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Patient Motion Tracking in the Presence of Measurement Errors

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Abstract—**The primary aim of computer-integrated surgical systems is to provide physicians with superior surgical tools for better patient outcome. Robotic technology is capable of both minimally invasive surgery and microsurgery, offering remarkable advantages for the surgeon and the patient. Current systems allow for sub-millimeter intraoperative spatial positioning, however certain limitations still remain. Measurement noise and unintended changes in the operating room environment can result in major errors. Positioning errors are a significant danger to patients in procedures involving robots and other automated devices. We have developed a new robotic system at the Johns Hopkins University to support cranial drilling in neurosurgery procedures. The robot provides advanced visualization and safety features. The generic algorithm described in this paper allows for automated compensation of patient motion through optical tracking and Kalman filtering. When applied to the neurosurgery setup, preliminary results show that it is possible to identify patient motion within 700 ms, and apply the appropriate compensation with an average of 1.24 mm positioning error after 2 s of setup time.**

I. Introduction

Image Guided Surgery (IGS) has had a major impact on the practice of neurosurgery, orthopedics and other specialties in the past few decades. In general, IGS requires 3–5 mm accuracy, whereas 2 mm is recommended for IG neurosurgery. However, in robot-assisted IGS, sub-millimeter accuracy might be necessary. While the intrinsic accuracy of mechatronic systems may satisfy this need, the overall error during the procedure can be much higher. Application accuracy is affected by many factors, such as measurement noise and accidental changes in the operating room (OR) environment. Positioning inaccuracy is a significant danger to patients in procedures involving robots and other automated devices, and can only be tested in real or simulated OR conditions [1].

The vast majority of the currently approved surgical navigation systems uses a *Dynamic Reference Base* (DRB) frame and provides the position of hand-held (or robot-held) surgical instruments with respect to this frame. This way, the effect of camera motion can be excluded; however, if another computer-integrated system, such as a robot, (with a different base frame) is incorporated, unintended patient motion can lead to significant errors [2]. Although it is possible to track the robot base frame relative to the *DRB*, this solution may be impractical due to issues such as line-of-sight limitations. Using an additional rigid body might also make the system more complex; mounting can be cumbersome and increase the overall costs. Our research considers the situation where the navigation system can only measure the position of the robot tool with respect to the *DRB*. Hence, it is necessary to combine navigation measurements with robot kinematics to estimate the transformation between the robot base and the *DRB*.

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II. Intraoperative Patient Motion

A. Background of patient motion and tracking

In the case of robot-assisted IGS or radiation therapy, the precise delivery of treatment is vital, therefore requiring accurate positioning of the surgical tools. Application accuracy can be affected by many factors, and unintended changes are prone to happen in the OR setup. The main sources of external (i.e., excluding physiological) patient motion during surgery include:

- large forces applied by surgeon (e.g., bone milling)
- bumping into the operating table
- leaning against the patient
- inadequate fixation
- equipment failure

Different strategies have been applied to keep the robotic device's position and the tracking data consistent throughout the operation. The most basic solution is to have a rigid mechanical fixation between the robot and the patient. Smaller robots, such as the SmartAssist [3] (Mazor Surgical Technologies Inc., Caesarea, Israel) may be bone-mounted. However, this requires more invasive fixation on the patient side, and large forces still can cause relative motion between the patient and the fixator/robot. Another solution is to use multiple *DRB* markers to track the robot base and the patient separately. Unfortunately not every tracking system supports this, and it may be difficult to maintain the line-of-sight without disturbing the physician. Robotic setups could include accelerometers and gyroscopes to detect sudden changes; however, this requires electronic coupling and the resolution may not be sufficient for proper compensation. Additionally, this alternative increases the costs and complexity of the system. CCD cameras can also survey the OR, yet again, the resolution may not be high enough.

Some commercial systems combine surface-mounted and in-body fiducials to track external and physiological organ motion, though a separate surgery is required to place the markers. A successful example is the CyberKnife radiation therapy system (Accuray Inc., Sunnyvale, CA) that can track parallel skin surface motion through a special marker equipped suit worn by the patient. Organ motion is followed in real-time by taking bi-plane x-ray images and locating fiducials (gold beads) that were preoperatively implanted into the patient [4].

