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An Integrated Computer-Aided Robotic System for Dental Implantation

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Abstract

This paper describes an integrated system for dental implantation including both preoperative planning utilizing computer-aided technology and automatic robot operation during the intra-operative stage. A novel two-step registration procedure is applied for transforming the preoperative plan to the operation of the robot, with the help of a Coordinate Measurement Machine (CMM). Experiments with a patient-specific phantom were carried out to evaluate the registration error for both position and orientation. After adopting several improvements, the Target Registration Error (TRE) of the system was significantly minimized. The TREs and orientation errors after registration were 0.38±0.16 mm and 0.92±0.16 °, respectively (N=5). The orientation error with phantom experiments were 1.99±1.27 ° (N=14). This permits the ultimate goal of an automated robotic system for dental implantation.

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1 Introduction

Dental implantation is now recognized as the standard of care for tooth replacement [1, 2]. A dental implant is an artificial component, which is inserted into a patient's jaw bone to substitute for the root of a missing tooth. In the U.S., 3 million Americans have implants and that number is growing by 500,000 a year [3].

With a successful dental implantation surgery, the patient is expected to regain both function and appearance of a natural tooth. However, such success requires a high degree of accuracy in the insertion of the implant into the patient's jaw bone, which is hard to achieve by manual drilling as is done traditionally. Technological improvements advanced significantly the accuracy of implantation. Computer-aided planning is becoming more and more popular in dental implantation because of three-dimensional (3D) visualization of patient-specific anatomical information and virtual preview of the implantation outcome. The transferring the virtually planned surgical scheme into real operating outcomes is still a significant challenge. Nowadays, mainly two principles are applied: navigation and surgical guide. Navigation dynamically tracks the position of the surgical tool utilizing a tracking device and shows it to the surgeon in real-time along with the patient's anatomic structures and sometimes with a pre-planned surgical route. Alternatively, a surgical guide (a template) can be fabricated with structures indicating designated positions for drilling, which can be physically accessed by the surgical tool thus tracking is not necessary. Lots of research has been accomplished applying either of these two methods [4-6]. However, in both strategies, the surgical plan is still executed manually by the surgeon, which remains a huge risk for instability and sacrifices the accuracy brought by the computer-aided technology utilized during the preoperative stage.

In this paper, an integrated design of a computer-aided robotic system including both pre- and intra-operative stages for dental implantation is implemented.

2 Methods

In our design, a robot is used for automatic execution of the planned surgical operation, instead of manual drilling by the surgeon. In essence, it can be considered as an improvement of the "surgical guide" type of dental implantation. For a surgical guide system, the guide which assists the surgeon during drilling can be fabricated automatically using a laboratory robot [5]. Therefore, it is rational to skip this step and let the robot do the drilling directly on the patient. In this way, the error introduced by the extra procedure can be eliminated and a more stable and accurate result can be expected.

Registration is essential to transforming the designated parameters from the computer site to the robot site. In order to avoid direct contact of the robot to the patient before the surgery, a third Coordinate System (CS) called the reference CS is introduced to act as a bridge in the registration procedure, therefore enhancing the patient safety. A two-step registration method is proposed with the reference CS.

Since real-time tracking is not necessary in our robotic system, a mechanical measurement device is utilized as the reference CS. It not only avoids the line-of-sight problem of an optical tracking device and the metal-distortion of an electromagnetic tracking device caused by the robot in our application, but also provides superior localization accuracy.

2.1 System Design

The design we proposed is an integrated system for dental implantation, which covers the entire flow of the surgery including preoperative planning, surgical scheme registration and final execution. The components and workflow of the system are shown in Fig. 1. First, the patient's anatomic information is recorded by taking preoperative Cone-beam CT (CBCT) images and a 3D virtual model of the patient's jaw bone is reconstructed accordingly. This model is imported into a planning software for surgical plan generation. A Coordinate Measurement Machine (CMM, Gold Faro from FARO Technologies Inc.) is utilized as the reference CS for registration to transform the preoperative plan to intra-operative surgical parameters. Finally, these parameters are sent to a robot (MELFA RV-3S from Mitsubishi), to which a dental drill-bit is rigidly attached, in order to conduct the designated operation on the patient. The details of each step of our system are discussed below.

