Novel 3-D free-form surface profilometry for reverse engineering

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Abstract. This article proposes an innovative 3-D surface contouring approach for automatic and accurate free-form surface reconstruction using a sensor integration concept. The study addresses a critical problem in accurate measurement of free-form surfaces by developing an automatic reconstruction approach. Unacceptable measuring accuracy issues are mainly due to the errors arising from the use of inadequate measuring strategies, ending up with inaccurate digitised data and costly post-data processing in Reverse Engineering (RE). This article is thus aimed to develop automatic digitising strategies for ensuring surface reconstruction efficiency, as well as accuracy. The developed approach consists of two main stages, namely the rapid shape identification (RSI) and the automated laser scanning (ALS) for completing 3-D surface profilometry. This developed approach effectively utilises the advantages of on-line geometric information to evaluate the degree of satisfaction of user-defined digitising accuracy under a triangular topological patch. An industrial case study was used to attest the feasibility of the approach.

1. Introduction
Reverse Engineering has emerged as a crucial design tool in integrating Computer Integrated Manufacturing (CIM) systems and achieving the ultimate goals of Rapid Prototyping Manufacturing (RPM). The main aims of Reverse engineering (RE) are to retrieve the true geometric form from physical objects, and to update CAD models. In RE, problems associated with time-consuming and incomplete digitisation always result in loss of surface detail and difficulty in data processing for surface model generation. Some fast 3-D digitisers, such as laser range finders, stereo image detectors, moiré interferometers and structured lighting devices can scan dense measurement data in a short time; but the scanning result may not be satisfactory when strict measurement accuracy is required [1,2]. If there are sensor limitations, measurement disturbance, or improper digitising set-up, then data processing algorithms or strategies in surface reconstruction can never be correct. Therefore, to minimise the effect of probe limitations, a feasible solution combining the advantages of the two (or more) different digitising sensors is required [3]. Cooperative sensor integration between different kinds of sensors is one of these. This article then proposes an automatic 3-D optical profilometer for fast and accurate surface digitisation of free-form surfaces.

2. Overview of the integrated methodology
This new approach consists of two innovative processes, the rapid shape identification (RSI) process for surface triangulation and automated scanning path planning, and the automated laser scanning...
(ALS) process for automated surface digitisation and on-line digitising accuracy evaluation. The first stage, RSI, effectively utilizes a single CCD camera to rapidly detect the surface boundary coordinates using the 3-D mapping function method in cooperation with the redundant-point removing strategy. The ALS step then performs an on-line automated laser scan and evaluation for ensuring digitising quality.

The proposed methodology has been implemented by integrating required optical scanners and a four-axis coordinate measuring machine. The architecture of the automated free-form surface profilometer is shown in Figure 1, in which four system control modules, namely sensor control and image processing, system central management and probe exploration modules are integrated. The role of the sensory processing system is to monitor and analyse information from digitising sensors (CCD and laser probe). The images, detected from the CCD camera, are processed by image filtering techniques adequate for generating the input for 3-D surface detection. The 3-D information is then used in the automatic path planning of laser scanning. The central management module generates the commands for probe exploration according to the proposed model-based digitising strategies. The hardware setup of the developed surface profilometer is illustrated in Figure 2.

3. The rapid shape identification (RSI) process
In the RSI process, a series of 2-D cross-section images are first acquired from a sequential number of angles around the object, shown in Figure 3 as an example. The volumetric data is then constructed from this stack of cross-section contours by using the 3-D mapping algorithm as described in the following paragraphs. Unlike a conventional stereo detection method of using stereo pairs of images, this topographic backprojection method does not suffer from the laborious corresponding problems, however, due to the inherent optical occlusion condition, this method cannot detect any concave shape. Fortunately, since the detected surface data will only be used to plan the initial probe scanning paths for subsequent laser measurement, this drawback does not impact on the quality of surface reconstruction.

