REVERSE ENGINEERING OF POLYMERIC SOLID MODELS USING REFRACTIVE INDEX MATCHING (RIM)

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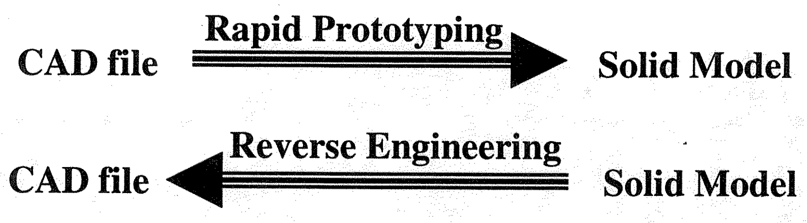
Abstract

Reverse engineering (RE) techniques allows the creation of 3-D CAD files from a solid model. The benefits of reverse engineering are not new to the industrial design and manufacturing arena though wide spread applications are yet to be seen. A novel approach is used to reverse engineer polymeric parts with its internal features in a low cost, non-destructive manner. Solids created from polymers with an index of refraction matching that of an immersion liquid are reverse engineered using a CCD camera. The images are then used to create digital solid models from a physical model. Design and development of this novel low cost tool for reverse engineering of polymeric solid models is described in this paper.

Introduction

The concept and the advantages of reverse engineering (RE) are not new to the industrial design and manufacturing arena [1-3]. But still the wide spread application of reverse engineering is yet to be seen. The simplest definition of reverse engineering is probably designing a product from its physical model, where as RP does reverse of reverse engineering as it builds solid models directly from CAD files.



Though the first impression of RE could be copying an existing product, which could be illegal in nature, but in reality, effective utilization of RE could save a significant amount of time and money in manufacturing. At present, some of the applications of RE are limited to redesign old products by the same company, or for products that are in use but whose vendor is no longer in business. Moreover, as rapid prototyping techniques are becoming more and more popular [4-5], the demand for better surface finish, better accuracy and tolerances are clear. Common customer complaints are dimensional accuracy, warppage, and surface finish of the parts. If the customer can receive a CAD file of the actual solid model built using RP along with its physical model, then they can compare their CAD model with the original CAD model.

Among the various systems that are available today for RE, probably coordinate measuring systems and laser scanning systems are the most popular ones. In the case of coordinate measuring system (CMM), a coordinate measuring arm with a probe at the end scans the part surface point by point and measure the X, Y and Z coordinates. These machines are relatively low cost and scan almost any parts irrespective of its materials. But these machines can not measure internal features, and for parts with a lot of critical features, this is an extremely laborious process. Moreover, the process generates a huge file of "point cloud" data that then needs to be converted to a solid or surface(s).

For laser scanner systems, the process certainly has some advantages over CMM but is more expensive. Some scanning systems, first machines a thin layer out and then scans the part and repeats this process for the complete part. For computed topography (CT) scanning system, the scanning process continues in a non-destructive manner. These scanning processes are fast and are capable of scanning large objects. The accuracy of these processes is also very good. But the equipment is expensive. Moreover, the resulting file that is generated is a large "point cloud" data set, similar to CMM.

The novel reverse engineering technique that is being described in this paper is primarily designed for application to polymeric solid models using the concept of refractive index matching (RIM). It is believed that simple RE equipment like this one will help significantly in designing and manufacturing of numerous engineering components.

Concept of Refractive Index Matching

When a clear solid with a different index of refraction is placed into a clear liquid, the solid is usually easily seen because light passing through the two mediums changes its direction (Figure 1b). However, if the solid's index of refraction matches that of the liquid, the direction of the light passing through the two mediums will not change and the immersed solid can not be

