Real-Time Marker-Free Patient Registration and Image-Based Navigation Using Stereovision for Dental Surgery

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Abstract. Surgical navigation techniques have been evolving rapidly in the field of oral and maxillofacial surgery (OMS). However, challenges still exist in the current state of the art of computer-assisted OMS especially from the viewpoint of dental surgery. The challenges include the invasive patient registration procedure, the difficulty of reference marker attachment, navigation error caused by patient movement, bulky optical markers and maintenance of line of sight for commercial optical tracking devices, inaccuracy and susceptibility of electromagnetic (EM) sensors to magnetic interference for EM tracking devices. In this paper, a new solution is proposed to overcome the mentioned challenges. A stereo camera is designed as a tracking device for both instrument tracking and patient tracking, which is customized optimally for the limited surgical space of dental surgery. A small dot pattern is mounted to the surgical tool for instrument tracking, which can be seen by the camera at all times during the operation. The patient registration is achieved by patient tracking and 3D contour matching with the preoperative patient model, requiring no fiducial marker and reference marker. In addition, the registration is updated in real-time. Experiments were performed to evaluate our method and an average overall error of 0.71 mm was achieved.

Keywords: marker-free registration, image-based navigation, image tracking, stereovision, dental surgery.

1 Introduction

Computer-assisted oral and maxillofacial surgery (OMS) has been rapidly evolving in the last decade [1]. The categories of the computer-assisted OMS technology can be roughly divided into surgical simulation and surgical navigation in terms of whether it is performed in the surgical planning phase or the surgical phase. In preoperative simulation, 3D models of the surgical site are created from preoperative medical images as the counterparts in the virtual space. Surgeons can perform various inspections, measurements and labeling on the models and make detailed surgical planning

C.A. Linte et al. (Eds.): MIAR/AE-CAI 2013, LNCS 8090, pp. 9–18, 2013.

with the help of a computer. In addition, virtual surgical procedures could also be carried out to simulate the real ones by means of special software and haptic devices [2-4]. In intra-operative navigation, a tracking device is used to track the surgical instrument whose position and orientation are mapped into the corresponding model space via a registration procedure. By this way, the relative spatial relationship between the instrument and the surgical site is related and visualized, hence being able to transfer the premade surgical plan accurately.

In one branch of OMS, dental surgery is carried out within the limited space (i.e. the mouth) and the surgical navigation for dental surgery is subjected to patient movement especially when the surgical site is located on the mandible. Some commercially available navigation systems and prototypes for dental surgery have been reported and evaluated [5-11]. However, several disadvantages still exist in these navigation systems. Firstly, all of the systems employ either optical trackers or electromagnetic (EM) trackers to locate surgical instruments intra-operatively. Currently used optical markers are bulky compared with the small operative field, which makes it inappropriate to be attached on either the patient or the instrument. An EM tracker has relatively lower accuracy and is susceptible to metallic materials, which may cause the tracking to be unstable in an operating room environment. Secondly, a reference marker is required to be attached to the patient to deal with patient movement. The use of a reference marker is either invasive (screwed into the bone) or error-prone (attached on the skin or using specific casts). Lastly, the image registration procedures are cumbersome and invasive. For better registration accuracy, fiducial markers are usually used. Similar to the attachment of the reference marker, the attachment of fiducial markers either is invasive to patients or requires a cumbersome patient-specific casts which is error-prone.

In this paper, a new solution is proposed to overcome the mentioned disadvantages. A stereo camera is designed as a tracking device for both instrument tracking and patient tracking, which is optimized and configured for the limited surgical space of dental surgery. A small dot pattern with the size 30 ×30 mm is mounted to the surgical tool for instrument tracking, which can be seen by the camera at all times during the operation. The patient registration is achieved by patient tracking followed by real-time 3D contour matching with the preoperative patient model, which requires no fiducial marker or reference marker.

