Geometrical Compensation of Injection-Molded Thin-Walled Parts in Reverse Engineering

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ABSTRACT

A geometric compensation of thin-walled molded parts in reverse engineering is presented. Researches in reverse engineering have focused on the fitting of points to curves and surfaces. However, the reconstructed model is not the geometric model because the molded parts have some dimensional errors in measurements and deformation during molding. Geometric information can give an improved accuracy in reverse engineering. Thus, measurement data must be compensated with geometric information to reconstruct the mathematical model. The functional and geometric concepts of the part can be derived from geometric information. LSM (Least square method) is adopted to determine the geometric information. Also, an example of geometric compensation is given to improve the accuracy of geometric model and to inspect the reconstructed model.

Key Words : Reverse engineering, CMM(Coordinate Measuring Machine), Laser scanner, Molding error, Measuring error, Probe force, Geometric compensation, LSM(Least Square Method)

1. Introduction

Reverse engineering is the extraction of a mathematical geometrical model from a physical model [1]. It has been applied to develop new models in design and manufacturing, as well as in other fields[2,3]. Researches in reverse engineering have focused on the fitting of scan data to curves and surfaces[1,4,5]. However, the scan data contains some errors arising from molding and measurement processes. It does not give a good mathematical model for interpolation of scan points to pass through them accurately.

Injection molding parts have replaced pressed parts because of their accuracy and flexibility in form. The molded parts have thin walls and are lightweight, which are properties that improve the accuracy in forming. However, molding errors are unavoidable; therefore, the scan data from the molded parts also contain some errors.

Reverse engineering focuses on the fitting of the scan data to curves and surfaces. These fittings can be classified into three types: (1) NURBS fitting to scan data[1], (2) polyhedron approximation of scan data[1,6] and (3) section curve of the scan data with the generation of the surface[1,7]. These methods have considered the scan data as the exact points on the object. However, due to some errors in the scan data, reverse engineering cannot show its full potential in recovering the mathematical model.

Therefore, geometric information on the parts intended for its function and the molding errors induced by the molding process have to be incorporated in reverse engineering to compensate for the errors in the scan data. Using the selected data that satisfy the

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geometrical feature and transformation is much more effective and accurate than using all the scan data. The concept of parts can be derived from the geometric compensation. Geometric compensation in reverse engineering is an important procedure in obtaining the concept of parts and geometric model.

2. Errors in Measured Data

2.1 Errors in Injection Molded Parts

Molded parts have dimensional errors due to the shrinkage of the plastic materials. The deformation leads to the decrease in dimensional accuracy and geometrical feature. The shrinkage in molding causes deformations in the part, such as a sink mark, twisting and bending. A sink mark makes the part concave; the concavity being formed at the thick wall - boss, rib and bead - of the part. Twisting and bending are due to the different cooling rates of the areas, as well as other factors such as the different directions of the plastic flow stream, the residual stress, the molding conditions including mold temperature and so on.

To prevent shrinkage, thin-walled molding is used in precision molding[8, 9]. However, the deformation of the parts cannot be entirely eliminated. The sink mark and deformations remain in the molded part, decreasing the precision of the dimensions and geometric feature of the part.

2.2 Errors in Measuring

2.2.1 CMM

CMM is a highly accurate measurement machine. If the probing directon is normal to the object, exact points on the object can be measured. In Fig. 1 and Eq. (1), the tip of probe can be calculated by moving the center of the probe tip in the probing direction. However, the tip of the probe(P_t) is not the contact point(P_s) on the object.

$$P_t = P_c - r\vec{T}, \quad P_s = P_c - r\vec{n} \tag{1}$$

where, P_t is the tip of the probe, P_c is the center of the probe, and P_s is the point on the object. $\vec{T}$ is the measuring attitude, r is the radius of probe ball, and $\vec{n}$ is the normal vector to the offset surface of the probe center.

The center points of the probe are fitted to the surface, and then are projected by the radius of the probe tip in the direction normal to the surface. The projected points are the contact points on the object[7].

However, CMM can apply a probe force when the probe makes contact with the thin-walled parts. The thin-walled parts are deflected by the probe force, which is 0.1N, 0.2N, or 0.4N (Carl Zeiss co., Prismo Vast). Fig. 2 shows the apparatus that is need to measure the deformation on the thin-walled parts.

