



Electromagnetic Tracker Measurement Error Simulation and Tool Design

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OBJECTIVE

- Model the measurement error of electromagnetic (EM) trackers due to field distortion.
- Characterize the measurement error in various environments.
- Mathematically model the measurement distortion as a function of position and orientation (pose) of the sensor.
- Determine error in a given measurement and compensate during real-time tracking.
- Use the distortion model to predict the error for an arbitrary sensor pose.
- Simulate the tracking error of a tool of an arbitrary configuration with respect to a reference of arbitrary configuration.
- Predict performance of an EM tool and reference before ever building it in various environments and use this to aid in tool design.

SIGNIFICANCE

- EM trackers are susceptible to measurement distortion, in particular in metallic environments such as the OR (Fig. 1).
- Analytical tool development can be misleading due to complex and variable field distortion.
- Experimental tool design involving building and testing each configuration is expensive and very time consuming



Fig.1 - Typical OR scenario for ENT surgery with NDI Aurora tracker artificially inserted.

SYSTEM CONCEPT

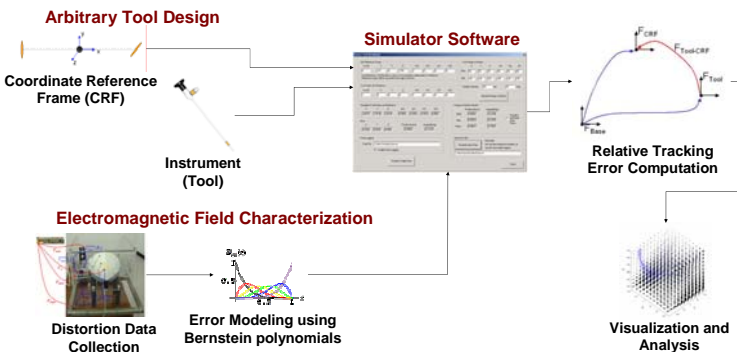


Fig.2 - Flow chart representing the procedure for simulating relative tracking error of arbitrary tool configurations in various environments.

DISTORTION MAPPING

It is very important to obtain maps of the measurement error in many different environments in order to get good representative results when designing tools. For large data collection, a hybrid tracked system (EM & optical) is used with a robot to manipulate the sensor coils. However, in environments such as the operating room, it is infeasible to bring in a robot and Optotrak.

Data is collected using a fixture that collects 12 orientations at 216 positions each (Fig. 3). The fixture is digitized using the Optotrak and is repeatable to 0.05mm. Therefore, no auxiliary tracking is necessary during data collection. This makes collection in environments such as the operating room practical.

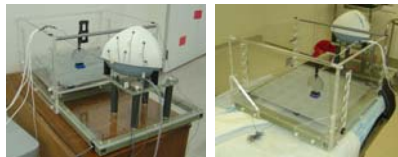


Fig.3 - Aurora calibration fixture digitized with Optotrak (left) and being used for data collection in the OR (right).

Error Definition: Position error is the translation required to align the ideal reference position to the distorted EMTS position. Orientation error is defined as a Rodriguez vector that corresponds to the magnitude and axis of rotation.

The measurement error for 5-DOF Aurora sensor coils is determined in real environments such as the OR. As shown in Fig. 4, the error is clearly a function of both the position of the sensor and the orientation of the sensor coil.

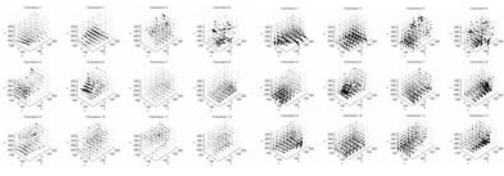


Fig.4 - Error distribution separated by orientation in OR. Position error (left) and orientation error (right).

