Accuracy Identification of Markerless Registration with the DLR Handheld 3D-Modeller in Medical Aplications

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Abstract:
Handheld systems for markerless, contact free registration such as the DLR 3D-Modeller are a current topic in research. These systems are advantageous due to their non-invasiveness, furthermore they do not take up valuable space in the operating room. The scope of this work is to provide a state of the art accuracy evaluation and feasibility study of the handheld DLR 3D-Modeller applied to markerless, contact free registration of the patient face. Therefore, the tested markerless methods are compared to a gold standard method based on titanium markers. A mean accuracy of approx. 2 mm is reported, and the registration procedure is very fast, taking between 1-2 min. Main source of inaccuracy is the used optical tracking system. An accuracy sufficiently high to allow for application in a variety of medical applications can be shown. These applications range from port placement in minimally invasive surgery to osteotomies, image guided bone segment navigation, and foreign body removal.

Keywords: Contact free surface based registration, Handheld system, Accuracy evaluation

1. Motivation

Patient registration is necessary whenever planning data (e.g. biopsy needle trajectories or bone cutting planes for knee surgery based on preoperative images) have to be transferred into the operation room (OR). In numerous medical interventions a successful registration is crucial for the quality of the medical procedure, including radio surgery and navigated surgery [1]. Often standard approaches in clinical use are based either on artificial landmarks (e.g. a dental splint with markers or bone implanted markers) or anatomical landmarks. These landmarks are segmented in the preoperative image data and localized in the OR with e.g. optically tracked pointing devices. Corresponding intra- and preoperative landmark positions are then determined, and the (rigid) transformation matrix is calculated using least square fitting algorithms. Markerless methods using e.g. the patient skin or bone surface are in clinical use, too (e.g. z-touch from BrainLAB [2]). However, contact free systems still lack of dexterity and accuracy and are a current research topic [3, 4].

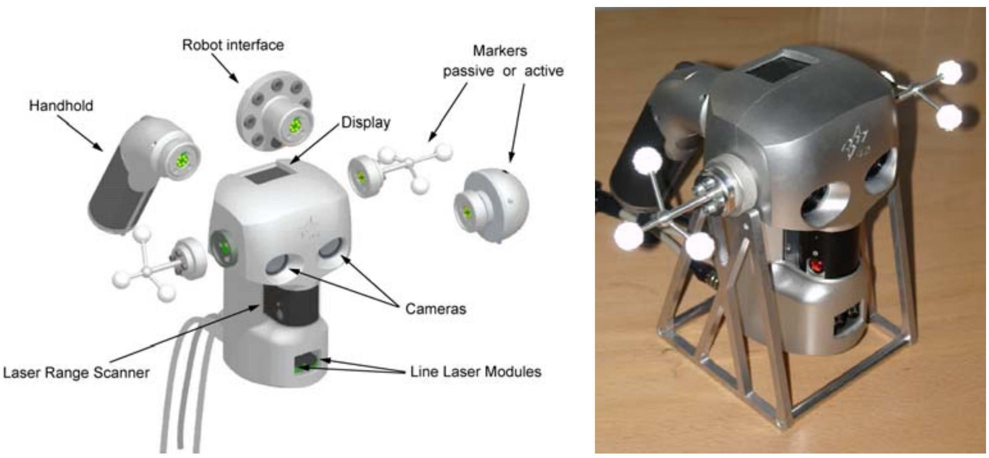

Figure 1: The DLR 3D-Modeller.

This work analyses a markerless and contact free registration using the DLR 3D-Modeller (3DMo) as shown in Fig. 1. The 3D-Modeller [5] is a hand-guided device that allows for acquiring the patient surface intraoperatively. It provides three different range sensors: a stereo camera sensor (SCS), a laser-range scanner (LRS), and a light-stripe profiler (LSP). A medical application as presented in [4] was considered during the development period in order to make the 3DMo suitable for usage in the OR.