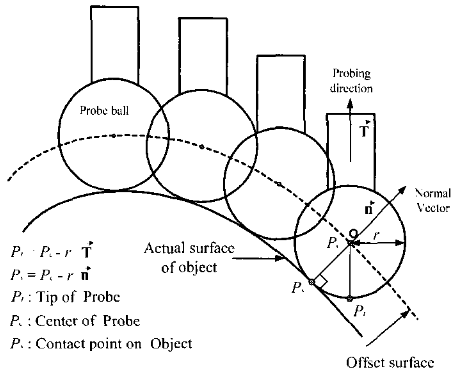


Fig. 1 Offset surface concept during measurement of a CMM

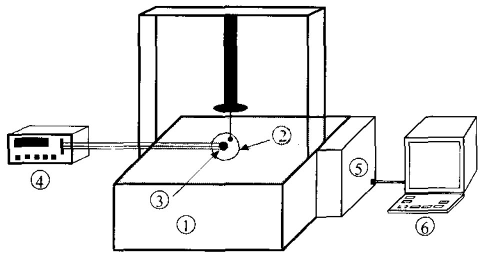
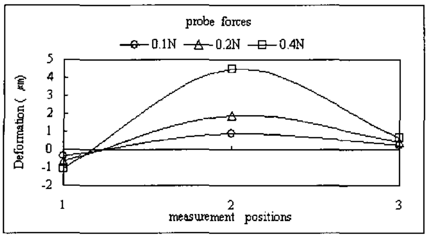
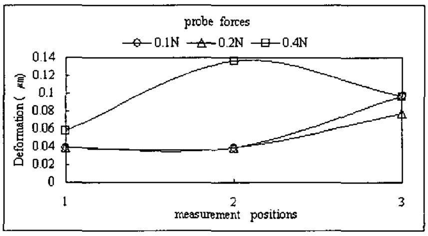


Fig. 2 Apparatus for measurement of deformation on the thin-walled parts

The results of the error measurements are given in Fig. 3. The thin-walled parts have 2 shapes. One is a beam-type, and the other is a shell-type. The beam-type is a fan as shown in Fig. 3(a), and the shell-type is a DY separator as shown in Fig. 3(b). Deformation of the beam-type is much worse than the other. Molded plastic parts have some deformation, especially the beam-type plastic fan, which has the largest error. The deformation in the molded part cannot be neglected in precision measurements.



(a) In the case of Fan



(b) In the case of DY(Deflection Yoke) separator

Fig. 3 Error due to probe force

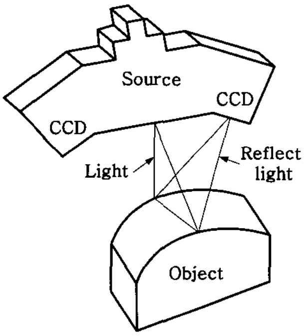


Fig. 4 Principle of a laser scanner

2.2.2 Laser Scanner

Non-contact type laser scanners use a laser beam during the measurement. Fig. 4 shows the principle of a laser scanner. The intersection of a plane and a line, which is made by a slit beam from a laser source, CCD and the reflected light merge on the object. A laser scanner is not as accurate as a CMM. Non-contact measurement often produces a noise spike. The approximate error is about ± 10 μm [10]. Also, the effect of the shadow can cause measurement errors.

CMM and non-contact scanners show different errors for the measured points . CMM is more accurate than a laser scanner. However, the deformation of the part due to the probe force decreases the accuracy of the measurements.

3. Geometric Compensation

As stated above, since the parts have both forming and measurement errors, the surface data is uncertain with no geometric features or dimensional accuracy. Least square method can derive mathematical and geometric data from the uncertain data. To recover the geometric information, one must determine the geometric features and calculate the dimensions of the geometric entity. These features and dimensions are found by the least square method.

Least square method is one of the approximation representations. First, the geometry of the parts must be determined. Second, the least square method is applied to the uncertain data to find the geometries of the parts.

3.1 Geometric Feature and Transformation

Geometry entities are points, lines, curves, polygons, and surfaces. Geometric transformations are translations, rotations, reflections, shearing, and so on. Geometry entities and their transformations set the features and functions of the parts.

The functional feature of a parts consists of the geometry and the transformation of the geometry. An impeller can give an efficient fluidic stream with its tangent, continuous free-formed blade. An LED (Light Emission Diode) optical unit can have emission and detecton of light with its spherical surface and composite surface. However, the uncertain data have no geometric information about its parts.

Also, the measurement data contains some error from molding and measurement. When the scan data are connected to each other, they cannot recover the geometry of a part entirely. The interpolation of the scan data is not sufficent to generate a smooth geometric part. The feature of a part can be recovered by adding the geometric information to the measured data.

