Given the primary concern for sensor position error (compared to rotation), the accuracy of the source rotation fixture is particularly important, since source rotation error is converted to sensor position error by the source to sensor radius.

The source and sensor fixtures are machined to be orthogonal and to have a common origin between their rotational axes. Beyond that, positioning the actuated axis coincident with the sensor fixture coordinates is the only precision mechanical alignment required. This is done by nulling the reading on a mechanical dial test indicator as the and Z axes are moved. While it is crucial that the source and sensor fixtures each have a single center of rotation (defining the fixture origin), the fixture transforms (§IV.D) permit us to leave ill-defined the mechanical relation between the source and sensor and their fixtures.

We estimate by combining the error specifications for the stage components with measured fixture errors.

Stage accuracy/repeatability

The small scale that we are targeting in the ILEMT microsurgical application is particularly demanding for the calibration stage. The accuracy as a fraction of the source to sensor distance is similar to other EMTs, but the workspace is smaller, so the absolute accuracy required for calibration is also more demanding. To characterize an accuracy of 200 µm we require a ground truth position accuracy of 20—70 µm. Expressed as an angular error at 200 mm, this is 100—350 microradians, or 0.006—0.020 degrees.

(The use of this pole does create stronger demands on the ideality of the stage motion, with minimal incidental off-axis motion (runout).

We already require a precise positioner to collect the calibration data, so precise test data is also easily collected, however the methods of finding the error are worth clarifying.

Also,

It may be possible to calibrate a low order measurement model using only translation data, but it then remains unclear what accuracy can be expected when the sensor is rotated.

Project description, medical application, general open technology. Paper is somewhat general and tutorial. Not only can ILEMT hardware and software be used outside of the medical application, with different source and sensor configurations and workspaces, there is also a lack of specific and comprehensive literature on EMT calibration methods. Open source, pointer to repository.

Specific performance goals: speed, noise, workspace, accuracy

Evaluation: methods and results. Linearity and cross-coupling

[might go in related work] A huge number of magnetic trackers have been developed in the nearly 50 years that this technology has existed. EMTs have been a niche technology, with optical and computer vision techniques being more easily applied, often more accurate, and increasingly much less expensive due to the high production volume of cameras and wide availability of computer vision libraries. The niche of EMTs remains those uses where clear sightlines cannot be guaranteed.

But the use of EMTs is often not considered even when they might be appropriate because of the need to largely reinvent the technology each time. While the ILEMT tracker has specific aims for medical application, we hope that our open-source signal processing code and hardware designs will help more engineers succeed in applying EMTs across a broader scope. It is only the small size of the market that causes standalone EMTs to be so expensive.

It may help intuitive understanding of the problem to realize that the source and sensor are magnetically interchangeable. Our actual measurement is the coupling between the source and sensor coils (mutual inductance), and this is a symmetrical relation. If it were possible to drive the sensor coil at high current, then the same small voltage would be induced in the source coil as was previously measured in the sensor. With this view, we can model the sensor as though it were a source, and in particular, use multi-dipole configurations such as the magnetic quadrupole. [Given weak value of high-order sensor models, not clear how important it is to have this in the paper. But it is part of what we have implemented, and lack of usefulness is somewhat interesting.]

Our current calibration code only supports configurations with three source coils and three sensor coils, but generalization to other models is straightforward because the details of the coil arrangements and magnetic model

In the dipole model, each coil has a 3DOF position and a 3DOF moment, giving 6 parameters per coil. The moment is a vector representing the orientation and magnitude of the coil’s response. The field is modelled as axially symmetric, so the coil pose is only characterized in 5DOF. The extra degree of freedom out of 6 is in the moment magnitude, which is a magnetic and electronic sensitivity parameter, not kinematics.

EMT performance has often been specified and evaluated primarily by the position error [cite], with fewer attempts to consider sensor angular error. While an EMT could be used in ways where rotation error would become particularly important, the most common application is measurement a tool tip position where the tool tip and sensor may be at opposite ends of the tool. The tool length creates a moment which converts angular error and noise into tip position error. With optical trackers, angular error can often dominate the tip position error [cite ASAP]. But an EMT measures position using a polar principle. For the sensor position with respect to the source, the tangential position error is larger than the radial error, but the angular error at the sensor is a similar magnitude to the source-referred angular error. This means when the tip offset moment is well less than the source to sensor distance, the tip position error due to sensor angle error is small compared to the sensor position error alone. This is a rarely mentioned benefit of EMTs, and should be considered when comparing to other technologies.

[use moment in position error reports?] [picture of moment effect] Gets into sensitivity