Title:
Generation of Solid Models with Surface Properties from Scanned Triangular Meshes of Castings

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Keywords:
Castings, Scanned triangular mesh, Surface extraction, Solid model generation

DOI: 10.14733/cadconfP.2018.342-346

Introduction:

Reverse engineering which is a process to create solid models of products from their physical models using 3D scanning is necessary to produce high quality products. The models resulting from the reverse engineering are used in re-design, duplication, performance analysis, inspection and so on. On the other hand, castings are used in a wide range of machining products. Castings consist of casting surfaces and machining surfaces, and in the use of the castings, precise machining surfaces are required. However, precision is often not strictly required for the casting surfaces. Therefore, a reverse engineering method based on the separation of casting and machining surfaces has the potential to realize efficient reverse engineering of castings. Moreover, the solid models with rich surface information, such as casting surface, machining surface, screw thread surface, through hole, small feature and so on, are suitable for efficient use of the solid models. Much research on reverse engineering has been conducted in the last several decades [2-3],[5], however, efficient reverse engineering based on the surface separation and creation of solid models with rich surface information considering the application of solid models have not been realized. A research develops the reverse engineering method based on the surfaces separation for castings [4], however, the methods can only extract planar and cylindrical surface from castings, therefore, additional surface extraction and recognition methods are required for generation of solid models with surface information.

In this paper, an efficient generation method of solid models with surface information based on the surface separation [4] from the scanned triangular meshes of castings is proposed. The proposed method consists of the following functions, and the overview of our method is shown in Fig. 1.

1) Separation of the scanned triangular mesh surfaces into casting surfaces and machining surfaces, and extraction of machining planar surfaces and cylindrical surfaces [4]
2) Extraction of the screw threads, through holes, and small features between the machining surfaces
3) Boundary modification of the casting surfaces for solid model generation, and alignment of the machining surfaces
4) Creation of the solid model from the extracted surfaces using Boolean operation

Proposed Method:

Separation of the scanned triangular mesh into casting and machining surfaces

Using the existing method [4], the surface of the input scanned triangular mesh is separated into the casting and machining surfaces based on the estimated roughness. In this process, first, roughness of the scanned triangular mesh is estimated on each triangle. The triangle roughness of a triangle t, r_t, is

Proceedings of CAD'18, Paris, France, July 9-11, 2018, 342-346

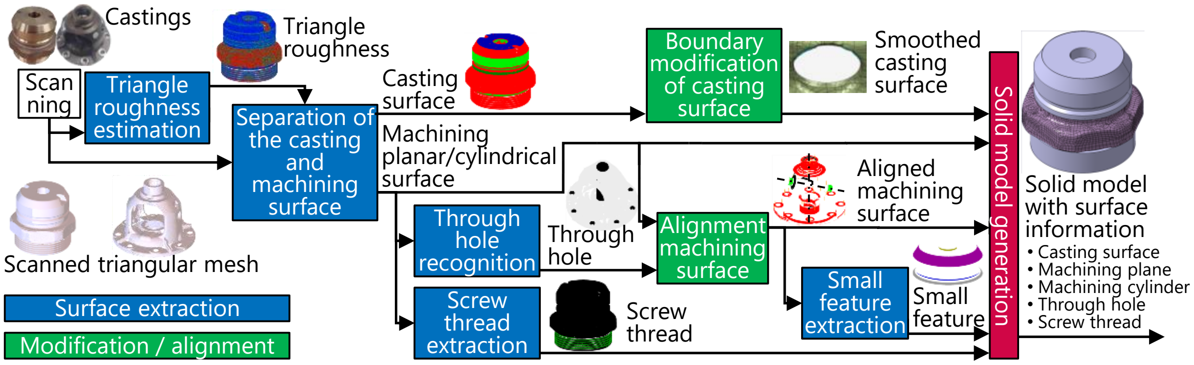


Fig. 1: Overview of the proposed method.

