easy to use.

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