Some methods for patient fixation do not provide adequate rigidity, thus requiring further compensation. In orthopedics, there are larger interaction forces, making it necessary to use more invasive fixations. One example is the ROBODOC system [5] (ROBODOC, a Curexo Tech. Co., Fremont, CA), the first automated bone milling robot for hip replacement approved by the US Food and Drug Administration (FDA). The system uses a bone-attached fixation with a bone motion sensor to detect fixation failures. One clinical report on 900 ROBODOC surgeries indicated that bone motion was detected in 11% of the cases [6]. There is a clear trend in applications to shift towards less invasive surgical solutions.

B. *New concept for motion compensation*

We propose a minimally invasive concept for patient motion compensation that can support systems with less rigid fixation setups or limited tracking capabilites. During regular operation, the surgical tool mounted on the robot can be used to relate the different control frames (Figure 1). Note that depending on the physical realization, the tracking marker (*ToolFrame1*) and the tool center point of the robot (*ToolFrame2*) can be different. In this case, the fixed transformation between them is either known a priori or obtained from calibration. Control signals computed in the *DRB* frame can be acquired in the *RobotWorld* frame (also called *RobotBase*) through the homogenous transformations:

$$Control\big|_{DRB} = {}^{\mathrm{DRB}}_{\mathrm{Nav}}T \cdot {}^{\mathrm{Nav}}_{\mathrm{Tool1}}T \cdot {}^{\mathrm{Tool1}}_{\mathrm{Tool2}}T \cdot {}^{\mathrm{Tool2}}_{\mathrm{RW}}T \cdot Control\big|_{RW} \quad (1)$$

Our solution for a robot-integrated IGS is to close the control loop through calibration, acquiring the transformation between the *RobotBase* and the *DRB*. This can be computed under stationary conditions (during registration) by closing the loop:

$${}^{\mathrm{DRB}}_{\mathrm{RW}}T = {}^{\mathrm{DRB}}_{\mathrm{Nav}}T \cdot {}^{\mathrm{Nav}}_{\mathrm{Tool1}}T \cdot {}^{\mathrm{Tool1}}_{\mathrm{Tool2}}T \cdot {}^{\mathrm{Tool2}}_{\mathrm{RW}}T \,. \quad (2)$$

Throughout the surgery, we maintain the ability to detect

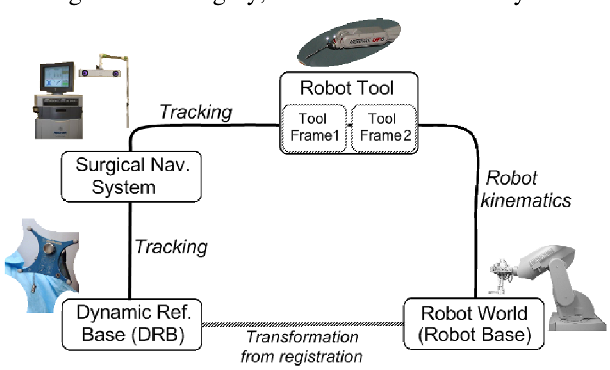

Fig. 1. General control view of an image guided system with a surgical robot. Homogenous coordinate transformations link the different nodes (frames).

unintentional patient motions with respect to the robot, i.e., deviations from the original *RW* to *DRB* transformation. We propose Kalman filtering (KF), a well-established method, to compensate for changes of the transformation [7]. The *RW* to *DRB* registration is updated based on the localizer readings. The state vector of the KF is:

$$X_{est} = \left[P\big|_{x,y,z}, Euler\big|_{\phi,\vartheta,\psi}, \dot{P}\big|_{\dot{x},\dot{y},\dot{z}}, \dot{Euler}\big|_{\dot{\phi},\dot{\vartheta},\dot{\psi}} \right] \quad (3)$$

where X_{est} is constructed from the Cartesian positions, the Euler representation of the orientation, and the velocities of the aforementioned variables. The position and orientation parameters determine the dynamically changing *RW* to *DRB* transformation. The discrete input of the filter derives from the measurement of the surgical navigation system. We can use (2) as the measurement model of the KF to compensate for patient motion, provided the other transformations are known with high accuracy.

