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INTEGRATING MULTIPLE ENGINEERING RESOURCES IN A VIRTUAL ENVIRONMENT FOR REVERSE ENGINEERING OF MECHANICAL PARTS

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ABSTRACT

In order to better aid reverse engineering of mechanical parts, we propose the use of multiple engineering resources in a unified environment. To this end, we have developed the "Multiple Engineering Resources aGent Environment"(MERGE), an interactive virtual environment that allows a reverse engineer to create a feature-based CAD model of a physical part using information from multiple (possibly incomplete or inconsistent) sources. The MERGE system aims at making the reverse engineering process more effective by enabling intuitive interaction with the resources and allowing quick identification and resolution of inconsistencies between the resources. The MERGE system also aims at simplifying the reverse engineering process by integrating various computational "agents" *with available resources to assist the reverse engineer in processing information and in creating the desired CAD model. This paper presents the current capabilities of MERGE.*

INTRODUCTION

Complex mechanical systems are often used well beyond their intended lifetime due to the cost of acquiring replacements, and thus must be maintained. It is also possible that the original manufacturer does not produce replacement parts any longer. A part that belongs to this genre is termed a "legacy" part. In addition, computer-aided design and manufacturing(CAD/CAM) techniques have become the de facto standard for engineering of mechanical parts. Hence, in order to support maintenance and re-manufacturing, digital representations of legacy parts have become a necessity. The process of obtaining a digital representation of a legacy part is essentially a reverse engineering process with the goal of allowing extended maintenance, modification and re-manufacturing of the part.

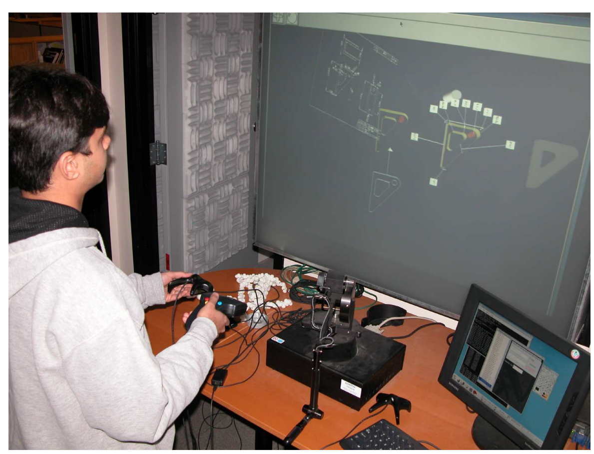

Figure 1. User interacting with the MERGE system.

Traditionally, the process of reverse engineering has been

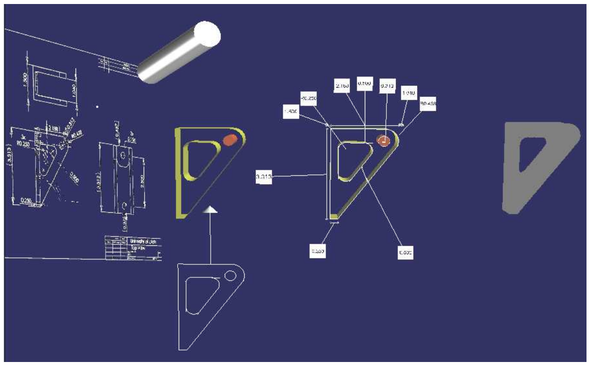

Figure 2. Multiple engineering resouces in a unified environment. Starting from left, an engineering drawing, a dependency graph visualization, a CAD model and a point cloud. Also shown is the tracked wand represented by a grey cylinder.

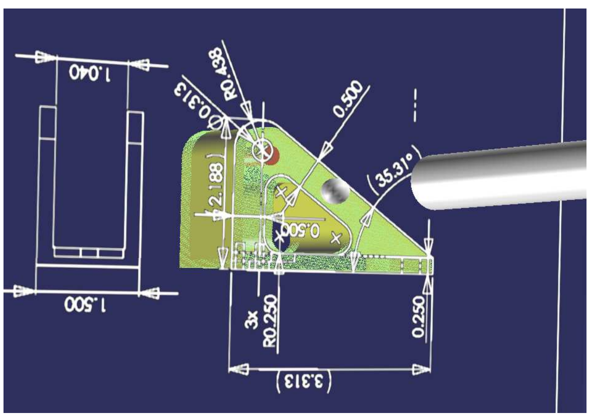

Figure 3. An engineering drawing directly compared with a reconstructed CAD model and point cloud.

