A 3D-OBJECT RECONSTRUCTION SYSTEM INTEGRATING RANGE-IMAGE PROCESSING AND RAPID PROTOTYPING

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ABSTRACT

This paper describes a system which integrates computer vision and rapid manufacturing technologies to scan physical objects and to replicate the reconstructed shapes as steel faced dies using shaping deposition processes. A light-stripe range finder is used to scan the 3-D data of the object. Range data is then processed in order to generate a solid model representation. The computer model is then replicated as a plastic prototype with stereolithography. Finally, this prototype is used as a pattern in a thermal spray process to build a metal-faced die replica of the original object. The system is demonstrated by scanning a human face which is then replicated as a stainless-steel sculpture.

1. INTRODUCTION

Manufacturing technology has experienced a significant improvement in productivity in the recent years due in part to the development of Computer Integrated Manufacturing (CIM) and its enabling technologies. Two such technologies are computer vision systems and solid-freeform-fabrication (SFF) processes. While these technologies have unique roles in rapid object scanning/reconstruction and rapid part fabrication applications, respectively, their integration can produce novel rapid object replication systems.

Consider a situation where the model of a part to be evaluated or to be fabricated first comes from a physical object instead of being a computer generated model. For example automobile designs may be originated as a clay sculpture of a new car body. The shape of the object must then be encoded into a CAD data base. In such cases the object can be scanned by means of a coordinate measuring machine (CMM) or by computer vision. Computer vision has the potential to be faster and to produce a higher density of sample points than CMM. After the data is gathered, it must then be transformed into a valid computer representation of the object for use in subsequent CIM operations. For example, Finnigan [6] has recently developed a system which takes computer-aided tomography (CAT) scans of industrial parts, and converts them into finite element models. In another example, Choi [2] describes an algorithm to transform sampled points from scanned 3-D data to surface and solid

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representations using a non-manifold geometric modeling system.

The system presented in this paper integrates computer vision and rapid manufacturing technologies to scan physical objects and to replicate the reconstructed shapes as metal faced dies using SFF processes. The system is composed of several modules including: scanner, data reconstruction, stereolithography, and thermal spraying. The system incorporates a novel thermal spray process which enables the rapid fabrication of steel-faced dies. Previous spray technology has been limited to softer metals such as zinc alloys. While the system has been demonstrated by fabricating a stainless steel sculpture of a scanned human face, it also has industrial significance. In principal therefore, we can go from clay sculpture of a new car design to stamping die to make prototype metal hoods.

The paper has been organized as follows. Next section contains an explanation of the object scanning procedure. Section 3 is devoted to explain the Data Reconstruction Module of the system. The Rapid Fabrication Module is explained in section 4. Concluding remarks are gathered in the summary section.

2. OBJECT SCANNING

The object scanning system consists of a slide projector with a liquid crystal shutter [9], a CCD TV camera, and a point light source. The range finder provides three images, $X(i,j)$, $Y(i,j)$, $Z(i,j)$, which contain the world coordinates of the pixel, (i,j). Another additional intensity image $I(i,j)$ of the scene is also provided at the same time. Range resolution rounds 1.5mm for this specific setup Accuracy depends on calibration but it is around 0.5mm in the actual implementation. Provided range images are 240 by 256 pixels wide and less resolution is obtained in practical just by using image demagnification procedures. Figure 1 shows the four input images as they are given by the range finder. Notice that Y coordinate remains almost constant over image column, and Z coordinate does so at every row. This is because the image plane of the sensor is parallel to the world YZ plane.

The range finder generates depth information as follows. A set of coded light striped patterns are sequentially projected onto the scene (i.e., object plus background). Whenever a striped pattern is projected, an associate intensity image is registered. Afterwards, the set of intensity images are decoded and, by using simple triangularization, the distance from the camera to the point represented at every pixel (i,j) is easily computed and then transformed to the world coordinate system.

Several measurement errors are generated in the process of scanning a human face in part because it is difficult to remain perfectly motionless during scanning. Other sources of inherent sensor noise and measurement error exist. The noisy images are processed in the Data Reconstruction Module.