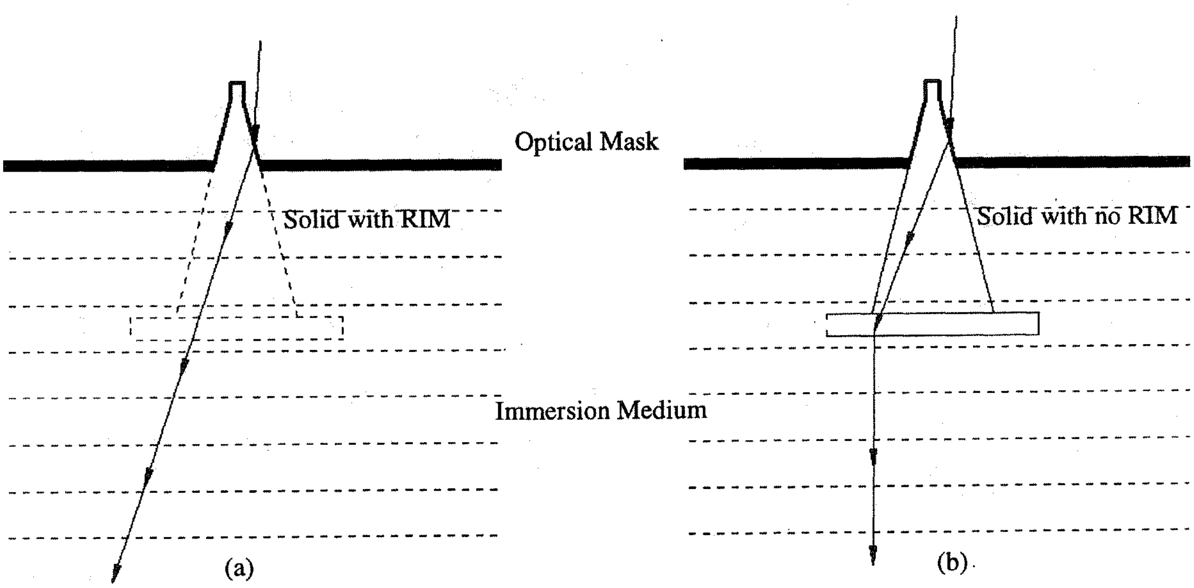


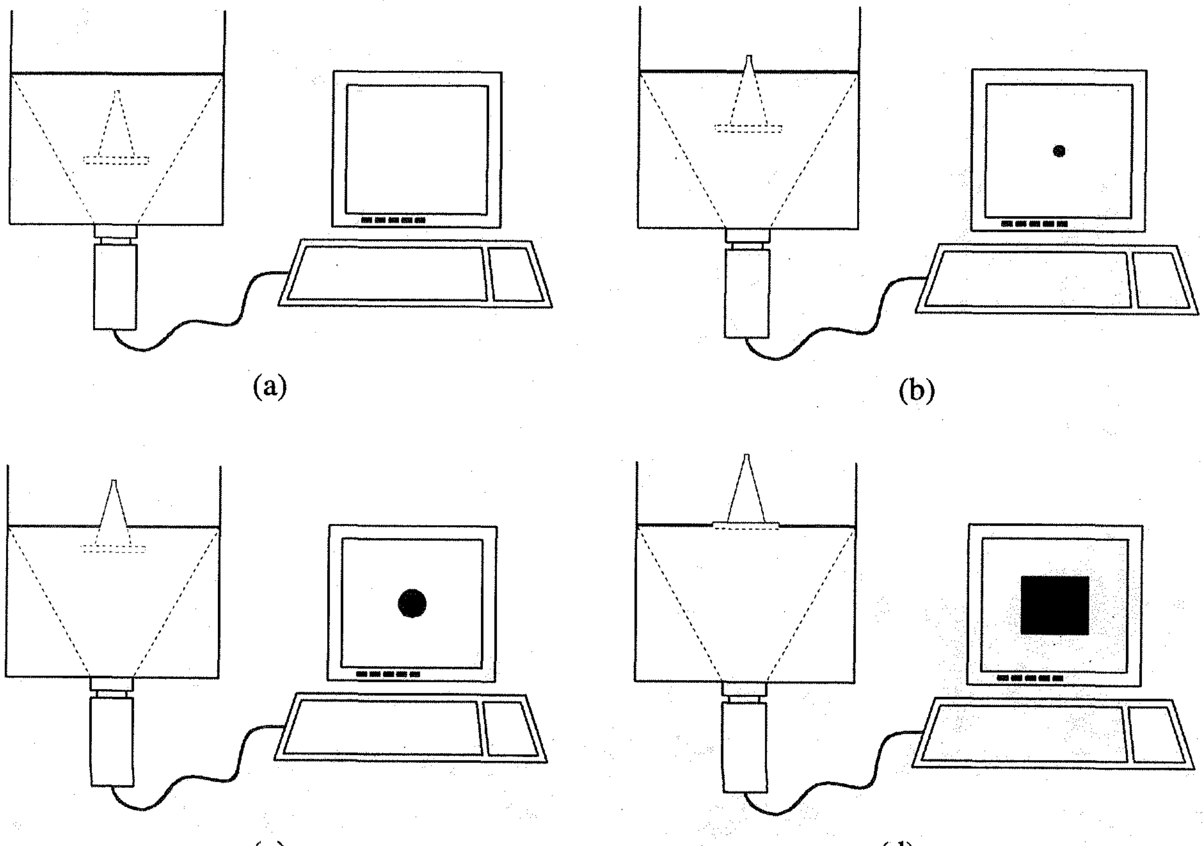
Figure 1 Concept of refractive index matching

