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Intraoral 3D optical measurement system for tooth restoration

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ABSTRACT

In this paper we present a new miniaturized 3D optical measurement system for tooth restoration. The system is designed for scanning tooth within human mouth. The measuring process is based on the structured light measurement principle. The novelty in the approach is characterized by the following features: a flexible optimization convergence algorithm is taken as the calibration of the special miniaturized system, a rapid phase-shifting method is used to measure the tooth shape, multi-view 3D registration is completed based on matching between scale invariant features of 2D image and the miniaturized device is constituted with the LCoS micro-display module and camera. Some experiments are performed to validate the availability and reliability of the developed system. This miniaturized measurement system has a wide applications for dental CAD/CAM restoration system.

1. Introduction

Structured 3D shape measurement techniques have been widely applied in various fields, such as manufacturing, healthcare, computer science, family safety and digital entertainment [1]. It is used to acquire the 3D profile of objects for CAD/CAM. However, there are not too many measurement systems specially designed for the narrow and small space environment of 3D profile measurement.

There are some difficult to perform miniaturized 3D measurement system. First, the size and volume of the components of system device presently available in the market are either too voluminous or inappropriate for performing accurate measurement; second, the miniaturized system is commonly used for hand held, so rapid or real time measurement method is needed for the system; third, robust multi-view registration is difficult without constraint; at last, the miniaturized system need a special system calibration. The traditional calibration algorithm is not suitable for the system.

Now there are some miniaturized systems for special application in industrial CAD/CAM system. One commercial system has been developed by the company Sirona, named CEREC, which realizes a scanning within the mouth for the first time by fringe projection [2]. Fan [3] proposed a micro 3D measurement system utilizing the merits of flexible, bendable, and long distance signal transmission of the image fiber bundle. Chen [4] developed a miniaturized 3D surface profilometer system with a miniaturized probe. The probe comprise coherent image fibers, a digital micro-mirror device (DMD) chip, a micro charge coupled device (CCD) and a set of optical lenses. Wang [5] also use the similar mode construct a miniaturized programmable patterns projector. It contains fiber image bundle and common digital light processing (DLP) projector. Vishnyakov [6] presents a dental CAD/CAM system including the miniaturized intraoral camera for noncontact 3D object measurement. The miniaturized system consists of CCD, LED light source, grid-transparency and a projection objective. Kuhmstedt [7] also proposed a miniaturized 3D scanning system for CAD/CAM in dental industry. The main component of system is LCOS micro-display. It has a 25 mm × 15 mm measurement fields. All of the micro-system is constructed based on the miniaturized components and flexible 3D measurement principle. They meet huge demand of special industrial CAD/CAM.

In this paper, we also present a miniaturized 3D measurement system. Besides shown the principle and components of the system, we mainly show our system's features. The remainder of this paper is structured as follows. In Section 2, the system principle and model are provided; Section 4 describes the realization of the intraoral 3D measurement system. The conclusion is stated in Section 6.

2. System mathematical model

The intraoral 3D optical measurement system is based on structured light principle as shown in Fig. 1. When the camera captures the image from a direction different from the projector, the fringe image projected on the tooth is modulated by the height of the

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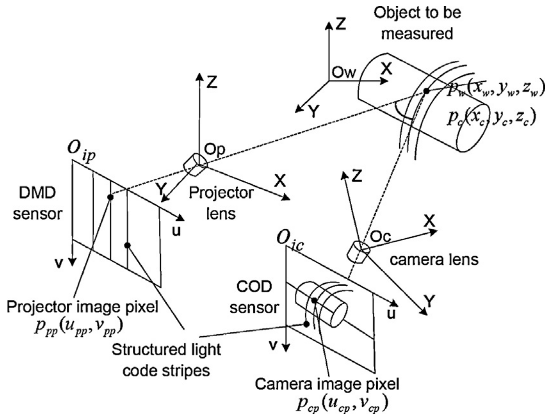

Fig. 1. The system model.

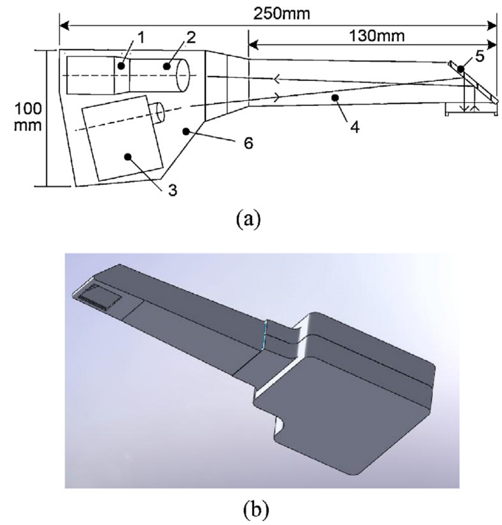

Fig. 2. Device structure design of miniaturized system: (a) system structure map and (b) 3D design model.

object. The functional relationship between the modulation and the height is the system parameters that need to be calibrated [8]. This system has less modules compared with stereo vision 3D measurement system.