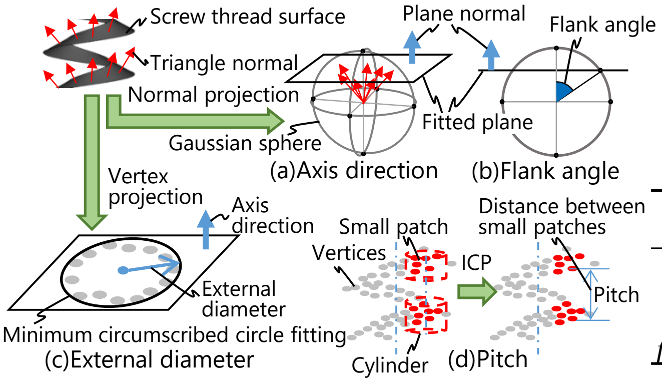


Fig. 2: Parameters of the screw thread surface

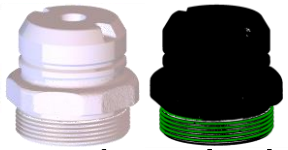


Fig. 3: Extracted screw thread surface

	Proposed method	manual extraction	G2 JIS B 0202
external diameter [mm]	59.7	59.61	59.5
pitch[mm]	2.3	2.3	2.3
flank angle[deg]	29.0	27.5	26.5

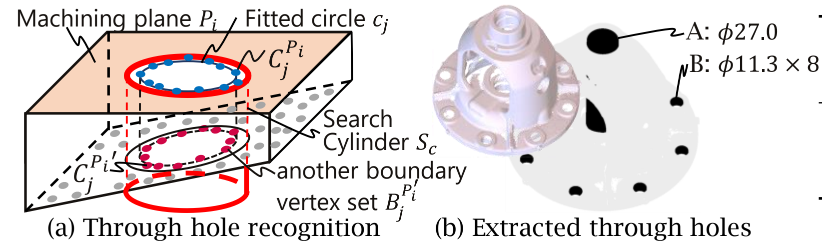
Tab. 1: Extracted parameters

defined as the unit normal difference before and after mesh smoothing at each triangle. Then, the scanned triangular mesh is separated into the casting surface and machining surface based on the triangle roughness by thresholding for the r_t. Finally, machining cylindrical surfaces are extracted by the cylinder fitting and region growing method for the machining surface, and then, machining cylindrical surfaces which have large radius are extracted as the machining planar surfaces.

Screw thread surface extraction

Much of the research on the screw thread parameter extraction is from the scanned data for inspection [1], but screw thread surface extraction from the scan data of the mechanical parts has not been done. In our method, the screw thread surfaces are extracted from the scanned triangular meshes of castings by using the fact that the same shapes are arranged in the regular intervals along with its axis direction of the screw thread surface.

First, extracted machining surfaces are separated into equal-area regions by Lloyd's algorithm for obtaining a separated region set R which is used for same shape detection. Next, for each region $r_a \in R$, its neighborhood region $N(a)$ is searched. Non-adjacent neighborhood regions $r_n \in N(a)$ are aligned to the r_a by ICP algorithm. If the energy of the ICP between the r_a and r_n is less than the threshold, r_a and r_n are labeled as candidates of a part of the screw thread surfaces. The above processes are applied to each of the separated regions in R, and a screw thread surface is detected as connected sets of the separated regions with candidate labels. Here, two connected regions are extracted from one screw thread surface, but in our research, only one region is used for the following parameter extraction as shown in Fig. 2. The axis direction of the screw thread surface is defined as a normal of the plane fitted to the images of triangle normals on the Gaussian sphere, as shown in Fig. 2(a). The flank angle is calculated using the distance between the center of the Gaussian sphere and the fitted plane as shown in Fig. 2(b). The external diameter is computed as a diameter of the minimum circumscribed circle fitted to the projection of the vertices onto the plane orthogonal to the axis direction, as shown in Fig. 2(c). The pitch is defined as the distance between the closest small patches, each of which is a connected

