Model-Free Subtractive Manufacturing from Computed Tomography Data

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Abstract

Great effort has been put into simplifying model reconstruction and tool path planning for machining in traditional reverse engineering with laser scanning. This paper proposes an alternative to reverse engineering using computed tomography (CT) scanning and voxel models. The new approach eliminates common issues faced in traditional reverse engineering, such as the need for parametric surface reconstruction in order to create toolpaths for a computer numerical control (CNC) machine tool. Successful duplication of a machined part with this new method demonstrates great potential for voxel models generated from CT data in reverse engineering applications.

Keywords: computed tomography, reverse engineering, voxel, machining, CNC

1. Introduction and Background

Reverse engineering has become a widely used practice in manufacturing, as it allows for duplication of parts without original design data in terms of computer-aided design (CAD) and product manufacturing information (PMI) [1,2]. Reverse engineering is composed of three general steps: sampling objects for digitization; reconstruction of geometry of objects with computation; and fabrication of the physical objects with additive or subtractive manufacturing processes [3]. Traditional reverse engineering often uses point cloud data, which can be processed to reconstruct triangulated surfaces that can then be parameterized with curve fitting algorithms [4]. Despite significant progress in this domain, the approach has a number of drawbacks such as surface approximation errors, sparse point cloud sampling, and the expert-level manual interaction with the processing software to achieve acceptable results [4,5].

The present work explores a processing concept based on model-free manufacturing (MFM) wherein a part can be manufactured without a reconstructed CAD model. The elimination of an analytical CAD model removes the need for feature approximation or excess manual input. To facilitate this MFM concept, a voxel-based discretized data structure, referred to as a hybrid dynamic tree (HDT), is proposed as an alternative geometric representation. Voxels are the three-dimensional equivalent of pixels that represent discretized volumes [6]. Voxel models are advantageous over analytical volumetric representations as the unit-level voxels are capable of representing geometry of any complexity [7]. Furthermore, voxel model reconstruction does not require calculated regressions to fit parametric curves. An HDT structure employs dense grids at the root and the leaves with traditional octrees in between [8]. The root and leaf grids in HDTs are tunable variables that offers the ability to control effective resolution of the voxel representation without trading off memory storage sparsity [9].

This paper uses an industrial CT platform as an alternative method for dense sampling of part geometry, as opposed to commonly used laser scanning [10]. Currently, CT scanning is the only non-intrusive method that can completely sample both outer and inner structures of objects [11]. CT scanners output accurate and complete voxel models of physical objects rather than sparse point cloud data whose sampling quality may be difficult to manage [12]. While CT scanners do not need manual meshing of the scanned data, they do possess greater dimensional errors than optical systems [14, 15]. CT scanning produces data that can be processed into slices of scanned object in tagged image file format (TIFF) for HDT reconstruction. SculptPrint, the CAM software used here, allows direct rebuilding of object geometry from TIFF images and is capable of automated toolpath generation [14].

2. Method

The scope of the work in this paper is concerned with the duplication of an axisymmetric part. Figure 1 demonstrates the workflow of the digitization process. With these general steps, an arbitrary form can be reproduced through CT scanning.