labor intensive and time-consuming, performed via manual inspection of the physical part with or without the use of drawings. More recently, scanners have been used to speed up the process of inspection. The scanners generate a point cloud that is used to reconstruct a model [1]. Feature based fitting techniques for model reconstruction have also recently emerged [2, 3]. However, a unified framework for the process of reverse engineering does not exist. Moreover, information is usually available from multiple resources including paper drawings, legacy CAD files, point clouds, etc. In addition, these resources may contain incomplete, inconsistent, or even obsolete data.

Our goal is to provide a unified environment in which a reverse engineer can visualize and process information simultaneously from multiple resources to obtain a CAD model that more accurately captures the design intent of the physical part. In particular, we aim at presenting the available information in a coherent and comprehensible manner, allowing intuitive interaction with the information, so as to aid the reverse engineer in identifying and resolving inconsistencies between the various resources.

We have developed an interactive virtual environment called the Multiple Engineering Resources aGent Environment(MERGE), that satisfies the requirements of this problem. Figure 1 shows a user interacting with the MERGE system. MERGE provides a unified environment for comparing and manipulating original data sources, such as engineering drawings and laser-scanned physical artifacts, with derived engineering models, such as fitted surfaces and parametric model features. Agents in the system analyze the original data sources, provide interaction between data types, and present the original data and derived models in a unified and accessible fashion. Figure 2 shows the various engineering resources present in the environment. It presents a snapshot of the system during the process of reverse engineering a legacy part, wherein a partial CAD model has been generated from the front view of the part.

The MERGE system is built on top of the Alpha_1 advanced CAD research testbed. The virtual reality interface in the MERGE system includes 3D stereo display and 6DOF head/hand tracking. The Intersense IS900 system is used for tracking over a medium-room sized workspace. A back-projected stereo-wall screen is used for 3D display. Alternatively, a head-mounted display can be used for 3D display and head tracking can be employed to achieve a more immersive effect. The user interacts with the system using a 6DOF tracked wand and other 6DOF trackers. In figure 1, for sake of simplicity, the stereo-wall screen is shown with the user interacting with the system using a tracked wand and another tracker. The tracked wand is visually represented by a cylinder as shown in figure 2.

Our contribution is a system that allows a user to readily compare heterogenous sources of information of a legacy part, which is accomplished by transforming all the resources into higher-level forms that can be queried for their attributes, such as dimensions. This makes it more intuitive and less cumbersome than a traditional 2D menu-driven interface where one would have to associate names with objects and traverse through series of menus in order to inspect, manipulate and modify the 3D objects. Figure 3 shows one such scenario from the MERGE environment where an engineering drawing visualization is placed over a fitted model for direct comparison of features.

We present as as-is visualization of the data structure representing the derived feature-based CAD model and enable interaction with it to inspect and modify the features of the CAD model. We also present a simple algorithm that interactively maintains a comprehensible layout of labels(annotations) around a 3D model based on the relative orientation of the model with respect to the user.

BACKGROUND/RELATED WORK

Virtual environments have been explored for *ab initio* design [4], distributed design review [5] and analysis [6] of mechanical parts. The DVDS system proposed by Arangarasan and Gadh [4] discusses intuitive interaction techniques in an immersive environment including hand motions, gestures and voice commands for *ab initio* CAD design. Daily et al.'s DDRIVE system [5] utilizes a virtual environment for multi-party distributed design review. A virtual environment for interactive simulation and analysis has been developed by Yeh et al. [6]. Virtual environments have also been previously used for assembly simulation and planning as presented in the VADE [7] and VEGAS [8] systems.

There are a variety of commercial CAD-based reverse engineering software tools available such as Raindrop Geomagic®and Metrix Build!IT™. Although these tools provide significant functionality, they use 2D menu-driven interfaces and support automated reverse engineering from only point clouds. To the best of our knowledge, our system is the first that explores reverse engineering of mechanical parts using multiple heterogenous resources in a virtual environment.

