

EXHIBIT 1025

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Retrieving Matching CAD Models by Using Partial 3D Point Clouds

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ABSTRACT

The ability to search for a CAD model that represents a specific physical part is a useful capability that can be used in many different applications. This paper presents an approach to use partial 3D point cloud of an artifact for retrieving the CAD model of the artifact. We assume that the information about the physical parts will be captured by a single 3D scan that produces dense point clouds. CAD models in our approach are represented as polygonal meshes. Our approach involves segmenting the point cloud and CAD mesh models into surface patches. The next step is to identify corresponding surface patches in point clouds and CAD models that could potentially match. Finally, we compute transformations to align the point cloud to the CAD model and compute distance between them. We also present experimental results to show that our approach can be used to retrieve CAD models of mechanical parts.

Keywords: Shape Matching, 3D Scanning, CAD Database

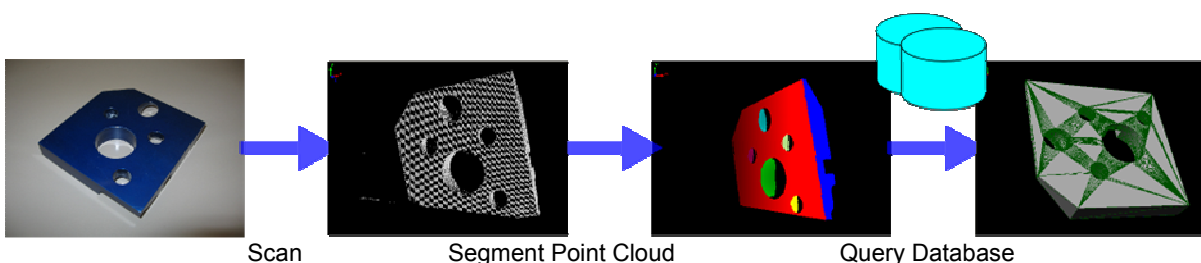


Fig. 1: An overview of the scan-to-CAD-search system.

1. INTRODUCTION

The ability to search for a CAD model that represents a specific physical part is a useful capability that can be used in many different applications. The following scenario illustrates the usefulness of being able to search for a CAD model based on point cloud generated by a partial scan. Let us assume that a part needs to be replaced in a complex machine. There is no label on the part. Hence the user does not know the part number. The user scans the physical part using a 3D scanner and generates the point cloud. This point cloud is then used by the user to search the CAD database and find the CAD model of this part. The CAD model has the information about the part number and the user is able to order the replacement part using the part number.

In order to initiate the search, one needs to describe of the desired physical part. 3D scanning can provide the models for initiating the search. A single part scan only takes a few seconds. However, to scan a part completely by using optical digitizing instruments can be a time consuming process, because it often requires a large number of scans to complete the acquisition from multiple sides. Each scan can only cover one side, practically about 150 degrees, of the target part. Furthermore, occlusions create holes on the resulting point cloud. Hence, it may be necessary to scan the same side from multiple angles to resolve any uncovered area. Lengthy post-processing is also required to remove noise, register, merge, and triangulate the point clouds to form a complete model. Hence, we believe that building a complete part scan is not practical in this application due to registration difficulties and increase in the scanning setup complexity. We assume that the information about the physical parts will be captured by a single 3D scan (also called

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partial scan because it only captures a portion of the part's boundary) that produces dense point clouds. Hence, we are interested in developing an approach that can work with partial part scans.

In order to meet the application requirements, the search algorithms have to have the following characteristics.

- There might be many similar parts in the database that may differ only very slightly in terms of feature and dimensions. Hence the algorithm has to be precise enough to find the right CAD model as a match and successfully reject the CAD model of the very similar parts.
- The algorithm has to be computationally fast enough to search through a large database. Hence, approaches based on global registration of point clouds to CAD models are not likely to work well in this application.
- Finally, the scan may produce partial point clouds for some faces. Hence the algorithm cannot make any strong assumptions about the completeness of the point cloud.

Previous research on CAD model retrieval was focused on locating similar models by using their gross shape information. These approaches often first compute shape descriptors of parts by extracting representative features from the gross shape of the models, and then subsequently compare the descriptors to evaluate the similarities. To accurately compute the shape descriptors, it often requires complete models of the query and database objects. Hence these methods do not work well for meeting the above three requirements.