3. DATA RECONSTRUCTION MODULE

The Data Reconstruction Module is organized into two blocks. In the first block a filtering and feature extraction stage is carried out on the input range data images. The second block is the computer model generator which tessellates the converted range images and creates the solid representation. These two blocks are explained in more detail next.

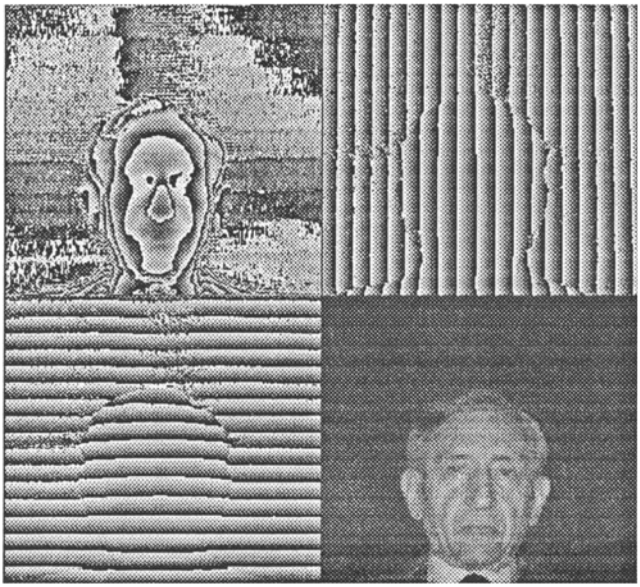

Figure 1.- Original images provided by the range finder: *X(i,j)* (up-left), *Y(i,j)* (up-right), *Z(i,j)* (bottom-left) and *I(i,j)* (bottom-right)

Filtering and Face Extraction

Image processing algorithms are applied here to clean the input range images and to extract from them the information required to generate the geometric model of the face. Basically, the sequence of filters and extraction operations is as follows.

In a first step, the face area is selected from the complete range image. In order to do this, several image processing algorithms have been used. A Sobel operator is the first image processing operator applied to the depth image, *X(i,j)*, to find the edges which, in this case, represent depth discontinuities. A segmentation is performed on top of this resulting image by chosing a threshold in such a way that a set of disconnected regions appear. The biggest region is selected as the face area and all the others are discarded. After smoothing and interpolation, a new range image is created.

A second step is responsible of noise elimination. Spurious noise values are still detected in the lately generated image, mainly in the boundaries of the selected face area, due in part to the range data acquisition process. By using a grassfire operator, a shrink-expand process is carried out. Several layers of the face area contour are removed in this step, eliminating the zone where erroneous values were observed.

Small blob regions, previously connected to the main face region by narrow paths, are also removed in this step.

In the last step a coordinate frame conversion is performed on the range data. Because of the special requirements of the rapid manufacturing module, a coordinate frame transformation has to be performed before generating the solid representation.

Figure 2 contains a surface representation of the 3D data before and after processing the Data Preparation Module, and shows the efect of this stage on the input data.