The camera model used in this system is a combination of the pinhole camera and lens distortion models. The model for the projector is similar to the camera as the projector can conceptually be regarded as a camera [8] acting in reverse. The mathematical model of the projector can be expressed with Eq. (1):

$$\begin{cases} (u_{pp} - C_{pu})s_{pu}^{-1}d_{pu} + D_{pu} = f_p \dfrac{r_{p1}x_w + r_{p2}y_w + r_{p3}z_w + T_{px}}{r_{p7}x_w + r_{p8}y_w + r_{p9}z_w + T_{pz}} \\ (v_{pp} - C_{pv})d_{pv} + D_{pv} = f_p \dfrac{r_{p4}x_w + r_{p5}y_w + r_{p6}z_w + T_{py}}{r_{p7}x_w + r_{p8}y_w + r_{p9}z_w + T_{pz}} \end{cases} \tag{1}$$

The principle of the structured-light system is similar to stereovision; the only difference is that the projector in the structured-light system is taken as an inverse camera. According to the photography geometry, the perspective projection principle, the 3D object point $p_w(x_w, y_w, z_w)$ can be translated into the 2D image pixel point $p_{cp}(u_{cp}, v_{cp})$ of the camera. However, the projector cannot capture the image because the image pixel points of the projector are acquired indirectly through coding fringes. When vertical stripes are projected, each stripe has a unique coding; thus, in the horizontal direction, the camera's image point $p_{cp}(u_{cp}, v_{cp})$ has a unique code τ_x that corresponds to the projector image pixel coordinate u_{pp}. Furthermore, the horizontal stripes are projected, the vertical direction image pixel coordinate v_{pp} is found, the image pixel $p_{cp}(u_{cp}, v_{cp})$ and $p_{pp}(u_{pp}, v_{pp})$ of two devices are matched successfully, and the 3D coordinate point $p_w(x_w, y_w, z_w)$ is computed [8]. The computation of 3D point only requires three equations; thus, only the 1D stripes need to be projected.

3. Structure design for miniaturized 3D scanner system

It is a special requirement for measuring tooth in the mouth directly. The space within mouth is small and narrow. We design the structure of system as shown in Fig. 2. Fig. 2(a) is measurement system structure. Fig. 2(b) is 3D model of system. The miniaturized 3D measurement system consists of two parts. The left half part of the scanner is system module which consist of image capturing component (numbers 1 and 2) and projector component (number 3). The right half part of the scanner is optical transmission probe (number 4), consists of a set of optical lenses designed for light coupling and reflecting, and an image acquisition unit utilized for detecting reflected structured light patterns. The projected fringe image pattern form the projection light source is first straightened by the optical collimating lens and passes through a set of optical lenses and a 90° optical reflection mirror, and then projected onto the 3D contour of the object to be measured. For structured light vision system, the deformed structured fringe patterns, formed by the structured light of the projection light source and 3D object contour, then pass through the 90° optical reflection mirror (number 5), set of optical lens to form images on the image display sensor element. A mini charge coupled device (CCD) was used to capture the deformed structured fringe patterns.

The projector component is liquid crystal on silicon (LCoS or LCOS) based on "micro-projection" or "micro-display" technology typically applied in projection televisions. It is first developed by Intel at the 2004. It is a reflective technology similar to DLP projectors; however, it uses liquid crystals instead of individual mirrors. By way of comparison, LCD projectors use transmissive LCD chips, allowing light to pass through the liquid crystal. In LCoS, liquid crystals are applied directly to the surface of a silicon chip coated with an aluminized layer, with some type of passivation layer, which is highly reflective. The resolution of the LOCS chip in our scanner is 640×480 pixels and the projected area of fringe patterns on the measured object can controlled to obtain a FOV of $20\,\text{mm} \times 20\,\text{mm}$.

4. Realization algorithm for system features

4.1. The flexible calibration feature of intraoral measurement system

The miniaturized 3D measurement system has a small view. It is not easy to acquire the accurate system parameters with the traditional calibration methods. Therefore we develop a new optimization convergence algorithm for accurate system parameter calibration.

We take this problem as a nonlinear optimization problem. The system parameters with initial sets are taken as the initial values to measure the 3D gauge, then the objective error function is created to optimize the implicit projector parameters. After several cycles, the final system parameters are obtained.

The optimization procedure can be divided into two parts: the creation of the objective error function and the adjustment