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Hybrid Attitude Estimation for Laparoscopic Surgical Tools: A Preliminary Study

Hongliang Ren Peter Kazanzides

***Abstract*—Laparoscopic surgery poses a challenging problem for a real-time navigation system: how to keep tracking the surgical tools inside the human body intraoperatively. This paper proposes a sensor fusion method for a hybrid tracking system that incorporates a miniature inertial measurement unit and an electromagnetic navigation system, in order to obtain continuous orientation information, even in the presence of metal objects. The sensor fusion algorithm employs an extended Kalman filter to integrate the data from the two sensor streams, based on a quaternion formulation of the system dynamics. The preliminary experimental results show that the integration of low-cost inertial measurement is able to compensate the distortion of EM tracking.**

***Index Terms*—Laparoscopic surgery, surgical navigation, Extended Kalman Filter, Sensor fusion**

I. INTRODUCTION

Recent advances in Electro-Magnetic (EM) tracking technology make it an alternative to optical tracking in surgical navigation, without the constraint of Line Of Sight (LOS). However, EM tracking is notorious for its sensitivity to surrounding metallic or conductive surgical tools. We informally examined the behaviors of two EM tracking systems: Aurora (Northern Digital Inc.), as shown in Fig. 2, and mediSAFE (Ascension Technology Corp.). Both systems yield relatively stable measurements in a clean environment, but we observed significant distortions in both position and orientation measurements when metal objects were placed near the coils or field generators. Even a rather small metal tool, such as a pointer probe from an optical tracking system, caused position distortion of several millimeters and orientation distortion of up to 10 degrees. More comprehensive distortion evaluations can be found in [1], [2].

Other tracking techniques, such as ultrasonic localization [3] or mechanical tracking [4], [5], have not been widely used in operating rooms due to the inherent limitations of laparoscopic surgery. A good survey regarding the state-of-art tracking technologies was summarized in [6]. Therefore, we are studying a hybrid tracker that integrates inexpensive MEMS inertial sensors to compensate the distortion of the EM tracker. The technical approach is to fuse the measurements from the EM tracker and inertial sensors using an Extended Kalman Filter (EKF) algorithm.

The paper is organized as follows. Section II reviews the state of the art in hybrid tracking systems. Section III specifies the system modeling and algorithm implementation for the hybrid-tracking problem. Section IV validates the system design and evaluates the attitude estimation algorithm.

II. RELATED WORK

A. *Calibrating EM trackers*

Distortion mapping is generally used to improve the accuracy of an EM tracking system, as reviewed in[7]. Other researchers in our lab [8], [9] experimentally mapped the EM measurement field distortion by combining an Aurora EM tracking system with an optical tracking system, and then characterized the distortion for specific environment setups. This mapping technique is time-consuming and can only compensate for static disturbances.

B. *Integrating EMT with OTS*

Using assistive measurements is another way to correct the distortion of EM tracking. It has been shown [10] that combining assistance from an optical tracker can improve EM tracking accuracy by one third for specific surgical environments. There exists a study [11] of tracking the outside segment of laparoscopic tools using optical trackers, while localizing the distal end inside the human body by attaching EM sensor coils. This is based on the assumption that the laparoscopic tool is rigid and causes no significant interference to the EM tracking. But, the main disadvantages of integrating optical tracking are that it makes the operating room even more crowded with two tracking systems and still suffers from the LOS constraint.

C. *Motivation for the proposed hybrid tracking method*

In this paper, we propose an integrated EM tracking aided inertial navigation system for laparoscopic surgery. This is motivated by the goal of eliminating the LOS constraint of optical tracking and providing a self-contained compensation source for EM tracking inside the human body. This is quite similar to the features of a Global Positioning System (GPS) aided Inertial Navigation System (INS) [12].

III. HYBRID ATTITUDE ESTIMATION SYSTEM

A. *Hardware system setup*

The first prototype of the hybrid tracker is composed of a three-axis accelerometer, a three-axis gyroscope, a three-axis magnetometer, and a 6DOF NDI Aurora sensor (consisting of two 5DOF coils). The inertial sensing unit was designed by our colleagues at the Fraunhofer IPA in Stuttgart, Germany. It was designed only for the validation of the sensor fusion

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Hongliang Ren is with the Laboratory for Computational Sensing and Robotics (LCSR), Department of Biomedical Engineering, The Johns Hopkins University `hlren@jhu.edu`

Peter Kazanzides is with LCSR, Department of Computer Science, The Johns Hopkins University, `pkaz@jhu.edu`

