ROBUST SURFACE BASED REGISTRATION IN AN OPEN FRAMEWORK FOR IMAGE GUIDED SURGERY

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ABSTRACT
Image guided surgery has established as a valuable routine methodology in modern operation theatres, especially when targeting obscured morphology or for exact positioning of tools. In cerebral surgery image guidance has a long tradition, even in orthopedics; recently it also extends to abdominal surgery. The software packages are highly task specific and complex, thus the systems are hardly extendible. But in a research environment, an open software architecture is highly desirable. In this work a surgical navigation framework is presented based on a hardware abstraction layer, with a DeviceServer as a central service. It allows seamless communication with any type of tracking, video, and haptic devices via network and makes the actual application platform and language independent. The top software layer is a generic surgical navigation framework based on the Matlab® scripting language. The great functionality and easy handling of Matlab® facilitates rapid prototyping of new components in image guided surgery. The development needs no highly specialized software experts and is suitable for the interdisciplinary staff of a research lab. As a showcase for the newly developed system, a registration algorithm to match the coordinate systems of an optical tracking system and patient image data is implemented. It is a surface-to-points algorithm, characterized by robustness, stability and usability. Iterative registration is implemented as a steepest gradient procedure and distances are measured with a three dimensional chamfer map. The registration yields accurate overlay of the coordinates, allowing exact positioning of surgical tools. Because of the easy handling and extensibility, the developed rapid prototyping environment has high potential in clinical research facilities.

Keywords: image guided surgery, medical image processing, virtual reality, augmented reality

1. INTRODUCTION

Modern image based surgical navigation developed within the last three decades. The historical roots of intraoperative navigation go back to frame-based stereotaxis, a technique utilizing preoperative images to facilitate inter-operative guidance, thus enabling the exact targeting of intracranial structures to place needles, catheters or electrodes. The surgical trajectory is guided to avoid damage in functional centers of the brain and to minimize craniotomy, thus providing saver surgery and shorter anastasis.

In the 1990s the concept of frameless stereotaxis was introduced to neurosurgery. It was the first modern navigation system employing the capabilities of novel imaging modalities and real-time tracking of surgical instruments, both merged by powerful computer technology and graphics (Enchyev 2009). Image guided navigation is characterized by two phases, the planning phase outside the operating room (OR) comprising preoperative data acquisition, visualization and planning, and the intra-operative phase in the OR, with registration of image and patient coordinates, tool-tracking and intraoperative visualization. This needs special equipment to meet the standards of an aseptic environment. This modern methodology was highly beneficial for patient care and economical aspects of treatment (Paleologos et al. 2000).

The technique is refined with the development of functional MRI, enabling the exact localization of functional foci, e.g. the centers of motoric activities, speech, or visual perception in the brain cortex. The planning of the surgical trajectory accounts for avoiding functional handicaps after surgery (Nimsky et al. 2005).

Preoperative image acquisition is not sufficient for exact localization of tools in the image volumes, especially in soft tissue surgery, e.g. the brain-shift after opening the dura mater. It is compensated by intra-operative imaging or computational assessment of the deviations with respective virtual deformation of the image volume (Hatiboglu et al. 2009, Liu et al. 2014, Reinbacher et al. 2014, Scheufler et al. 2011).

Orthopedic surgery is a broad field for surgical navigation techniques, ranging from hip and knee to spine surgery. The applications comprise exact replacement of pathologic morphology, the positioning of artificial joints or screws and the use of surgical robots (Blackeny et al. 2011, Kelly and Swank 2009, Mason et al. 2007, Verdú-López et al. 2014).

Much research effort is done in this field on model based navigation. In contrast to the previously discussed image guided methods, a model of the surgical target is adopted according to intra-operative measurements of control points. This needs no imaging modalities and prevents the patient from potential risk of radiation (Habor 2013).

The development leads to navigation of information, i.e. the aggregation of all kind of information from all available sources stored in Pictures Archiving and Communication System (PACS) and the Hospital Information System (HIS). Data are filtered and processed for intuitive representation in the OR. This “digital OR” is the high end development of the top system providers (Malarme et al. 2008).