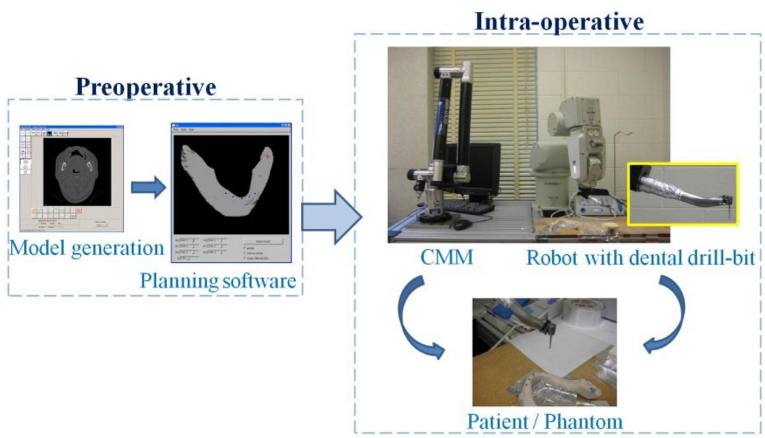
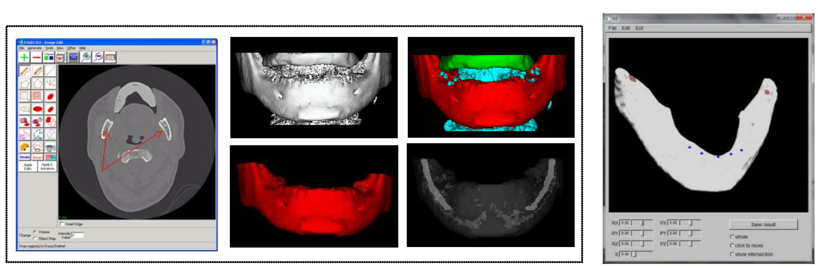


Fig. 1. System design.

2.2 Preoperative Imaging and Model Reconstruction

Before surgery, CBCT images of the patient's jaw bone is taken. A specially designed piece with several fiducials (artificial markers) that are identifiable in CBCT images is fixed on the patient for registration purposes. A patient-specific 3D model with the fiducials and also the inferior alveolar nerve (if mandible) are segmented and reconstructed from the CBCT images, utilizing commercially available software - Analyze 8.1 (AnalyzeDirect, Inc, USA). The lower-right image of Fig. 2(a) shows a mandible model with the inferior alveolar nerves (the light grey curves) segmented.



(a) (b)

Fig. 2. (a) Model reconstruction from CBCT images; (b) Screenshot of the planning software

2.3 Computer-Aided Planning

The patient-specific surgical plan is built by utilizing a planning software implemented by the author. The 3D model of the patient is imported into the software, allowing the user (the dentist) to insert an implant into the patient's jaw bone and check the implantation result virtually. The site-preparation for a single implant requires a cylinder shape hole that fits the implant to be drilled with designated orientation. It can be defined by three parameters: the start and end points of the cylinder's center line, and its diameter. With the help of the planning software, the surgical plan is developed by the dentist, and parameters for drilling are automatically recorded. A screenshot of the software is shown in Fig. 2(b).

2.4 Registration

The preoperative surgical plan needs to be transformed to the intra-operative space of the robot. Three coordinate systems are involved in our system: virtual CS, operation CS and reference CS. The virtual and the operation CSs refer to the patient-specific virtual model and the surgical tool, respectively. Coordinates in the virtual CS are recorded by mouse clicking. In the operation CS, a dental drill-bit is attached to the end-effecter of the robot and their relative position and orientation are calibrated so that when the robot is commanded, the tip of the drill-bit moves accordingly.

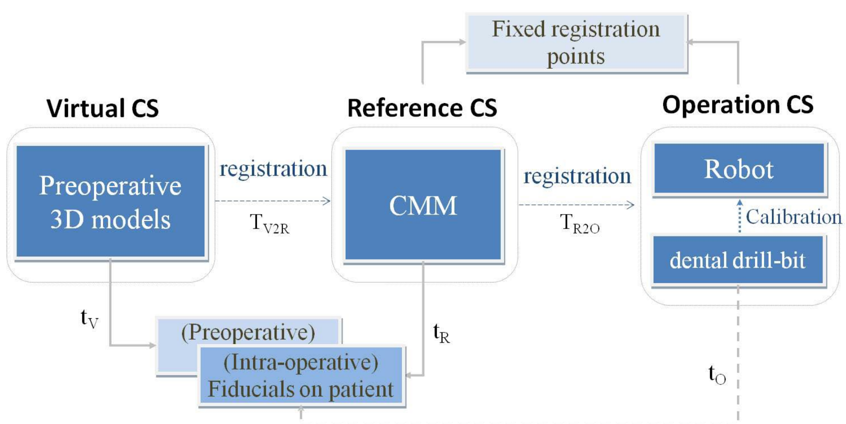


Fig. 3. Relationship of different CSs and registration procedure among them.