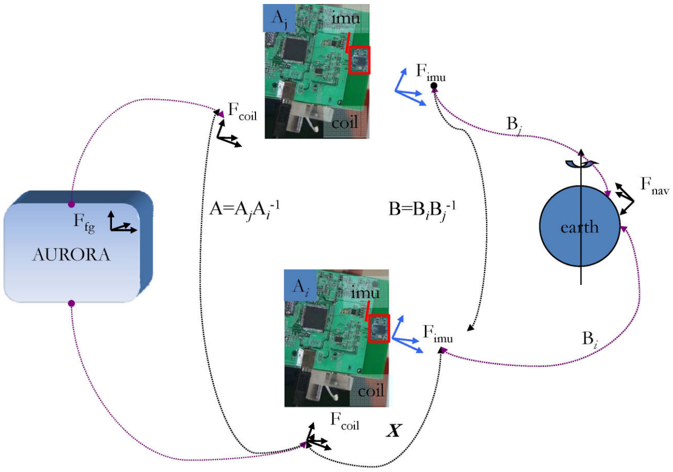

Fig. 1. Definition of coordinate systems and AX=XB problem

algorithm, so it is a relatively large circuit board. The main functional (sensor) part of the hybrid tracker is only about $10 \times 10mm$, as marked in Fig. 1.

B. Coordinate System Registration

The coordinate systems are depicted in Fig. 1. The EM tracking system produces pose measurements of the sensor coils relative to a field generator. Hence, the coil frame, F_{coil}, is fixed to the 6DOF sensor. The EM tracker base frame, F_{fg}, is affixed to the field generator.

The Inertial Measurement Unit (IMU) yields measurements relative to geographical coordinates. Hence the IMU frame, F_{imu}, is defined on the rigid body of the IMU. The inertial navigation reference frame, F_{nav},is defined with x-y-z axis pointing to north-east-down, and is used in this paper as the base frame for final fused poses.

For the notations representing rotation matrices R or homogeneous transformation frames F, a subscript denotes the source frame and a superscript indicates the target frame. For example R^{imu}_{coil} is a rotation from the coil frame to the IMU frame.

The next issue is how to associate the measurements from the two base frames. Because the inertial sensor does not provide absolute position measurements, it is only necessary to determine the rotation matrix R^{nav}_{fg}. This can be obtained by first estimating the rotation R^{imu}_{coil} using a standard AX=XB formulation [13], as illustrated in Fig. 1. Then, R^{nav}_{fg} is given by $R^{nav}_{imu}R^{imu}_{coil}R^{coil}_{fg}$. Although this can be computed from a single set of measurements, R^{nav}_{imu} and R^{fg}_{coil}, from the IMU and EM tracker, respectively, we use several measurement pairs to obtain a more accurate result.

C. System dynamic model

We use a quaternion to represent the attitude of the hybrid tracker, because of the concerns of avoiding gimbal lock and singularities of Euler angle representation. In a conventional manner, the unit quaternion is defined by the relationship $q = [q_w; (q_x, q_y, q_z)]^T, ||q|| = 1$. Note that the quaternion can easily be converted to Euler angle or rotation matrix representations.

Due to the imperfect sensing from the low-cost MEMS gyroscope, a gyroscope sensor model should be identified. We construct a seven-state vector, x, to indicate the quaternion attitude and gyroscope bias simultaneously:

$$x = [q, \quad b]^T, \tag{1}$$

where $b = (b_{roll}, b_{pitch}, b_{yaw})$ is the bias estimation of the angular velocity from the three-axis gyroscope. The trend in the gyroscope drift can be modeled as a random walk process: $\dot{b} = 0 + \epsilon$, where ϵ is zero-mean white noise.

The IMU attitude dynamics without bias can be derived in quaternion form:

$$\dot{q} = \frac{1}{2} skew(\omega) q, \tag{2}$$

where $skew(\omega)$ is the 4×4 skew-symmetric matrix of the angular rate vector $\omega = (\omega_{roll}, \omega_{pitch}, \omega_{yaw})$.

Therefore, the augmented system dynamics can be written in the form of a continuous time state-space model,

$$\dot{x} = f(x, \omega) + w = 1/2 \begin{bmatrix} skew(\omega - b)q \\ 0 \end{bmatrix} + w, \tag{3}$$

where w is the zero mean multivariate Gaussian noise with covariance of Q.