3.2 Curve Fitting

Eq. (2) is a B-spline free-formed curve. The curve has many advantages in controlling a point and changing a shape, while maintaining a low degree.

$$r(t) = \sum_{i=0}^{n} B_i N_{i,k}(t) \tag{2}$$

where, t ranges from 0 to 1, and B_i is the control point. $N_{i,k}$ is the blending function of the B-spline, defined as below.

$$N_{i,k}(t) = \frac{(t - x_i)N_{i,k-1}(t)}{x_{i+k-1} - x_i} + \frac{(x_{i+k} - t)N_{i+1,k-1}(t)}{x_{i+k} - x_{i+1}}$$
$$N_{i,1}(t) = \begin{cases} 1 & if \quad x_i \le t < x_{i+1} \\ 0 & otherwise \end{cases} \tag{3}$$

where, x_i is a knot, and k is the degree.

If points P are given, the control point of the B-spline curve is determined by

$$B_0 = r(0), \quad B_n = r(1) \tag{4}$$

The parameter may be obtained from the chord-length parameterization given by

$$t_j = \frac{\sum_{k=0}^{j-1} |P_{k+1} - P_k|}{\sum_{k=0}^{m-1} |P_{k+1} - P_k|} \tag{5}$$

where, j ranges from 1 to $m-1$.

The least square method to approximate the scan data is applied as follows[11]. The error function of the B-spline curve is expressed as

$$f = \sum_{j=0}^{m} |P_j - r(t_j)|^2 \tag{6}$$

For unknown control points, the error function is a derivative.

$$\frac{\partial f}{\partial B_j} = 2\sum_{j=0}^{m} \left[P_j - r(t_j) \cdot \frac{P_j - r(t_j)}{\partial B_j} \right] \tag{7}$$

When the control points are determined, then the B-spline curve can be calculated by Eq. (2).

3.3 Surface Fitting

A sweep surface is used to generate a mathematical model. If the section curve and the guide curve are continuous, the surface is faired[12].

$$S(u, v) = \alpha(v)\, S_0(u,v) + \beta(v) S_1(u,v) \tag{8}$$

where, S_0 and S_1 are the blending surfaces of the guide curve and the section curve, respectively, and u and v are parameters.

The S_0 and S_1 are given as below.

$$\begin{aligned} S_0(u, v) &= \alpha(v)[G_0(u) + D_0(v)] + \beta(v)[G_0(u) + D_1(v)] \\ S_1(u, v) &= \alpha(v)[G_1(u) + D_0(v)] + \beta(v)[G_1(u) + D_1(v)] \end{aligned} \tag{9}$$

where, $G_i(u), i = 0, 1$ is the section curve, and $D_i(v), i = 0, 1$ is the guide curve. α and β are tangent continuous blending functions.

4. An Example and Inspection

Geometric compensation, as mentioned above, is applied to a separator in DY (Deflection Yoke). Fig. 5 shows the separator. The rib to reinforce the stiffness is along ①, and the attachment to the assembly is in ②. The separator and the other face meet at ③. ④ is the separator, which is the main object. The surface is free-formed for light emission, blending section curve of arc and guide curve of free-formed curve. The part has the geometric feature of tangent continuity and arc symmetry about the rib. Fig. 6 is the process flow of geometric compensation in the reverse engineering process. Fig. 7

shows the measured points on a separator with a laser scanner and a CMM.

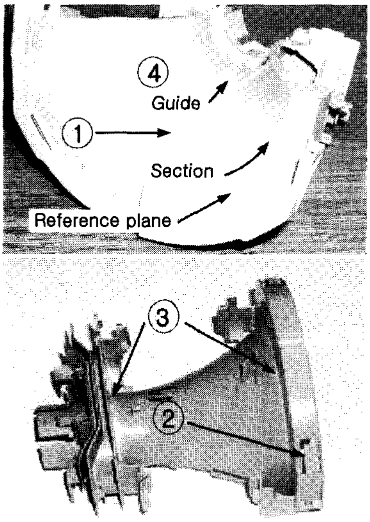


Fig. 5 Separator in DY

At first, the error area, where the part is deformed during molding, has to be deleted out of the uncertain data. Fig. 8 shows the deleted error area such as the sink mark and the deformed area. The reference plane is fitted onto the smallest deformed area or the most finished side. Then, the scan data are sliced into 1 mm intervals along the normal to the reference plane. The geometry of the separator was determined with the design data. The surface of the separator is symmetrical, free-formed about the rib. And the section curve of the surface is an arc. Guide curve of the surface is a free-formed curve with tangent continuity. Each section data are treated by the least square method. Section points can be approximated into an arc, the guide point being approximated as a tangent continuous free-formed curve.