seen easily (Figure 1a). This disappearing effect of polymeric solids in a RIM liquid can be used to reverse engineer the part geometry. Using an optical mask, which floats on top of the immersion liquid (Figure 1), only the cross section of the part at a specific height/depth can be seen. The use of closely matched RIM liquid is needed in order to avoid inaccurate cross-sectional data due to possible distortion that can be seen in Figure 1b, where the light changes its direction due to a mismatch in refractive index.

System Design

System Description

There are two main components in this reverse engineering (RE) system: hardware and software. Figure 2 shows a series of schematic illustrations of the process flow describing how both hardware and software work together to reconstruct a digital image from its polymeric physical solid model. First the object to be reverse engineered is made from a clear polymer. In our case, we used General Electric RTV615 silicone. The silicone part is then placed in the RIM immersion liquid making it virtually invisible to the CCD camera placed at the bottom of the tank. In Figure 2a, the picture on the screen shows only the color of the optical mask. The optical mask is a dyed liquid with an opposite polarity and a density less than that of the RIM immersion liquid. Because of these properties the mask floats on top of the immersion liquid. As the part is raised up through the mask (Figure 2 b, c, and d), cross-sectional images can be seen, by the CCD camera, where the part penetrates the mask or the dyed liquid. By maintaining



(a) (b) (c) (d)

Figure 2 Schematic representation of the RIM RE process of a polymeric solid the Z level of the mask, a series of cross-sectional pictures of the part is taken as it is raised up through the mask. These pictures can then be used to create a 3-D model of the part by following this order:

Polymer tool → Serial images → Raster to vector conversion → CAD file

System hardware

There are four primary hardware components in this RE system and they are:

- Containment tank for the immersion liquid and the mask
- Z axis linear slide/stepper motor and its controller
- Liquid solutions (immersion and mask)
- Imaging system (CCD camera and computer)

The containment tank is a simple glass tank with a Z-axis linear slide mounted on the back to raise the solid model up through the mask. A CCD camera is mounted on the bottom of the tank, below the glass wall. The RIM liquid is placed inside the tank and the mask or the dyed liquid is placed on top of that. In order to remain environmentally safe, a simple sugar water solution is used as a RIM liquid. The concentration of sugar in water determines the index of refraction and can be matched with many clear polymers with refractive indexes varying from 1.33 to 1.45 with up to 2 g/ml sugar concentration. For RTV615, a sugar solution of concentration 0.79 g/ml is used whose refractive index is 1.406. Figure 3 shows the refractive index of sugar-water solutions experimented with thus far along with corresponding sugar concentrations. The refractive indices of these solutions were measured using a Bausch and Lomb refractometer.