2 Stereo Camera Tracking System

2.1 Stereo Camera

The stereo camera consists of two CMOS cameras with USB3.0 interface separated at a distance of approximate 120mm, as shown in Fig. 1(a). The maximum frame rate is 60 frames per second (fps) with image resolution 1280×1024 pixels. The stereo camera is calibrated using a 7×7 dot array pattern plate with the size 100×100 mm. The left and right images are undistorted and rectified so that only horizontal parallax exits between them. The intra-operative configuration of the stereo camera is illustrated in Fig. 1(b). The camera is looking down at the operative field (including the upper and lower teeth) at a distance of approximate 460 mm. The overlap view of the two cameras sufficiently covers the entire range of motion for the surgical instruments. This configuration has two advantages: one is that the measurement geometry is customized optimally for the limited operative field so as to achieve better accuracy; the other is that it is easy to maintain the line of sight between the camera and the instrument during the operation.

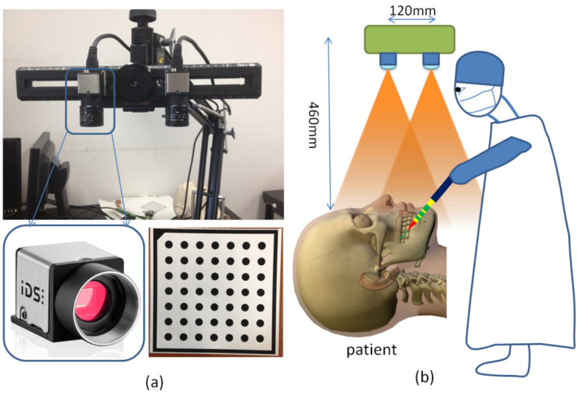

Fig. 1. (a) Stereo camera and calibration plate (b) Intra-operative configuration

2.2 Instrument Tracking

A small tool marker is designed to be attached on the surgical tool for the instrument tracking task. As shown in Fig. 2(a), the tool marker is composed of a resin mounting base fabricated by a 3D printer and a 3×3 dot array pattern for stereo tracking. The surgical tool has a cylindrical profile whose axis is perpendicular to the plane of the pattern. Fig. 2(b) shows the assembly of the two parts. The tip offset of the tool in the tool marker frame is determined by the geometry of the design (or, pivot calibration). The dot array patterns are recognized in both left and right images after which dot centroids are extracted with sub-pixel accuracy. Three-dimensional coordinates of the dot centroids are then calculated by triangulation. The pose of the tool marker frame is therefore calculated by matching the local coordinates in the marker frame to the calculated coordinates in the stereo camera frame. The pose of the tool tip frame is further obtained by a post concatenation of the fixed transformation matrix from the tool marker frame to the tool tip frame.

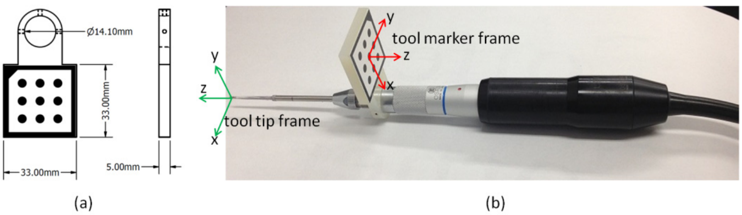

Fig. 2. (a) Tool marker (b) Surgical instrument with the tool marker

3 Real-Time Marker-Free Patient Registration

Patient registration or image registration is a key procedure to associate the surgical object with its virtual counterpart. The resulting transformation matrix is used to map the pose of the surgical tool tracked by the stereo camera to the pose in the preoperative image frame, by which computer graphics (CG) techniques could be applied to navigate the surgical procedure. The proposed patient registration is achieved by patient tracking followed by matching the 3D contour of the tracked object to its preoperative image in real-time.