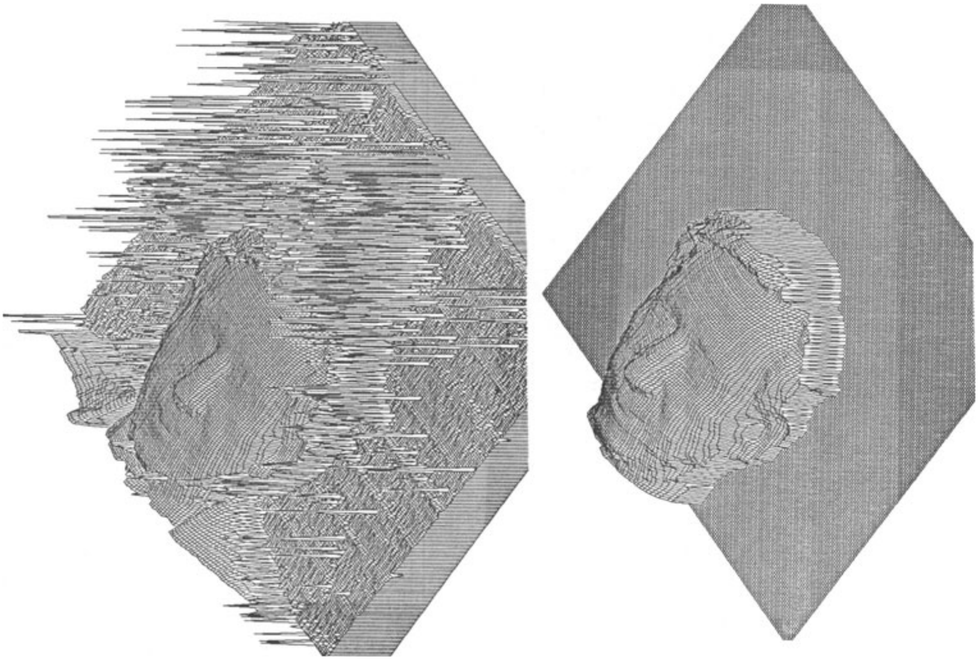

Figure 2.- Input range data (left) compared to range data after filtering and face extraction (right).

Computer Model Generator

The output of the previous stage is a set of three new range images $X_n(i,j)$, $Y_n(i,j)$ and $Z_n(i,j)$. They represent a set of points in the stereolithography module coordinate system that define, point by point, an irregular and open surface corresponding to the human face to be reproduced.

A valid solid geometric computer model must be generated from this data. A boundary representation is the required representation such that the object is described in terms of the set of its boundary surfaces which conform a closed surface. A tessellation technique has been used to generate the computer model from the actual range data, and it has been developed in three steps. The first one deals with the tessellation of the upward facing boundary surfaces which come directly from the face area points. The second step creates a completely synthetic wall-fashion surface obtained as a projection of the contour points of the face area. The last one deals with the task of closing the solid by creating a bottom boundary surface. Algorithms involved in these steps can be found in Cerrada [1].

4. RAPID FABRICATION MODULE

The capability to manufacture a wide variety of quality products in a timely and cost-effective response to market demands is the goal of todays manufacturing industry. The introduction of solid free form fabrication techniques is helping to achieve this goal and the improvement global competitiveness. This new technology has the ability to rapidly produce prototypes and even the final parts directly from design models. Solid freeform fabrication processes are a relatively new class of fabrication technologies which build three-dimensional shapes by incremental material buildup of thin layers, and can make geometrically complex parts with little difficulty. These processes include selective laser sintering [4], laminated object manufacturing [3], ballistic powder metallurgy [7], three-dimensional printing [8] and stereolithography [5]. These processes are suited for rapidly producing physical prototypes from CAD representations.

In the present work two processes based on shaping deposition techniques have also been used to deal with the physical reconstruction of the sculpture in steel: stereolithography and thermal spraying. The steel deposition process to create a 3-dimensional die shape is novel to this system. Implementation details of the two fabrication processes are described next.

Stereolithography Process

Stereolithography is a technique which quickly builds plastic prototype parts, of arbitrary geometric complexity, based directly upon computer part models. The system described in this paper uses the commercially available stereolithography apparatus (SLA), Model 250, manufactured by 3D Systems, Inc. of Valencia, CA. The input to SLA is a linearized "tessellated" surface boundary representation of the part, and consists of a series of three sided facets and a corresponding facet normal. The Data Reconstruction Module transforms its internal representation to the tessellated format.

The SLA is composed of a vat of photosensitive liquid polymer, an x-y scanning ultraviolet laser beam with a 0.25 mm (0.01 in.) beam diameter, and a z-axis elevator in the vat. The laser light is focused on the liquid's surface and cures the polymer, making solid forms wherever the liquid has scanned. The depth of cure is dosage-dependent. The physical object to be created, as described by the boundary representation model, is first "sliced" into the cross-sectional layers along the z-axis. For each slice, the laser's trajectory is dictated by the cross sections boundary and the bounded region.

The elevator platform is initially positioned at the surface of the liquid. As the laser draws a cross section in the x-y plane, a solid layer is formed on the elevator platform. The platform is lowered and then the next layer is drawn in the same way and adheres to the previous layer. The layers are typically between 0.13 and 0.5 mm (0.005 and 0.020 in.) thick. A three-dimensional plastic object thus grows in the vat, starting at the object's bottom and building to the top.

