ADAPTED ICP ALGORITHM FOR SURFACE BASED REGISTRATION IN IMAGE GUIDED SURGERY

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ABSTRACT
Image guided surgery has established in modern surgery rooms, enabling high technology support for complicated surgical interventions. The ability to exactly position surgical tools, even if the target of surgery is subsurface, relying just on pre-acquired image data, causes the great success of surgical navigation. In cerebral surgery, image guidance has a long tradition, even in orthopedics; recently it also appears to abdominal surgery.
A major prerequisite for accurate position navigation is the careful mutual registration of patient-, tracking- and imaging-domains. Only intuitive and precise handling of the registration procedure leads to satisfying results. An easy to use and accurate registration method, integrating the iterative closest point (ICP) algorithm was developed and implemented as showcase in a Matlab® based tracking environment.
Image data from a diagnostic scan are preprocessed by anisotropic diffusion filtering and reformatted to cubic voxels. The point sets for registration are extracted from the image volume and acquired by a tracked pointing device. Rough re-orientation of registration data is achieved by equalization of principal components. The ICP algorithm is applied to fully register both data sets. Accuracy of registration is quantified by distance-measurements of the transformed tracking points from the surface and by measuring the summed distance of physical landmarks on the object's surface. The registration yields accurate overlay of the tracking and patient image domains, allowing exact navigation of surgical tools. The easy handling and accuracy of the developed registration method manifests the specific potential for clinical application.

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

1. INTRODUCTION

The combination of modern computer visualization techniques, accurate diagnostic imaging techniques and further development of exact position tracking, facilitated advances in image guided surgery during the last three decades. Modern intra-operative navigation was inspired by frame-based stereotaxis; a technique using preoperative images for intra-operative guidance to exactly place needles, catheters or electrodes into intracranial structures. The challenge is to avoid collateral damage when accessing subsurface targets, thus preserving neural functionality. Careful preoperative planning helps minimizing craniotomy, resulting in less risk of surgery, shorter anesthesia, contributing to more successful rehabilitation.
These experiences gave rise to the development of frameless stereotaxis in the 1990s. For the first time the enormous potential of recently developed volume imaging modalities and real-time tracking of surgical instruments was combined. The integration of powerful computer based methods and graphics makes it a powerful tool in the surgery room (Enchyev 2009). Image guided navigation is divided into two phases, the non-realtime procedures outside the operating theatre (OT), e.g. radiological image acquisition, visualization and planning, and the real-time intra-operative phase during surgery. In a sterile and time critical environment registration, tool-tracking and intra-operative visualization is performed. These special requirements demand well designed hard- and software tools. The introduction of this modern methodology is highly beneficial for patient care and economical aspects of treatment (Paleologos et al. 2000).
The development of functional MRI further improves the method. Exact cortical localization of functional foci, e.g. the centers of motoric activities, speech, or visual perception, can be considered in the planning of the surgical aditus. This minimizes functional handicaps as a post-surgical manifestation (Nimsky et al. 2005).
During extensive brain surgery, a shift of brain tissue is observed, after opening of the hard meninx, the dura mater. For further exact localization of the tools these shift-related deviations are compensated either by intra-operative imaging or by computational assessment of offsets performing elastic modelling of preoperative

image (Hatiboglu et al. 2009, Liu et al. 2014, Reinbacher et al. 2014, Scheufler et al. 2011).

Orthopedic surgery offers a broad range of surgical navigation applications, ranging from hip and knee to spine surgery. The tasks 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 the field of model based navigation. In contrast to the previously discussed image guided methods, a generic model of the surgical target is individually adopted to the patient, according to intra-operative measurements of control points. This needs no imaging modalities and prevents the patient from potential risk of radiation (Habor 2013).

Most recent and comprehensive research paradigm is the "digital OT". The navigation of information, i.e. the aggregation of all kind of information, from all available sources in Pictures Archiving and Communication System (PACS) and the Hospital Information System (HIS) is the basis for all treatment. Data are filtered and processed for intuitive representation in the OT. This "digital OT" is the high end development of the top system providers (Malarme et al. 2008).

