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Using analytical redundancy to increase safety of a synergistic manually guided instrument for craniotomy

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***Abstract*—In this paper, two methods for bridging line of sight interruptions occurring during the use of the synergistically operated semiautomatic trepanation system (STS) are presented. In the STS, position information is acquired using an optical tracking system with the disadvantage of possible line-of-sight interruptions. Their compensation is crucial, as a real-time control system automatically adjusts the cutting depth of the instrument on the basis of position information and a-priori data. The surgeon is only responsible for guiding the instrument along the resection line. Hence, availability of position information is crucial for depth control, set point generation, and thus for patient safety. In favour of enhancing reliability of position and orientation acquisition, two approaches were developed which are intended to estimate the position during line of sight interruptions on the basis of a-priori system information and process parameters. To assure patient's safety during this procedure, several parameters of the system (e.g. cutting radius, skull gradient) are used in order to estimate the possible cutting error while the redundant system is activated. These two algorithms and the online risk assessment were implemented, and afterwards evaluated. The evaluation was performed using a skull phantom, and yielded promising results.**

I. INTRODUCTION

THE Semiautomatic Trepanation System (STS) is a synergistic operated handheld instrument for trepanation of the skull in neurosurgery. The concept is supposed to protect the dura mater, and to reduce the cutting gap by applying a soft tissue preserving saw whose depth of indentation is automatically fitted to the local skull thickness. A control system automatically adjusts the cutting depth of the saw based on information from CT data and optical tracking in real-time (see fig. 1) [1]. In order to cope with small errors in the adjustment of the cutting depth, and the inevitable contact between the saw blade and cranial structures (e.g. dura mater) a soft tissue preserving saw is used to cut the bone. Follmann et al. showed that when this type of saw is used errors of up to 2.5 mm are tolerable without injuring the dura mater [2]. In contrast to a surgical robot system automatically controlling several degrees of freedom, the STS only requires one automatically actuated degree of freedom (cutting depth). The synergistic man-machine cooperation enables the surgeon to control the remaining degrees of freedom. In this case he has to guide the instrument along the resection trajectory on the patient's skull in three (more uncritical) degrees of freedom. These are 2DOF on the surface plus orientation of the saw along the cutting trajectory. The orientation of the instrument is defined by the manual motion along the skull surface (direct haptic guidance by the surface) and the depth is automatically controlled by the system. However, the operation of an instrument close to delicate structures like the brain induces potential risks, which have to be countered with dependability of the whole system [3].

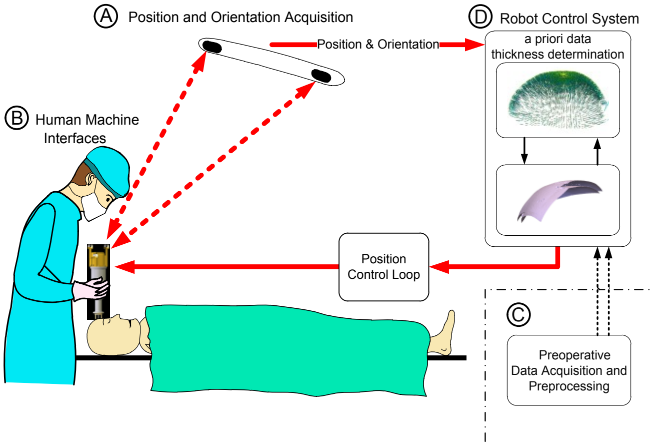

Fig. 1 Synergistic control concept of the Trepanation System [1]

In this context, the use of an optical tracking system (OTS) has some drawbacks, as it needs a direct line-of-sight to the instrument to be able to determine its position relative to the situs [1]. Whenever the line of sight (LOS) is interrupted and the system is not able to acquire position/orientation information, the generation of further set points for the depth regulation is no longer possible. Thus cutting depth cannot be adjusted correctly, which could lead to severe injuries, a perforation of the dura mater, the underlying central nervous structures, and blood vessels or to an incomplete transection of the skull bone. To avoid those negative effects, a safety strategy was integrated which retracts the saw blade in case of a persistent interruption of the line of sight. This contradicts a predictable reaction of the tool, which is essential to minimize potential human-induced errors [3],

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[4]. Such interruptions can not only lead to unforeseen reactions of the user, but also reduce the efficiency of the process.

Redundant position acquisition, which allows adjustment of the cutting depth even during a LOS interruption, might help to bridge the interruption time. Moreover, with additional time to warn the surgeon of pending retraction, the safety and efficiency of the procedure could be enhanced.

