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„Instrument Characterization of Surgical Optical Localizers for an Estimation of Measurement Stability: Concept and Preliminary Results“

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Instrument Characterization of Surgical Optical Localizers for an Estimation of Measurement Stability: Concept and Preliminary Results

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Introduction

Surgical optical measurement systems with rigid localizers (instruments) have spread due to a good price/performance ratio, good usability, i.e. standardized Application Program Interface, and serial/USB connectivity. The challenge is to interpret the measurements returned by the system. It has to be assessed which influences on the measurements exist, how the influences are reflected by the measurements, and whether or not these influences are of interest [1].

The manufacturers of surgical measurement systems usually characterize each individual system to determine their model parameters, e.g. using a coordinate measuring machine and a certain manufacturer-defined optical localizer, [1]. Protocols and statistical measures are known in principle at best.

In contrast, the localizers and instruments being tracked are user-defined and not part of the manufacturer's characterization process. Nevertheless, measurement accuracy/trueness depends on the localizer's geometry, marker type, tool center point (TCP) position, and other influences, [4]-[5]. Additionally, these instruments are used in a highly specific user environment (position, angle, movement). This emphasizes just a subset of the parameters used during the manufacturer's characterization process. Therefore, the accuracy of a measurement taken in such a situation can not be judged by the general accuracy stated by the manufacturer. The majority of measurement systems deliver an error indicator value along with the positional data. The indicators either lack in a standardized unit or there is no significant correlation, e.g. between the error indicator and the current distance between measurement system and localizer, as shown in [7].

This work introduces a concept for individually characterizing different kinds of localizers in a static setup to obtain regression models. Afterwards, the regression functions are used to constantly assess the lower bound of the measurement error (noise) of a certain localizer. Several experiments with a static setup were conducted to check the feasibility of the concept. This concept does not include changes in accuracy caused by moving the localizer, because it aims at the lower bound of the error.

Material and Methods

The static setup consists of a spatial grid in which the pose of a localizer is recorded for every grid position. The translations and rotations in all three dimensions are the six independent variables. The translation's and rotation's standard deviations (SD) for every grid position are then used as six dependent variables to obtain six separate regression functions to assess the SD in translation and rotation in all three spatial dimensions, [8]. The calculation of the regression functions is done to characterize every kind of localizer in form of the model's coefficients.

The feasibility of this concept was checked by several experiments. The measurement system was a stereo-camera NDI Polaris Vicra system. The z-dimension of the Vicra's coordinate system aims away from the Vicra. We reduced the grid to eight positions with x and y centered in the middle of the volume and z equally distributed over the volume. We used two localizers and one probe.

We recorded the z-coordinate as one independent variable and calculated six regression functions for the SDs of translations x, y, and z and rotations ω_x, ω_y, and ω_z as described above. We choose a quadratic regression, because this relation is known from literature [9] and based on the fact that the error in z-direction is the product of the x/y errors between both cameras.

The vector **d** is the collection of the distances being examined. The vector **v** contains the accordant averaged SDs in either x, y, z, ω_x, ω_y, or ω_z. The residuals are defined by $\boldsymbol{\varepsilon}$. The linear system is given by

$$\mathbf{v} = [1 \quad \mathbf{d} \quad \mathbf{d}^2]\mathbf{a} + \boldsymbol{\varepsilon} \cdot$$

We solve the quadratic minimization problem

$$\min_{\mathbf{a}} \left\| \begin{pmatrix} 1 & d_1 & d_1^2 \\ ... & ... & ... \\ 1 & d_8 & d_8^2 \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \\ a_2 \end{pmatrix} - \begin{pmatrix} v_1 \\ ... \\ v_8 \end{pmatrix} \right\|_2$$

to obtain the polynomial coefficients a_0, a_1, and a_2. The experiments focus on drawing conclusions from the correlation coefficients (CC), the standard error (of the arithmetic averages) (SE), and the differences of the regression's coefficients for different kinds of localizers.

Experimental Setup

The system, including measuring cage, test control unit, and Measure software, can be used with optical or EM measurement systems. This experiment utilized a NDI Polaris Vicra. The stereo camera is fixed on top of a 190mm tall measuring cage (Fig. 1). The measurements were taken automatically with a real-time test control unit developed in our group. It has a touch-display to start/stop measuring procedures. The two localizers were passive, rigid with different geometries. Additionally, we checked one passive, rigid probe, i.e. localizer integrated into the instrument, Fig. 2. Localizers and probe have been tested with the TCP at different positions. They are always aligned to the x/y-plane of the volume's coordinate system, assuring an optimal view on the localizer or probe. Measurements have been taken at eight distances (456-1730mm). The first and the last three distances are defined to be out-of-volume by NDI, but they are still trackable. For every distance we took 100 (5s with 20Hz) measurements.