Accurate registration is still an essential requirement for successful employment of navigation techniques. The intuitive and efficient handling of the registration procedure, i.e. the overlay of world coordinates (tracking system) and patient coordinates (image), is inevitable. Most applications rely on point to point registration. This requires fiducial landmarks, since inherent anatomical landmarks are mostly not reliable or easy to identify. In addition, the fixation of fiducial markers needs certain effort, e.g. a set of bone screws drilled into the skull, or some bulky equipment, like dental casts bonded to the patient's teeth (Bettschart et al. 2012, Morea et al. 2011, Aldana et al. 2010).

Alternatively surface-to-points registration is developed. Using surfaces, the inaccurate detection of fiducial markers is eliminated as a source of error. The mean distance of a surface, extracted from radiological images, and points on a respective surface, acquired in the patient domain, is minimized. Chamfer matching combined with steepest gradient optimization is used for registration of tracked tools and radiological images (Backfrieder et Zwettler 2014). Methods based on the ICP algorithm exist for intraoperative assessment of organ position and size (Benincasa et al. 2008) and a recent work describes a feasibility study to match radiological images and calibrated stereovision data (An et al. 2015). The latter approach allows no interaction with tracking tools.

In this work an ICP based surface-to-points registration is presented. A user friendly and robust integration of tool tracking in the image domain is realized in an experimental MATLAB ® based surgical navigation system.

2. MATERIAL

In this work a new robust and user friendly method for registration is presented. It takes advantage of inherent landmarks, thus the efforts for mounting and careful conservation will be obsolete, and even the registration procedure is straight forward. As an inherent landmark any externally accessible surface of the patient is proper. The registration algorithm is tested with a physical head phantom, a model of a vertebra manufactured by a 3D prototyping printer, and an x-ray scan of a human head.

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 physical head 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 physical phantom.

The ICP algorithm matches two 3D point clouds, where the number of points in the data sets is different; there exists no fixed pair-wise reference between the points of both data sets. The two data sets are called the base set and the matching set. The base point set is generated by sampling the considered surface of the image volume.

The respective point sets for registration are acquired with the tracking system. The tip of the pointing device is moved along the physical surface and points are recorded. The points are not in the tracker's absolute coordinate system, but measured relative to a marker mounted on the object (patient). The recorded point sets are registered using the modified ICP algorithm.

3. METHODS

For surface based 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 R. 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)

$$T = \begin{pmatrix} R & t \\ 0 & 1 \end{pmatrix}, \tag{1}$$

and

$$R = R_z R_{y'} R_{z''} \quad , \tag{2}$$

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

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

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

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

with the rotation angles γ around the z-axis, β around y' and α around the z''. This is a popular notation with computer graphics and object movement. The calculation of the rotation matrix R is part of the registration algorithm described below.

3.1. Adapted ICP Algorithm

The iterative closest points (ICP) algorithm developed by Besl and McKay (Besl and McKay, 1992), is a recursive registration procedure, based on the idea of Procrustes analysis. Whereas Procrustes analysis strictly necessitates a rigid pairwise relationship of points in both datasets, which is a strong limitation, the ICP does not.

The ICP acts on a subset of the matching data set; the matching data is containing more data samples. From this set those points are selected, which are nearest neighbors to points of the base set. Each nearest neighbor pair builds a fixed assignment, valid during the current iteration step. Point data are centralized and normalized, i.e. the centroid of the point set is subtracted from the position values and the samples are normalized to standard deviation *1*. These procedures yield surfaces of the same size and basic overlay. But the surfaces are still not congruent, since rotation is not considered.

The rotation matrix is calculated by singular value decomposition (SVD) of the correlation matrix from above transformed data sets

$$C = X_B \cdot X_M^T \quad . \tag{4}$$

The coordinate matrix X_B, consists of the base points (each column is a point). It is multiplied with the transpose of the matching point's matrix X_M. The correlation matrix C is decomposed into a diagonal matrix D of singular values and two orthonormal matrices U and V representing the base vectors of respective domains

$$C = UDV^T \quad . \tag{5}$$

The rotation matrix R is the product of the vector bases U and V^T.

$$R = UV^T \tag{6}$$

The transformation, assessed in the current iteration, is applied to all points of the matching set and the algorithm is repeated by choosing a new set of nearest neighbors.