II. STATE OF THE ART

In literature, two different approaches are described to optimize the performance of tracking systems. The first one is the improvement of the LOS by optimizing the visibility of the instrument. Another approach is to combine different tracking modalities, into a hybrid tracking system.

To improve the visibility of the STS instrument, Fuertjes et al. suggested the use of an active multi surface rigid body [5]. However, line-of-sight interruptions cannot be avoided reliably using this technique. Several hybrid tracking systems for medical applications are described in literature. Approaches combining an OTS with electromagnetic tracking (EMT) or an Inertial Measurement System (IMU) are presented. Parnian [6] described the combination of an optically tracked tool with an IMU (MicroStrain 9DOF, Microstrain Inc., USA) suited for applications which require millimeter accuracy tracking. The OTS used in this work is based on several cameras resulting in a relatively large working volume. To fuse the data of OTS and the IMU, an Extended Kalman Filter (EKF) was used. He was able to increase the position sampling rate of the OTS from 5-20Hz to about 100Hz. In contrast, Tao et al. [7] applied a Particle Filter (PF) and an EKF for data fusion of an IMU (MT9, Xsens), and an OTS to optimize tracking of human motions.

Roetenberg et al. [8] used a Kalman filter for data fusion in a system for human motion tracking. Data of inertial sensors (MTx, Xsens Technologies, The Netherlands) and an EMT system are fused to perform an error compensation of the EMT system and increase the sampling rate. Ren et al. [9] presented a similar approach, as they also fused EMT with IMU data. The system is intended for the use in endoscopic surgery. In previous work, we presented an Unscented Kalman Filter (UKF) applied to fuse data from an IMU (ADIS16405, Analog Devices Inc., USA) with an OTS (Polaris Spectra, Northern Digital Inc., Canada) to bridge LOS interruptions [10]. The system is able to interpolate position and orientation information (6DOF) at high rates. However, due to the high drift of the sensors used, the bridging times are very short. Schneider et al. [11] fused information from an IMU (MTi, XSens, The Netherlands) and OTS using a Kalman filter. The authors concluded that sensor drift and bad signal-to-noise ratio of the inertial sensors are the main factors limiting the bridging time [12].

III. MATERIALS AND METHODS

To provide redundant 6DOF information which can be used in the STS control system, the current system structure (see fig. 1) has to be modified. In addition to the redundant system, a fault management structure has to be added (see fig. 2), which assures the patients' safety.

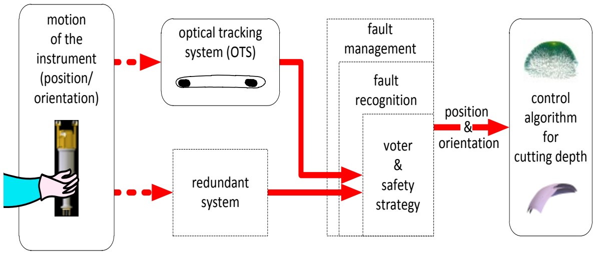

Fig. 2: Integration of a redundant structure into the STS

A. Fault management and safety strategy

The fault management has three modes of operation. First, it has to recognize system faults (e.g. LOS interruption), secondly, it asses reliability of both data sources, and third, it uses this information to switch the system into a safe state. An approach based on online risk assessment is chosen to estimate the time which is tolerable for the application of the redundant structure to supply the system with position and orientation information. To calculate the potential error, the minimal cutting radius of the saw, the current position on the skull, the minimal size of a trepanation trajectory, and the directional motion vector are used to determine the area where the saw will most probably be in the next five seconds (maximal bridging time with 2.55 mm/s feed rate) (see fig. 2). For this region, thickness gradients are computed. Operation is most probably safe as long as the gradients are less than 2.5 mm (soft tissue preserving capability).