![Figure 1. The architecture of the proposed methodology](image1)
![Figure 2. Hardware setup of the developed surface profilometer with automated reconstruction capability](image2)
![Figure 3. A series of cross section images acquired in the RSI process](image3)
In the RSI process, an effective mapping algorithm based on least-squares optimisation was proposed to accurately transfer an image coordinate to its corresponding physical 3-D point, by using a multiple variable polynomial fitting and a calibration procedure [4]. Assuming the cross-section profile to be reconstructed is orientated along a predefined \( X \) coordinate, the object coordinate \( S(X,Y,Z) \) can be derived from its corresponding image coordinate \( (u, v) \) using the following equations based on the least-squares optimisation scheme:

\[
Y(u,v) = \sum_{i=0}^{n} \sum_{j=0}^{n} C_{ij}u^iv^i \quad (1)
\]

\[
Z(u,v) = \sum_{i=0}^{n} \sum_{j=0}^{n} d_{ij}u^iv^j \quad (2)
\]

Furthermore, according to the rigid body transformation between the projection plane and the actual object orientation, the series of object coordinates \( S(X,Y,Z) \) can be transformed into the volumetric surface coordinates [4]. Once clouds of the volumetric surface points are acquired, a Delaunay triangulation algorithm is used to generate surface triangular patches for laser scanning path planning. This surface triangulation scheme ensures the whole measured surface region is subdivided into an adequate number of triangular regions, such that each region is a simply-connected convex region which is free of conspicuous shape changes [5]. The purpose of using Delaunay Triangulation is to construct a triangular patch from the extracted points by considering natural neighbouring geometric relationships between the points. Shown in Figure 4 is an example of reconstructing a computer mouse object, its triangular surface patches can be established, by using the RSI process, within 5 seconds.

4. The automated laser scanning (ALS) process

To digitise free-form surfaces following the geometric trend, an adaptive digitising strategy is proposed to automate and optimise the digitisation of free-form surfaces. It is important to note that the laser scanning process should follow a geometric trend of the measured surface in order to precisely capture data for surface reconstruction [2]. To obtain the best next orientation of the laser probe, a gesture measure \( (O_g) \) is proposed as Equation (3), which is based on the evaluation of probability of the laser projection and the CCD imaging to be orientated against the normal of the triangular surface patches being reconstructed (shown in Figure 5) [4].

\[
O_g = \left( \sum_{x} \sum_{y} \sum_{z} \sum_{\theta} P_L(x,y,z,\theta) \cdot P(x,y,z,\theta) \right) \cdot \left( \sum_{x} \sum_{y} \sum_{z} \sum_{\theta} P_L(x,y,z,\theta) \cdot P(x,y,z,\theta) \right)
\]

\[
\text{Where } P_L(x,y,z,\theta) = \begin{cases} 
1 & \text{if } \hat{N}_e \cdot \hat{N}_z \Rightarrow 0.5 \\
0 & \text{otherwise} 
\end{cases}
\]

\[
P_L(x,y,z,\theta) = \begin{cases} 
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0 & \text{otherwise} 
\end{cases}
\]

The estimated digitising deviation can be also simply determined by the distance between the actual measured coordinate and the pre-estimated surface point. A more precise estimation in determining the conformity of the reconstructed surface fitting with the object contour can be predicted from the sum of the deviations from all the measured points within the digitised triangular regions.

5. Measurement examples and results.

A sculptured face model was taken as a case study to verify the feasibility of the proposed approach. As shown in Figure 6(a), the size of the physical model is approximately 100 x 120 x 100mm³. By using the new approach, all required surface triangular patches and reconstructed surface of individual surface patches were generated. Figure 6(b) shows the initial surface model of the measured object.
being reconstructed from the RSI process. In this case study, the user-specified digitising accuracy and the minimum digitising side length were set at 0.150 mm and 2 mm, respectively. Using the ALS process, the object triangular and surface models (see Figures 6(c) and (d)) with satisfactory user-specified digitising tolerances can be generated efficiently. From observing the surface triangular patch, it was found that more surface points were captured in surface areas with high curvature. The data distribution of the digitised surface points basically conforms to the local surface curvatures.

6. Conclusions
This paper presents an innovative cooperative-sensing methodology for free-form surface profilometry with improved efficiency and accuracy. A framework of cooperative sensor integration has been established to integrate an accurate laser scanning probe with fast vision sensors. In addition, the developed strategies in the ALS process have been employed to ensure success of the automation of surface reconstruction. The presented example has shown that the proposed strategies provide an achievable method in achieving automated surface model reconstruction with used-specified digitising accuracy.

Figure 4. Example of reconstruction of initial surface triangular model

Figure 6. An industrial example of reverse engineering a sculptured face model: (a) physical model; (b) initial model being obtained from the RSI process; (c) the refined triangular patches obtained from the automated laser scanning (ALS) process; and (d) the reconstructed surface model generated from the ALS process, where different colour surface sections represent different surface regions being reconstructed during separate surface scanning stages.

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