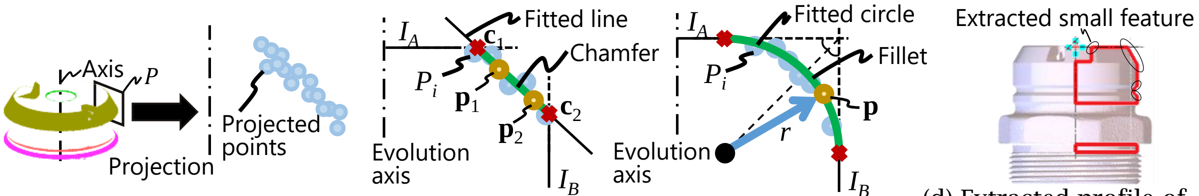


(a) Through hole recognition (b) Extracted through holes

Fig. 4: Through hole

Number of extraction (extracted/actual)		9/11 (81.8%)
Error [mm]	A	0.20
	B	max: 0.24 min: 0.08

Tab.2: Accuracy of the extraction



(a) Vertex projection (b) Straight line fitting (c) Circle fitting (d) Extracted profile of surface of revolution

Fig. 5: Small feature extraction

triangle set in the cylinder with the axis direction of the screw thread surface, as shown in Fig. 2(d). Finally, only the screw thread surfaces with the parameters which do not match the standard of the screw thread are removed. A result of the screw thread surface extraction is shown in Fig. 3 and Tab. 1. It was confirmed that the method can extract the screw thread surface with accurate parameters and identify the screw thread standard.

Through hole recognition

In 3D scanning, surfaces of through holes are often hard to scan due to the occlusion. Therefore, it is difficult to recognize through holes by simple surface extraction methods. Our method can recognize the cylindrical through holes from the scanned triangular mesh, even if the surfaces of the cylindrical through holes are not scanned. In this method, it is assumed that at least one circular boundary of the cylindrical through hole exists on the machining plane.

First, by applying a circle fitting based on the RANSAC [2] to the boundary points of the mesh of the extracted machining plane P_i, a boundary vertex set $C_j^{P_i}$, which is a set of inliers of the fit circle c_j is extracted as one of the through hole boundaries as shown in Fig. 4(a). Next, a search cylinder S_c is defined by using the enlarged fit circle c_j and the normal of P_i. Then mesh boundary vertices in the cylinder S_c is extracted as another boundary vertex set $B_j^{P_i'}$. Then, all vertices in $B_j^{P_i'}$ are projected onto the plane P_i, and a circle is fitted by RANSAC. If the circle has similar parameters to c_j, $B_j^{P_i'}$ is extracted as an another through hole boundary $C_j^{P_i'}$. Finally, parameters of the through hole are calculated using the vertices in S_c. A point on the axis is defined as the center of $C_j^{P_i}$, the axis direction is the normal of P_i, and the radius is one of the maximum inscribed circle to the projected points, which are the projection of vertices in S_c onto P_i. A result of through hole recognition is shown in Fig. 4(b). and Tab. 2. Precise through hole parameters are estimated, however two holes are not recognized because their two boundaries are not lying on planar regions.

Small feature recognition

Small features, such as chamfers and fillets, often exist between the machining planar and cylindrical surfaces, and recognition of them is required for solid model generation. In our method, we extract small torus and conic surfaces between the machining planar and cylindrical surfaces as the surface of revolution, therefore, the profile curves are extracted.