D. Measurement model

The attitude (orientation) measurement can be obtained from two sources: the IMU and the EM tracking system. The low-cost MEMS gyroscope is not sensitive enough to give accurate earth rotation rate, so only the readings from the three-axis accelerometer and magnetometer are useful measurements. Because the gravity in nav-frame is sensed by the accelerometer in imu-frame, we can establish the following relationship between the gravity vector, $\vec{g}^{nav}$, and the acceleration vector, $\vec{a}^{imu}$:

$$\vec{a}^{imu} = R^{imu}_{nav}\vec{g}^{nav}, \tag{4}$$

from which the roll and pitch angles in the rotation matrix R^{imu}_{nav} can be solved.

Similarly, given the known magnetic field in the nav-frame, the three-axis magnetometer can give the measurements in imu-frame. Thus, the heading angle can be solved from the transformation between earth field and IMU sensing vector.

Note that the roll and pitch angles derived from the acceleration vector are based on the assumption that the hybrid tracker is quasi-static or moving at uniform speed. This is true at least some of the time for hand-held laparoscopic tools. Further, we can experimentally specify a threshold indicating when the acceleration is small enough so that the gravity measurements are "good" for use. Otherwise, if accelerations are too high or the magnetometer reading is disturbed, we use the orientation from the EM tracking system, transformed

Fig. 2. Experiment setup

by R_{fg}^{nav}. Hence, the measurement equation in the state-space model is a function of the orientation,

$$z(x) = g(q) + v, \tag{5}$$

where g represents the conversion from quaternion to the representation used for the measurement (e.g., Euler angles) and v is the zero mean Gaussian observation noise with covariance matrix O.

E. EKF sensor fusion algorithm

We implement an Extended Kalman Filter (EKF) to fuse the two streams of data, though there are other well-developed sensor fusion algorithms as described in [14].

After discretization of the dynamic models, the linearized state transition and observation matrices can be derived in the form of Jacobian equations:

$$A_k = \left[\frac{\partial f_k(x,\omega)}{\partial x_k}\right]_{(\hat{x}_k)}, \qquad C_k = \left[\frac{\partial g(q)_k}{\partial x_k}\right]_{(\hat{x}_{k|k-1})}. \tag{6}$$

Then the conventional Kalman prediction and updating process can be done following the procedures in [14].

IV. PRELIMINARY RESULTS

For the preliminary evaluation, we tested the attitude estimator in both a robot-mounted hybrid tracking scenario and a hand-held tracking scenario as follows.

A. Tests on surgical robots

In this experiment, we installed the hybrid tracker onto the NeuroMate surgical robot in our lab, as shown in Fig .2. The reason is twofold: first, to get a ground-truth orientation reference from the robot; and, second, to test the behaviors of EM tracking and inertial tracking in the environment of robot-assisted laparoscopic surgery.

We ran a set of tests and compared the attitude estimation between EM tracking and the proposed hybrid (EM+IMU) tracking. The NeuroMate robot is programmed to rotate all its five joints at a constant angular velocity, so that we can test the rotation about three axes at the same time. The roll angle was estimated without any manually introduced metal interference, as shown in Fig. 3. The tracker was rotated around $[-60, 0]$ degrees repeatedly with constant speed. The hybrid tracking has less fluctuation than EM tracking during both the static phase and the movement phase. The intensive jitter behavior of the EM tracking is due to the distortion induced by unforeseen and inhomogeneous environments surrounding the moving coil.