Work similar to visualization of the dependency graph has been done by Cicirello and Regli [9] and Bronsvoort et al. [10]. The model dependency graph described in Cicirello and Regli's work [9] presents a symbolic design history of a model. While they use symbols to represent features, our visualization presents the actual geometry of the features and enitites with the correct spatial orientation relationships. The feature model graph described in Bronsvoort et al.'s work [10] is a visualization of the structure of a feature-based model. While they also use the actual geometry to represent features, our system allows a user to interact directly with the visualization to modify the geometry of the target CAD model.

There has been extensive work on automated interpretation of engineering drawings [11–15]. Most of these algorithms require noise free conditions which is an unrealistic assumption in many cases. The proposed engineering drawing interpretation system in MERGE tries to overcome such problems and is based on the system described by Henderson [16].

Out of prior literature on layout management for annotations of 3D visualizations [17–20], the approach presented in Rose et al.'s work [17] is closest to ours. They also use connecting lines that attach the annotation with the corresponding objects, and also avoid having the annotations occlude the objects of interest. While our algorithm is not meant to replace these solutions, we provide a simple interactive solution and allow the user to select a subset of annotations to be displayed to avoid clutter. We also allow users to interact with the annotations to modify the target CAD model.

REVERSE ENGINEERING A ROCKER MOUNT IN THE MERGE ENVIRONMENT

We present our system functionality through an example scenario of reverse engineering a rocker mount, a typical legacy part. **(image of rocker mount)**. Resources available for reverse engineering the rocker mount include an exemplar physical part and documentation in the form of an engineering drawing. These resources are imported into the MERGE environment. Agents in the system including drawing analyzer agents, visualization manager agents and layout manager agents, extract information from these resources and present them to the user in a coherent and comprehensible manner. An initial CAD model is fit from the drawing. The CAD model can be compared directly with available resources and presented information in order to identify incorrect fits and fix them using information extracted from the resources.

Importing Multiple Resources into the MERGE Environment

The exemplar part is laser scanned to create a point cloud representation. The engineering drawing is scanned and imported as an image file. The image file is then rendered into the alpha channel of a transparent texture map, so that lines and annotations show as solid lines without occluding other objects in the MERGE environment. Figure 2 shows the drawing and the point cloud in the MERGE environment. Before being used in the virtual environment, drawing analyzer agents extract key data elements from the engineering drawing. In particular, drawing analyzer agents extract the individual 2D views(top, front, right) of the parts and also interpret the geometric dimensions of the part specified on the drawing.

Fitting an Initial Feature-based CAD Model

A feature-based CAD model of the part can be automatically generated from either the individual views extracted from the drawing or from the point cloud representation as described in de St.Germain's work [3]. In our example, the features of the CAD model have been derived from the drawing. This model is imported into the virtual environment, which serves as a starting point from which the reverse engineer can create a more accurate CAD model of the exemplar part. In Figure 2, a partial feature-based CAD model derived from the front view of the part is shown.

Visualization of the Dependency Graph

The results of the process by which the features of the CAD model are derived are stored in a data structure called the "Dependency Graph".**(Cite Dep.Graph paper.)** The Dependency Graph is a directed-acyclic graph whose nodes store information about the formative geometry of the part. **(Explain with dia-**