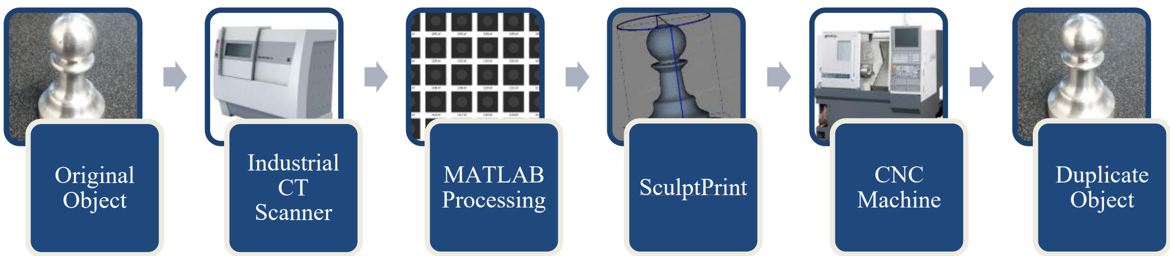
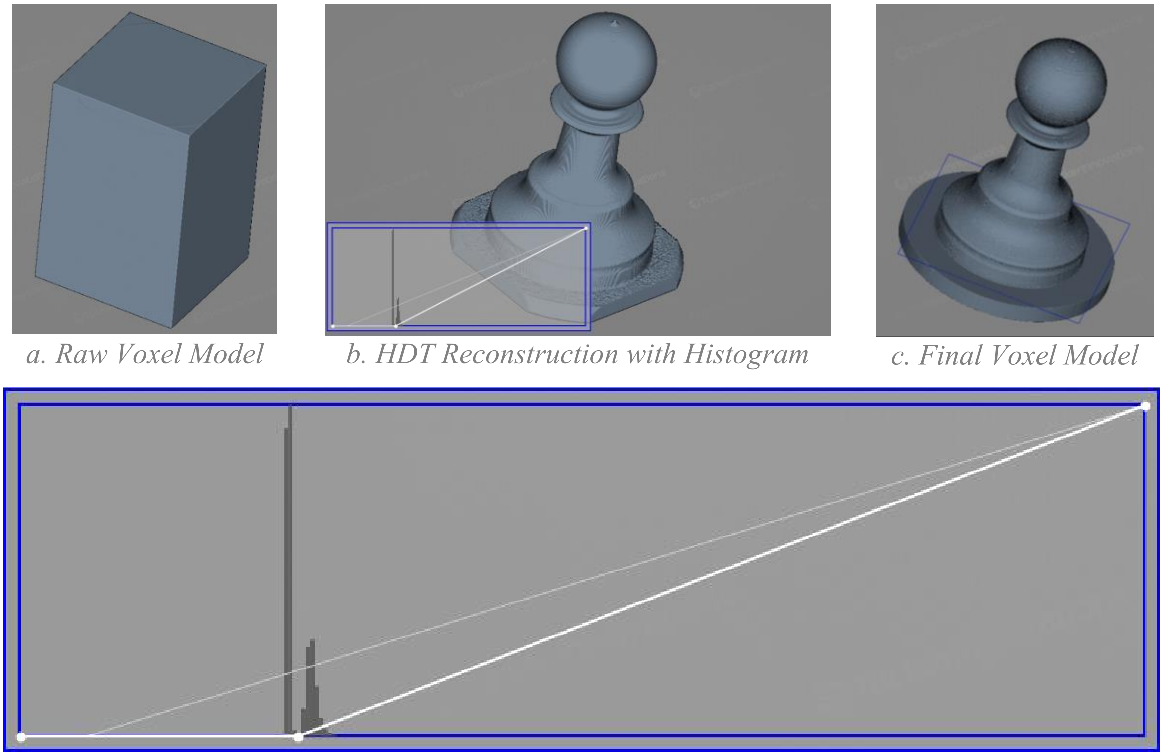


Figure 1. Work Flow of MFM with CT Scanner

The part geometry was a chess piece made with AA6061-T6 produced by a 2-axis CNC lathe. The specimen was scanned in a Zeiss Metrotom 800 CT scanner with a voxel size of 27.76 microns. The CT scanner outputs comma-separated values (CSV) files containing 16-bit image data matrices of the part. The image data were imported into MATLAB and made into image stack of the object cross sections. The greyscale images were then processed into slices and outputted as TIFF raster images. Using this procedure, layers of the specimen cross section in the axial (Z) direction were stored as single images. The resulting image stack enables SculptPrint to directly compile single slices and reconstruct an HDT voxel model without data interpretation or surface parametrization.

The voxel representation from the scan data, shown in Figure 2(a), includes both the data of the specimen (solid) and null (air) voxels, where the intensity value is based on local x-ray attenuation. Figure 2(b) and 2(d) shows the manipulation of the HDT histogram to eliminate grayscale values lower than the chosen threshold, which is the white dot in the histogram. The threshold value was chosen by visual inspection of the scan volume; as shown in Figure 2(d), the value was set between the two peaks of the histogram. The first peak indicates the collection of voxels with low density representing empty space around the part while the second peak indicates the voxels with higher density representing the part itself. Once the null voxels were removed, however, there were sparse null voxels and reconstruction noise around the bottom of the volume caused by the platform on which the pawn was seated. To further filter the noise, volume offset functionality in SculptPrint was used on the thresholded model. This volume offset operation is analogous to two-dimensional image erosion and dilation. First, the voxel model of the part was offset negatively (eroded) by a scaling factor that was an integral multiple of the size of one voxel; eroding the model this way caused the random noisy voxels around the model to be shrunk away. Next, the shrunk model was expanded through a positive volume offset with the same scaling factor to return to its original size. The final processed voxel model is demonstrated in Figure 2(c); the blue plane representing the limit of the turning pass was placed to exclude the platform from the actual pawn.



