

Best Practices in Electromagnetic Tracking System Assessment

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Abstract—Intra-operative navigation is the key enabling components of advanced minimally invasive surgical procedures. One of the most promising tools is Electromagnetic Tracking (EMT) that has found its use in various domains. EMT systems ideally provide the sub-millimeter-resolution position and orientation of small sensor coils—integrated into surgical devices. EMT does not require line-of-sight to the target as opposed to optical tracking, therefore can be used intracavitary. In the mean while, the distortion caused by conductive or ferromagnetic materials (laparoscopic tools, metal trays, operating table, etc.) and other electronic devices leads to a significant reduction in performance. The necessary step towards the wider use of EMT is improvement in tracking error detection and compensation. Together with our collaborating partners from six institutions in five countries, we started the development of a unified system assessment protocol. The fundamental aim of the workgroup is to provide guidelines and test cases to repeatable and widely applicable EMT system assessment.

Keywords: intra-operative navigation, electromagnetic tracking, system assessment, tracking errors

I. INTRODUCTION

Navigation for catheter-based interventions requires high targeting accuracy, to support heart ablation, or other Minimally Invasive Surgical (MIS) procedures. This can be ensured by different types of intra-operative tracking devices. In neurosurgery and orthopedics, optical tracking is the most prevalent IGS modality, despite the limitation that it needs full line-of-sight to the target objects (markers). This problem can be eliminated with the use of Electromagnetic Tracking (EMT) systems.

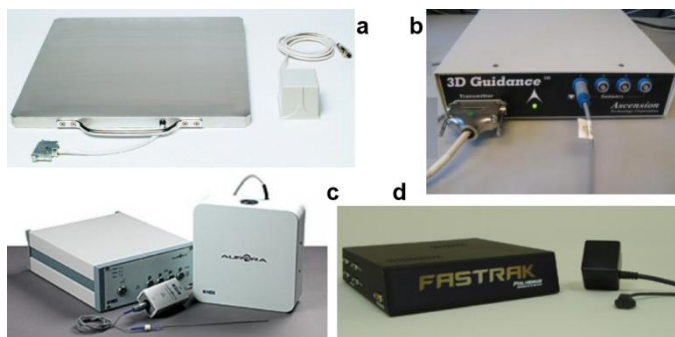


Fig.1. The Ascension 3D Guidance medSAFE, the NDI Aurora and the Polhemus Fastrak tracking systems. These are the most commonly used EMT devices. (Courtesy of the manufacturers.)

EMT systems' functionality is based on a transmitter generating a strong electromagnetic field, and then sensor coils picking up the signal, since proportional current is induced in them. Calculation of the position and orientation of the sensors (relative to a transmitter) is based on the real-time electrical measurement and the physical model of the EM field [1]. Research groups have long been dealing with the issue of accuracy assessment of EMT systems [2–5].

Although there are many techniques for determining the distortions of the EM field—yielding to inaccurate measurements—, no method became generally accepted, or standardized so far. Moreover, with the recent advancement in the field (new types of generators and controller units), new challenges have arose.

II. SYSTEM ASSESSMENT PROTOCOL

We work to elaborate a static and a dynamic measurement protocol that describes all important environmental and setup-related conditions, and can easily be repeated in other laboratories or at a clinical site. General requirements for a widely usable assessment technique are the following:

- simplicity—making the experiment as compact and practical as possible,
- reproducibility—requiring no specific hardware,
- usable for the all types of EMT systems,
- usable for all shapes and sizes of EMT generators,
- Providing recommendations for measuring new, currently not available systems and components.

We initiated a research collaboration between various groups to maximize the coverage and the impact of the future protocol. Current partners include: the German Cancer Research Center (DKFZ), Queens University, Children's National Medical Center, Medical University of Vienna, Austrian Center for Medical Innovation and Technology (Wiener Neustadt, Austria) and Johns Hopkins University. The final version of the protocol will consist of a description of the complete assessment for static and dynamic, clinical and un-distorted environments as well. Here, we report the first concept and results, focusing on static analysis in a laboratory environment.

