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Electromagnetic Tracker for Active Handheld Robotic Systems

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Abstract

We describe the development of the In-Loop Electromagnetic Tracker (ILEMT), designed to meet the demanding latency and resolution requirements for active stabilization of hand motion during precision manipulations such as microsurgery. The prototype surpasses the fastest commercial EM trackers by $> 4\times$ in root bandwidth/resolution and $2\times$ in latency. The use of two widely spaced carrier frequencies (e.g., 300 Hz and 10 kHz) enables a particularly simple way of reducing the eddy-current interference caused by nonferrous metals present in the workspace. Previously, metal compatibility has only been achieved at a large cost to measurement speed.

Keywords

position tracking; pose; orientation; eddy current; active stabilization; microsurgery

I. Introduction

Motion trackers measure the pose (position and orientation) of a freely moving object in 6 Degrees Of Freedom (6DOF) using a sensor or tracking target attached to the object and external devices that establish a fixed reference frame. Trackers are widely used for surgical navigation and human motion capture for virtual reality and animation. Optical tracking is most common; optics can be highly precise, and when only a 30–60 Hz measurement rate is needed, then sensing can be done using inexpensive video cameras. A main shortcoming of optical tracking is that it requires multiple sightlines to the tracker targets. Inertial tracking requires no sightlines, but can only track orientation and short-term relative motion, not absolute position.

We previously developed a PSD optical tracker (ASAP) for active cancellation of unintentional hand motion (tremor) during precise manipulation, such as microsurgery [1]–[3]. This use places extreme demands on measurement speed (latency) and resolution (noise level). The effectiveness of active disturbance cancellation is fundamentally limited by delay [4]. Hand tremor contains significant energy at up to 10 Hz; to compensate 90% of this motion requires a total system latency of only a few ms. Noise level is also critical, since measurement noise ends up being added to the tool motion. This optical tracker has acceptable speed and resolution, but we found it difficult to use in ophthalmic surgery because of frequent sightline obstructions, sometimes caused by the moving hands of assistants. Even a momentary failure is unacceptable in a safety critical control system.

II. EMT Operating Principles

In electromagnetic trackers (EMTs), a modulated magnetic field establishes a reference frame which is measured by a moving sensor, Fig. 2. The first AC EMTs appeared over 40 years ago [5]. These use a sine-wave source excitation with operating frequency near 10 kHz. This low-frequency field easily penetrates any non-metallic objects such as wood, plastic, and the human body. One common use for EMTs is to measure the position of a catheter or other surgical tool that is inside the body. A major weakness of such trackers is their intolerance of any metal in the workspace; this distorts the magnetic field, causing pose measurement nonlinearity [6]. Compatibility with ferromagnetic metals such as steel is an unsolved problem, but some EMTs tolerate the eddy current distortion created by non-magnetic metals (e.g., aluminum and some stainless steels) by exploiting the proportional decrease of eddy currents at lower frequencies. Yet low frequency measurement is necessarily slow. Table I shows latency and resolution performance of several EMT products. Ascension and NDI offer eddy current compensation, but have far lower *bandwidth/noise* figures of merit.

The ILEMT uses a novel compensation combining the best of AC and pulsed-DC trackers. Each reference field has two carriers; the high carrier is near 10 kHz, but the other is much lower (≈ 300 Hz). Eddy current is roughly proportional to frequency, so the low carrier suffers up to $30\times$ less interference. Sensor output also drops, but is compensated by reducing the low carrier bandwidth. A Kalman filter estimates the pose bias from the high/low difference and uses this to correct the fast high carrier, with no added high rate latency.

The ILEMT source emits all of the reference fields simultaneously by giving each a distinct carrier frequency. Such Frequency Domain Multiplexing (FDM) has long been known [7], but is not used in current EMT products. FDM helps high-speed operation by measuring all source fields in parallel, rather than sequentially switching between axes. This is important when the application is dynamic, because error is created when the sensor pose changes significantly during the time taken to cycle between the three reference fields. Existing trackers show increases in tracking error at frequencies as low as 9 Hz [8], [9]. These errors during rapid motion may go unnoticed by human observers, but not by control loops.

Source input power $P = VI$, but the source is highly inductive; although only $\text{re}(P)$ is actual loss, the driver must deliver VI . A linear driver cannot do so without internally dissipating the entire reactive power. AC EMT's can solve this problem by placing the source coil in a resonant LC tank tuned to a single frequency. The difficulty of driving arbitrary waveforms has discouraged multi-frequency eddy-current compensation [10], and likely contributes to the poor noise performance of the NDI Polaris [4]. Our novel solution is a Class-D (switching) amplifier, which has a pronounced advantage with reactive loads. Energy stored in the load is shunted to a capacitor, and returned the load on the next cycle.