a. Raw Voxel Model b. HDT Reconstruction with Histogram c. Final Voxel Model

d. HDT Histogram

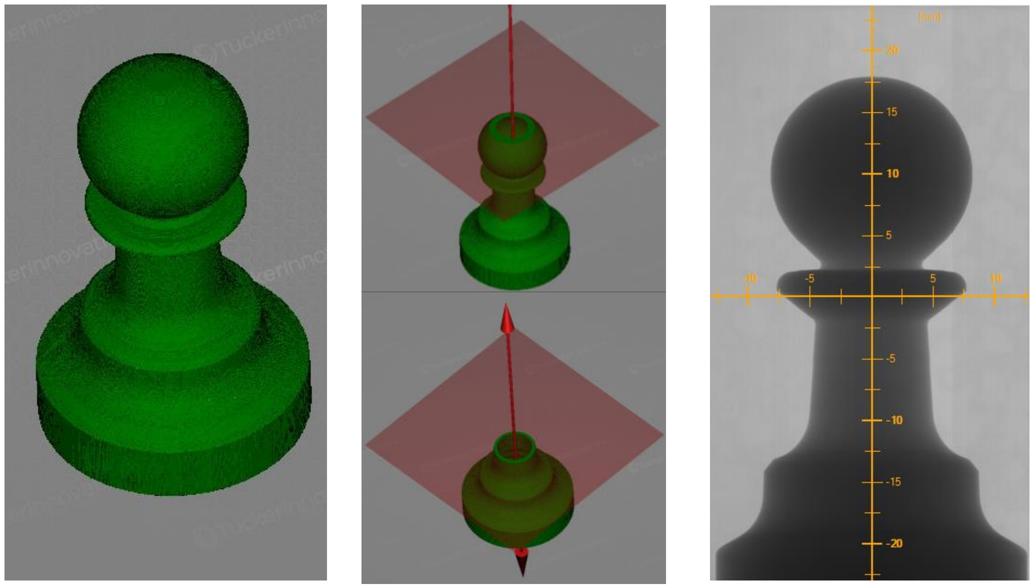
Figure 2. Noise Filtering Process

The last step in the digitization process was the generation of G-Code directly from the processed voxel model for a selected tool. With a user-defined starting volume (*e.g.*, cylindrical stock) and machining process (turning), SculptPrint generated toolpaths as a sequence of radial steps that brought the starting stock down to the final geometry using constant radial cutting depth. A sequence of linear movement commands (G1s) was created between the center points of adjacent voxels that comprised the revolved profile of the part to be turned. The resulting G-Code thus consisted of many small movements that were either the length of a voxel side or the diagonal distance between centers of voxels that shared only one edge [15]. A 35° right-handed turning tool was used to reproduce the original specimen on a CNC lathe.

3. Results and Discussion

Using the MFM process, a successful duplication of the aluminum pawn was accomplished. To study the accuracy of the duplicated part, a subtraction of the original model from the duplicated one was performed to yield the volumetric difference between the two. This result, shown in Figure 3(a), indicated that the duplication was larger than the original part. A closer examination of the cross sections in Figure 3(b) revealed an axisymmetric oversized shell.

Alignment was the main contributor to errors in duplication. Due to the nature of the reconstruction algorithms for CT scanners, the result of voxelization was very sensitive to horizontal misalignment of the specimen [17,18]. Figure 3(c) shows an image of the alignment process in the CT scanner. For an axisymmetric object, the center of the scanned part must be aligned with the center axis of the CT image system, shown the yellow vertical axis in Figure 3(c). In this study, the only method for adjusting the alignment was to observe the relative part position along the horizontal axis of the shadow image and to manually locate the part to a desired position. Slight misalignment propagated to create an axisymmetric difference between the scan image and the object when the specimen was rotated during scanning. Hence, a thin shell resulted as the difference between the duplicate and original pawn; with poor alignment, this shell could be more than 1mm thick. With finer adjustment and proper realignment, a more dimensionally accurate duplicate piece was machined with a 0.622mm-thick shell offset, as shown in Figure 4.



a. Result of Boolean Subtraction

b. Boolean Subtraction Cross Sections

c. Specimen Alignment Process in CT Scanner

Figure 3. Volume Subtraction of Duplicate and Original Specimen with Improper CT Alignment

The successful duplication of the pawn implies great potential for MFM, as direct voxel model reconstruction and toolpath generation is possible using high fidelity volumetric CT scan data. However, limitations and improvements for the MFM process need to be further explored. Issues such as part alignment in the CT scanner can be reduced with better fixturing. Additionally, measurement uncertainty associated with image thresholding and noise filtering will need closer investigation for parts with more complex geometric features and narrow acceptance bands.

Figure 4. Original (left) and Duplicated (right) Pawns

4. Conclusion

In this paper, model-free manufacturing using CT scanning and voxel models was introduced as a new approach to reverse engineering and direct copy manufacture. An aluminum pawn was chosen as a test specimen, which was scanned and reconstructed into a voxel model. The voxel model was then filtered and used to create a toolpath that leads to the creation of a duplication. The duplicate part was scanned and compared to the original specimen scan data, revealing small differences associated with the MFM process. The major advantage of CT scanning is the reconstruction of internal features of parts, for which work is ongoing to validate the MFM process. The voxel model, a 3D elemental representation that can be processed using high performance computing, will lead MFM into broader applications. Future work will focus on employing MFM for additive manufacturing operations, as well as 3-, 4- and 5-axis subtractive operations.

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