III. PROTOCOL DEVELOPMENT—STATIC ERRORS

First step of system assessment is to measure the performance in an undistorted environment. This requires

eliminating or minimizing external sources of disturbance. In the initialization phase, consider the followings:

- Use only plastic or wooden structures,
- Pay attention e.g., to hidden screws in tables,
- Make sure there are no (obvious) metallic parts in the proximity of the setup (within 1.5–2 meters) ,
- Keep off from walls, as they may contain electric wires,
- Experiment with the location of the whole setup to avoid large metal structural elements hidden in the wall,
- Make sure the sensor cables run apart from the FG cable.

Prior research has shown the effectiveness of measurement phantoms in EMT assessment [5]. We recommend using any generic, or custom made phantoms, as long as it allows accurate and repeatable positioning. It can range from a simple LEGO plate to standard, industrial boards. We cannot require the use of high-precision mechatronic structures (such as robots and linear stages), since they are not readily available in every laboratory, and not necessarily compatible with the operating room (OR) environment. Manual data collection is tedious, yet the most trusted, and most adoptable solution. Experiment design should take care of the following:

- Document every details of the setup.
- If a Dynamic Reference Frame/Base (DRB) is used, its location needs to be specified and preferable put in a location, clinically relevant, yet close to the middle of the workspace for better accuracy.
- Static measurements should be taken in every possible location on the phantom, as long as it is within the FG's working volume. Number and arrangements of used points should be documented.
- Number of measurement taken should allow for good statistics. The total number should always be recorded.
- Evaluation should follow standard mathematical tools, and methodology should always be described. (E.g., a mean error value does not describe truly the accuracy.)

We investigated that the noise distribution of an EM sensor is not Gaussian, however, this assumption is commonly taken in the literature. With the newest generations of EMT systems, the error resulting from this approximation is negligible. The number of measurements to be taken at every point should be determined based on the scale of the error. Assuming that the samples arrive according to an $N(0;\sigma^2)$ Gaussian distribution, then the distribution of the average of k samples is $N(0; \sigma^2/k)$. The density function the average distribution is:

$$f_k(x) = \frac{\sqrt{k}}{\sigma} \phi\left(\frac{\sqrt{k}}{\sigma}x\right),$$

where $\Phi(x)$ is the standard normal density function. Thus the probability that a sample falls into the $\pm t$ interval:

$$F_k^t = \int_{-t}^t f_k(x) dx$$

This allows for the calculation of the required number of samples for any given σ . If the error is larger, we need more data samples to create statistics with the same spatial

accuracy. Let us assume, we want to achieve a 0.01 mm accuracy of the averaging with a 95% probability. Table I. gives the required sample numbers for different errors. We recommend performing a longer, static measurement in the middle of the workspace to acquire the average jitter error, and then employ the same sampling number for all the measurement points.

STD (mm)	Sample number
0.03	250
0.04	400
0.05	750
0.06	800
0.07	870
0.08	930
0.09	1200
0.1	1500<

Table 1. Number of samples to collect at every location, in order to ensure high quality statistics at different levels of error.

IV. SETUP FOR DIFFERENT FIELD GENERATOR TYPES

Companies sell various types of trackers. Our preference can be based on factors like pricing, available sensors (in terms of size and type), accuracy and resolution (spatial and temporal). The most commonly used system is the NDI Aurora (Northern Digital Inc., Waterloo, Canada). It has various types of generators, differing in shape and size of working volume, but all run on alternating current (AC). Here, we describe our protocol and setups through the hardware of Aurora, but these equally apply to other systems, such as the Ascension 3D Guidance medSAFE. Aurora has five different field generators (FG), presented in Fig. 2:

- **Aurora Planar FG:** The *Planar FG* has been commercially available since 2005, and has three generations—continuously improving in performance.
- **Aurora Tabletop FG:** the *Tabletop FG* was released in autumn 2011. It is to be placed under the patient and the patient stretcher. It provides some shielding against distortions caused by conductive or ferromagnetic materials located below the FG.
- **Aurora Compact FG:** The *Compact FG* is designed to be mounted onto other medical devices. At present, the FG is an evaluation model for research and development purposes only.
- **Aurora Handheld FG:** Introduced in 2009, this model is a custom, integrated version of the Compact FG. Only for research purposes.