The discussed systems differ in complexity and performance, but most of them are software monoliths with even closed source code and specifications, thus adaption to special user needs or extension of functionality is bound to vendor-specific customer support or it needs extensive knowledge of modern software technologies. In this work an open software framework for rapid prototyping of surgical navigation tools with the high level scripting language Matlab® on top is presented. Matlab® covers a wide range of mathematical, statistical and computational problems and allows easy development of complex solutions. As a showcase, a surface-to-points registration algorithm is developed and implemented for user friendly and robust registration with an optical tracking system.

2. METHODS

Accurate registration is an essential requirement for the transformation of world coordinates, acquired by the tracking system, into the patient (image) coordinate system. Most off-the-shelf applications for surgical navigation use point to point registration. This requires fiducial landmarks, since inherent anatomical landmarks are mostly not reliable or strongly manifested. These fiducial landmarks often need minor surgical intervention, e.g. a set of bone screws is fixed at the skull, or some bulky equipment, models as they are used for dental casts, is bonded to the patient’s teeth (Bettschart et al. 2012, Morea et al. 2011, Aldana et al. 2010). In the next step, the markers are measured sequentially with the pointing device of the tracking system, where a strict order has to be kept to guarantee point-to-point relationship of the markers and the respective positions in the image volume. Summarized, since point-to-point registration is still the method of choice, it may be erroneous and needs some practice. A further pitfall is the stability of the markers, since they must not move during the time interval between image data acquisition and actual surgical intervention.

In this work a more robust und user friendly method for registration is presented. It takes advantage of inherent landmarks, thus the efforts for mounting and careful conservation are obsolete, and even the registration procedure is elementary. As an inherent landmark any external surface of the patient is proper. In the testing environment at the surgical lab of the Biomedical Research Facility at Hagenberg, Upper Austria, a plastic skull phantom with a 6 part rubber brain model is available. Image volumes are acquired with a Siemens Cardiac Sensation 64 scanner, 220 slices with a 512x512 matrix, 16 bit per pixel, voxel-size $1x0.4x0.4mm^3$. A three panel display of the phantom is shown in Fig. 1. The skull bone is mimicked by plastics and the soft tissue parts, i.e. the brain, are modeled with rubber, the darker gray indicates the lower attenuation coefficients of the brains.

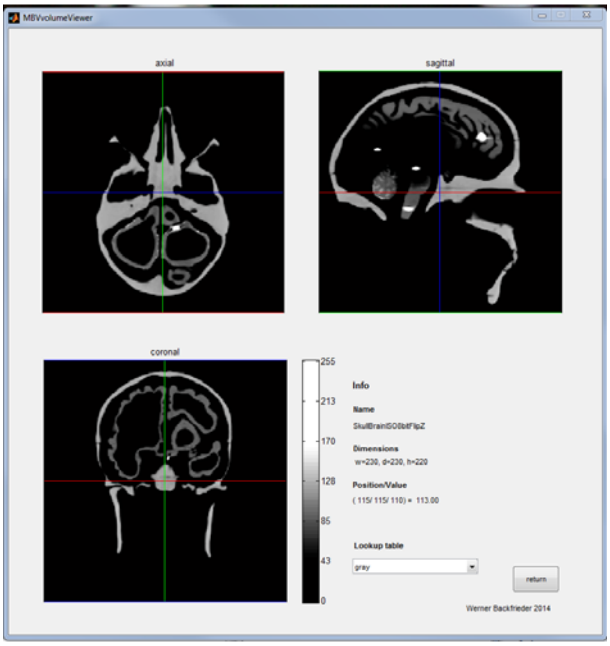

Figure 1: Transversal, sagittal and coronal slices through the x-ray CT scan of the phantom.