Fig. 3 illustrates the two-step registration method in our system. Firstly, registration between the virtual CS and the reference CS is done with a set of points defined by several fiducials rigidly attached to the patient; Secondly, the reference CS and the operation CS are registered using another set of fixed registration points. The transformation matrix transforming coordinates from the virtual CS to the reference CS and from the reference CS to the operation CS are denoted as T_{V2R} and T_{R2O}, respectively. Let the coordinate of the target position be t_V in the planning software (which is the virtual CS), then its corresponding coordinate in the operation CS can be calculated using the following equation, where t_V, t_R, and t_O are the coordinates of the target position in the virtual, reference and operation CS, respectively:

$$t_O = T_{R2O}(t_R) = T_{R2O}(T_{V2R}(t_V)) \ . \qquad \textbf{(1)}$$

A Matlab toolbox for point set registration is used for registration, which applies the Coherent Point Drift (CPD) algorithm [7].

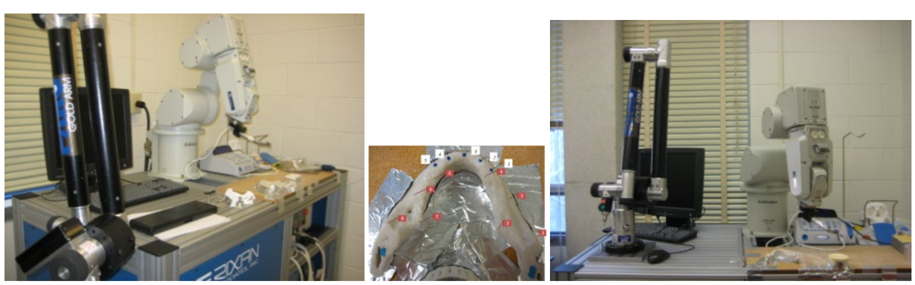
2.5 Robotic Implantation

The robot adopted in our system has 6 Degrees-of-Freedom (DOF) and a position repeatability of ±0.02 mm. Instead of requiring changing drill-bits with different diameters during the implantation as the way manual drilling does, with a single drill-bit rigidly attached to its end-effecter, the robot can function as a high accuracy milling machine. Therefore, no tool changing is necessary. The operation of the robot is controlled by Mitsubishi Electric Factory Automation (MELFA) commands. A sub-routine for cylinder-shape drilling is implemented. Cylinder shape drilling can be done automatically with the coordinates of the start and the end points after registration as well as the diameter of the cylinder.

To ensure the safety of the patient, a point named the "standby" position is defined a certain distance above the start point along the drilling direction. The robot is commanded to move the tip of the drill-bit to this position first while adjusting the orientation of the drill-bit to align the drilling direction. The automatic drilling will begin only if the dentist who supervises the surgery confirms that the position and orientation of the drill-bit are as planned.

3 Phantom Experiments and Results

Phantom experiments were carried out to validate the feasibility of the proposed system. In our earlier work, preliminary position registration results of the system were reported [8]. CBCT images of a patient collected from a Toshiba CBCT scanner with a slice thickness of 0.5mm was reconstructed to a patient-specific 3D model. Five semi-spheres (diameter=1 mm) were artificially created and virtually attached to the model, whose apexes acted as both fiducials and targets (one of them was defined as a target while the remaining four as fiducials for registration). A phantom of the jaw model with the five fiducials attached was printed out using a 3D printer (Spectrum Z510, Z Corp., Burlington, MA, US). Another eight points on the jaw model were defined as fixed registration points for the second step registration. The two-step registration procedure as described in 2.4 was performed. Fig. 4(a) below shows the setup applied in the previous experiments. Two widely used indicators: Fiducial Registration Error (FRE) and Target Registration Error (TRE) [9] were calculated to evaluate the error of the two-step registration procedure. FREs smaller than 0.30 mm and a TRE of 1.42±0.70 mm (N=5) were achieved.



(a) (b) (c)

Fig. 4. (a) Previous phantom experiments setup; (b) Fiducials (italic letters) and registration points (normal letters); (c) Modified phantom experiments setup

3.1 Improvement of Registration Accuracy

As discussed in paper [8], one of the problems affecting the registration error might be the relative movement between the Faro Arm (the reference CS) and the robot (the operation CS). Therefore, we fixed the Faro Arm onto the same table of the robot, so that the spatial relationship of the reference and the operation CS remains rigidly unchanged during the whole procedure. From Table 1, one can tell that the final TREs decreased from 1.42±0.70 mm to 1.14±0.61 mm after the fixation of the Faro Arm.