Fig.2. The different types of EMT field generators (Developed for the NDI Aurora system.)

- **Aurora Window FG:** Developed specifically for CT-use, with a special design to reduce artifacts on the images. Only for research purposes.

The height adjustment in all of the cases should be achieved with a uniform extender, e.g., LEGO/DUPLO elements. Different levels should be measured from -10 cm to +10 cm of the centerline of a planar generator, with a recommended resolution of 5 cm. This total of 20 cm volume is comparable to the area covered in a typical catheter-based MIS procedure. It is important to note, that most FG has a dead volume, close to the generator. This area should be excluded from measurements. Similarly, no points should be included in the evaluation that has already been flagged by the software as being *corrupt*, *bad fit*, or *out of volume*.

A. Planar-type FG placement

Two setups are recommended for a Planar-type FG. In the case of the first setup, we immobilize the FG on the wooden table and the measurement board takes place in front of it. During data collection, we need to lift the plate, and adjust height as described above (Fig. 3).

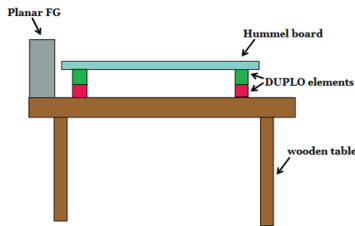


Fig. 3. Measurement arrangement for a Planar FG

In the second case, the Planar FG's fixation shall be done with the special mounting arm, typically used in the clinical environment. We can fix the generator above at 40 cm the measurement plate. The data collection can be made reproducible and easy to register, if we place a DRB on the board (Fig. 4).

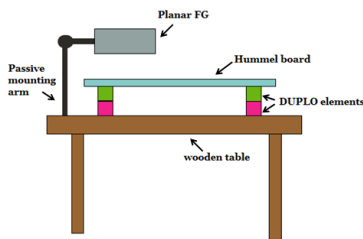


Fig. 4. The second measurement protocol for Planar FG

B. Tabletop/Window FG placement

Using these generators cause some problems. The size of the Tabletop is larger than the other FGs, and it needs to be placed under the patient (the phantom). For elevation, we can employ DUPLO towers, and put them under the four corners of the phantom until we reach the target height (Fig. 5).

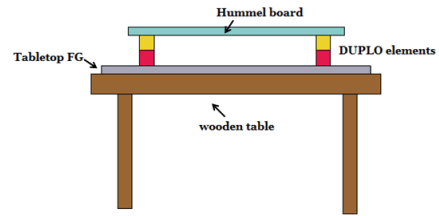


Fig.5. The measurement setup for Tabletop FG

C. Compact/ Handheld FG placement

We should take into consideration that these generators' working volume is smaller than of others. We put it into practice according to the earlier defined instructions. In addition, we provide rigid fixation for the FG on a wooden plate/support. (Prior experiments confirmed that the wood does not distort the EM field.) For precise data collection, the sensor mount and the sensor's cable should fit into the place between the generator and the phantom. We increase the height until we reach the desired levels (Fig. 6).

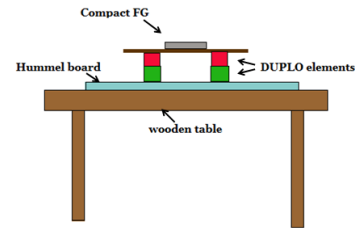


Fig. 6. The measurement setup for Compact FG

V. USING THE PROTOCOL

Two different measurements were designed for each FG. First, data collection is performed in a reduced (ideally metal-free) environment, in a laboratory environment. Then, an application-oriented test is performed in a CT-suite (or with C-arm).

Based on previous experiments, a suitable phantom is the "Hummel" polycarbonate measurement plate, developed at the Medical University of Vienna [6, 7]. It allows data collection with different sizes of sensors both for position and orientation, and has already been used by various groups. Wooden bricks, LEGO, or similar elements can be used to set the elevation of the phantom, as required by the measurement. The plate allows the positioning of sensors at known relative distances and orientations and a mount for positioning either 5 Degree of Freedom (DOF) or 6 DOF sensors at known locations relative to the plate. The phantom is 14.7 mm thick, 55 cm wide square-shaped polycarbonate plate that provides a grid of 9×10 holes, where the holes are 50 mm apart. A circle in the center of the plate provides an additional 32 holes spaced 11.25° apart at a radius of 50 mm, which enables accurate measurement of rotation (along one axis at a time). The sensors are mounted and fixed into a hole on the opposite side of the pins for position measurements labeled with POS in Fig. 6a. To enable two different rotation setups the sensor can additionally be mounted into holes ROT1 and ROT2, and the sensor mount can be manually inserted into various pinhole on the board (Fig. 6b).