III. Implementation Status

Our current prototype (Fig. 3) uses a USB audio interface (Steinberg UR44) to acquire sensor signals and generate analog output for the source drivers. Because of buffering

delays, this is not usable for real-time control, but the demodulation and EM interference rejection algorithms are running at full rate in a PC Labview application. The pose solution itself is currently implemented offline using Matlab `lsqnonlin`. Input is at 96k samples/s (~20 bits resolution), and is demodulated using FFT blocks of 64 and 16K samples, with order $2n$ window. This gives a high-rate bandwidth of 300 Hz; latency would be 1.3 ms with a one sample processing delay. The high rate output is 1500 samples/s, and the low-rate is $2\times$ oversampled at 12 samples/s. The high carriers are 7.5, 10.5, and 13.5 kHz; unoccupied guard channels improve isolation and provide a noise estimate. International Rectifier IRAUDAMP7 audio amplifier modules are used to drive 30V and 2.5A into each source coil, giving a source power dissipation of 9 W. This 225 VA output requires only 40W of supplied power.

IV. Results

3D RMS noise magnitude in 300 Hz bandwidth is $6.4\ \mu\text{m}$ for position and $60\ \mu\text{rad}$ for rotation. In Table I, we see the ILEMT figure of merit already significantly exceeds the fastest commercial trackers. Noise is currently limited by ADC dynamic range and power line interference. We expect noise to improve considerably in the future as we develop custom hardware with higher performance ADCs and better EM interference rejection algorithms. Typical output during freehand motion, Fig. 4, shows the large dynamic range. Fig. 5 shows the action of eddy current error compensation by the dual-carrier high/low approach. We will further research ways to best combine the high and low rate measurements in to a single output, but the current approach is already satisfactory when metallic interference is not rapidly changing.

V. Discussion

These preliminary results show that it is possible to considerably improve on the speed and resolution performance of current EM trackers, while also maintaining the desirable rejection of eddy-current interference shown by pulse-DC and other dual-frequency tracker designs. The possibility of using multi-sine signals for source excitation opens a wide range of strategies of compensating for metallic interference based on the different frequency responses of different disturbing objects. Until now, it has been necessary to trade off speed and resolution against eddy current interference rejection.

We intend to develop a reusable reference design for this tracker technology which we will release under an open license for any desired use. The basic technology is old (key patents long expired), and the electronic requirements are not too demanding, but building a usable system requires enough “art” to be an impractical undertaking for researchers and companies whose primary expertise is elsewhere. Although our need is for a tracker with better speed/resolution performance in a small workspace, there are many other possible applications for this technology which may require adaptations in the design. This is where an open design is vastly superior.

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Fig. 1. Micron stabilized microsurgical tool. The tip is actuated to counteract undesired motion, based on feedback from optical tracking of two LED targets, one fixed on the handle, and the other on the output. Note that it is impossible to rotate the tool axially without obstructing the sightlines.

Fig. 2.

Simplified 2D EM tracker: a fixed source creates AC magnetic fields which sensor coils convert to a voltage $\mathbf{v}$ corrupted by noise $\mathbf{n}$. Under a point source approximation, $\mathbf{v}$ is easily determined when the sensor pose (r, θ, ϕ) is known, but the nonlinear inverse problem is intractable, and must be solved numerically. For a 6DOF solution, source and sensor need three coils each.

Fig. 3.

Test setup with 200 mm source/sensor distance. Source (50 mm cube) is wound with Litz wire to minimize AC losses, since source strength (and so signal/noise) is limited by heating of the source. Sensor (13×13×4 mm) is a commercial RFID antenna. Each consists of three orthogonal windings on a ferrite core. Ball is used in eddy current interference testing.

Fig. 4. Example of tracked motion (a), with details showing typical unintentional hand motion (b) and measurement noise (inset). Motion rolls off above 10 Hz, but is unpredictable, so active compensation needs a much higher measurement rate than the Nyquist criterion implies. The sample rate is 1500 samples/s and bandwidth is 300 Hz.

Fig. 5.

Effect of introducing a 19 mm aluminum ball between source and sensor when there is no actual sensor motion. This creates >1 mm errors in the high rate position measurement, but has little effect on the low rate result. The Kalman filter creates a combined output that tracks the high rate output at high frequencies and the low rate output at low frequencies. This minimizes the effect of eddy current interference on static accuracy. Error is reduced even when the level of interference is changing, though at the cost of steps in the combined output each time it is updated to agree with an incompatible low rate measurement.

Table I

EM Tracker Comparison

	Best Latency (ms)	Noise (μm RMS, bandwidth 1 Hz)	Figure of merit $\frac{\sqrt{\text{bandwidth}}}{\text{noise}}$
Polhemus Liberty™ AC, inductive sensor –eddy current error	3.5	1.4	7.8
Ascension trakSTAR™ Pulse DC, fluxgate sensor –LF EM interference	7	19	0.47
NDI Aurora™ AC dual frequency, –worst figure of merit	14	140	0.031
ILEMT (<i>described here</i>), AC frequency domain	1.5	0.37	47