Computer-Aided Design 42 (2010) 744–748

Contents lists available at ScienceDirect

Computer-Aided Design

journal homepage: www.elsevier.com/locate/cad

Identification and optimization of key process parameters in noncontact laser scanning for reverse engineering

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ARTICLE INFO

Keywords:
Laser scanner
Design model
ANOVA
Standard deviation
Genetic algorithm
Reverse engineering

ABSTRACT

This Extended Technical Note shows that the final accuracy level of reverse engineered surfaces depends on scanning distance and scanning angle of the laser beam, hence it also depends on the morphology of the scanned objects. On scanning strongly curved objects, such as the ones with free form surfaces, the distance and impact angle of the laser beam are changing continuously during the scanning process. On the basis of these, two critical parameters are specified for the design model, which make it possible to predict these two factors in advance, depending on the morphology of the scanned object. First, a mathematical–statistical design model of the scanning process is generated, which relies on ANOVA (analysis of variance) and DOE (design of experiments). In the next step, a fitness function is optimized by the genetic algorithm (GA) program. This optimization improves the accuracy of the final scanned surfaces, in terms of the minimum standard deviation values of reverse engineered 3D surface model. The proposed approach was confirmed in a case study, which is presented at the end of this Technical Note.

1. Introduction

Laser scanning is a well known noncontact measuring and scanning technology that is widely applied in reverse engineering processes and used for capturing surfaces of 3D objects. A general setup of laser scanning is shown in Fig. 1.

As previous studies showed, there are in general five parameters that influence the physical properties of scanning [1,2]. Unfortunately, the morphology and local geometry of the captured surfaces have not been considered in most of these studies, or not with sufficient depth [3,4]. This Technical Note points at the importance of these 'neglected' parameters and their influence on the quality of the surfaces produced by reverse engineering. Parameters influenced by the morphological properties of the scanned surface are the inclination angle, and distance between the scanned object and the scanning laser head. Our experimental studies showed that it was possible to establish an optimal range of scanning, where the standard deviation (stand. dev.) of captured surfaces could be minimized. Knowing this range, we were able to optimize all other parameters. In addition, these parameters could be predicted in advance.

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doi:10.1016/j.cad.2010.02.003

2. Current state of accuracy analysis of laser scanning

In [6,7], interesting surveys of sensor planning strategies are provided, considering model-based vision algorithms (including elements such as the camera, range sensor, and illumination systems). In [8,9], the influence of the relationship between object, image, and the error of the measuring system are studied. However, the surface morphology and surface geometry relations are neglected. These researchers attributed complete error only to the nonlinear relationship between precalibrating parameters. This problem has been widely studied in [10], where it was found that scan distance contributes to the out-of-plane effect. This is also one of the reasons why parameters 'lean angle' and 'object distance' have been considered as the two most influencing factors investigated in the presented Technical Note, considering the object surface morphology. On the basis of these findings, a design model was established, which was confirmed in the ANOVA analysis.

3. Description of the experiment

Red colored prismatic plate of dimensions 150 × 50 × 30 mm, made of stone and polished (in order to get a really smooth surface), was used to investigate the dependencies of the lean angle, object distance and standard deviation (std. dev). The plate was chucked in a rotary head, which rotated from 0° to 75° in

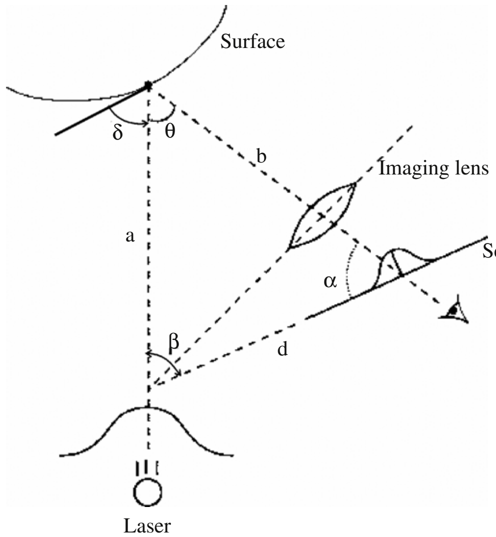

Fig. 1. Geometry in triangulation process (δ is surface lean angle) [5].

successive order, with 5° increment. For each point cloud captured at every 5°, the surface was reconstructed using Matlab. Std. dev. was calculated relative to a perfectly flat surface (plane). This procedure was repeated at different scan distances, ranging from 60 to 120 mm, with an increment of 10 mm.