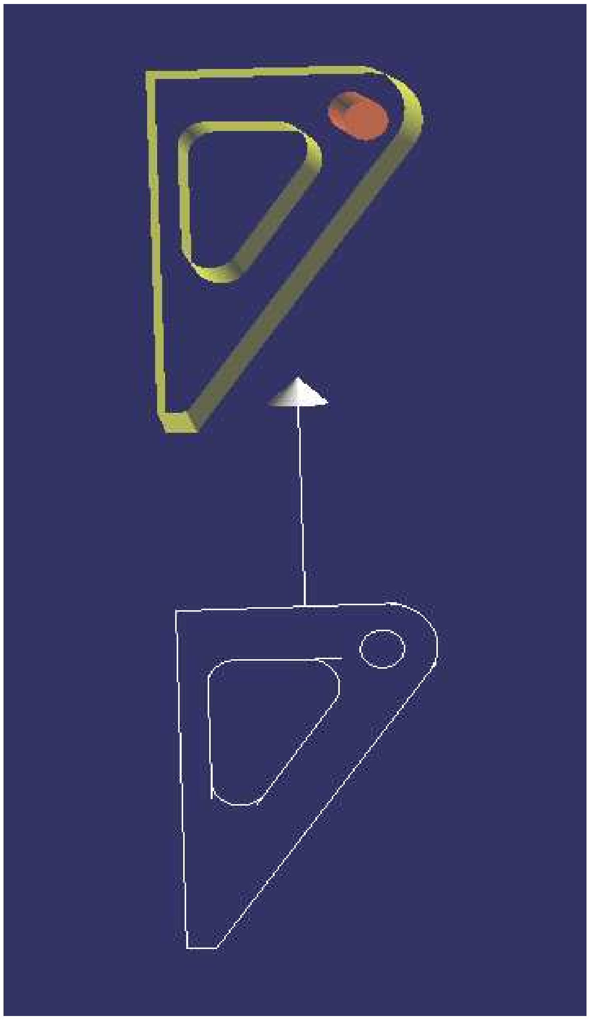

Figure 4. The Dependency Graph Visualization.

gram of the dependency graph for the exemplar part). Modification of any parameters of the features of a model is achieved by modifying the corresponding nodes of the dependency graph. An as-is visualization of dependency graph is presented to aid the reverse engineer in understanding how the final CAD model is generated and thus enabling him to decide how to modify given parameters in order to obtain the desired model. The features and the entities comprising the feature(lines, arcs) are represented visually with their actual geometry and the actual spatial orientation relationships. Visualization manager agents maintain comprehensible visualization of the dependency graph for each individual part and updates them as and when any of the features are modified by the reverse engineer. Figure 4 shows the dependency graph visualization at the point in the algorithm where a partial CAD model has been generated from the front view of the part. In this figure, the hole feature and inner and outer profile features of the partial CAD model are defined by various lines and arcs which are shown in the lower node of the dependency graph visualization. The MERGE environment allows a reverse engineer to work directly with this data structure via its visualization in an intuitive manner. The reverse engineer can pick features of interest using the wand to view information about their parameters or modify them.

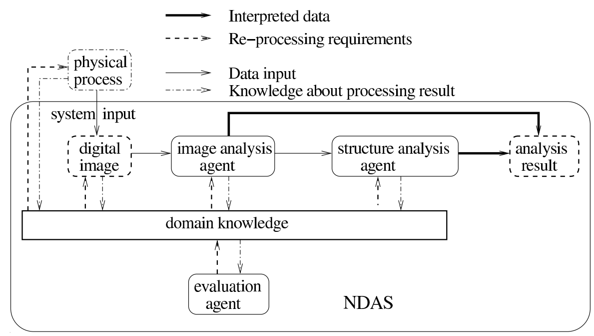

Figure 5. Overview of the NDAS system.

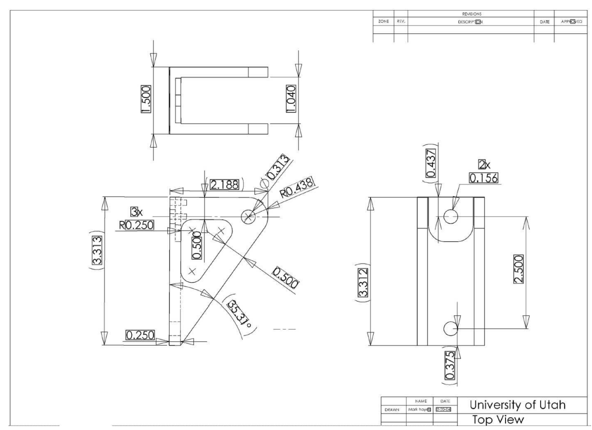

Figure 6. Results of dimension interpretation. The dimensions extracted are outlined with boxes.