The registration procedure starts with the sampling of surface points on the upper skull. The tip of the surgical device is moved along the skullcap and these points are recorded. This set of points is registered against the surface, extracted from the image volume. This is a typical surface-to-points matching algorithm. It differs from the well-known point-to-point techniques in the aspect, that there are no correspondent points in the image volume. An alternative is the ICP algorithm, where always the closest subset of points out of the total surface set is registered against the sampled points.

2.1. Surface to points matching

Registration is a classical optimization problem, where the extremal values of a cost function are determined. In this case the cost function is the sum of the shortest distances of the points to the surface. The assessment of this shortest distance is generally costly. In the worst case the distances to all available surface points must be calculated and then the minimum is chosen. As part of an iterative procedure, this approach needs a high amount of computing power. In contrast a pre-calculated surface-to-distance map allows the direct lookup of the closest distance. The chamfer algorithm is an extremely efficient method to calculate such a distance map by only two passes of a volume-mask through the image volume. The algorithm takes advantage of already known distances in the direct neighborhood of the pixel, whose distance is just determined and comprises the steps described below.

2.1.1. Initialization

The surface map is initialized with known distances; these are the voxels building up the surface. The surface is determined by interactive thresholding the image volume, gaining the parts of interest in the intensity interval. Dilation, a basic operation from binary mathematical morphology, with a cross shaped structure element is applied to the thresholded object (Heijmans and Ronse 1990). The original binary image volume is subtracted from the dilated, yielding the outer surface of the object. The surface voxels are assigned zero distance and all other voxels are set to infinity, cf. Fig 2.

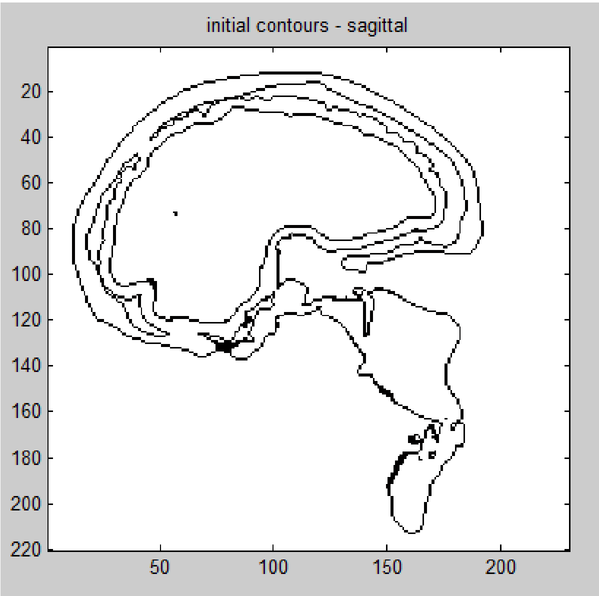

Figure 2: Contours of a sagittal slice, defining zero distance in the initial distance map.

2.1.2. Calculation of distances

The shortest distances are calculated accordingly to chamfer transform in two passes (Treves et al. 1998). In the first pass the image stack is decreased, slice by slice. Within each slice the calculation is proceeded from the top left corner down to the bottom right corner. The volume mask comprises the 26-neighbourhood of a pixel, but in the first pass only a subset of this neighborhood is considered; cf. Fig 3, where all three layers of the mask are shown. At an actual pixel position all known distances in the vicinity defined by the mask are considered. Then the distance-difference from the actual pixel to these selected vicinity pixels is added. Finally the minimum value is assigned as new distance to the central position. The second pass processes the voxels in the opposite direction and the volume mask is complementary. As a result a volume map with distances is obtained, with comparatively little computational effort, proper for even greater volume data. The three main sections of the volumetric distance map are shown in Fig 4.