The paper is organized as follows: The next section describes the evaluation procedure. Details on use and sources of inaccuracies of the implemented LRS and LSP methods are identified and the overall accuracy is determined thereafter. A discussion on methods to improve accuracy in future setups and propositions of eligible applications close the paper.

2. Methods

In order to evaluate the new registration techniques presented in this article, plaster cast models of three different patient faces were manufactured. In the backside of the masks, up to 15 artificial markers were placed. Tomographic data for each mask were obtained through a CT-scan with a Siemens CT Sensation Open (resolution: 512x512 pixels, 1 mm slice thickness). Due to the small size of the artificial markers (titanium spheres with a diameter of 1 mm), the CT slices were 3 times oversampled to obtain an interpolated slice thickness of 1/3 mm with better visibility of the markers.

The next paragraph describes a method based on implanted markers used as reference measurement. The subsequent paragraph presents the range sensors of the 3DMo that were used in this work. Eventually, the evaluation procedure and the used accuracy measures are described.

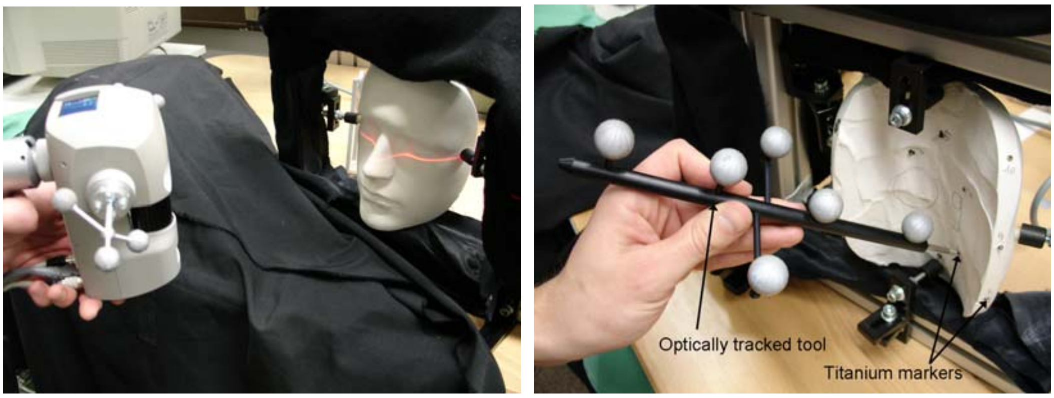

Figure 2: Surface based method (left) and gold standard method (right).

2.1. The Gold Standard Method Using Implanted Markers

Currently, registration based on implanted markers is considered the gold standard method [6, 7]. The comparison of this method with the surface based methods evaluated in this paper allows for identification of inaccuracy sources during the whole registration workflow.

For the gold standard method, the implanted markers are preoperatively segmented in the CT image data, resulting in point coordinates $\mathbf{m}_i$ in the CT coordinate system. In the OR, the position of the spheres $\mathbf{d}_i$ can be measured using an optically tracked tool with a calibrated socket fitting to the diameter of the artificial markers, see Fig. 2 right.

The transformation matrix $\mathbf{T}_{gold}$ has to be determined for registration. It minimizes the quadratic error e^2:

$$e^2 = \sum_{i=1}^{n} \left\| \mathbf{d}_i - \mathbf{T}_{\mathrm{gold}} \mathbf{m}_i \right\|_2^2 , \quad \text{with} \quad \mathbf{T}_{\mathrm{gold}} = \begin{bmatrix} \mathbf{R}_{\mathrm{gold}} & \mathbf{t}_{\mathrm{gold}} \\ 0 & 1 \end{bmatrix} .$$