Approximated section arcs are compared between the left side of the separator to the right side of the separator. Fig. 9(a) and Fig. 10(a) show the difference in the radius between the left and right sides of the separator, treating the uncertain data with geometric compensation of the section points. The surface is symmetrical, but shows some errors. The section arcs are selected within the tolerance of 0.2 mm in a CMM and 0.5 mm in a laser scanner. Fig. 9(b) and Fig. 10(b) show the difference in the radius between the left and right sides of the separator, treating the uncertain data with geometric compensation in the section direction and guide direction. The mean error for both case is within 0.202 mm and 0.172 mm. The difference between the design data and the geometrically compensated surface is shown in Fig. 11. In Fig. 11, the difference between the design data and the geometrically compensated data is within 0.125 mm (the right side of separator) in the laser scanner data and 0.128 mm (the left side of separator) in the CMM data. CMM is known to give highly accurate measurement. However, CMM data is not better compared with the laser scanner data. The result shows that geometric compensation is more important than the type of measuring machine and the accuracy of the measured dimensions. Fig. 12 shows the reconstructed surface using the geometric information.

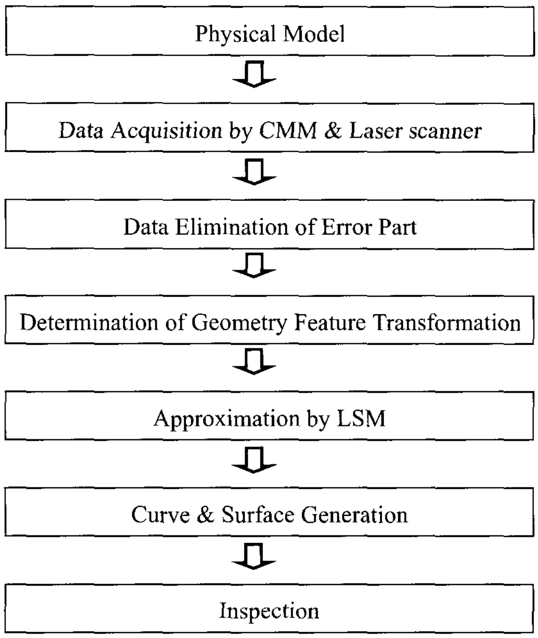
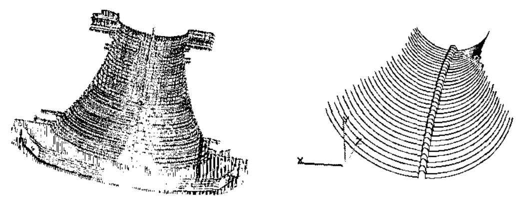


Fig. 6 Procedure of reverse engineering using geometry information



(a) Laser scanner (b) CMM

Fig. 7 Measured data

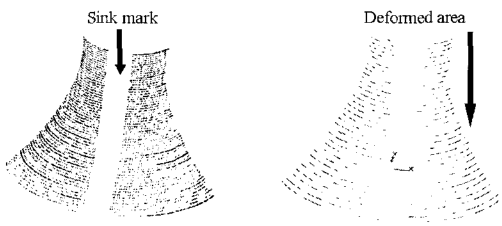
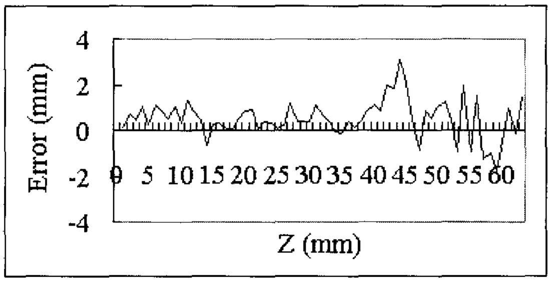
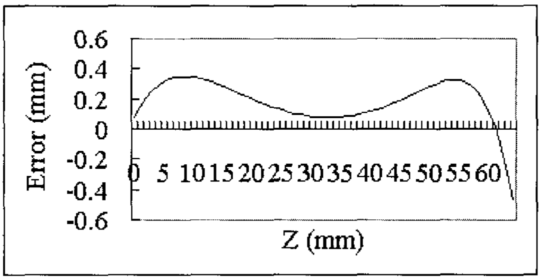


Fig. 8 The error area in separator

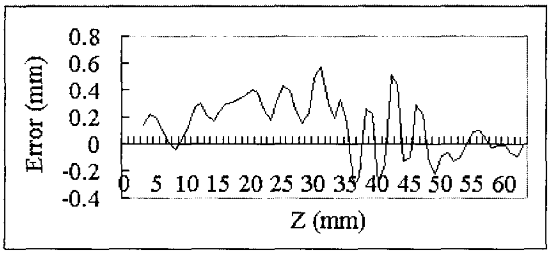


(a) Error between left and right radii
[mean error: 0.78mm]