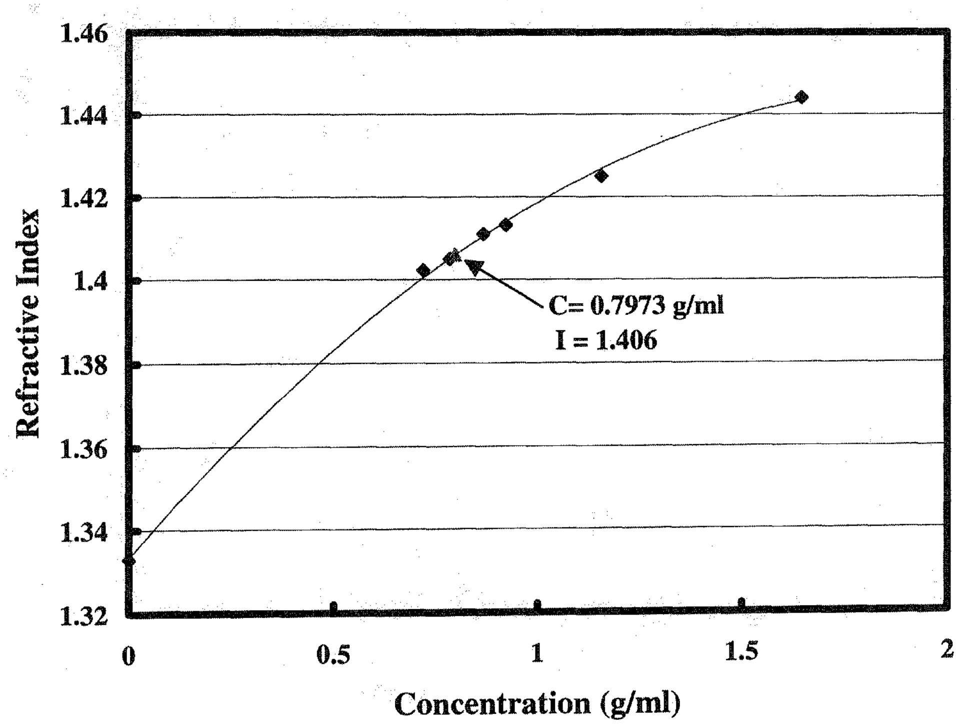


Figure 3 Refractive indices of solution made from sugar and water.

Imaging in the test system is done with a 640x480 pixel, ViCAM digital camera. The camera is attached to a Pentium II-266 computer for data acquisition.

Software

Software development is required for four different tasks in this RE system. First, cross section images must be saved serially according to its Z-axis position. Second, simple positioning of software is required to drive a stepper motor that is triggered after each picture is taken. In order to use the pictures for RE, the cross section edges must be detected with edge detection algorithms and then converted to a vector format. Currently the DXF file format is being used. Once created, each cross section is then imported into a CAD program with its corresponding Z level. This whole process will been automated so that no user intervention is needed unless part feature editing is necessary. Processing time takes about 7 seconds for each cross section.

Accuracy

Model accuracy is probably the most important parameter during reverse engineering. With the optical RIM technique of reverse engineering a complete analysis of achievable accuracy has not been performed so far. Several test parts have been used to test the system and these parts show that a high degree of accuracy can be achieved. Various factors that can affect accuracy have been discussed in the order that it is believed they affect the accuracy most.

RIM and mask liquid surface tension plays a significant role in model accuracy. If the surface tension is high, the liquid will not easily flow around the part to the correct Z level because it may cling to the part as it is being drawn up out of the tank. In parts that have horizontal surfaces, parallel to the surface of the liquid, surface tension may cause considerable inaccuracies. Low surface tension fluids can greatly reduce this source of error.

The part geometry has also been found to affect accuracy. Parts having many internal features that are not open to the free flow of liquid will not have those features reverse engineered. It has yet to be determined how complex of a part can be reverse engineered before the accuracy drops off significantly.