The rotational part $\mathbf{R}_{gold}$ of $\mathbf{T}_{gold}$ can be calculated using a singular value decomposition (SVD) [8]:

$$\mathbf{R}_{gold} = \mathbf{V}\mathbf{U}^T, \quad \text{with} \quad \mathbf{U}\Lambda\mathbf{V}^T = \sum_{i=1}^{n} \mathbf{m}_{ci}\mathbf{d}_{ci}^T,$$

$$\mathbf{m}_{ci} = \mathbf{m}_i - \bar{\mathbf{m}} \quad \text{and} \quad \mathbf{d}_{ci} = \mathbf{d}_{ci} - \bar{\mathbf{d}}.$$

In case the determinant $|\mathbf{U}\Lambda\mathbf{V}^T| = -1$, the matrix $\mathbf{R}_{gold}$ is calculated as follows:

$$\mathbf{R}_{gold} = \left[\mathbf{v}_1 \ \mathbf{v}_2 \ -\mathbf{v}_3\right] \mathbf{U}^T,$$

with $\mathbf{v}_i$ the column vectors of $\mathbf{V}$. Eventually, the translational part $\mathbf{t}_{gold}$ of the matrix $\mathbf{T}_{gold}$ is determined:

$$\mathbf{t}_{gold} = \bar{\mathbf{d}} - \mathbf{R}_{gold}\bar{\mathbf{m}}.$$

2.2. Surface Based Methods Using the 3D-Modeller

The 3D-Modeller is a handheld device, integrating three different range sensors [5]. Its pose (position and orientation) is optically tracked using the ART[1] navigation system. The evaluated methods LRS and LSP are described in the following.

In case of the LRS method [9], the reflected light of a projected laser point is recorded with a position sensitive device (PSD), integrated in the rotating part of the LRS (see Fig. 3 left). With the known pose of the 3DMo measured by the navigation system (in addition to the instantaneous rotation angle ψ of laser and PSD) it is possible to calculate the absolute position of the laser point in Cartesian space. With a complete rotation of the laser, a line on the surface is acquired point-wise. Moving the scanner parallel to the surface and perpendicular to this line, the whole surface can be scanned.

The LSP method [10] uses a laser line module to illuminate a complete stripe on the patient surface (see Fig. 3 right). A CCD camera records the reflection, and 3D information about the stripe is then obtained through triangulation, intersecting the laser plane with the rays of sight corresponding to the laser stripe projection in the image frame (see Fig. 3 right). Again the whole surface can be scanned by moving the scanner parallel to the surface and perpendicular to the projected stripe.

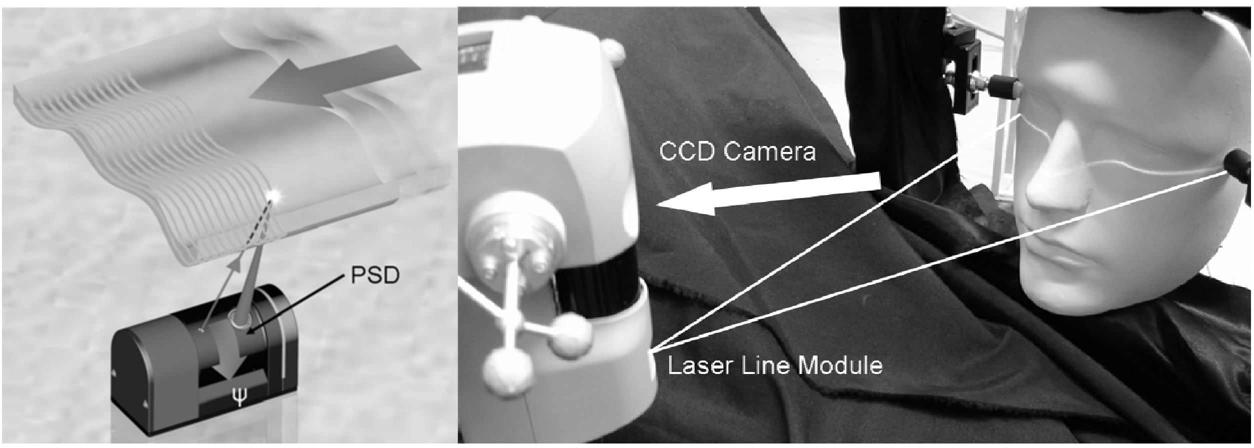

Figure 3:The LRS method (left) and the LSP method (right).