3.1 Patient Tracking

The patient tracking here refers to the 3D contour tracking of the teeth. Fig. 3 shows the stereo images of a surgical scene (simulated) of dental surgery on lower teeth. The operative field indicated by the red rectangles is exposed to the stereo camera using a dental clamp. Owing to the high contrast between the teeth and the background oral cavity, the 3D contour of the teeth (front teeth) could be easily extracted by the following algorithm. The region of interest (ROI) indicated by the yellow rectangle is selected manually only in the first frame of the left camera, which is used as a 2D template. Normalized cross correlation based template matching is performed in the corresponding right image and following frames to locate the ROIs. 2D contours of the front teeth within the ROIs in the stereo images are then extracted with sub-pixel accuracy. For each point on the left contour, the corresponding point on the right contour is obtained by epipolar constraint searching (they are supposed to have the same y image coordinate). The 3D contour is finally reconstructed using stereo triangulation. The algorithm also can apply to the upper teeth. By this way, the 3D contour is tracked in real-time.

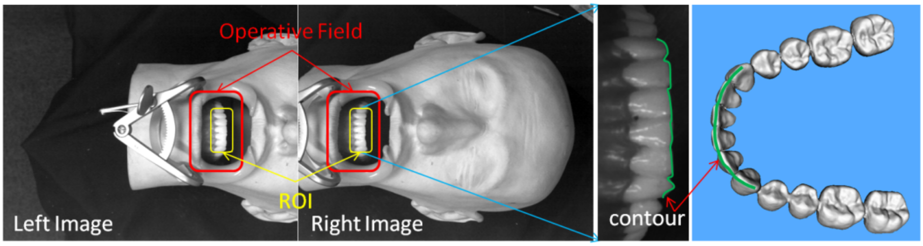

Fig. 3. Simulated surgical scene and 3D contour of teeth

3.2 3D Contour Matching

We have so far explained the intra-operative acquisition of the teeth's geometric data. Next, this intra-operative data will be registered to the preoperative one. As the teeth are rigid objects, there is a high fidelity between their intra-operative shapes and the model created from the preoperative CT image. We first obtain the same contour on the model preoperatively and then match the two contours intra-operatively.

Model Contour Extraction. The triangle mesh model of the lower tooth crowns is created by an iso-surface extractor and is rendered by OpenGL as shown in Fig. 4(a). The OpenGL camera is adjusted to prepare a view for front tooth edge extraction shown in Fig. 4(b). The foreground and background of rendered image (b) are segmented using the OpenGL z-buffer as shown in Fig. 4(c). Those pixels whose z-buffer value is -1 are classified as background (white), otherwise they are classified as foreground (black). Then the edge detection of the front teeth could be easily carried out to obtain the 2D contour indicated by the red curve. Finally, 3D coordinates of the extracted 2D contour is reconstructed according to the additional z-buffer values held in the OpenGL frame buffer. The recovered 3D contour (red points) is shown in Fig. 4(d). Note that the above procedure needs to be done only once preoperatively.

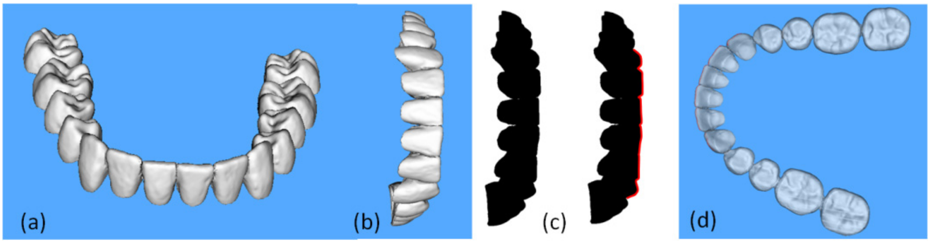

Fig. 4. (a) Surface rendering of lower tooth crowns (b) Prepared view for contour extraction (c) Binary z-buffer image and edge extraction (d) Recovered 3D contour