Lighting for the camera has been found to be another important factor in accuracy. If the picture is over-exposed, the cross sectional edges can be distorted. In experiments with monochromatic light, it has been found that light in the same frequency range as that of red (visible) LASERS would not penetrate the mask. The monochromatic light source provided an excellent contrast with very sharp edges. In the example part, normal room lighting was used which gives a lower accuracy.

Edge detection software is a critical factor in this method of reverse engineering. While the human eye does an excellent job, it is not be very efficient for this task! A good quality, edge detection algorithm is an essential tool to get accurate cross sectional information to reconstruct an accurate 3-D image. However, if lighting is good then this is not a very difficult task.

Example

In order to see how sample parts can be reverse engineered, a simple cone with a rough-cut rectangular base was created from silicone. It was then placed in the RE system. Cross sections on this example were taken every 0.050 of an inch in the Z direction. Because custom software has not yet been created to automate the entire procedure slice intervals have been kept at or above 0.025 inches. Figure 4 shows the results of the raw data after it was imported into CADKEY 97. In this example, the accuracy ranged from 0.004 inches to about 0.029 inches across the X-Y plane. In the top view, the small deformations on the left side of the rectangle that showed up in the RE model was actually a small tear in the silicone part. In Figure 4a, the cone looks slightly elliptical which is the true representation of the part, because the mold for the original part was deformed during its cure cycle.

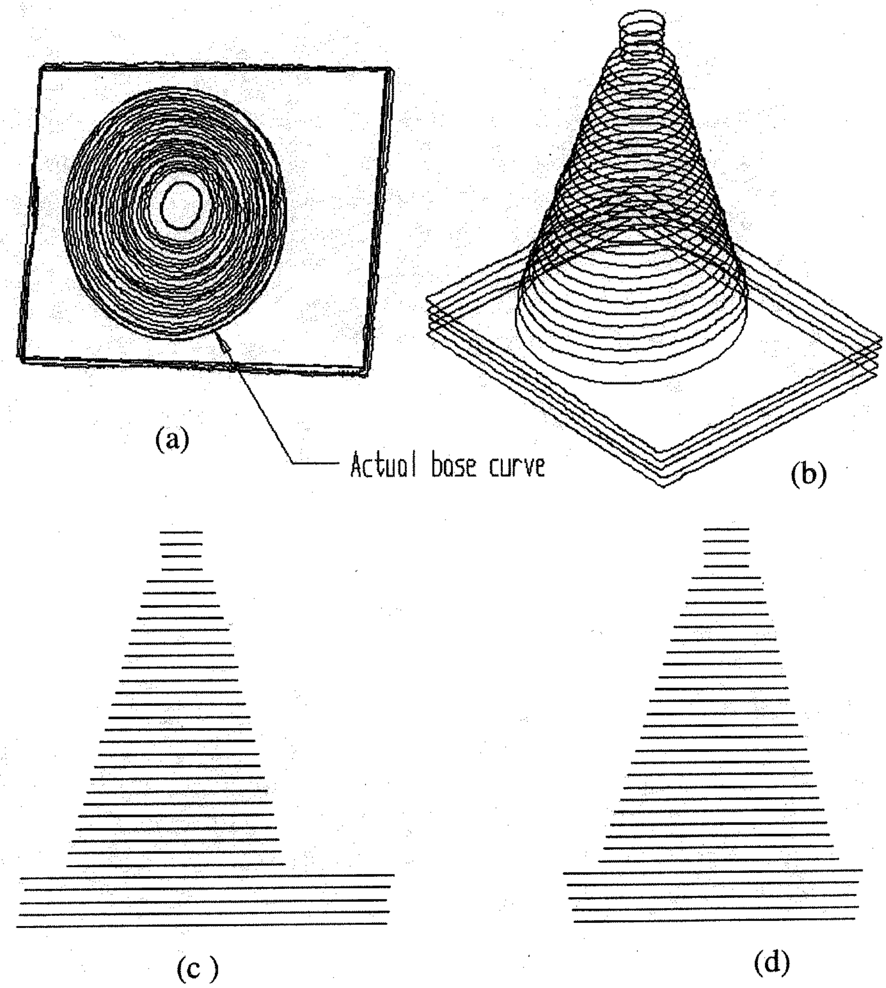


Figure 4 CAD pictures of imported DXF cross sections. (a) Top view, (b) Isometric view, (c) side view and (d) front view.