Registration is achieved when a stopping criterion is satisfied, e.g. minimum in distances of base to matching points.

3.1.1. Initialization

The ICP algorithm in general is rather robust with respect to the displacement of both initial datasets. But in the case of acquired images in the CT reference system and the position measures form the tracking system, the differences are too big. A direct application of the ICP algorithm would not yield substantial convergence, thus an initial overlay is necessary. For an initial rough guess of the orientation of both data sets, principal components analysis is performed with each particular coordinate set. The principal axes and the centroid are the parameters of the surrounding ellipsoid of each data set, giving an estimate of the position and orientation of both data clouds against each other. This allows a first initial registration prior to the ICP algorithm.

4. IMPLEMENTATION

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

4.1. Architecture

The developed registration procedure is implemented upon a three layer architecture. It comprises

- application layer
  It is the top-most layer providing support for user-interaction, display and manipulation of medical image data in 3D. This is the general interface to human interaction.
- hardware abstraction layer
  This layer allows transparent access to the tracking and acquisition hardware. It encapsulates the vendor specific protocols, providing a unified scripting language for control of hardware devices interfacing the application layer. The hardware abstraction layer allows the connection of the application layer via the internet, enabling remote control of the tracking environment. This is of special interest if complex technical equipment is not suitable for a sterile surgical environment. It also enables the concurrent use of the same tracking hardware, maybe for development purposes or teaching.
- hardware layer
  In this layer the connection to one or more tracking and/or sensing devices is realized and proprietary communication is accomplished.

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 of 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.2. 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.

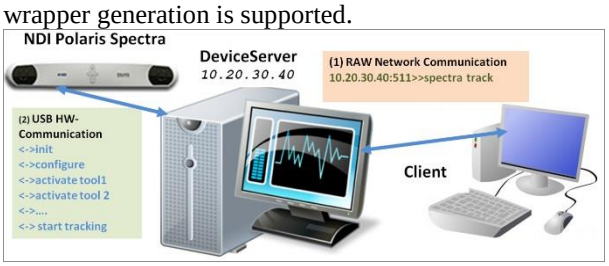

Figure 2: Sketch of a basic surgical navigation configuration. The devices are attached to the host computer running the DeviceServer as a central service. A client application communicates via network with the tools.

5. RESULTS

The surface based registration achieves proper results for registration. Results show a certain potential to substitute the newly developed ICP based method in place of the widely used point-to-point registration.

Figure 3: Phantom with attached position tool, surgical pointer and tracking unit (a), and segmented image space (b).

For testing the accuracy and usefulness of the novel registration procedure the position of five fiducial control markers (plastic spheres, 5mm diameter), mounted on an anthropomorphic head phantom, are measured with the registered tracking tools and assessed from image data. The displacement of position data is systematically calculated. Figure 3 shows a picture of the head phantom with attached fiducial markers and reference sensor and the pointing tool (a). A visualization of the segmented image volume is shown in Fig. 3.b. In this rendering the skull cap is displayed fully opaque. During the planning step the markers are segmented and the center of mass of each marker is calculated; this is taken as the markers image reference position. During the control step, the tip of the pointing-tool is moved to each marker, recording the position in the registered coordinate system. Figure 4 shows the recorded point cloud pattern relative to a 3D rendering of segmented objects. The upper row, cf. Fig. 4a and 4b, shows the unregistered points, the lower row, Fig. 4c and 4d, the registered sets. Both are rendered from a standard 3D view and a lateral camera position.

The upper skull is rendered slightly transparent with an opacity coefficient of 0.5. The images show sufficient congruence of the data sets.