ICP Matching. The intra-operatively tracked tooth contour is registered to the preoperative one using the iterative closest point (ICP) algorithm [12]. To avoid converging to local minima, the principal axes of the two point sets are calculated which are used together with their centers for initial match. The initial match is easily achieved by transforming the frame consisting of the center and the three orthogonal principal directions of the tracked contour to that of the extracted model contour. After the initial match, the ICP algorithm is applied to further refine the alignment between the two contours. By this way, the transformation from the model frame to the stereo camera frame is obtained, which is used to map the surgical instrument to the atlas for surgical navigation. The above procedure is carried out just after the intra-operative tooth contour is successfully tracked.

4 Experiments and Results

All experiments were performed using a computer with an Intel Core i7-3960 CPU@3.30GHz and 16GB memories. The stereo camera worked in a monochrome mode with 60 fps and was connected to the computer workstation by USB3.0 interface. C++ and OpenGL4.3 were adopted for algorithm implementation.

4.1 Instrument Tracking Evaluation

The experimental setup is shown in Fig. 5. The instrument with the tool marker is fixed on a 3D stage whose step resolution is 0.01mm.

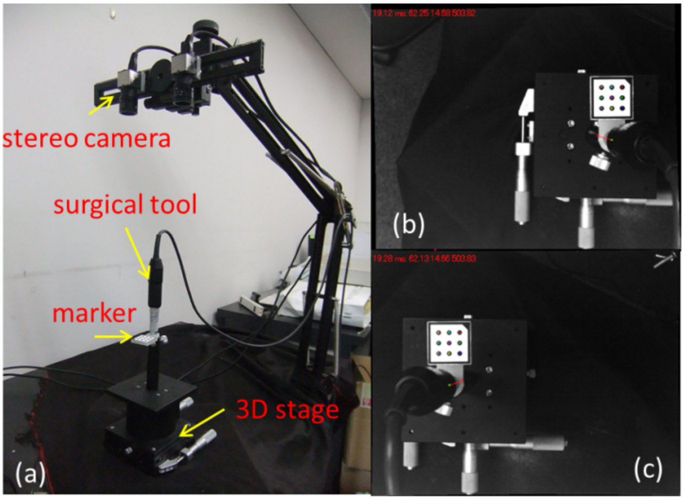

Fig. 5. (a) Experimental setup (b) /(c) Left/right image of instrument tracking

Tracking Precision Evaluation. The tool tip frame (represented by the origin x, y, z and the XYZ type Euler angles α, β, γ) was tracked while keeping stationary. 6400 samples were acquired to evaluate the tracking precision statistically and the results are shown in Table 1, where the range is defined as the absolute difference between the maximum and the minimum; std represents the standard deviation. The average tracking time was 18 milliseconds.

Table 1. tracking precision evaluation

	x(mm)	y(mm)	z(mm)	α(deg)	β(deg)	γ(deg)
range	0.305	0.340	0.098	0.199	0.188	0.031
std	0.043	0.044	0.013	0.026	0.026	0.004

Tracking Accuracy Evaluation. For accuracy evaluation, the stage was moved every 10 mm along its x, y axis and 5 mm along the z axis. The tool tip position was recorded at each position to create a 5×5×5 spatial dot array which would be registered to the ground truth using a point-based registration algorithm. The FRE (fiducial registration error) was used to evaluate the tracking accuracy which is given by

$$FRE = \sqrt{\frac{\sum_{i=1}^{N} \left\| \boldsymbol{y}_i - (\hat{\boldsymbol{R}}\boldsymbol{x}_i + \hat{\boldsymbol{t}}_i) \right\|^2}{N}} \tag{1}$$

Where $\boldsymbol{x}_i$ and $\boldsymbol{y}_i$ are corresponding points; $\hat{\boldsymbol{R}}$ and $\hat{\boldsymbol{t}}$ are the estimated transformation to transform the recorded dot array to the ground truth; N is the number of points (equal to 5×5×5). The alignment result is shown in Fig. 6 and the FRE was 0.15 mm.