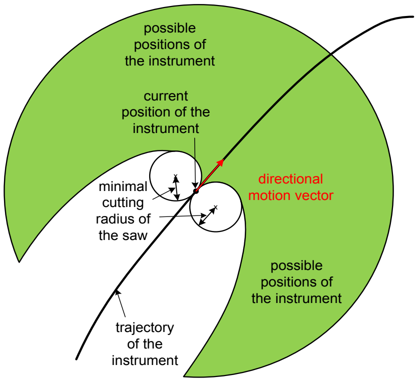

Fig. 3: Error estimation concept,using constraints and parameters of the process

B. Concept of the redundant structure

Bridging time is the central criterion for the redundant structure. A first evaluation of LOS interruptions occurring in a laboratory setup during 25 trepanations conducted by five different persons revealed that 96% of all LOS interruptions are less than one second, and none of it was longer than 5 seconds. The necessity to bridge these long interruption times excludes the use of IMUs, which are unable to bridge such long line of sight interruptions, due to drift, bias and noise of these sensors. Also, the use of hybrid

EMT-OTS systems (e.g. [13], [14]) is not possible due to the high distortions resulting from the STS instrument. Hence, a new concept for redundant position acquisition has been developed. Similar to the online risk assessment method, process inherent data, especially information regarding the instruments trajectory plus information about the skulls surface and the assumption that the instrument moves along this surface, can be used to perform an estimation of position and orientation. On this basis, two different approaches are conceivable. The focus of the first approach is to use system inherent data (CT data/skull surface, feed rate, the path already covered by the instrument, maximal cutting angle), whereas the second approach tries to predict the instruments position by using information from a preplanned trajectory.

C. Motion predictor

Several concepts for motion estimation are described in literature. Most of them are based on the Newtonian equations of motion, while they differ with regard to modeling of the random processes, and the way motion history is included. An efficient approach for motion prediction of moving objects is proposed by Elnagar and Gupta [15]. Their motion estimation algorithm is based on an autoregressive model (ARM), a linear predictor for stochastic processes with conditional maximum likelihood estimation of the model's parameters. For the STS two motion estimators of this kind were implemented, one for the translational degrees of motion, and one for rotational degrees of motion (see fig. 4).

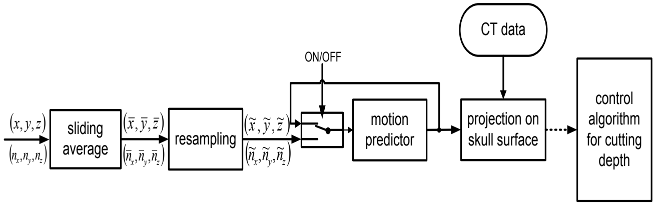

Fig. 4: Structure of the motion predictor

Before sending data from the OTS to the estimator, data is filtered using a sliding average filter and then resampled. Resampling is necessary in order to equalize the distance between the points, and to have lower variations in acceleration between the measurements. During established LOS, this data is continuously used to train the motion estimator. After activation of the predictor in case of an interrupted line of sight, position and orientation of the normal vector are estimated, and subsequently reinserted into the predictor (see fig. 4). In a final step, the position and orientation information is projected on the skulls surface to reduce the prediction error under consideration of the geometry of the instrument. By further restricting the probability space regarding the positions of the instrument, the likelihood of predicting the correct position can be increased.

A. Motion prediction based on a preplanned trajectory

In a second approach, data from a preplanned trajectory is used for the prediction of the instruments position on the skull. The surgeon uses a sterile liner to draw the resection line on the skull. By fixing a calibrated optically tracked rigid body to this liner, this procedure can be used to record the trajectory. Subsequently, the recorded trajectory is preprocessed using a sliding average filter, and finally resampled. Possible small LOS losses are bridged by linear interpolation. In the next step, this data is used to compute virtual positions and orientations of the saw, for each position on the trajectory, by application of the RANSAC (RANdom SAmple Consensus) algorithm (see fig. 5) [16].

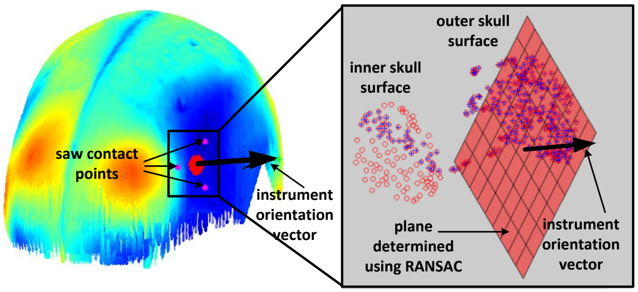

Fig. 5 Using RANSAC to project feets on surface

Subsequently, the data is used in the real-time control system to estimate the position of the saw on the preplanned trajectory in case of LOS interruption. This is accomplished by using the average speed over the last measurements to be able to interpolate the further steps on the a-priori trajectory.

IV. RESULTS

The evaluation of the system was focused on the bridging characteristics of the two presented algorithms (table I, II).