In the concept described above, accuracy is dependent on the positioning precision of the robot and the tracker. First, the spatial accuracy can be corrupted by noise. For the most commonly used optical trackers, noise varies with the marker type, lighting conditions, and position and angle of the rigid bodies in the cameras' field of view. Beyond measurement noise, latency can also be a major problem, making it difficult to close the control loop for compensation through (2). A robotic system typically runs in 20–100 Hz cycles at the highest control level; however, commercially available tracking systems are not capable of more than 5–60 Hz data acquisition, depending on their modality.

The algorithm was tested on our neurosurgery setup, as described in the next sections. The solution is generalized for other applications involving tracking (with different modalities) and robots. Automated registration updates could lead to safer and more accurate surgical treatment.

III. NEUROSURGICAL ROBOT SETUP

A. *Integrated system components*

We used the neurosurgical robot system developed at the Center for Computer-Integrated Surgical Systems and Technology (CISST ERC) at the Johns Hopkins University for testing [8]. Figure 2 shows the setup consisting of a robot arm, a visualization console, a surgical navigation system, and a robot controller computer.

The NeuroMate manipulator (Integrated Surgical Systems Inc., Sacramento, CA) is a 5 degree-of-freedom (DOF) IG robot designed for stereotactic procedures. The StealthStation intraoperative navigation device is also commercially available (Medtronic Inc., Louisville, CO). It tracks the 3D position and orientation of sets of optical markers forming a rigid body. This version of the StealthStation only allows for the detection of two frames (i.e., a fixed reference frame and a moving pointer frame). Both devices are FDA approved.

An Anspach eMax 2 high-speed surgical bone drilling instrument (The Anspach Effort Inc., Palm Beach Gardens, FL) was attached to the tip of the robot through a

6 DOF force sensor (JR3 Inc., Woodland, CA) to measure the forces and torques applied to the end-effector.

The control software successfully integrates open source and proprietary software. It extensively relies on the *cisst* open source libraries (https://trac.lcsr.jhu.edu/cisst), developed for surgical robotic applications at Johns Hopkins.

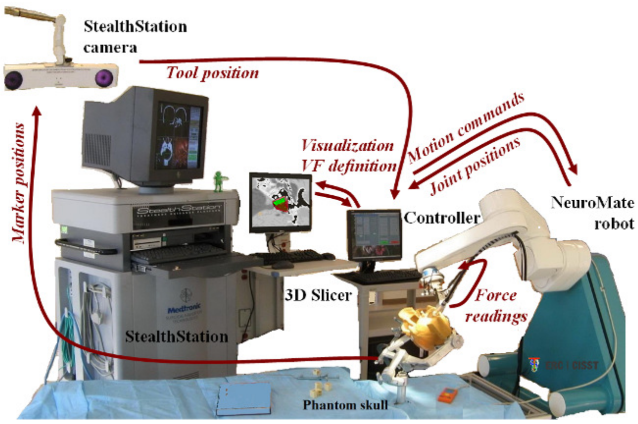

Fig. 2. The image guided neurosurgical robot at Johns Hopkins University, with the major flow of information in the system.

B. *Neurosurgery robot operation*

The robot and surgeon share control of the cutting tool in a cooperative control mode (hands-on surgery). Forces exerted by the physician are translated into joint motions to move the NeuroMate. The platform was optimally built to reduce the operating time of a complex procedure. It provides a safer and more reliable surgical tool for bone milling at the skull base.

Figure 3 shows the integration of the different components for control through homogenous transformations. The stationary links are acquired through calibration and registration, while the robot kinematics and optical marker positions are computed dynamically. The drill's position is also read through the *Robot Rigid Body* (RRB) attached to the tip, while the *DRB* is mounted directly on the skull or the Mayfield head clamp. The controller program on the PC communicates with the embedded processors in the robot over CAN bus with an update period of 18.2 ms.