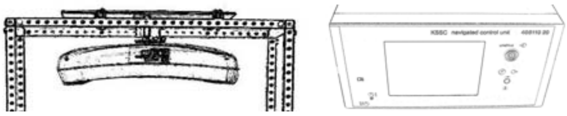

Fig. 1: Cage with NDI Vicra and Test control unit

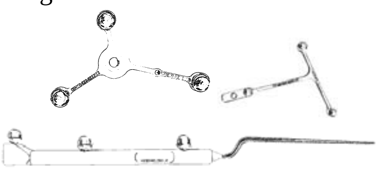

Fig. 2: Rigid optical localizers 1/2 and probe.

Results

The data points and regression functions for localizer 1 are shown in Fig. 4. The CC was always significant (0.558-0.999, mean 0.883). A significant difference between the two definitions of TCP can be recognized at the SD in translational z-direction (0.37mm and 0.07mm at 1.7m distance), Fig. 3a. The SE in translation is always <0,015mm (N=1000).

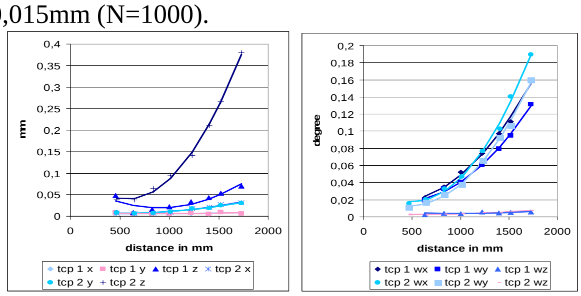

Fig. 3a,b: SD of translation (a)/rotation (b) of localizer 1. TCP at two different positions.

Therefore, for a further analysis, we picked the SD in translational z-direction to compare localizers and probe, Fig. 4. The regression functions differ significantly in most cases, reflecting different geometries and TCP positions.

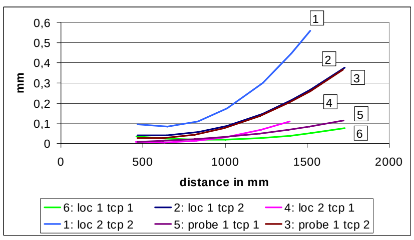

Fig. 4: Translation's SD. Localizers loc1/2, probe. TCP at two positions. Compare Table 1.

Table 1: SD z-direction. Compare Fig. 4.

no.		a_0	a_1	a_2	r
6	Loc 1, TCP 1	8,74 E-02	-1,50 E-04	8,32 E-08	0,82
2	Loc 1, TCP 2	1,20 E-01	-2,85 E-04	2,51 E-07	0,99
4	Loc 2, TCP 1	6,81 E-02	-2,06 E-04	1,68 E-07	0,99
1	Loc 2, TCP 2	3,07 E-01	-7,24 E-04	5,85 E-07	0,99
5	Probe, TCP 1	1,67 E-02	-4,27 E-05	5,81 E-08	0,99
3	Probe, TCP 2	9,99 E-02	-2,71 E-04	2,48 E-07	0,99

The SD in rotation (Fig. 3b) is comparable between all localizers/probe and TCP definitions. Therefore, no conclusion can be drawn.

Discussion and Conclusions

A total of 48 experiments were conducted with a reduced grid size and the localizers/probe's rotation being constricted to optimal visibility. It was shown that the pose's SD can be assessed by regression functions based on the camera-localizer distance (CC > 0.558). The SE < 0.015mm suggests repeatability with similar regression coefficients.

The regression functions differ significantly between different localizers/probe and TCP positions, thereby reflecting different accuracy. Therefore, we conclude that the concept of individually characterizing different kinds of localizers to obtain regression models is feasible. Following, the regression functions can be used to constantly assess the lower bound of the measurement error of a certain localizer at the current pose.

In further experiments, the spatial grid will be extended to the entire measurement volume of the measurement system. Additionally, the localizer rotation will be included to account for changes in tracker's visibility what might influence the quadratic correlation.

When applied over time, the assessment could also be used for an inspection of the condition of a certain localizer by calculating the pose's SD and comparing the result to the prediction gained from the regression functions.

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