In the separation of casting and machining surfaces, all triangles are classified into the ones on the casting and machining surfaces, and through the surface extraction processes described above, almost all triangles on the machining surfaces are classified into the ones on the planar surfaces, cylindrical surfaces, screw thread surfaces, through holes, and the others. The small features to be recognized in this step consist of the other remaining triangles T_o on the machining surfaces. First, connected triangle sets C_i from T_o are extracted. Then, as shown in Fig. 5(a), using an axis of the adjacent machining

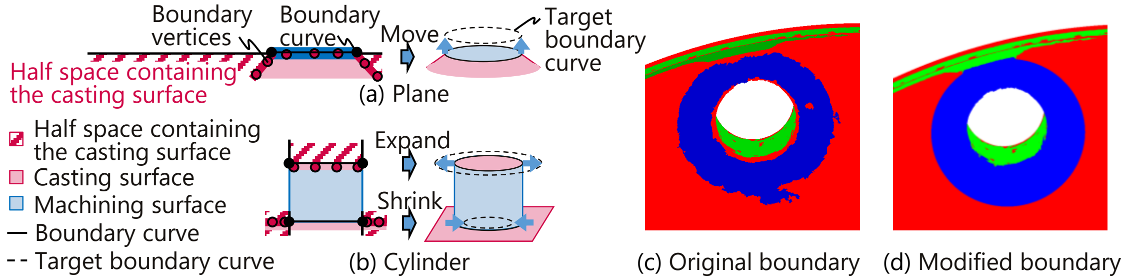


Fig. 6: Boundary modification of casting mesh

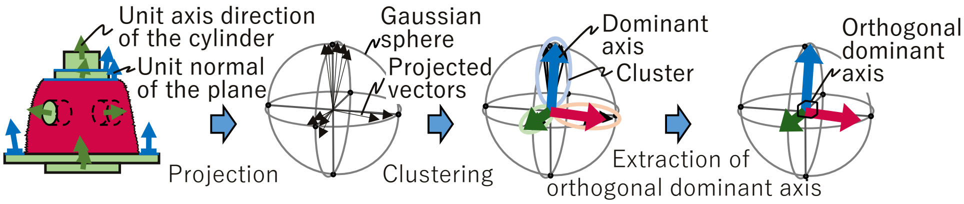


Fig. 7: Extraction of the orthogonal dominant axis

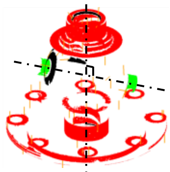


Fig. 8: Aligned machining surface

cylindrical surface, vertices of the C_i are projected onto a plane P. The projection is defined by the distance from the axis and the position along the axis. Next, straight line fitting based on RANSAC is performed to the projected points as shown Fig. 5(b). If the straight line fits well, a line segment bounded by the intersection points ($\mathbf{c}_1$, $\mathbf{c}_2$ in Fig. 5(b).) of the straight line and images of the adjacent machining surfaces on the plane P (I_A, I_B in Fig. 5(b).) is recognized as a profile curve of a chamfer. If the straight line does not fit well, we fit a circle to the projected points, which is tangent to the images of adjacent machining surfaces. A result of the method is shown in Fig. 5(d). It was confirmed that the profile curves of the small features are extracted from the scanned triangular mesh.

Boundary modification of casting mesh

In our research, a Boolean operation between generated free-form surfaces from the extracted casting surfaces and extracted machining surfaces are applied to obtain a solid model of overall castings. Here, it is necessary that there are no gaps between the free-form surfaces and the machining surfaces to generate a solid model. Therefore, our method modifies casting surface boundaries to intersect the casting surfaces with its neighbor machining surfaces. In addition, our method modifies boundaries of the casting surface to generate high quality free-form surface without distorted patches. In the method, we assume that the boundary between the casting and machining surfaces can be approximated by a set of straight line segments and circular arcs.

First, a set of straight line segments and circular arcs is extracted from boundary vertices on the casting surfaces by RANSAC. Then, a target boundary curve is obtained by moving, expanding or shrinking of a set of straight line segments and circular arcs, as shown in Fig. 6(a), (b)., so that the target boundary curve guarantees the intersection between the casting and the machining surfaces. Finally, a modified boundary of the casting surfaces is obtained by moving the boundary vertices to the nearest position of the target boundary curve as shown in Fig. 6(c), (d).