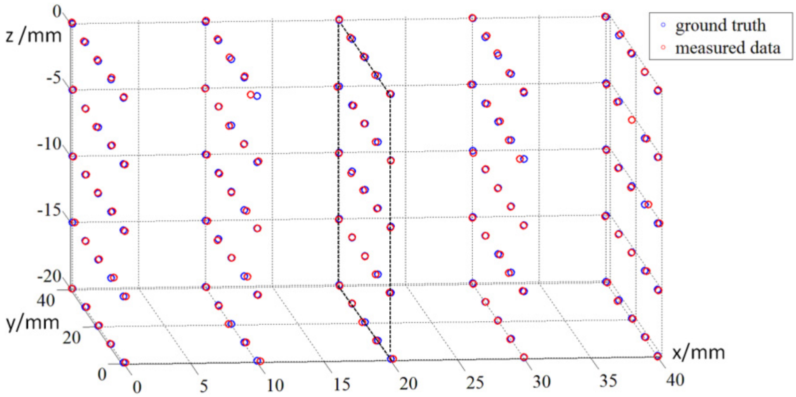

Fig. 6. Tracking accuracy evaluation

4.2 Patient Tracking and Matching Evaluation

Tooth models (lower and upper teeth) were created using a 3D printer from the segmented CT data of a patient and were assembled with a head phantom, which aimed to simulate the real surgical scene. The phantom was moved with different position and orientation. The stereo camera tracked the teeth and matched them to the preoperative model in real-time. The tracking and matching results of upper teeth are shown in Fig. 7. The average time cost was 35 milliseconds for one pair of frames.

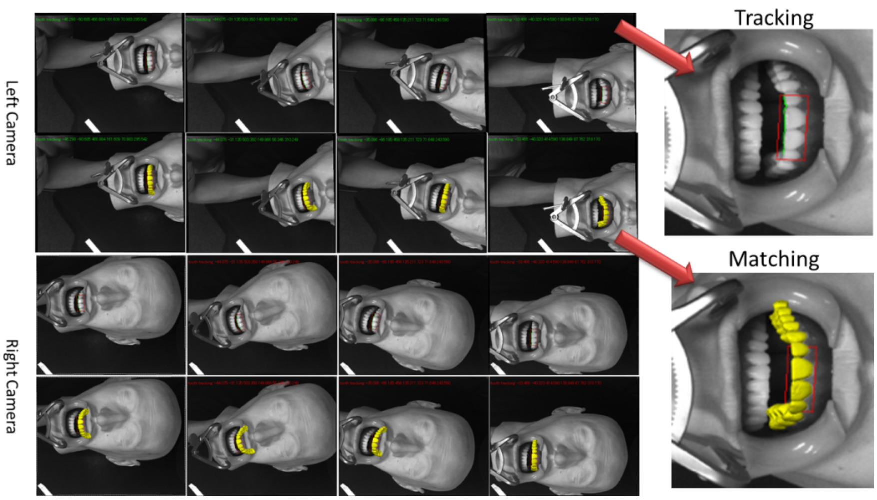

Fig. 7. Patient tracking and matching evaluation

4.3 Image-Based Navigation Evaluation

Dental navigation experiments were carried out to evaluate the overall error of the proposed method, which includes the device tracking error, the real-time registration error (further including the patient tracking error and the ICP matching error) and the manual error caused by hand tremor. For each frame pair of the stereo camera, both patient tracking and instrument tracking are performed. The former is to update the registration matrix and the latter is to map the surgical tool into the CG model space for visualization. Fig. 8 shows the navigation interface demonstrating a drilling process between adjacent tooth roots.

