Computer - Aided Implant Dentistry

– An Early Report –

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Abstract. Computer-aided implant dentistry (CAID), the direct translation of preoperative prosthetic planning to the operating theater by means of image guidance technologies, is a novel application of computer aided surgery (CAS). This work deals with the application of a modular software system for computer-aided interventions to CAID. The system is based on AVW-2.5, a software library dedicated to biomedical image processing, and a custom interface for communication with an optical tracker. A specific CAID toolset was also manufactured. We assessed the performance of two different point-based registration algorithms for this specific application of computer-aided preprosthetic surgery on several jaw models. The fiducial localization error (FLE) achievable with our system was found to be 0.7 mm, the fiducial registration error (FRE) accounted for 0.7 mm, and the target registration error TRE (the overall navigation accuracy) was found to be 1.3 mm. Since these results compare well to the resolution of the high-resolution computed tomography scan used we consider the precision of our system to be sufficient. Future enhancements of our system include the implementation of a medical augmented reality display system and the customization of the software package for exploration of other clinical applications of CAS.

1 Introduction

Implant dentistry is an established therapy for partially and completely edentulous patients. Esthetic, phonetic and functional outcome, the long-term stability of the implant, and the decrease in alveolar ridge atrophy depend on the optimum placement of the implant in the jawbone. A number of techniques are aimed at transferring the preoperative planning data obtained from high resolution computed tomography (HRCT, Dental CT) [5,15] to the operating room. A

straightforward approach is to produce a template of the patients jawbone with drillguides, a so-called splint [5]. The splint can be adapted in such a manner that the preoperative prosthetic planning matches the position of the drillguides. This approach, however, has some severe drawbacks. In completely edentulous patients the severe atrophy of the alveolar ridges renders a reproducible fixation of the splint difficult; this is confirmed by our clinical experience with earlier applications of computer-aided surgery (CAS) and registration techniques based on dental molds [10,16]. Furthermore the distance of the drill tip to critical structures such as the inferior alveolar nerve, the floor of the nasal cavity, or the maxillary sinus cannot be determined exactly during surgery, and interactive decision making based on the intraoperative situation is not possible. Therefore the authors in [10] and [13] have used a commercial CAS system (ARTMA Virtual Patient System, ARTMA Medizintechnik Vienna, Austria) for implantology. These experiments utilized electromagnetic trackers which exhibit erratic behavior in metallic environments [2]; furthermore, a patient-to-CT registration protocol requiring a slice thickness of 3 mm was used. Therefore the accuracy reported was in the vicinity of 3 mm. Visualisation was done on frontal and lateral cephalograms and the original CT-scan. Taking into account the small dimensions of the oral cavity, a more accurate solution had to be found.

In a further step these techniques were refined by adding an optical tracker to the ARTMA system [16]. While the precision of implant drill positioning improved significantly, refining the registration protocol to meet the high accuracy requirements in computer-aided implant dentistry (CAID) was still essential to enhance the clinical applicability of this method. Furthermore, advanced visualization techniques like oblique reformatting, perspective volume rendering, segmentation of anatomical structures like the mandibular canal [14], image fusion of Dental CT with dental magnetic resonance (Dental MR) images [6], and augmented reality visualisation techniques were desired features for visualisation in complicated indications for endosteal implantology.

We therefore decided to develop a programming shell providing a graphical front end to a powerful library for medical image processing; routines for communication with an optical tracker system were added. The modular structure of the system allows for the rapid development of specialized research prototype navigation systems for a wide range of indications. This work deals with the features of VISIT, a first application of this system to CAID.

2 Materials and Methods

2.1 Visualization Hard- and Software

The graphical user interface was developed under Tcl/Tk 8.0p2 (Scriptics Corp., Palo Alto/CA), a scripting language for programming graphical user interfaces [9]. The image processing functionality was added using the Tcl/Tk interface of the AVW-2.5 library functions (Biomedical Imaging Resource, Mayo Clinic, Rochester/MN). A well known software package based on AVW is the Analyze_{AVW} image processing software [12]. A set of routines for communication

Fig. 1. An implant drill (a) and a 5 degree - of - freedom (dof) probe (b). The position and orientation of the drill bit are measured with the LED assembly mounted to the implant drill. The LED assembly can be rotated relative to the drill handle.

with the tracking system over the serial port was also developed and can be found under <http://www.bmtp.akh-wien.ac.at/people/birkwo1/home.htm>. Software development was undertaken in ANSI-C using gcc 2.71 (Free Software Foundation, Boston/MA). The system was finally implemented on a Sun Ultra Sparc 10 running Solaris 2.6 (Sun Microsystems, Palo Alto/CA).

2.2 The Optical Tracking System

The optical tracker used was a Flashpoint 5000 system (Image Guided Technologies, Boulder/CO). A set of light-emitting diodes (LED) for position measurement purposes was attached to a frame made of polyamide and epoxy (Figs. 1, 2). The tools have shown good sterilizability by ethylene oxide, formaldehyde or H_2O_2 plasma. Since the probes do not contain additional softening agents and all cavities in the epoxy resin were removed by evacuation during the curing process, no residual accumulation of ethyleneoxide was detected after several sterilization cycles.