TABLE I
REAL MEASUREMENTS FOR THE MOTION PREDICTOR

	Error in bone thickness estimation during LOS [mm]			Error in position estimation during LOS [mm]		
#	mean	std. dev.	max.	mean	std. dev.	max.
1	0.024	0.004	0.031	3.95	2.36	8.01
2	0.281	0.352	1.208	1.86	1.14	4.26
3	0.062	0.066	0.218	7.35	4.38	15.24
4	0.323	0.173	0.573	1.92	1.08	3.83
5	0.201	0.073	0.313	5.40	3.90	17.50

A setup including an artificial skull (Sawbones AB, Sweden), an OTS (Polaris Spectra, NDI) was used for evaluation. A CT dataset was acquired and processed according to the workflow described in [1].

TABLE II
SIMULATIONS OF THE A-PRIORI PREDICTOR

	Error in bone thickness estimation during LOS [mm]			Error in position estimation during LOS [mm]		
#	mean	std. dev.	max.	mean	std. dev.	max.
1	0.118	0.079	0.250	2.02	1.60	5.15
2	0.367	0.836	1.296	3.05	2.27	7.93
3	0.220	0.468	7.982	12.78	6.77	25.06
4	0.080	0.032	0.126	4.35	0.66	5.56
5	1.158	0.745	3.069	10.60	7.40	35.10

In the first part of the evaluation, the motion predictor was used to compensate line of sight interruptions during five different trepanations conducted on the skull (see table I). During these trepanations, LOS interruptions ranging from 0.56 to 2.42 seconds occurred. On average, the feed rate of the saw along the skull surface was 5,642 mm/s. The error in position and thickness prediction by the motion estimator is described in table I. To be able to compute these values, the line of sight interruptions were interpolated. In the second part of the evaluation, the same procedure was conducted for the a-priori predictor. To produce comparable results, position and orientation information recorded in the first trial were used in an offline simulation (see table II). During trepanation 3 and 5 large thickness errors occurred and the error estimator stopped the process. These two evaluations demonstrate the performance of the two algorithms using the real instrument. To evaluate the dependency of the skull thickness error from LOS interruption time, a simulation with artificial LOS interruptions was performed. The same trajectories used in the prior experiments were acquired using an optically tracked probe with high visibility, and with an average speed of 2.55mm/s.

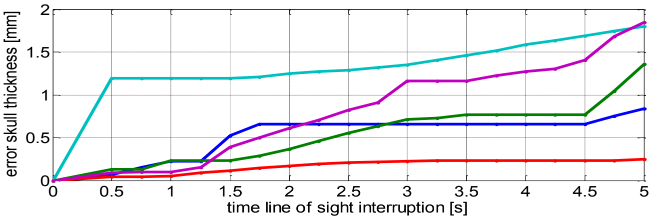

Fig. 6: Simulative evaluation of the motion predictor

During several simulations using these five trepanation trajectories, the LOS interruption time and the position of the LOS interruption on the trajectory were varied and resulted in the values described in fig. 6.

V. DISCUSSION AND CONCLUSION

The results of the evaluation show the successful performance of the proposed motion estimators, which are used as a redundant system for the cutting depth control of the STS instrument in case of LOS interruptions.

The evaluation of the motion predictor (see table I) using the real instrument revealed a low maximal error in thickness determination with less than 1.21mm. This is a strong result, as it is lower than the 2.5mm safe zone of the soft tissue preserving saw mechanism. Moreover, the trepanation process was not interrupted due to emergency stop during LOS losses, and remained safe for the patient at all times. The results from the simulation are similar (see fig. 6). They show a high dependency of the resulting error from the chosen trajectory (local anatomy of the skull).

During the evaluation of the a-priori predictor (see table II) based on the preplanned trajectory, in most cases the error remained below 2.5 mm. Only in two cases (trajectory 3 and 5) the error was significantly larger. Most likely, this could be explained by either the sensitivity of the algorithm to speed variations of the instrument which might cause ambiguities in the determination of the starting point or a deviation from the preplanned trajectory occurring during the real trepanation process.

Future work will focus on an optimization of the a-priori predictor, and on improving reaction of the system to unexpected movements of the surgeon. A combination with the motion prediction algorithm might help to increase the location accuracy on the preplanned trajectory. Improving reaction on sudden very dynamic movements of the instrument could also be realized using data from an IMU. Additionally, redundant online sensor information (ultrasound, impedance, OCT, etc.) can be considered.

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