Alignment of the machining surface

Generally, machining planar and cylindrical surfaces of castings are often designed to have the same direction of their normals and axes for functional purposes. Therefore, we propose an alignment method of the machining planar and cylindrical surfaces. In this paper, we align machining surfaces according to the following four relationships: parallel, orthogonal, co-planar, and co-axial.

In our method, orthogonal dominant axes of the castings are estimated by the extracted machining surfaces, and then the extracted machining surfaces are aligned by the estimated orthogonal dominant axes. First, as shown in Fig. 7., unit normal vectors of the machining planar surfaces and unit axis direction vectors of the machining cylindrical surfaces are projected onto the Gaussian sphere, and k-means clustering is applied to the projected images. The barycenters of each cluster are extracted as the dominant axes. Combinations of the dominant axes C_{comb} which have almost-orthogonal

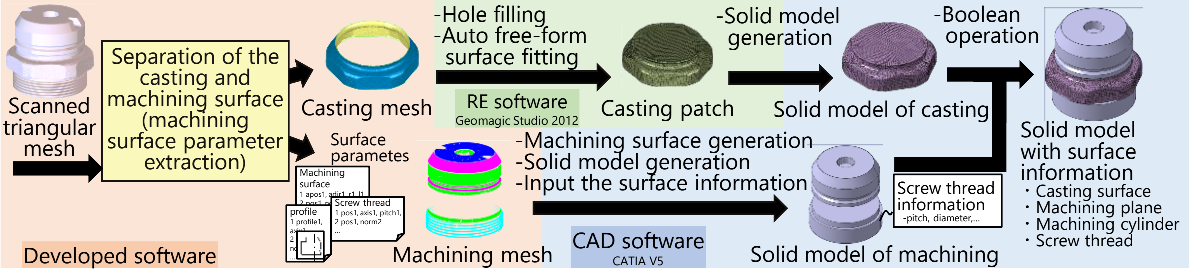


Fig. 9: Solid model generation process.

relationships are detected with the Brute-force search. Next, the weighted PCA is applied to the normals and axis directions belonging to the C_{comb}, then orthogonal dominant axes are obtained as the resulting eigen vectors of the PCA. In our method, it is assumed that the machining surfaces with a large area have a high degree of reliability, therefore, the normals and the axis directions are weighted by the areas of the corresponding machining surfaces in the PCA. Finally, the positions of the planes estimated as co-planar are modified to the area-weighted average position. Similarly, the axes of the cylinders estimated as co-axial are aligned to the area-weighted average axis. Fig. 8. shows the aligned machining surfaces (red: the machining surfaces aligned by the orthogonal dominant axis corresponding to the first eigen vector, green: the machining surfaces aligned by the orthogonal dominant axis corresponding to the second eigen vector, black: the machining surfaces not aligned by the orthogonal dominant axis).

Solid model generation

Fig. 9. shows the solid model generation process from the scanned triangular mesh using extracted casting surfaces and machining surfaces. First, the scanned triangular mesh is separated into the casting surfaces and machining surfaces. Then, the solid models of the casting surfaces are created by hole-filling, free-form surface fitting, and solid model generation. On the other hand, the solid models of machining surfaces are generated from the surface parameters of each machining surface. Finally, a solid model with surface information is generated by the Boolean operation of the solid models from casting and machining surfaces. It was confirmed that our method can generate a solid model with surface information from the scanned triangular mesh. In our system, a commercial CAD system and RE software are used for solid model generation, as shown in Fig. 9.

Conclusions:

In this paper, we proposed a solid model generation method of castings based on the separation of the scanned triangular meshes into casting and machining surfaces. The method consists of some surface extraction methods for screw thread surfaces, through holes, and small features, modification of casting surface boundaries, and alignment of the machining surfaces. The experiments show that our method can generate a solid model with surface information of castings.

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