Interpretation of Dimensions on Drawings

The geometric dimensions are extracted from the drawing using a NonDeterministic Agents System(NDAS) [11, 16]. As shown in Figure 5, NDAS is an automatic, domain-knowledge-guided system. It is an autonomous multi-agent system in itself. It consists of image analysis agents, structure analysis agents and evaluation agents. The image analysis agents interprets lines, arcs and characters (e.g., digits, letters, etc). The structure analysis agents identify dimensions that represent geometric information about the part. The evaluation agents calibrate, monitor and guide the analysis agents using explicit and persistent knowledge of the engineering drawing analysis process through stochastic optimization techniques. The physical process represents the process of digitizing the paper drawing. NDAS's evaluation agent can request the physical process to rescan the drawings with some requirements, such as higher resolution. In Figure 6, the dimensions extracted from the drawing of the rocker mount are outlined. These dimensions can be used to verify and correct the feature parameters derived from the model fitting process.

Manipulating Objects in 3D

In the virtual environment, the reverse engineer interacts with the resources using a 6DOF tracked wand in one hand and a 6DOF tracker in the other hand. The wand can be used to pick various objects such as the drawing, the CAD model or the point cloud which is then manipulated using the tracker in the other hand. The user can pick an object in the environment by pointing the wand at it at pressing one of the buttons on the wand.

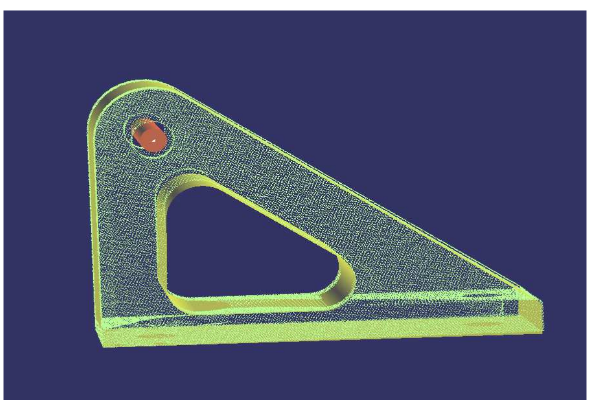

Figure 7. The CAD model registered with the point cloud.

Direct Comparison of Features

The reverse engineer can place the transparent drawing over the CAD model and/or the point cloud for direct comparison of features as shown in figure 3. The reverse engineer can also compare the fitted features with the point cloud as shown in figure 7. The CAD model and the point cloud have currently been registered manually. In this example, the fitted hole is slightly undersized compared with point cloud repesenting the physical artifact. **(include using drawing to navigate the view)**.

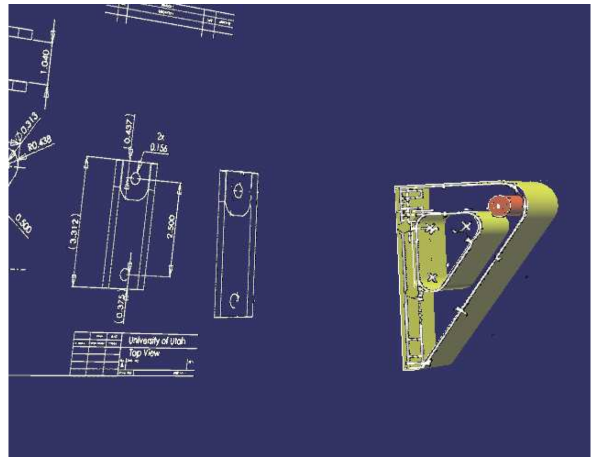

Figure 8. Right view of model from drawing being registered with 3D model.

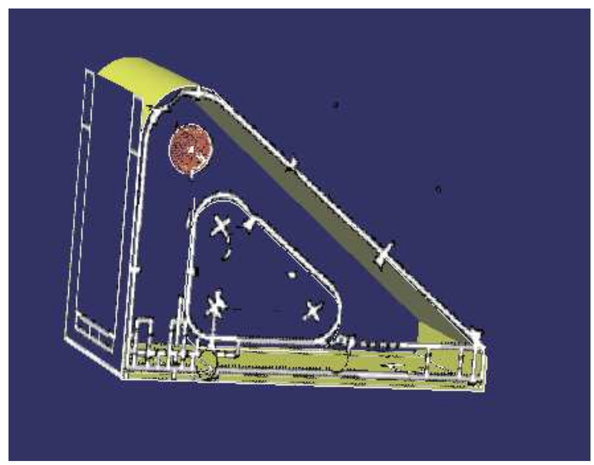

Figure 9. 2D views from the engineering drawing superimposed on the 3D model.

