Fiducial-free Endoscopic Vertebra Referencing

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1 Introduction

Over the past decade computer aided, navigated surgery has evolved from early laboratory experiments to an indispensable tool for many interventions in spine surgery.

Accurate patient registration with the pre-operative imaging modalities or referencing of the target anatomical structure is an essential component of these procedures. Many of today’s approaches are invasive and use either mechanical fixation devices, fiducial markers, ionizing radiation or require tedious manual registration with a pointing device.

While the potential of ultrasound imaging for non-invasive registration and referencing is currently explored \cite{1} its usability is constrained by the presence of air-filled cavities in the body.

In this paper we present a novel approach that uses a tracked monocular endoscope to register and reference vertebrae during spine surgery. By tracking natural landmarks over multiple views, a 3D reconstruction of the surgical scene can be computed using photogrammetric methods. The proposed algorithm consecutively refines the 3D model with each additional view. This reconstruction provides quantitative metric data about the target anatomy which can be used for 3D-3D registration of the anatomy to the pre-operative data and for further referencing. Our aim is to create an intra-operative support environment, which relies as much as possible on the tools and instrumentation used anyway during surgery and does not increase the invasiveness of the intervention just for navigation purposes.

The presented method is general and can be used for any rigid anatomical structure with sufficiently textured surfaces. In this paper, the results of a series of cadaver experiments are presented.

2 Related Research

Various approaches have been proposed to provide the surgeon with more information during endoscopic interventions. Most of them are tailored to specific procedures and are of limited general applicability. In particular the following application fields can be identified: (a) registration and referencing, (b) navigation aids, and (c) augmented reality.

A fiducial marker based system for referencing the vertebrae using an endoscope has been presented in in \cite{2}. The use of markers, however, often forces
the surgeon to increase the invasiveness of the intervention just to be able to perform referencing during the surgery. In [3], a hybrid tracking system is proposed using a magnetic tracking sensor and image registration between real and virtual endoscopic images to compute the pose and position of the camera in the CT coordinate frame.

A non-tracked calibrated endoscope for 3D reconstruction and motion estimation from endo-nasal images is used in [4] for registering the CT to the endoscopic video.

Augmented reality systems are not necessarily aiming at quantitative measurements but rather want to improve the visual perception for the surgeon by extending the image with additional information. In [5] externally tracked cameras are used to augment the surgeon’s view by fusing pre-operative data with the actual endoscopic view. In contrast, [6] uses a stereo endoscope instead of a tracker for 3D-3D registration of the surgical scene with the pre-operative model data.

3 Methods

The entire setup is depicted in Fig. 1a). For all experiments a 10 mm radial distortion corrected endoscope (Richard Wolf GmbH) with an oblique viewing angle of 25° was used. To avoid interlacing artifacts, a progressive frame color CCD camera with a resolution of 800 × 600 pixels and 15 fps was used. As the depth-of-field of the endoscope/camera combination is in the range of 3 – 8 cm the focal length of the camera can be kept constant during the entire procedure, allowing to avoid the recalibration of the system during surgery.

A marker is attached to the endoscope that is being followed by the active optical tracker (EasyTrack500, Atracsys LLC). The EasyTrack provides accurate position (less than 0.2 mm error) and orientation information in a working volume of roughly 50 × 50 × 1500 cm³. An external hardware triggering logic ensures the synchronized acquisition of the tracking data and the camera images during dynamic freehand manipulation.

The entire setup is portable and can be installed in a sterile OR environment within minutes. The intrinsic camera and the extrinsic camera-marker calibration can be performed pre-operatively in one step by the surgeon without requiring assistance from a technician [7].

The near real-time 3D reconstruction algorithm developed in [8] is used to process the endoscopic video stream and to build the 3D point cloud of the surgical scene as it can be seen in Fig. 1b). Although containing all necessary information, the point cloud model is not very intuitive for the surgeon. Therefore an additional rendering step has been introduced, which converts the point cloud into a textured triangle mesh, resulting in nearly photorealistic 3D models of the surgical scene, refer to Fig. 1c). This facilitates the manual initialization for the 3D-3D registration. A point to surface registration variant of the iterative closest point (ICP) algorithms is used. The initialization for the ICP is done manually by roughly overlaying the models on the screen.

As the reconstructed model usually also covers the surrounding tissues of the C2 vertebra as well as parts of C1 and C3, and the CT model represents also parts of the C2 vertebra that are not visible to the camera, this creates additional constraints for the ICP registration. Therefore an additional filtering
step is introduced, identifying the C2 points in the reconstructed model and the surface parts of the CT model that actually overlap. This is based on the manual initialization and removes point to surface constraints that might falsify the registration. In order to compute a good registration it is mandatory that both the CT and the reconstructed model show distinguishable structure. The result from the registration step can be seen in Fig. 1d).

Figure 1: a) The setup used throughout these experiments, b) example point cloud from C2 vertebra, c) registered CT model, d) nearly photo-realistic rendering of the scene

4 Results

For this experiment the vertebra of the cadaver was fixed and 20 different sequences recorded followed by the 3D reconstruction. Each of the resulting models then was registered to the CT data using the Point to Surface ICP. Then the spatial transformation between the registered models was measured, resulting in a standard deviation of $\pm 1.5$ mm in the position, and $\pm 2.0^\circ$ for the rotation around the mean transformation. In average 150 images ($\pm 30$) per sequence were used to reconstruct a point cloud of averagely 2400 3D points ($\pm 400$). The pre-filtering step, deciding which parts to use for registration for both models significantly improves the accuracy, as experiments without that step showed inferior results ($\pm 4.2$ mm and $\pm 5.1^\circ$).

5 Discussion

In this paper, a purely optical natural landmark based registration and referencing method using a tracked monocular endoscope was presented. The method is non-invasive and no fiducials or other synthetic landmarks are required. Rigidly registering the 3D reconstruction to the pre-operative 3D CT model using point-to-point ICP resulted in an error of 1.5 mm proving the applicability of the proposed procedure for non-invasive registration or referencing during navigated spine surgery. The errors are significantly higher compared to the phantom experiments, but the main contribution to the error is coming from the registration step. The current implementation is very sensitive to the manual initialization. Thus further work focuses on the improvement of this step and allow fully automatic registration. The need for texture and distinguishable
structure on the object for the registration are the two main short-comings of the algorithm.

References