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ERROR MODELING

Measurement distortion is modeled using Bernstein polynomials that are fit in the least squares (LS) sense to the collected measurement error data. If orientation were not a factor, the model for a single components of the error could be described by:

$$e(x, y, z) = \sum_{i=0}^n \sum_{j=0}^n \sum_{k=0}^n c_{i,j,k} B_i^n(x) B_j^n(y) B_k^n(z)$$

Orientation space is divided into a set of basis orientations. One set of the above polynomial coefficients, $c_{i,j,k}$ is generated for each error component of each basis orientation. A given measurement is spherically interpolated between the three most similarly oriented basis vectors to determine the contribution, w_b , to each one's set of Bernstein coefficients. Incorporating orientation into the model, all 6 components of error can be described by:

$$\vec{e}(x, y, z) = \sum_{b=1}^3 w_b \left(\sum_{i=0}^n \sum_{j=0}^n \sum_{k=0}^n \vec{c}_{i,j,k}^b B_i^n(x) B_j^n(y) B_k^n(z) \right) = \begin{bmatrix} \vec{e}_{pos} \\ \vec{e}_{ori} \end{bmatrix} \in \mathbb{R}^6$$

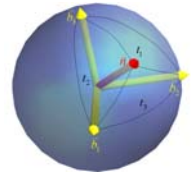


Fig.5 - Sensor orientation is spherically interpolated between three closest basis orientations.

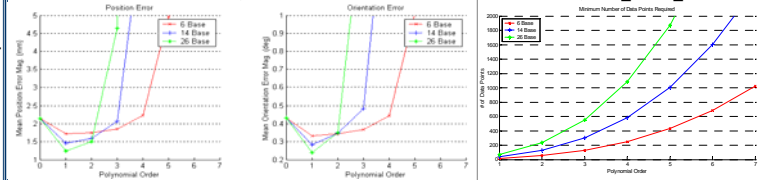


Fig.6 - Representation of modeling effectiveness (residual error) as a function of number of basis orientations and polynomial order when applied to an independent data set.

Fig.7 - Minimum required number of measurements required per orientation to generate model (# of coefficients).

TRACKING ERROR SIMULATION

The error model can be used for two purposes: 1) real-time compensation of measurement error in a characterized environment and 2) simulation of measurement error for arbitrary sensor pose in a given environment. We propose using the later for use as a design tool for development of EM tracked tools.

In this case, the predicted error for a given sensor pose is calculated; the distorted measurements are arrived at from the above model as follows:

Position: $\vec{p}_{distorted} = \vec{p}_{actual} + \vec{e}_{pos}$ **Orientation:** $R_{distorted} = R_{distortion}^{-1} R_{actual} = e^{\hat{\omega}} R_{actual}$, where: $\vec{e}_{ori} = \hat{\omega} \theta$

As with generating the model, the orientation of the sensor is spherically interpolated between the 3 closest basis orientations and the respective weights are calculated and used to determine the modeled error.

APPLICATIONS TO TOOL DESIGN

Up to this point, all distortion measurements have been based upon raw single 5-DOF sensor coils. The reason for this is that we can now apply this information to any 6-DOF tool that is built using one or more of these sensors (up to 8 with the Aurora since we do our own frame fitting).

A 6-DOF tool is simulated by: 1) assign a sensor coil configuration to a tool, 2) pick a tool pose to simulate, 3) determine sensor locations in space, 4) apply distortion model to individual sensors, 5) fit the sensor configuration back to the distorted sensors in the LS sense, 6) repeat for coordinate reference (CRF) and 7) determine the relative tracking error.

The tool design procedure is detailed in Fig. 8. Tools are simulated in environments of varying degrees of distortion and virtually placed throughout them in a realistic range of motion (ROM) for a particular application. The goal is to generate tool and reference frame combinations that provide stable and accurate results for a particular application in a particular set of environments.

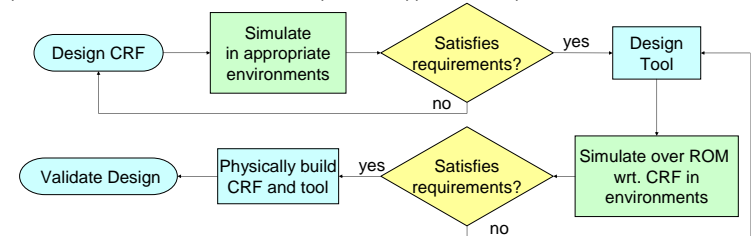


Fig.8 - Flow chart representing the tool and corresponding CRF design procedure using the simulator.

DISCUSSION

Our system can be used for data collection, measurement error modeling, real-time measurement compensation and measurement error simulation. *The novel aspect of this work is the use of EM tracker distortion models as a way of evaluating 6-DOF tracked instruments composed of 5-DOF raw coils before the instrument is even physically built.* This allows for rapid prototyping of tracked instruments to determine the optimal configuration that will be effective in a given set of environments. These design tools have been used to design and evaluate various instrument and references in many environments, in particular for development of ENT tools.