Interactive View Folding

The individual views of the part from the drawing can be interactively folded over the fitted model and/or the point cloud to further aid the reverse engineer in associating and comparing features sketched in 2D and the features of the 3D model. The user can pick one of the views from the drawing using the wand and then request it to be registered with the 3D model using other buttons on the wand. The view is then animated by showing it flying from the drawing and registering itself with the 3D model. Figure 8 shows the front view registered with the model and a snapshot of an animation of the right view registering itself with the model. Figure 9 shows the result of all the views registered with the model. In the current system, the orientations of the views relative to the model are determined manually.

Visual Representation of Feature Parameters via Labels

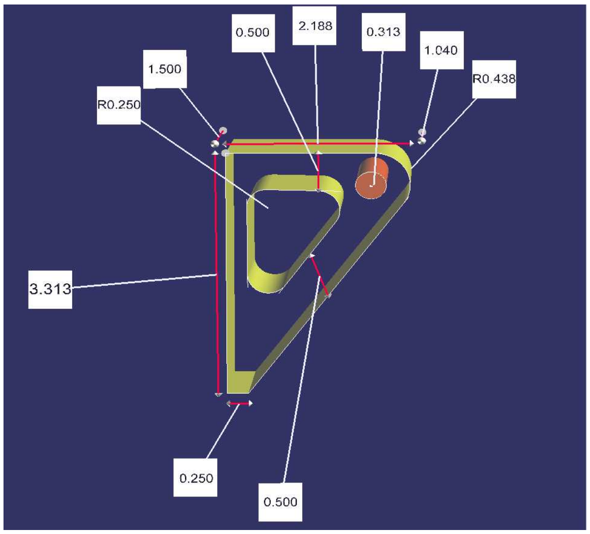

Figure 10. Layout of labels around the model in an arbitrary orientation.

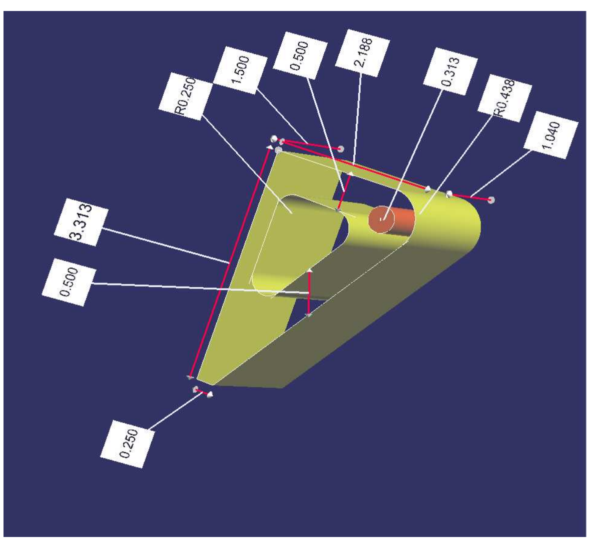

Figure 11. Layout of labels around model in another orientation.

The current value of feature parameters are displayed using labels connected to the corresponding features in the 3D CAD model for quick verification and correction. Each label is connected to a symbolic line or a point on the 3D model that represents the set of features about which the label provides information. These symbolic primitives help the reverse engineer in associating dimensions specified on the drawing with the features on the 3D model. Figure 10 shows a set of labels arranged around the CAD model. The symbolic lines are drawn in red.

Layout manager agents are responsible for maintaining a comprehensible layout for the labels. The labels are rendered as planes on which the parameter value is texture-mapped and lines connecting the labels to their symbolic primitives are drawn. The layout manager interactively updates the position of the labels based on the orientation of the 3D CAD model relative to the reverse engineer.

In order to maintain a comprehensible view of all the labels, the layout of the labels must satisfy the following constraints:

1. Ideally, the labels must be located as close to the feature or set of features about which it describes. At the same time, the labels should not occlude the 3D CAD model.
2. The labels must not occlude each other.
3. The connecting lines should not cross each other.
4. The labels should not occlude any other label's connecting line.