This paper presents an approach to use partially scanned 3D point cloud of an artifact for retrieving the CAD model of the artifact. In this paper, we introduce an approach based on partial matching to support retrieval of CAD models based on partial point clouds. CAD models will be represented as polygonal meshes. Hence, we will use term CAD mesh model to refer to faceted CAD models. Our system is designed to match point clouds, acquired by a single 3D scan, to complete CAD mesh models. This is accomplished through a segmentation procedure and local matching. Our approach consists of the following steps: (1) segmenting the point cloud and CAD model into similar sets of surfaces patches using the same algorithm, then (2) matching up corresponding patches according to their properties, and (3) computing the possible transformations and evaluate the matching error. Fig. 1 shows schematically how the proposed approach will work.

Based on the approach outlined above, we have built a scanning-based-shape-search system that compares partial point clouds for mechanical parts to their CAD models and enables users to retrieve a CAD model that matches a given point cloud. The rest of this paper is organized in the following manner. Section 2 presents a brief review of related work. Section 3 describes our problem formulation. Section 4 explains the details of our approach. Section 5 demonstrates how our system works by retrieving CAD models using synthetic and scanned point clouds. Section 6 presents the concluding remarks and discusses possible future work.

2. RELATED WORK

2.1 Comparing Shape Models of CAD

In this paper, we focus on the matching of point clouds to CAD models. Most CAD models are solid models that are defined parametrically. Due to the development of rapid prototyping and visualization areas, approximate shape models represented by a polygonal mesh and dense point clouds are becoming another useful alternative to CAD representations. As mentioned earlier, we will use polygonal mesh models as the approximation of CAD models in our work.

Shape model representations of 3D objects are approximate models characterized by a mesh of polygons or a cloud of points for presentation or rendering purposes in computer graphics. Rather than exact parametric equations, polygons or densely sampled points are used to approximate curved surfaces. Only the geometry of triangles and points are stored without any topological information. In contrast to proprietary solid model formats, open mesh file formats such as VRML, STL, and ASCII point clouds are widely available. Although shape models are not suitable for many tasks in CAD/CAM systems, polygonal meshes can serve as the lowest common denominator in comparing CAD models. CAD mesh models can be generated by faceting solid models from different modeling systems. Shape

models of objects can also be acquired easily by using 3D scanners or CT to enable comparison of digital and physical artifacts.

From the polygon mesh, different transformation invariant attributes can be extracted as the means of similarity among 3D models. Thompson et al. [28] examined the reverse engineering of designs by generating surface and machining feature information off of range data collected from machined parts. The method of Osada et al. [24] creates an abstraction of the 3D model as a probability distribution of samples from a shape function acting on the model. Novotni and Klein [23] demonstrated the use of 3D Zernike descriptors. Kazhdan et al. [20] compared 3D models with spherical harmonics.

While these techniques target general 3D models, Ip et al. [14, 15] focused on comparing shape models of CAD with shape distributions. Iyer et al. [17] presented a CAD oriented search system, based on shape, voxelization and other approaches. Pal et al. [25] extracted features from CAD models using genetic algorithms. Cardone et al. [4] compared prismatic machined parts by using machining features. Various database techniques for CAD are discussed in [6, 7, 12].

Recently, research efforts in industry and academia are examining the use machine learning techniques to train a 3D shape recognition system with CAD data. Work in industry has explored the use of neural networks to identify parts based on multiple 2D views [27]. Hou et al. [13] attempted to use shape information to cluster the semantics of parts with SVMs. In the context of shape model matching, Elad [8] used linear SVMs to adjust retrieval results from a 3D shape database according to users' feedback. Ip et al. [16] classified models according to manufacturing processes by a curvature descriptor and SVMs.

There are recent approaches that employ partial matching of models. Bespalov et al. [3] used scale-space representations to segment different features of meshes. Funkhouser et al. [9] partially matched shape features according to different priorities. More extensive surveys and literature reviews in this area can be found in references [5], [18], and [29].

2.2 Point Cloud Alignment and Registration

The availability of 3D scanning technologies (Laser, white light, and CT scanners) has stimulated the interest in 3D point cloud alignment and registration. Given two point clouds with overlapping regions, registration based on iterative closest points (ICP) aims to rotate and translate a point cloud to match the other one. Because laser scanners and range finders often come with limited measure volume, registration becomes a critical process when acquiring 3D images of large scale parts in the industry. Since Besl et al. [2] published the original ICP algorithm, there have been many variations with different kind performance improvements in some of the recent work. Rusinkiewicz et al. [26] published a survey of the ICP techniques and demonstrated a fast variant that registers point clouds in real time. Mitra et al. [22] optimized the registration according to the point cloud geometry. Gefland et al. [11] proposed a method to find a good initial alignment of overlapping point clouds in an arbitrary orientation for ICP.