The concept of virtual fixtures (VF) has been applied to the system. A VF is used as a 3D boundary, created preoperatively in the 3D Slicer medical software (www.slicer.org). After registration, it constrains the tool to the predefined area by decreasing the robot's velocity towards the virtual wall proportional to its distance from the wall. Once the VF is reached, the robot does not allow further motion in that direction, and the stiffness of the structure prevents significant overcut. However, change in the robot (*RW*) position relative to the reference frame (*DRB*) (i.e., patient motion) results in the displacement of the VF, decreasing its effectiveness. The VF computations are done in the *DRB* coordinate system, and once the desired velocities are computed, they are transformed back to *RW* to generate the joint velocity commands for the NeuroMate.

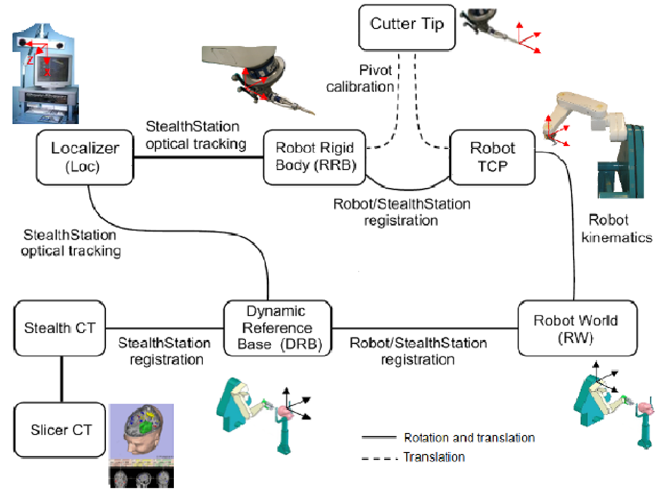

Fig. 3. Different coordinate frames used to control the robotic neurosurgery system. The lines represent coordinate transformations.

C. *System characteristics*

According to our tests, measurement noise is present in the StealthStation's data, with a standard deviation (STD) of 0.26, 0.22 and 0.24 mm in x, y and z directions respectively and with normal distribution. The position information acquired through the StealthLink research interface is delayed with respect to the robot's motion by an average of 247 ms. Additionally, the temporal resolution of the navigation system is limited, since position updates are only possible every 131 ± 19.7 ms (mean ± standard deviation). This variance appears as random error in the measurements.

Although prior phantom experiments with the neurosurgical system yielded sub-millimeter accuracy (0.79 ± 0.82 mm), cadaver experiments showed errors up to 3 mm, which was believed to be due to intraoperative motion [9].

IV. Patient Motion Compensation Test

A. *Applying the new motion compensation algorithm*

The new concept presented in Section II was applied to the neurosurgical robot system. The algorithm was adaptable as the position information attained from the robot's kinematics and through the StealthStation can be used together for a better estimation. The transformation between the robot's base frame (*RW*) and the reference frame (*DRB*) is determined through a preoperative registration procedure, where the robot tool is moved to several different poses and measured by both the robot encoders and navigation system. We employed a paired-point registration method that directly estimated ${}^{DRB}_{RW}T$, then computed ${}^{RRB}_{TCP}T$. Alternatively, it is possible to use a "hand-eye" calibration method [10] to directly estimate ${}^{RRB}_{TCP}T$. Once ${}^{RRB}_{TCP}T$ is known, it can be used to compensate for patient motion via equation (2), which is rewritten below for the frames identified in Fig. 3:

$$ {}^{\mathrm{DRB}}_{\mathrm{RW}}T[k] = {}^{\mathrm{DRB}}_{\mathrm{Loc}}\tilde{T}[k]\cdot {}^{\mathrm{Loc}}_{\mathrm{RRB}}\tilde{T}[k]\cdot {}^{\mathrm{RRB}}_{\mathrm{TCP}}T\cdot {}^{\mathrm{TCP}}_{\mathrm{RW}}T[k'] \qquad (4) $$

where $[k']$ represents the latency compensation applied to the robot data. Patient motion is checked at discrete times, when