2.3. Evaluation Procedure

Each plaster cast model is scanned 10 times with each scanning method. The scans are then registered with the preoperative data using an iterative closest point (ICP) algorithm [11], a frequently used algorithm for local registration of rigid structures. The scanning time is varied to identify the influence of fast movement

[1] Advanced Realtime Tracking GmbH: http://www.ar-tracking.de/

of the 3DMo during scanning. To protect the eyes of the patient from the laser beam, it may be necessary to cover them with e.g. opaque glasses. These glasses lead to inconsistency between CT data (without glasses) and intraoperative scan. Therefore glasses were added during some of the intraoperative scans in order to investigate their effect on the registration result.

2.4. Comparison of Measurements

To obtain an accuracy measure, the transformation matrices between CT data and OR coordinate system are calculated through registration for both the gold standard ($\mathbf{T}_{gold}$) and the presented methods ($\mathbf{T}_{surface\ based}$) as explained above. Thereafter, the CT coordinates of all n artificial markers $\mathbf{x}_{i,\ CT}$ are transformed into the OR coordinate system:

$$\mathbf{x}_{i,\text{gold}} = \mathbf{T}_{\text{gold}} \cdot \mathbf{x}_{i,\text{CT}} \quad \text{and} \quad \mathbf{x}_{i,\text{surface based}} = \mathbf{T}_{\text{surface based}} \cdot \mathbf{x}_{i,\text{CT}}.$$

The deviations between $\mathbf{x}_{i,\ gold}$ and $\mathbf{x}_{i,\ surface\ based}$ are used as accuracy measures:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} \left\|\mathbf{x}_{i,\text{gold}} - \mathbf{x}_{i,\text{surface based}}\right\|_2 \quad \text{and}$$

$$x_{\max} = \max_{i=1,..,n} \left\|\mathbf{x}_{i,\text{gold}} - \mathbf{x}_{i,\text{surface based}}\right\|_2 .$$

3. Results

Each scan of the plaster cast takes only few seconds (ranging from 10 s-20 s for LSP and 15 s-30 s for LRS). The LRS method takes more time since the 3DMo has to be positioned closer to the surface, and the range of recorded data is thus smaller than in case of the LSP method. However the LRS method is more robust against illumination changes and lighting conditions as compared to the LSP method.

Using the software Visu3D [12], fast surface reconstruction is possible and allows for very good online visualisation during the scanning procedure. An ICP algorithm is integrated in the software and registration takes between 30-90 s, depending if manual adjustment of the initial pose is necessary or not. Table 1 shows the mean deviations and worst values for all artificial landmarks, obtained during 10 different scans for each table row. As shown, three different plaster cast models were considered. Mean deviations between gold standard and surface based methods are in the range of 1.6 mm - 2.2 mm.

In the following, these results are discussed through a closer investigation of the error sources.

		$\bar{x}$ [mm]	x_{max} [mm]
LRS	Mask 1	1.9	2.8
	Mask 1, with glasses	2.2	3.0
	Mask 1, scan time <10s	2.1	2.9
	Mask 2	1.6	2.7
	Mask 3	1.7	2.2
LSP	Mask 1	2.1	2.9
	Mask 1, with glasses	2.3	3.0
	Mask 1, scan time <10s	2.0	2.5
	Mask 2	2.2	2.8
	Mask 3	1.8	2.7

Table 1. Deviation of the surface based registration with respect to the gold standard $\bar{x}$ and worst x_{max}.