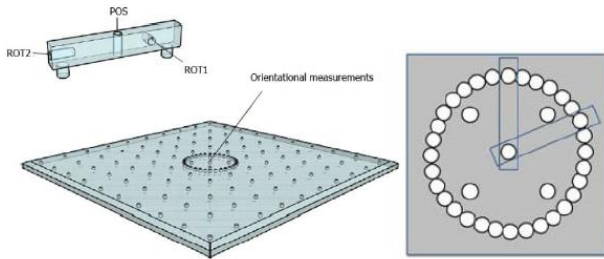


Fig. 6a. The 3D model of the “Hummel” phantom consisting of a plexi board and a sensor mount [3]

Fig. 6b. The arrangement of the central holes for rotational measurements

Alternatively, we recommend the use of LEGO. The setup should consist of a wooden table and a fixed LEGO palette on it. The LEGO palette can be divided into a 5 x 5 grid, where its points are 88 mm away from each other, and then can be employed the same way as the Hummel board.

We used the Hummel board. We chose the center of the palette for origin, and we determined the required sample number (400) based on the rate of the distortion (Table I.). After that, position and orientation data was collected at each point. When the measurements were done, we repeated the procedure for the next level (19.2 mm higher). We lift the height until we reach the ± 10 cm (Fig. 7), continuing data collection for all levels.

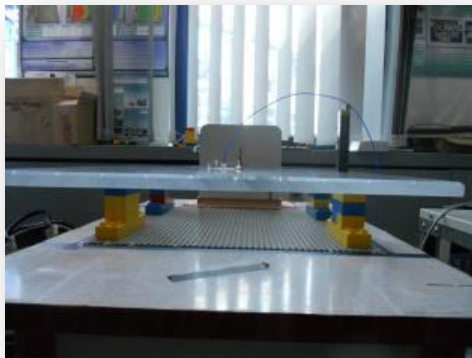


Fig.4. Employing the assessment protocol with a Planar FG, a Hummel board, and increasing elevation with DUPLO elements.

VI. RESULTS

We had the opportunity to work with three types of NDI Aurora generators. We compared the accuracy of the Planar-, Tabletop- and Compact Field Generators (PFG, TFG and CFG, respectively). We performed various measurements in laboratory and clinical environment, which will be reported in the future. We found that the protocol is practical and useful.

It is crucial to express accuracy numbers in a true and meaningful form. Mean \pm standard deviation (STD) is the most commonly used format. Also, rotational and position errors should be handled separately, since rotational errors only contribute to the overall error when used in an integrated form (6 DOF homogeneous coordinate transformations).

In our initial experiments, the averaged root mean square error for an Aurora system at level -10 cm, averaged on the entire 32 angled positions was computed to be 0.095 ± 0.024 mm for the *Planar FG* and 0.015 ± 0.009 mm for the *Tabletop FG* and 0.0473 ± 0.0030 mm for the *Compact FG*. The results for the *Planar FG* *Tabletop FG* in the laboratory environment were similar to those published previously but the results of the Compact FG have differences. We believe this is mainly due to the different approach taken for evaluation.

VII. CONCLUSION

Intra-operative electromagnetic trackers have numerous advantages, but to make them widely accepted, standardized assessment methods are needed. This paper presented our measurement protocol for EMT error determination. We developed a technique for all types of generators: Planar, Tabletop or Compact. Guidelines were created for future systems as well, and a unified method proposed to assess EMT static and dynamic errors. Further measurements are needed to confirm all aspects of the concept. Experiments are scheduled for a real clinical environment as well. The initial numeric results suggest that EMT manufacturers are continuously improving their systems for higher accuracy and better usability.

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