In order to simplify the problem, we restrict the location of the labels to a plane whose normal is oriented along the line joining the eyepoint of the camera and the center of the 3D model and is located between the user and the model. This plane is called the layout plane. Clearly, the layout plane changes with the user's orientation in the environment. We define an anchor as the point on the symbolic primitives to which the label is connected. These anchors are projected onto the layout plane and sorted radially around the projection of the center of the model on the layout plane. The location of the label's centers are further restricted to a circle that has a radius greater than that of the bounding sphere of the model to ensure that the labels do not occlude the model. For each label in sorted order, an inital location is determined as the point on the circle that intersects the ray from the projected center to its anchor. Then, this location is checked to determine whether it lies close enough to any other previously placed label to occlude it. If it does, the label is moved anticlockwise on the circle so that it does not occlude the previously placed label. Figures 10 and 11 shows the results of the layout management algorithm for two arbitrary orientations of the part.

Given sufficient number of labels, there may not be enough room available to retain a comprehensible layout. The user can avoid this problem by requesting a small subset of labels to be displayed. This can be done by selecting certain features of interest via the dependency graph visualization or the CAD model using the wand. Accordingly, labels corresponding only to these selected features are displayed.

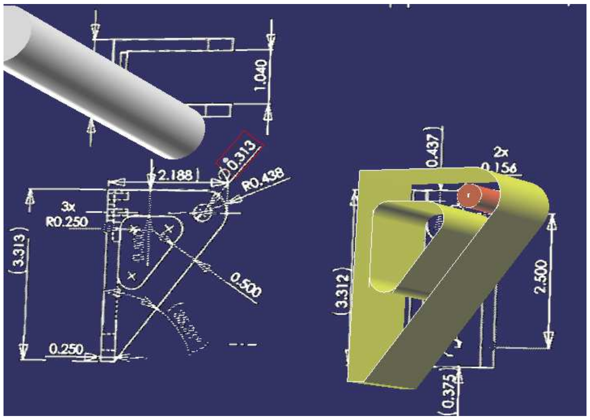

Figure 12. Picking dimension from drawing.

Modification of Feature Parameters by Direct Interaction with Drawings and CAD Models

Once the reverse engineer has identified an inconsistency in the parameter value of a feature(by direct comparison or by comparison of values on the label and the drawing), he can readily correct it using the dimension information extracted from the drawing. This can be achieved by picking the corresponding dimension from the drawing and then picking the appropriate feature on the 3D model using the wand to modify the parameter with the value picked from the drawing. For example, in order to fix the diameter of the hole feature of the CAD model, the reverse engineer can pick the corresponding dimension from the drawing as shown in figure 12 and transfer it to the hole feature in the model. The reverse engineer can also pick the feature to be modified from the dependency graph visualization or via the appropriate label using the wand. **(specify limitations of multi-parameter features/multi-feature dimension(angle between lines)?)**

SUMMARY AND CONCLUSIONS

This paper presents a new approach towards reverse engineering of legacy parts. Information about legacy parts is usually available from various sources, but, until now, reverse engineering from each of these sources has been a separate standalone solution. By using information from multiple hetergenous engineering resources simultaneously in a virtual environment, we believe that the problem of reverse engineering of legacy parts can be simplified. The MERGE system has been designed specifically to aid a reverse engineer in identifying and resolving inconsistencies between different resources using coherent visualiztion and intuitive interaction techniques. This paper gives an overview of the MERGE system and discusses its current capabilities by means of an example of reverse engineering a typical legacy part.

By transforming the available resources into higher-level forms, we enable intuitive interaction and transfer of data between them and allow the user to focus on the reverse engineering process, thereby speeding it up. Although each individual component of the system is not a significant technical advance in itself, when utilized together in a unified environment, they can collaboratively aid in simplifying the reverse engineering process and making it more effective.

FUTURE WORK

Ongoing work on the MERGE system includes providing more functionality, incorporating other interaction techniques such as gestures and speech and providing interactive analysis tools.

Currently, we have assumed that engineering drawings of the legacy parts are available. If they are not available, the reverse engineering process has to be performed using only the point cloud. In addition, if the physical part is worn out or broken, we will require information about the rest of the assembly where the part fits in. Design specifications for the assembly may not be available, in which case, it has to be scanned. Work needs to be done on interacting with point clouds or CAD models representing the part and the assembly.

ACKNOWLEDGMENT

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