From the above CAD file a *.stl* file was generated. This file was then used to create an ABS solid model using an FDM 1650. Figure 5 shows the original silicone part beside the ABS RP model for comparison.

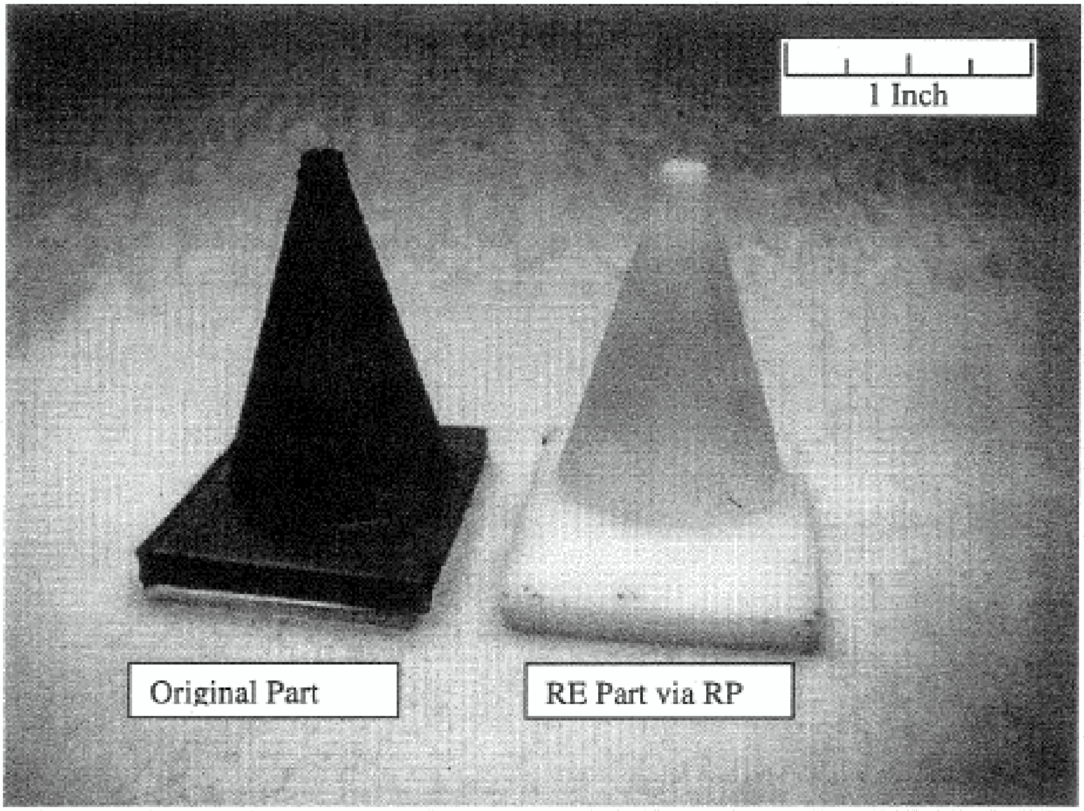


Figure 5 Original polymeric part next to the reverse engineered ABS RP model

Conclusions

Refractive index matching (RIM) concept is used to build novel reverse engineering equipment that can be used for polymeric materials. The equipment has been successfully used to reverse engineer both simple and complex shaped silicone parts. From different geometries, which have been tested so far, accuracy of better than 0.010 inches have been achieved. Further developmental work is currently in progress to understand the effects of various parameters on the accuracy of this process.

Acknowledgment

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