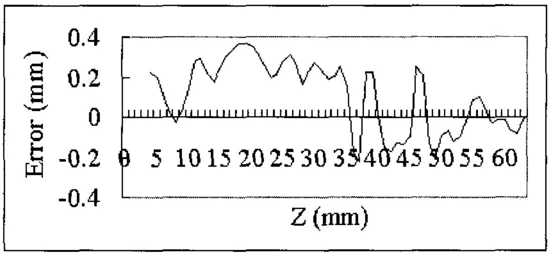


(b) Error between left and right radii by geometry compensation in section and guide curves
[mean error: 0.202mm]

Fig. 9 Difference of radius by LSM in laser scanner

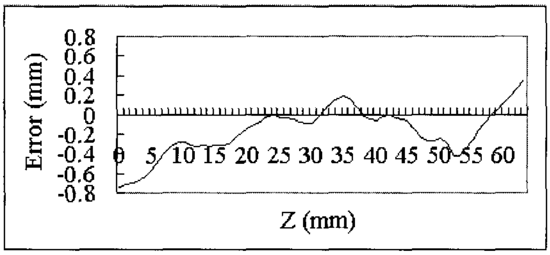


(a) Error between left and light radii
[mean error: 0.208mm]

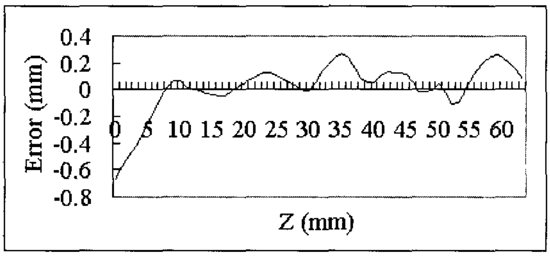


(b) Error between left and right radii by geometry compensation in section and guide curves
[mean error: 0.172mm]

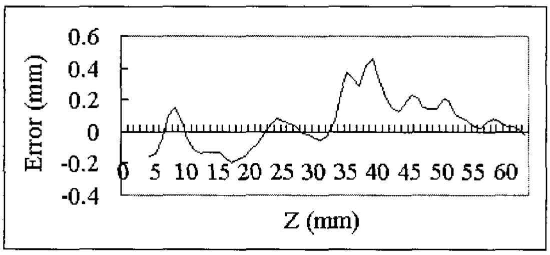
Fig. 10 Difference of radius by LSM in CMM



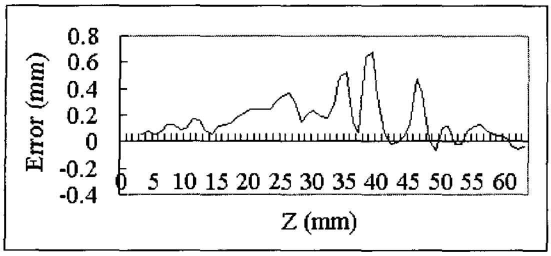
(a) Error in left side of separator by laser scanner
[mean error: 0.224mm]



(b) Error in right side of separator by laser scanner
[mean error: 0.125mm]



(c) Error in left side of separator by CMM
[mean error: 0.128mm]



(d) Error in right side of separator by CMM [mean error: 0.170mm]

Fig. 11 Error between radii in design data and compensated data

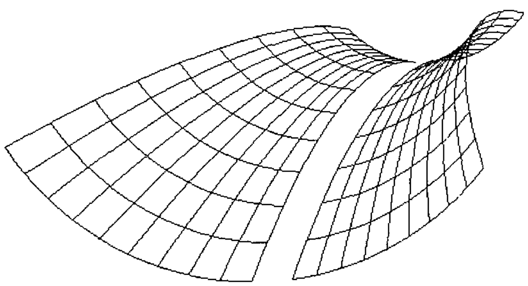


Fig. 12 Reconstructed surface using geometric information

5. Conclusion

A geometric compensation of molded parts in reverse engineering was discussed. Reverse engineering has focused on the fitting of points to curves and surfaces. However, molded thin-walled parts contain some measurement errors such as dimensional and deformation errors that occur during molding.

The least square method is applied to the scan data for recovering the geometric features and the dimensions. Geometric compensation can improve the accuracy when one is deriving the geometric concept of the parts. The points that satisfy geometry feature can give good geometric mathematical models.

In conclusion, by using the geometrical information of a part, geometrical compensation can support the reconstruction of a good mathematical model rather than the measuring accuracy.

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