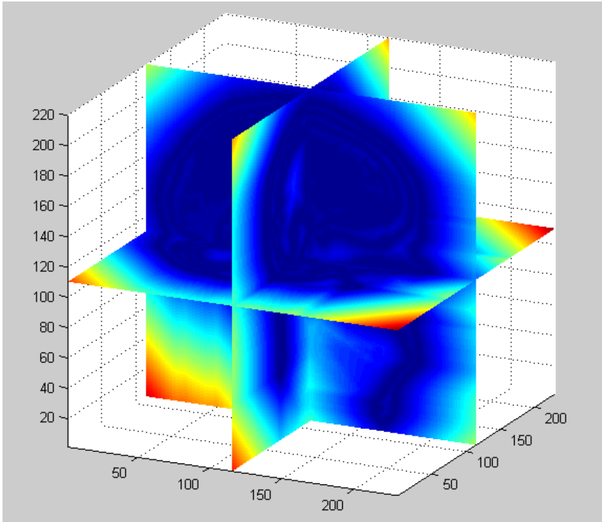

Figure 3: Chamfer distance map, displayed with intersecting slices.

2.1.3. Optimization

For surface-to-points registration rigid body transform is sufficient, since there are no systematic distortions, both in CT-image data and position data, provided by the tracking system. Rigid body motion is characterized by six degrees of freedom, both three for translation $\boldsymbol{t}=(t_x,t_y,t_z)^T$ into all directions and rotation. In this case we refer to the Euler angles in *(z,y',z'')* convention. The transform is described by the homogeneous 4 by 4 matrix (Goldstein 2006)

$$T = \begin{pmatrix} R & t \\ 0 & 1 \end{pmatrix}, \qquad (1)$$

and

$$R = R_z R_{y'} R_{z''} \quad , \qquad (2)$$

built by the rotation matrices around the axes, fixed to the object

$$R_z = \begin{pmatrix} \cos\gamma & -\sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$$R_{y'} = \begin{pmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{pmatrix}, \qquad (3)$$

$$R_{z''} = \begin{pmatrix} \cos\alpha & -\sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

with the rotation angles γ around the *z*-axis, β around *y'* and α around the *z''*. Optimization is implemented as steepest gradient method, with different relaxation parameters for rotation and translation.

3. IMPLEMENTATION

This registration procedure is a showcase for the rapid prototyping environment for surgical planning and navigation, based on Matlab®. The central module of this development environment is the seamless interface to the tracking tools and other surgical environments. The implementation is built on the Java library support of Matlab®, thus a stable and real-time integration of all surgical navigation devices is provided.

3.1. Architecture

The principal part of the rapid prototyping environment is the hardware abstraction layer (HAL) (Zwettler and Backfrieder 2013), it allows seamless communication with all types navigation hardware. In the center of the HAL is the DeviceServer (Zwettler and Backfrieder 2013b), it defines a communication standard enabling the integration of different hardware, like tracking environments, force sensors, haptic interaction devices or 3D surface scanners. These devices are directly attached to one or several host computers running the DeviceServer application. Thereby, communication between the attached devices and the DeviceServer is based on vendor-specific communication protocols and API's. When integrating a hardware device into the DeviceServer, abstraction from the complex API's, different messaging formats and transmission protocols is achieved. A compact set of harmonized scripting commands is defined for each device, utilizing extended Backus-Naur-Form (EBNF) grammar format for control command definition (ISO/IEC14977 1996).

Clients just communicate with the DeviceServer application over standard network protocols, thus achieving general connectivity and platform independence for all higher level applications demanding input and feedback from devices. The small set of HW-specific commands defined with the EBNF grammar is implemented with available vendor-specific API functionality. Commands can be transmitted to the DeviceServer via a console client, the application client port, a RAW network communication port and the telnet communication port, see Fig.5. The DeviceServer can handle an unrestricted number of clients concurrently. The EBNF command definition allows for wrapper generation in arbitrary programming languages. The command transfer is accomplished via network proxies to achieve programming language and platform independence. Currently C++ and Java wrapper generation is supported.

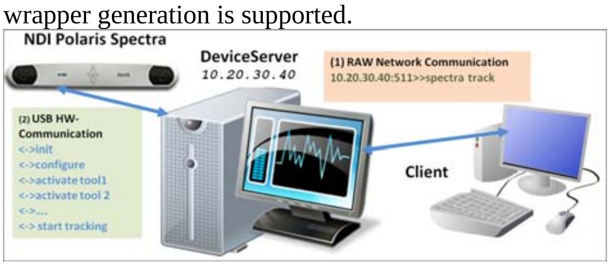

Figure 4: configuration of the surgical navigation environment. The devices are attached to the host computer running the DeviceServer. A client application communicates via network with the tools.