4. Experimental results

At the investigation of the light diffusion field of the surface morphology of the object, it was supposed that the surface is a Lambert reflector, and that the intensity of the diffused light is a function of the diffusion angle. As the laser beam moves, it generates a rectangular tubular volume that defines an acceptable scanning data region [11,12]. Results obtained by this procedure are presented in Fig. 2. It can be observed in Fig. 2 that the desired area of operation is at low distances, and the lean angles of the surface are in the range from 30° to 55°. These results were used for setting up the design model.

5. Mathematical model for std. dev. prediction

The general full factorial design consisted of 112 experimental runs (with two replicas), taken at 7 levels for distances and 17 levels for lean angles. This design of experiments was applied for the ANOVA analysis and for building up a suitable mathematical-design model. In live with the experimental results shown in Fig. 2, the ANOVA results for cubic response surface method imply that the model is significant. Consequently, on a basis of ANOVA results, it has been concluded that this design model can be used to navigate the evaluation of the design space. The ANOVA analysis also revealed that the cross effect of the two key parameters is not significant. The response surface method (RSM) helped us to quantify the relationships between one or more measured responses, and to present the design space in a topological form [13,14]. Further examination of the response surface shown in Fig. 3 indicates that maximum std. dev is achieved at distances about 70 mm and angle values between 30° and 55°. The final equation with regards to the actual factors is as follows:

$$\begin{aligned}\textbf{std. dev. YZ} = {} & 0.050339 - 7.72329\text{E}{-004} * \text{distance} \\ & + 2.92853\text{E}{-004} * \text{angle} \\ & - 3.93881\text{E}{-006} * \text{distance} * \text{angle} \\ & + 8.27884\text{E}{-006} * \text{distance}^2 \\ & - 6.39730\text{E}{-006} * \text{angle}^2 \\ & + 1.63340\text{E}{-008} * \text{distance}^2 * \text{angle} \\ & + 2.37570\text{E}{-008} * \text{distance} * \text{angle}^2 \\ & - 3.73264\text{E}{-008} * \text{distance}^3 \\ & + 4.45873\text{E}{-008} * \text{angle}^3. \end{aligned} \quad (1)$$

5.1. Experimental verification of the design model

Ten randomly chosen distance and angle values, which are shown in Fig. 3, were tested against Eq. (1), and compared with the values measured on the colored prismatic plate. These results are shown in Fig. 4. The mean absolute percentage deviation (MAPD) between measured and predicted results has got a value of 5.36%. This indicates that the predicted values implied by the mathematical (design) model are in sufficient agreement with the measured values, according to the ANOVA confidence interval.

6. Genetic optimization of the analytical model

The lean angle and the object scan distance are adaptive parameters, i.e., they can be changed by the CNC machine controller. Therefore, as a next step, the analytical model was optimized in order to achieve minimum values of the fitness function, presented in Eq. (1). This involved the selection of combinations of scan distances and lean angles to achieve the minimum values of std. dev. results for a given scanning conditions. Genetic algorithm (GA) was applied in the calculations. In a GA-based optimization procedure, selection, reproduction and evaluation actions are repeated until some termination criteria are satisfied [15,16]. Minimizing the objective function with respect to the initial population will yield optimized results in a form of new chromosomes. As a first step, a

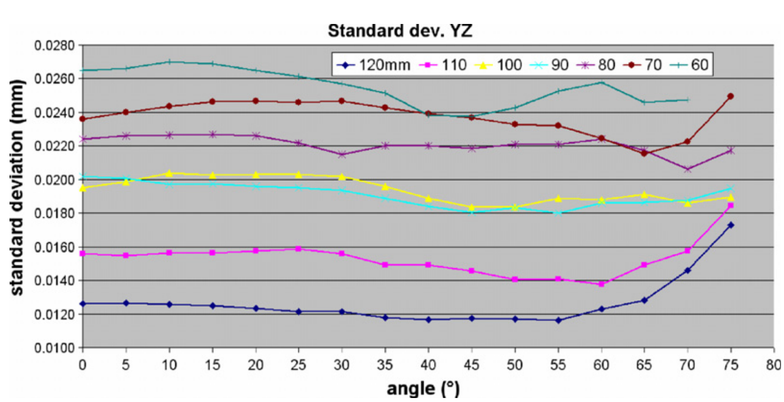

Fig. 2. Std. dev. versus angle at different distances.