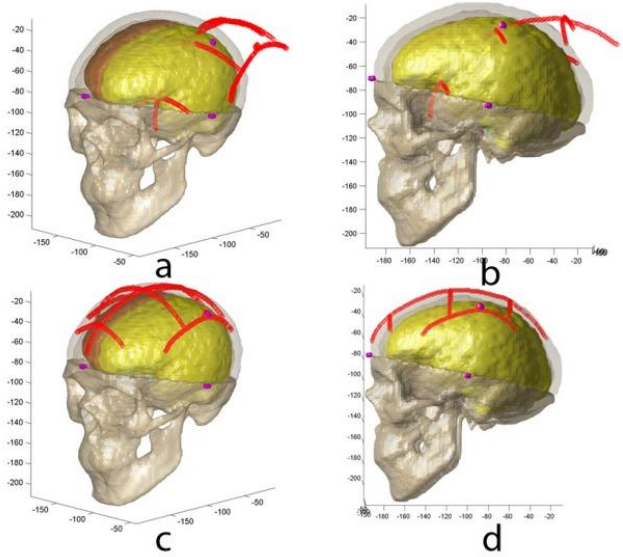

Figure 4: 3D Visualization of the head phantom as ttransparent rendering of the segmented objects in a standard 3D view (a) and from a lateral view (b). The measured and unregistered position data by sampling the upper skull with the tracking tool are displayed as red dots. Figures (c) and (d) show the dot cloud after ICP registration.

Table 1 summarizes the reference values R[1-5], the measured values M[1-5], and the resulting deviations. The mean difference is 2.93+/-0.92mm, 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.

Table 1: marker references

Name	x	y	z	Δr
R1	181.43	104.56	98.15	
M1	182,31	105,4	96,96	1,70
R2	179.63	59.58	56.47	
M2	177,92	61,32	58,05	2,91
R3	118.01	192.97	71.74	
M3	116,21	194,29	69,37	3,26
R4	56.49	84.93	28.53	
M4	57,31	85,33	26,12	2,58
R5	45.74	97.31	95.62	
M5	43,19	100,19	97,35	4,22
			ΣΔ	2.93+/-0.92

A rendering of the segmented objets, the fiducial markers, and the measured position of control points is shown in Fig. 5. From the numerical results and the renderings the evidence of sufficient overlap of both data sets is given. The methods is potentially useful for integration in an easy the use and robust registration tool.

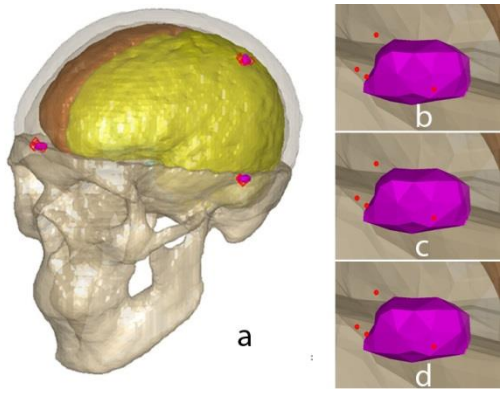

Figure 5: Visualization of the test procedure, rendering of the head phantom with segmented markers (turquoise spheres) with an overlay of measured reference positions as red dots (a), zoomed rendering of the three visible markers and respective control measures (b-d).

6. DISCUSSION

The development of surface based registration for registration of tracking coordinates and the patient domain proved to be reasonable. As shown by accurate registration results with the physical phantom random sampling of points by irregular movement of the pointing-device on the upper skull is easy and reliable; the curvature of the bone is distinct to provide good and unique matching of the contours, thus minimizing positioning errors during further navigation operations.
The full development of the registration algorithm in the Matlab® scripting language profits from small implementation cost and benefiting from the huge support with integrated mathematical instructions and graphical rendering options.
The Matlab® based system, comprising a hardware abstraction layer, not limited to devices from specific vendors, is an open alternative for easy development of new concepts and methods for image guided surgery. 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 is performed 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 the great deformations of the surface during surgery by turgor will cause inconsistent registration. But for spine surgery, when bone screws need exact targeting into the vertebral body, not penetrating the vertebral channel, this method has high potential for surgical application.

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