4. RESULTS

The integration of the device server into a Matlab® environment proofed to be a highly productive rapid prototyping tool. Ease of development, the diversity of software solutions, and quick proof of concepts are outstanding characteristics of that implementation. Communication with surgery tools is not disturbed by any significant latency and actually real time response is achieved.

Table 1: marker references

Name	x	y	z	Δr
R1	181.43	104.56	98.15	
M1	183.77	106.45	99.96	2.99
R2	179.63	59.58	56.47	
M2	177.42	62.71	57.00	3.21
R3	118.01	192.97	71.74	
M3	115.61	195.29	70.08	3.18
R4	56.49	84.93	28.53	
M4	57.15	85.10	26.00	2.62
R5	45.74	97.31	95.62	
M5	43.04	100.07	95.15	2.84
			ΣΔ	2.96+/-0.25

The proposed method for real-world to image registration proofed to be feasible. Point sampling on the upper skull bone is easy and reliable; the curvature of the bone is distinct to provide good and unique matching of the contours, thus minimizing positioning errors in further navigation operations.

As a benchmark of the novel registration procedure, the deviations of tracker measurement and image based positioning, at the fiducial markers (five plastic spheres, 5mm diameter), cf. Fig 6a, are summarized. In the planning step the markers are segmented and the center of mass of each marker is calculated. During the control step, the tip of the tool is pointed onto each marker and its position in image space, i.e. the registered position is measured. Table 1 summarizes the reference values (R), the measured values (M) and the resulting deviations. The mean deviation is 2.97+/-0.25mm, indicating good registration. With a radius of the marker spheres of 2.5mm, the efficient accuracy is in the range of the tracker tolerance of 0.5mm. A rendering of the segmented objet in comparison with a photo of the real scenery is shown in Fig. 6b.

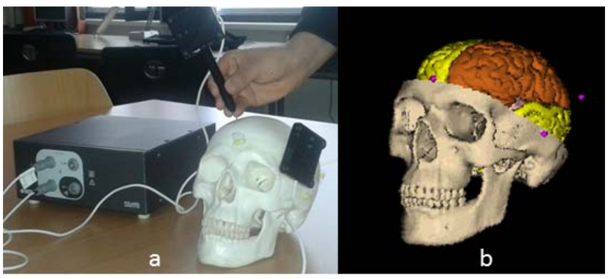

Figure 5: Phantom with attached position tool, surgical pointer and tracking unit (a), and segmented image space (b).

5. DISCUSSION

In this work a novel rapid prototyping environment for applications in surgical navigation and surgery planning is presented. As a showcase of the framework a robust, easy to handle method for registration of image and world coordinates was implemented and tested. Results manifest high accuracy of registration. There exists a great bunch of systems for surgical navigation, based either on virtual reality (VR) or augmented reality (AR), supporting variable hardware components and differing in complexity. But most of the systems are not open for further extensions and development by the user, or they need high level expertise in VR programming, mathematics or computational geometry. The proposed system, based on a hardware abstraction layer, is not limited to devices from specific vendors; it is open and allows unique access to all devices. On top is the scripting language Matlab®, with its enormous functionality, enabling rapid development of even complex extensions to an existing navigation environment. Access to hardware tools performs in real-time, display of complex sceneries may slightly lag behind. This can be solved by implementing critical code-pieces in Matlab-Mex, the native C interface.

The proposed registration method may not be applicable with soft tissue surfaces, since during surgery mostly turgor deforms the surface and registration becomes inconsistent. But for spine surgery, when bone screws must be positioned exactly into the vertebral body, not penetrating the vertebral channel, this method has high potential for intra-surgical registration.

This rapid prototyping environment allows the implementation of novel concepts and algorithms for surgical navigation with rather little effort.

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