2.3 CT Scanning Protocol, Image Postprocessing

We used a clinical Dental CT – scanning protocol (1.5 mm slice thickness, 1 mm table feed, fast incremental scanning, 120 kV, 150 mAs, 512 * 512 matrix, FOV 120 mm) on a Tomoscan SR6000 (Phillips AG, Best, the Netherlands). A Dental CT investigation usually consists of 20 to 40 slices. In order to achieve isotropic voxel size, we interpolated the raw scan with our software to cubic voxels using AVW-routines. This resulted in a voxel size of typically 0.25 mm^3 .

2.4 Registration Methods

A large number of surface points on the jawbone could be collected by optical or mechanical methods through the oral mucosal tissue and would allow for using point-to-surface registration methods. Since collecting the points has been proven to be difficult and cumbersome in clinical routine we therefore have tested the

Fig. 2. The reference LED emitter array mounted to a maxilla model. The tool is fixed to the patient by means of a single osteosynthesis screw (inserted through the channel denoted by the arrow) and three sharp pins which penetrate the oral mucosa.

Fig. 3. A screenshot of the dialog for identification of fiducial marker positions. The markers (surgical miniscrews made of titanium) are segmented by simple thresholding. By pointing the cursor to the approximate position of the fiducial on the original CT-scan (left part of the screen), a subvolume is identified. The segmented and magnified view at the cursor position can be seen in the middle of the screenshot. By computing an intensity centroid the exact location of the fiducial is determined.

performance of two point-to-point registration algorithms [1,7]. Both techniques utilize implantable fiducial markers and are mathematically equivalent – both solve a general linear least squares problem and yield identical results when using the same input data; the algorithm given in [1] may result in a rigid-body transformation containing a reflection in addition to a rotation. Therefore a larger number of fiducials is necessary. The algorithm in [7] does not show this behavior. To assess whether this difference renders one of the algorithms superior under the special conditions in CAID was an aim of our study. Mathematical algorithms for solving the optimization problem in the registration algorithms (singular value decomposition – SVD, or solution of an eigenvalue problem by Jacobi-transformation) were taken from [11]. Surgical titanium miniscrews used in oral surgery (Leibinger AG, Freiburg, Germany, 2 mm length, 1.8 mm head diameter) were chosen as fiducial markers. Clinical tests had shown that three or four of those miniscrews can be implanted preoperatively under local anesthesia. They show good stability, require little effort by the surgeon and cause only little discomfort to the patient.

Fiducial positions are allocated by identifying a miniscrew on the CT-scan and by segmenting the head of the screw by intensity thresholding using a semi-automatic segmentation technique. The resulting binary image is shown under 5× magnification (Fig. 3). The exact location of the screw head is determined by calculating the intensity centroid within the binary subvolume around

Fig. 4. The reformatted sets of orthogonal slices are determined as a plane perpendicular to the drill bit, a plane normal to a vector which is normal to the drill bit and intersects the central axis of the Dental CT scan, and a plane normal to both of these.

Fig. 5. Visualisation of the current drill position. Like in many other CAS systems, the drill position is visualised by means of three obliquely reformatted views orthogonal to each other (right half of the screenshot). The left half of the window shows the original scan.

the screw. Image processing functionality was again taken from the AVW-library. Completely automatic detection and segmentation of fiducial positions based on this method is also possible but is not recommended in our application since the performance of the automatic fiducial detection algorithm might be significantly reduced by spray artifacts from metallic materials like dental metallic fillings.

2.5 Visualization Methods

Positioning of the implant drill relative to the jaw was visualized by means of a set of orthogonal slices aligned relative to the implant drill axis. This technique has proven useful in many systems for CAS; the tool coordinate system is chosen according to Fig. 4. One slice is orientated perpendicular to the axis of the drill and another slice is perpendicular to this plane whereby it's normal vector intersects the central axis of the axial CT scan; the third slice is orthogonal to both of these.

2.6 Accuracy Tests

The accuracy of the complete system was tested using five epoxy models of typical situations in implant dentistry. The models were manufactured by casting molds from plastic teaching dummies (Fig. 6). Landmarks for assessing the accuracy of the complete setup (steel spheres, 0.5 mm diameter) were fixed to

Fig. 6. Partially edentulous models representing typical cases in implant dentistry; a.) represents a mandible with a single gap and a terminal gap, b.) a maxilla model with a terminal gap on both sides, and c.) a maxilla model with a frontal gap. Completely edentulous models with atrophic alveolar ridges were also prepared. d.) is a mandible model, and e.) represents a maxilla. Broad arrows indicate the location of some of the fiducial markers, and small arrows point to some of the landmarks used for assessing the system's accuracy.

the surface in addition to the fiducial markers. The landmarks were not used for registration. The total positioning error was assessed as the difference between the positions of the landmarks on the CT-scan and the position of the landmark after position measurement with the 5 degree-of-freedom (dof) probe transformed back to the CT-volume. The quantities influencing the precision of the navigation system were assessed experimentally as the intrinsic accuracy of the tracking system (or fiducial localization error – FLE), as the error in registration as reported by the cost function of the registration algorithm (fiducial registration error – FRE), and as the error in localization of arbitrary targets (target registration error – TRE). A detailed analysis of these quantities can be found in [4].