Concerning the gold standard, the following major sources of error can be identified and roughly approximated: (a) Resolution of the CT slices: with a slice thickness of 1 mm, even with a 3-fold oversampling the accuracy in segmenting the titanium markers from the images is expected to be about 0.3

mm. (b) Optically tracked tool: The ART optical tracking system reports an accuracy of approx. 0.2 mm in the used measurement volume. Additionally, calibration of the tool socket adds an error in the range of 0.1 mm. (c) Measurement procedure: the titanium markers are brought into contact with the socket of the measurement tool. Naturally, errors might be added due to tremor and partially hidden markers (leading to a shift of the marker centre and thus to an error of the calculated 3D position). According to experience, the latter error can roughly be estimated with an upper border of 0.4 mm. The worst case overall error of the gold standard is therefore assumed to be approx. 1.0 mm.

The following error sources account for the overall error during surface based registration: (a) Resolution of the CT slices: see above, approx. 0.3 mm. (b) Inaccuracy of the measurement system, excluding the optical tracking system: LRS: 0.3 mm and LSP: 0.2 mm [5]. (c) Optical tracking system: Additionally to the translational inaccuracy also the rotational inaccuracy of the tracking system has to be taken into account. This is due to the distance between 3DMo and scanned surface, resulting in errors in localisation of up to 0.5 mm in case of LRS and 1 mm in case of LSP [13]. (d) Measurement procedure: the errors due to tremor and partially hidden markers are estimated to be at 0.4 mm. The overall worst case error in surface based registration as described in this work is therefore expected to be in the range of 1.5 mm to 1.9 mm. Adding up both the errors from the gold standard and the surface based registration leads to the worst case of approx. 2.9 mm as confirmed with experimental data shown in Table 1.

Glasses to protect the patient did only slightly influence the overall accuracy during the performed experiments. This is mainly due to the fact that the black surfaces of the glasses are neither recorded by the LRS nor by the LSP method of the 3D-Modeller. The glasses thus add only few erroneous data to the plaster cast surface, and the implemented registration algorithm is robust enough to work also if the area of the patient eyes is missing.

Fast scan times did not show any influence on the overall accuracy. Therefore, it is possible to acquire accurate patient surface data within just a few seconds, and the presented method thus promises to be faster than current state of the art methods that require manual acquisition of the marker positions [2].

4. Conclusion

A key advantage of markerless and contact free registration as opposed to artificial marker based registration is the non-invasiveness of the procedure. However, the achieved accuracy is often reported to be lower and known systems often lack of dexterity. This work analyses two basic methods for surface based registration as implemented in the handheld DLR 3D-Modeller, namely the laser-range scan method and the light-stripe profiler method. Both methods show comparable results in worst-case accuracy of better than 3 mm. The main source of inaccuracy stems from the optical tracking system and in particular from its errors in measuring the correct orientation of the 3D-Modeller. Improvement of the tracking system accuracy is therefore a pressing demand. It is also suspected that a better choice of the marker target geometries will lead to less error in tracking of orientation. Issues to be investigated in future work are the penetration depth of the laser light into the patient skin and soft tissue displacements. These might lead to additional errors in the real environment. Furthermore, especially the LSP needs verification for operational robustness in OR environments. To further increase accuracy and reduce error proneness, the multi sensory concept of the 3DMo allows for fusion of additional pose estimation algorithms such as e.g. visual SLAM [14], subject to current work.

To conclude, our evaluation of the presented registration procedure shows a sufficiently good accuracy to be applied in a variety of medical applications, ranging from port placement in minimally invasive surgery to osteotomies, image guided bone segment navigation, and foreign body removal [15, 16]. Furthermore, the procedure promises to be faster than methods based on artificial markers. Further efforts have to be made to increase the accuracy of the entire system in order to be suitable for biopsy applications in brain surgery and other highly demanding surgical interventions. As another important step, evaluation of the accuracy of the presented approach using real data from test subjects is in preparation.

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