Figure 3 shows a picture of the plastic sculpture created with the SLA. Its actual dimensions are 4.8" long, 3.8" wide and 2.8" height and the current accuracy is of the order of 0.25 mm.

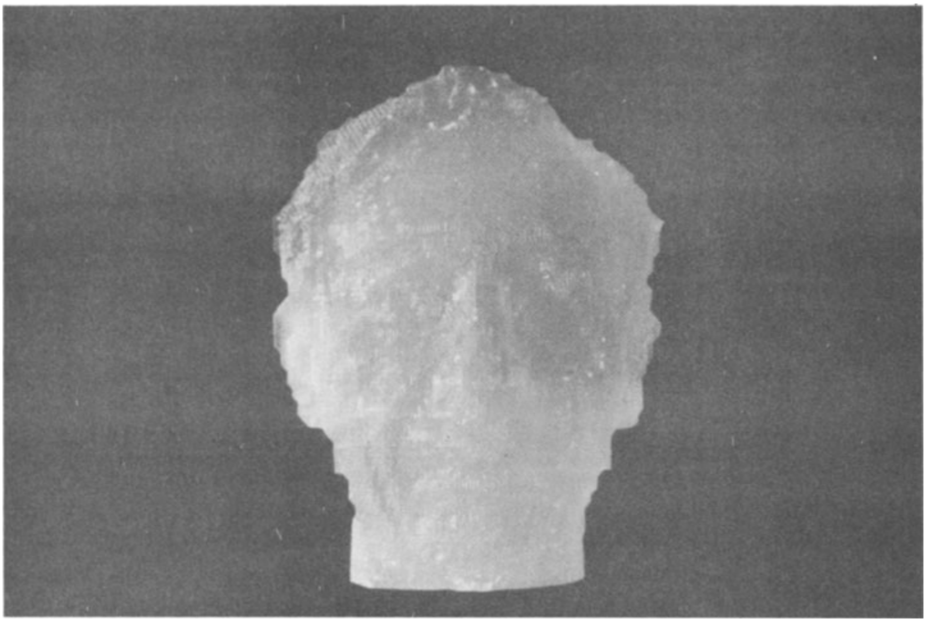

Figure 3.- Aspect of the plastic sculpture

Thermal Spraying Process

There are several thermal spraying processes available for depositing molten metal, ceramic, or plastic material. Our system uses electric arc spraying. In arc spraying metal wire is melted in an electric arc, atomized, and sprayed onto a substrate surface. On contact, the sprayed material rapidly solidifies and forms a surface coating. Spray coatings are built up by depositing multiple fused layers which, when separated from the substrate, form a free-standing shell with the shape of the substrate surface. By mounting the shell in a frame and backing it up with appropriate materials, a broad range of tools and dies can be fabricated including injection molds, forming dies, and EDM electrodes. For example, the cavities of injection molds can be fabricated by direct deposition of metal onto plastic SLA models of the desired part and backing the framed shell with epoxy resins or ceramic composites. Relative to conventional machining methods, the sprayed metal tooling approach has the potential to more quickly and less expensively produce tools, particularly for those parts with complex shapes (in particular free-flowing contours) or with large dimensions. Thus, with stereolithography, an initial part shape or prototype is quickly created. Thermal spraying is then used to make tools based on the part shapes produced by stereolithography.

Based on this concept the sprayed sculpture (i.e., equivalently a die) has been built using this process. An additional pattern transfer step is required for depositing steel. The result is the sculpture which aspect appears in Figure 4.

5. SUMMARY

A 3D-object reconstruction system which integrates range image processing and rapid manufacturing techniques has been described in this paper. The goal of the system was to scan a human face and to reconstruct it in the form of a steelsculpture. An initial range image of the face is taken using a light-stripe range finder sensor. The range image is transformed into a solid model representation with the aid of image processing algorithms. The solid model is in the form of a tessellated surface boundary representation. Once the solid model has been refined, a plastic prototype of the sculpture is fabricated using stereolithography. The prototype is used as a negative mold pattern for a thermal deposition process to build the final sculpture in the chosen material. Results for a 4.8" by 3.8" by 2.8" steel sculpture contained in a 6" by 6" frame has been presented along the paper.

Figure 4.- Final aspect of the sculpture in steel

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