2.3 Mesh Segmentation

Research in partitioning triangular meshes into separated meaningful surface patches is of great interest for many applications, such as, shape simplification, compression, analysis, and recognition. We briefly review some of the more recent approaches. Attene et al. [1] recently published a comparative study on recent mesh segmentation techniques. Mangan et al. [21] applied computer vision style watershed method to segment surfaces according to total curvature. Yamauch et al. [30] segmented surfaces with mean shift algorithm. Hierarchical decomposition is another popular approach. Garland et al. [10] introduced hierarchical face clustering. Katz et al. [19] used fuzzy clustering and cut to decompose triangular meshes.

3. PROBLEM FORMULATION

This paper describes an approach to locate a CAD model in a database by using a partial scan of the underlying artifact. In the subsequent description, a part is denoted by P , its point cloud is P_s , and the corresponding CAD model is P_m . Acquiring P_s by scanning P is very similar to evenly sample points on the surface of P_m . A partial scan of P , is

denoted by P_{ps} , where $P_{ps} \subseteq P_s$. The goal is to align P_{ps} with respect to P_m , such that, the distance of P_{ps} and P_m can be minimized. The distance between aligned P_{ps} and P_m can be used to determine if P_{ps} matches P_m . Since $P_{ps} \subseteq P_s$, all of P_{ps} must be lying on some parts of P_m . Since $P_{ps} \cap P_s = P_{ps}$, it is not necessary to identify the overlapping points. This subset assumption eliminates one of the hardest problems in general point cloud registration. The matching quality in between the point cloud and the part is evaluated by the statistics of distances in between every point in P_{ps} and the surface of P_m . As P_{ps} is just a partial scan, any uncovered area is assumed to be insufficient data rather than error.

4. TECHNICAL APPROACH

Partially scanned point clouds and polygonal CAD models (CAD meshes) are first separated into surface patches, then aligned and compared according to the principal components of the surface patches. Our approach of matching scanned point cloud to CAD meshes consists of three stages:

1. Segmentation of point cloud and CAD meshes into surface patches using an identical algorithm.
2. Identification of the matching patches in point cloud and CAD meshes.
3. Aligning the point cloud with the CAD meshes and evaluating the error associated with the alignment.

In the approach presented in this paper, point clouds are assumed to be evenly sampled on the target surface. This assumption is consistent with the raw data produced by many popular 3D scanners.

4.1 Segmentation of Point Cloud and CAD Mesh into Surface Patches

Point clouds and CAD meshes are segmented into surface patches using an identical algorithm. It is important to apply the same approach to both the point cloud and the CAD mesh to ensure the similar surface patches are produced from the matching point cloud and CAD mesh. Our approach segments the point clouds and CAD meshes according to curvature for comparisons. Partial matching of 3D models is a challenging problem for many global shape descriptors. The shape of a partial scan often differs from its complete scan counterpart, e.g. the change of total length, width, and height. Hence, many global shape descriptors will discriminate a model against its own fragments. In addition, many 3D scans are imperfect. Hence, lengthy post-processing is often required to fill holes and remove noises from the point cloud. In attempt to alleviate these issues, we first segment the point clouds and CAD meshes into local patches and use them as matching units. This approach removes the gross shape dependency problem by separating both the partial scan and the CAD meshes into similar local surface patches that can directly be compared. Any extra patches from the CAD mesh will be ignored during evaluation. The segmentation procedure also allows us to discard insignificant patches, which are possibly noise, from the scanned point cloud.

The surface patches of point clouds and meshes are created according to their surface curvature values. This simple method is generally sufficient to partition CAD surfaces. For complex freeform surfaces, more sophisticated or semantic based segmentation algorithm may be required in future. Curvature defines the variation of surfaces patches and it is a popular criterion among many previous segmentation approaches. The identical segmentation algorithm is applied to both point clouds and CAD meshes. This allows similar patches to be generated on corresponding point clouds and CAD meshes. It is very important to ensure the patches of the matching point clouds and meshes are close enough. These patches will be used as matching primitives and they will be compared with one another. Since the surface patches are similar, it is not necessary to perform many-to-many matching on the surface patches.

Total curvature is computed from the normal vectors distribution of local neighborhoods on the surface. Normal vectors on the mesh model are sampled according to the mesh connectivity, for smooth meshes, normal vectors in a 1-ring neighborhood are sufficient for curvature computation. At the same time, normal vectors on the point cloud are estimated by normals of the best fitted planes of small neighborhoods of points. Following the method described in [21], the total curvature of a small neighborhood can be estimated by the norm of the covariance matrices of its normal vectors. Neighboring points and triangles that share similar curvature are grouped into patches. Fig. 2 shows a side by side segmentation comparison of the patches identified in the point cloud and CAD mesh for Part A.

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