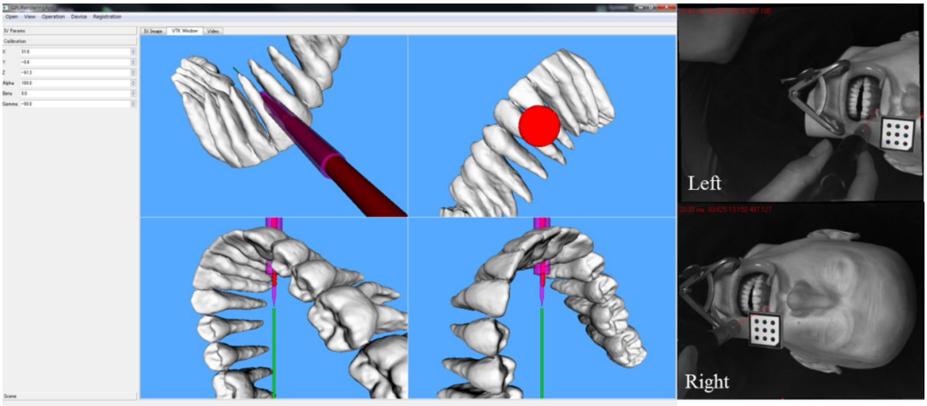

Fig. 8. Image-based navigation

A post evaluation method was used for accuracy evaluation. As shown in Fig. 9, 10 entry points were made on the CG model of maxillary teeth (a); drilling operation targeting at those entry points on the corresponding phantom (b) was guided using our proposed method; 3D scan (c) of the phantom after drilling were obtained and was aligned with the preoperative CG model (d). The deviation between the preplanned entry points and the real drilled points were measured on the overlaid CG models as overall navigation errors. The results are summarized in Table 2.

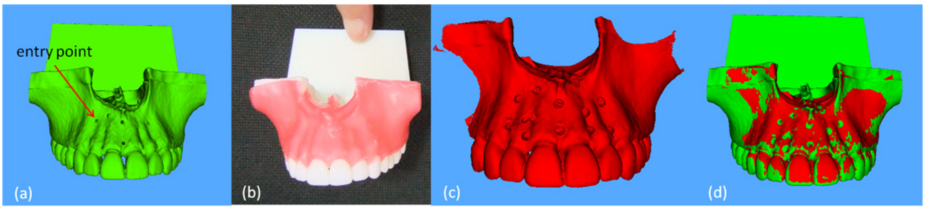

Fig. 9. Post evaluation (a) CG model with entry points (b) Model for drilling (c) 3D scan of the model after drilling (d) Overlay of the CG model and the post-3D scan

Table 2. error measurement

point index	1	2	3	4	5	6	7	8	9	10	mean
error (mm)	0.67	0.89	0.28	1.08	0.75	0.66	0.88	0.86	0.62	0.44	0.71

5 Conclusion

An image-based navigation method using stereovision for dental surgery without invasive and/or cumbersome patient registration procedures has been presented. The stereo camera has stable tracking precision and satisfactory accuracy of less than 0.2 mm. The proposed registration scheme works in a tracking-matching way which can deal with the patient movement. The total time cost of the instrument tracking and the patient registration is less than 60 milliseconds which is fast enough for clinical use. Benefitting from the real-time registration, it is free to adjust the stereo camera or move the patient intra-operatively, in which case the registration matrix can be accordingly updated within less than 1 second. Surgeons would not feel the existence of the registration procedure, although it indeed exists. Experimental evaluations on the stereo tracking device, the real-time registration and the overall accuracy of navigation were carried out and an overall navigation error of 0.71 mm was achieved. Note that the overall error also includes the manual error during drilling. That is why we chose to evaluate the error at entry points. Even though the navigation system gives correct current position and orientation, the drilling path may deviate owing to the hand tremor. A robotic arm or holder may help in reducing the manual error.

Acknowledgements. This work was supported in part by Grant for Translational Systems Biology and Medicine Initiative (TSBMI) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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