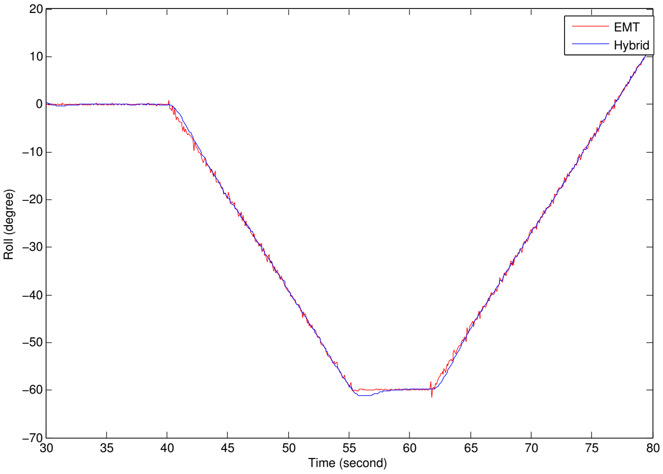

Fig. 3. Roll angle estimation without interference

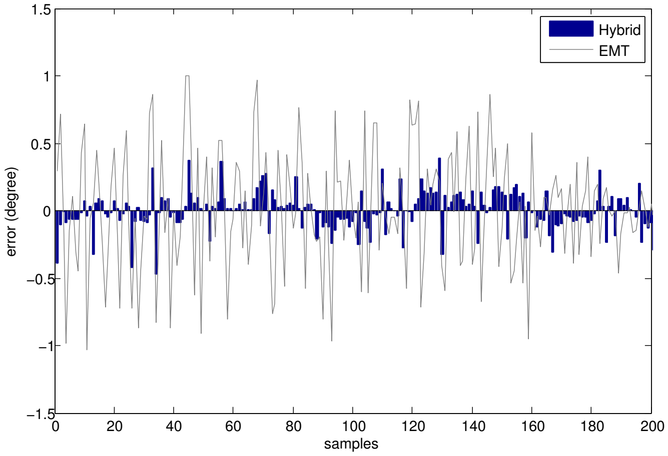

Fig. 4. Error plot of the roll angle estimation with uniform rotation

We plotted the corresponding residue, i.e., error between the estimator and the reference, in Fig. 4 for this run when the arm is moving. The other three independent runs were analyzed as well with the same setting. For this specific moving test, the Root-Mean-Square (RMS) deviation of hybrid tracking was around 0.2 degree, far less than that of EM tracking, 0.5 degree.

Overshoots of about 1.2 degree were observed for the hybrid tracker when the robot started or stopped rotating. The convergence time at these points is longer than that of EM tracking, which suggests that, in future work, the EKF parameters should be finely tuned for faster convergence.

Another test was performed to compare the pitch angle estimation under manually introduced metal disruption. We swayed an aluminum piece randomly around the hybrid tracker during the static or moving time. In these time instances, obvious severe fluctuations were observed for the EM tracking

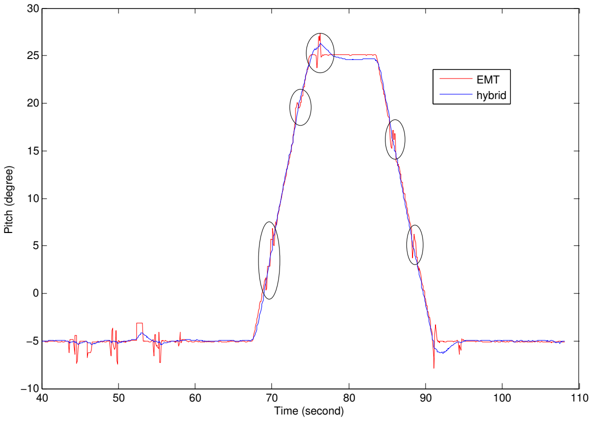

Fig. 5. Pitch angle estimation under manually introduced metal disruption

as circled in Fig. 5. The hybrid tracker demonstrated more resistant behaviors than EM tracking because the inertial sensors, except for the magnetometer, are not sensitive to metal interferences.

B. Handheld tests

This is to examine the performance in the scenario of handheld surgical operation. We manually moved the hybrid tracker randomly in 6DOF in the 3D space and recorded the attitude data. A rough observation was that the high-frequency IMU data played a significant role in compensating the EM tracking, especially while the tracker was moved around the boundary of the narrow working volume of EM tracking system. If the hybrid tracker had missing data from the EM tracker, the IMU could provide reliable attitude estimation for slow motions.

C. Remarks

We noted that the magnetometer in the IMU is in general vulnerable to environment interference, such as surrounding conductive materials or even the field generator of the EM tracking system. Therefore, the IMU heading information estimated from the magnetometer has non-negligible distortions. This could be partially compensated by building a magnetic field map, which is the subject of future work.

V. CONCLUSIONS

We proposed a hybrid attitude tracking method that integrates an EM tracker and a self-contained inertial unit. The data from the two instrumentation systems was fused by an Extended Kalman Filter. The preliminary experiments showed the hybrid tracker was more resistant to electromagnetic distortion because of the undistorted information from the inertial unit. It was free of drift due to the correction information from the EM tracking system. The proposed assistive IMU method could be extended to other similar hybrid tracking setups upon the requirement of applications. For example, integrating the IMU with an optical tracking system could potentially allow tracking even when the optical markers are not in the line-of-sight of the cameras.

For signal denoising, currently we simply use an average filter to exclude outliers. Advanced denoising methods, such as Allan variance analysis or wavelet filtering, should be further investigated to improve the system performance. We will further explore the hybrid position estimation based on the EM tracking and inertial navigation system, since both can provide position information with specific characteristics.

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