3 Results

3.1 Intrinsic Accuracy of the Tracking System – FLE

In a first step, we have estimated the fiducial localization error FLE by taking ten measurements of a fiducial marker on a jaw model while varying systematically the positions of the model and the 5 dof – probe (Fig. 1). The compound error of these point measurements relative to the reference sensor (Fig. 2) for ten different fiducials accounted for 0.69 ± 0.15 mm; details are given in table 1.

3.2 Fiducial Registration Error FRE, Target Registration Error TRE, and the Reliability of Registration Algorithms

The fiducial registration error and the target registration error were also measured by collecting position measurements of the fiducial markers and additional

Measurement #	Fiducial Localization Error - FLE [mm]
1	0.64 ± 0.52
2	0.87 ± 0.36
3	0.63 ± 0.32
4	0.67 ± 0.27
5	0.84 ± 0.29
6	0.91 ± 0.20
7	0.46 ± 0.31
8	0.60 ± 0.29
9	0.74 ± 0.28
10	0.54 ± 0.35
Average	0.69 ± 0.15

Table 1. FLE – The repeatability of fiducial position measurements using the optical tracking system. Each fiducial position was measured ten times while varying the location of the 5-dof measurement probe relative to the model. Positions were measured relative to the reference sensor (Fig. 2).

# of Fiducial Markers	Fiducial Registration Error [mm] - FRE -	Target Registration Error [mm] - TRE -	Success Rate of SVD-based Registration Algorithm
3	0.71 ± 0.12	1.23 ± 0.28	40 %
4	0.70 ± 0.12	1.25 ± 0.31	80 %
5	0.76 ± 0.06	1.31 ± 0.28	100 %

Table 2. Fiducial registration error FRE, target registration error TRE and the mathematical stability of the SVD-based registration algorithm given in [1] as a function of the number of fiducials used. Values were acquired in the five models shown in Fig. 6 and averaged.

landmarks on the models shown in Fig. 6. The two rigid-body point based algorithms (see section 2.4) were used on identical position data. No difference in the resulting registration error FRE and the localization error TRE (measured by comparing the target position transformed to CT-space to the original position in CT space) could be found for these two algorithms. An interesting finding when using three or four fiducials is, however, the fact that the SVD-based algorithm given in [1] occasionally fails. For CAID, the algorithm given in [7] appears to be superior under the aspects of reducing discomfort for the patient during the implantation of the fiducial markers and intraoperative time-requirements during registration; stable values can always be achieved by using only three markers. The usage of up to two additional markers did not improve TRE significantly. On average, FRE was found to be 0.7 mm, whereas TRE typically accounted for 1.3 mm. Results for the five models (Fig. 6) are shown in table 2.

3.3 Software Engineering Aspects of a Modular Software Toolkit for CAS

Within six man-months a prototype of the system was developed. The task of programming a graphical user-interface was significantly simplified by using Tcl/Tk. Since Tcl/Tk, AVW, and our custom developed routines can be used under different operating systems such as Solaris, IRIX, Windows NT and others,

this combination appears to be a flexible solution to develop further software applications for CAS.

4 Discussion

Dental CT is becoming a more and more used tool for planning of endosteal implants [5,15]. Image guidance is a logical adjunct to this method; pathologies of the alveolar ridge due to atrophy or bone augmentation can be easily visualized and might help even experienced oral surgeons to monitor the result to be expected in delicate intraoperative situations. The positive influence on postoperative outcome as well as surgical performance has yet to be assessed.

Despite the small dimension of the oral cavity which implies an inferior signal-to-noise ratio in fiducial localization, our results for TRE in CAID compare well to the accuracy of other CAS applications, and, more important, are close to the resolution of Dental CT (typically $0.25 * 0.25 * 1.00 \text{ mm}^3$) which limits navigation accuracy in general.

Future efforts should focus on reducing the variance of TRE. However, this is achievable by improving the tracker hardware and utilizing dual point-to-point/point-to-surface [8] registration approaches. We consider the usage of surface registration methods to be infeasible in CAID; nevertheless we believe that a point-to-point registration algorithm combined with a surface registration method applied to the small area accessible intraoperatively after surgical preparation of the mucosal flap might improve TRE.

Currently we are in the process of undertaking corpse studies and first clinical trials with our system. Besides refining the planning capabilities of VISIT, the most important visualization problem to be solved might be displaying the drill position in comparison to the planned implant site. The usage of head-mounted augmented reality display technologies for interactive visualisation at the operating field provides a method for achieving this goal. These technologies as well as the implementation of hybrid tracking technologies [3] might also further enhance the clinical impact of this technology.

Besides these technical aspects, the most important point in assessing the clinical relevance of CAID is the comparison of this method to common splint based techniques. From our clinical experience, however, we expect a dramatic improvement in implant placement precision in edentulous patients where templates are bound to fail.

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