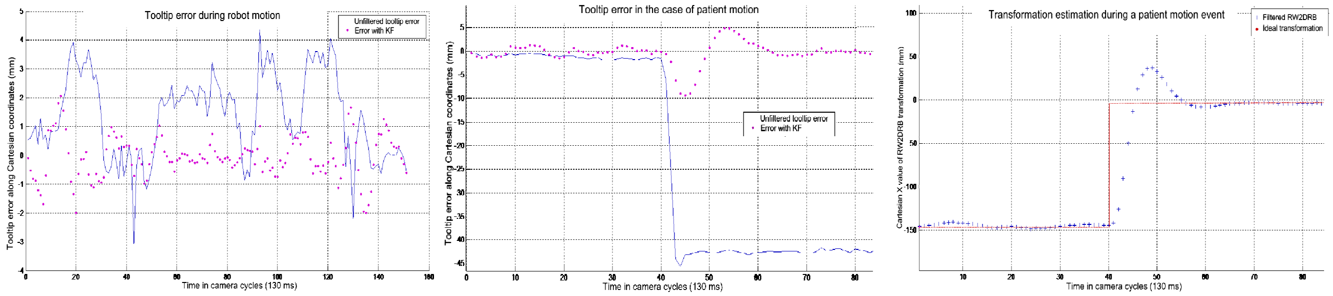

Fig. 4 a) Overall positioning error at the tooltip (blue) in mm, effect of Kalman filtering (purple); b) Positioning error in the case of patient motion, purple line is the compensated system; c) Estimation of the changing position of the *DRB*, red line is the theoretical value, blue is the filter output.

a new StealthStation update is available. The navigation system's measurements were pre-filtered to reduce the inherent measurement noise defined in Section III:

$$ {}^{\mathrm{DRB}}_{\mathrm{RRB}}\tilde{T}\left[k\right] = KF\left({}^{\mathrm{DRB}}_{\mathrm{RRB}}T\left[k\right]\right) \tag{6}$$

The Q covariance matrix, representing the model error in the KF equations, was adjusted between 10^{-5} and 10^{-1} in every cycle depending on the estimated tooltip speed. This strategy was applied to compensate for the overall error deriving from the variation in the navigation data updates. Q is adaptively changed through a logarithmic hyperbolic tangent function that is set to have the steepest rise above the maximum speed values typical for regular robot motions. This function allows for the identification of patient motion as that causes high gradient of speed. During the event of patient motion, the measurements of the navigation system should be trusted for faster convergence to the new *RW* to *DRB* transformation. Measurement noise covariance R of the filter was set according to the previously acquired camera noise parameters.

B. Experimental results

During the tests at Johns Hopkins University, the robot tool was first moved while the *DRB* frame remained stationary. In this case, the motion compensation method should not change the estimated *DRB* to *RW* transformation; thus, any change in this transformation represents an error. As shown in Figure 4a, the Kalman filter decreases this error from 3.05 mm to 0.68 mm. The STD of the transformation's estimation was 1.27 mm.

To test the patient motion compensation concept, the relative position of the skull (and therefore the *DRB*) was intentionally changed with respect to the robot during the experiments. Larger, sudden movements of the operating setup and the patient were performed, including motion of the operating table (Fig. 4b). On average, our method was capable of identifying the patient motion events within 700 ms, and compensating for the change of the *RW* to *DRB* transformation with an average position error of 1.24 mm and an acceptable 2 s settling time (Fig. 4c). This latency results because adjustment of the parameters is based on the a posteriori estimation of the KF. Overshoot of the signal is due to the sensitivity of the parameters to the speed of the changes; this is the subject of further research.

V. Conclusion

The potential of robotic surgery is rapidly increasing, due to continuous development by research groups all over the world. To provide better patient care, unique challenges, such as adaptation to the changing environment of the operating area, must be addressed.

Image guided surgical setups are especially sensitive to changes, for instance when the patient is moved relative to an interventional device, such as a robot. The most efficient method to compensate for relative motion between a surgical robot and the patient is to directly measure this motion (e.g., by tracking both the robot base and the patient). Our research has shown, however, that if this hardware setup is not feasible, it is still possible to compensate for motion when just the robot tool and patient are tracked.

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