Also, the original orientation of the X-, Y-, Z-axes relative to the phantom model matters to the registration accuracy. Before, we did not reorient the respective CSs prior to performing registration. However, it is important to realign axes of the "from" CS to align with the "to" CS, in order to get a better registration result. Table 2 gives the results when the CS orientation is pre-aligned. TREs after step1 decreased from 1.09±0.69 mm to 0.24±0.13 mm, and final TREs decreased from 1.14±0.61 mm to 0.38±0.16 mm. Thus, providing a significant improvement in the registration accuracy.

Table 1. Comparison of registration results before and after Faro Arm fixation, and CS orientation pre-alignment

	before Faro fixation				after Faro fixation				after Faro fixation and CS orientation pre-alignment			
	step 1		step 2		step 1		step 2		step 1		step 2	
Target #	FRE	TRE	FRE	TRE	FRE	TRE	FRE	TRE	FRE	TRE	FRE	TRE
1	0.23	1.82	0.19	2.29	0.20	1.90	0.19	1.74	0.10	0.43	0.19	0.42
2	0.29	0.80		0.89	0.27	0.86		1.15	0.15	0.23		0.50
3	0.42	0.16		0.74	0.43	0.26		0.42	0.15	0.23		0.51
4	0.28	0.80		1.18	0.33	0.71		0.64	0.18	0.07		0.13
5	0.23	1.80		2.03	0.26	1.72		1.76	0.16	0.25		0.31
MEAN	0.29	1.08	/	1.42	0.30	1.09	/	1.14	0.15	0.24	/	0.38
SD	0.08	0.71	/	0.70	0.08	0.69	/	0.61	0.03	0.13	/	0.16

3.2 Evaluation of Orientation Error

In order to calculate the orientation angle, a reference plane was introduced and its norm was considered as the reference direction. The physical jaw model was fixed on a wood board, thus we set this board as the reference plane. For the virtual model, a plane that can hold it as the wood board does in the physical world was generated and 10 points on it were measured. The angle between each drilling direction planned and the norm of this plane was calculated. After the two-step registration, orientation error defined as the difference between the angle in the operation CS and the angle in the virtual CS was calculated.

In the phantom experiments, five holes were drilled on a drilling base according to the drilling direction calculated for each target. We did not drill directly with the jaw bone because its material is not suitable for drilling. Further, this experiment was only for the evaluation of orientation error, and therefore, position information did not matter. After drilling, a metal stick magnetically attached to one of the blade edges of a digital protractor was inserted into the drilled hole. The other blade of the protractor was then adjusted to align to the reference direction of the wood plane, which was defined by one side of a rectangular box (Fig. 5(c)). The angle between the metal stick (the drilling direction) and the reference direction was recorded. Table 3 compares the angle for planning and actual drilling.

(a) (b) (c)

Fig. 5. 3D model on the reference plane in (a) the virtual and (b) the reference/ operation CS

Table 3. Orientation error after registration (unit in degree)

planned angle	15°		30°		45°	
Target #	actual angle	error	actual angle	error	actual angle	error
1	18.0	3.00	30.3	0.30	42.1	2.90
2	18.6	3.60	29.6	0.40	44.0	1.00
3	17.0	2.00	/	/	42.8	2.20
4	18.6	3.60	29.2	0.80	40.9	4.10
5	16.1	1.10	29.0	1.00	43.1	1.90
MEAN=	17.66	2.66	29.53	0.63	42.58	2.42
SD=	1.09	1.09	0.57	0.33	1.16	1.16

The orientation errors with three different designated drilling directions are listed in Table 3. The final orientation error in the operation CS after registration is 1.99±1.27°.

4 Conclusion

In this paper, an integrated computer-aided robotic system for dental implantation is described. The system combines both the patient-specific image-guided technology for preoperative planning and automatic robot milling for accurate and reliable intra-operative execution of the surgical plan. A two-step registration with the help of a coordinate measurement machine is utilized to provide high registration accuracy and also ensure the safety of the patient. Several actions were taken to improve the registration accuracy and phantom experiments proved their effectiveness. Our system has high accuracy for both position and orientation, with a target registration error of 0.38±0.16 mm and an orientation error of 1.99±1.27 °. These preliminary results with phantom experiments are encouraging and provide a very good base for ultimate goal of clinical applications. We plan to perform experiments with animal bones to evaluate the system performance in a more realistic scenario. A method for fixation of the patient's head and the design of a better fiducials configuration will be our future work.

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