

Measurement System for the Characterization of Micro-Manipulation Motion and Force

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1 Background

Vascular anastomoses are essential microsurgery tasks that demand levels of manual dexterity and precision barely tenable by even the most practiced and skilled surgeons. Teleoperated robotic micromanipulation devices have the potential to improve the availability and proficiency of procedures involving these anastomoses by enabling precise, repeatable motion while filtering out physiological noise that often hampers manual manipulation. In order to be clinically effective and commercially viable, such robotic microsurgery devices must provide significant improvements in the feasible workspace, motion bandwidth, precision, and dexterity achievable with current manual microsurgery procedures [1].

The research presented here constitutes further steps toward the empirical characterization of manual microsurgery motion and interaction forces, and the development of proper microsurgery robot performance requirements based upon that characterization [2]. We design a multimodal measurement device comprised of an electromagnetic (EM) motion tracking system, three-axis accelerometers, and a high resolution force-torque sensor to precisely record both the motions of microsurgical instruments and the forces applied at the tips of those instruments during a set of experimental anastomosis procedures. In addition to providing force data, this research aims to improve upon previous work by increasing motion tracking fidelity using sensor cross validation. The resulting data will be used to inform the design of dexterous robotic micromanipulation system components, including tactile sensors, which enable safe tissue handling and suturing on the sub-millimeter scale, robotic wrists, and microgrippers.

2 Methods

The measurement of microsurgical instrument motion is accomplished by the simultaneous use of two sensor systems: (1) an EM motion tracking system (Ascension Technologies Inc.) which can track position and angular orientation of tethered sensors with a spatial resolution of 0.5mm spatially and angular resolution of 0.1° , and (2) a three-axis accelerometer (ADXL 335, Analog Devices Inc.) capable of measuring $\pm 3g$ of acceleration which enables high-bandwidth measurement of instrument vibrations due to intended use or to natural hand tremor. One EM sensor and one accelerometer are attached to each of three surgical instruments using rapid-

prototyped polymer sensor mounts (Fig. 1), which are designed for use on flexure-based instruments (tweezers) and scissor instruments (forceps and needle drivers). The EM sensors are mounted with a 2.0cm offset from the instrument shaft to distance the sensors from metals in the instruments and reduce EM distortions.

The measurement of microsurgical forces is accomplished using a high-precision force-torque sensor (Nano17 6-axis transducer, ATI Industrial Automation, Inc.) capable of measuring forces with resolutions as low as 3.125mN and moments of 0.0156mNm. The Nano17 sensor is mounted in a rapid-prototyped force measurement device that includes a set of viscous polymer springs which prevent excessive torques on the measurement plate - due to the mass of the animal specimen used in the experiment - and dampen high frequency vibrations. The force measurement plate, at 200mm by 300mm, is large enough to hold the biological specimen on which small blood vessel and nerve microanastomoses will be performed in future motion characterization experiments.

The surgical instrument tracking system requires several calibration steps. First, the EM trackers are calibrated to determine the position of each surgical tool tip in relation to its mounted EM sensor. This is accomplished by mechanically fixing the instrument tip and rotating the tool about a fixed point while recording sensor positions. The kinematic transformation describing each tool tip position and orientation with respect to its sensor coordinates is estimated using a Nelder-Mead simplex search for the transformation parameters that minimize the variance of tool tip positions. Next, the accelerometer output voltages are sampled, with the Z-axis normal to gravity, to obtain reference voltages by which accelerations can be measured during the experiment. Finally, the six force-sensor outputs (force in X-Y-Z and torques about X-Y-Z) were sampled after the specimen is placed on the force plate to zero the force bias due to gravity before micromanipulation experiments commence.

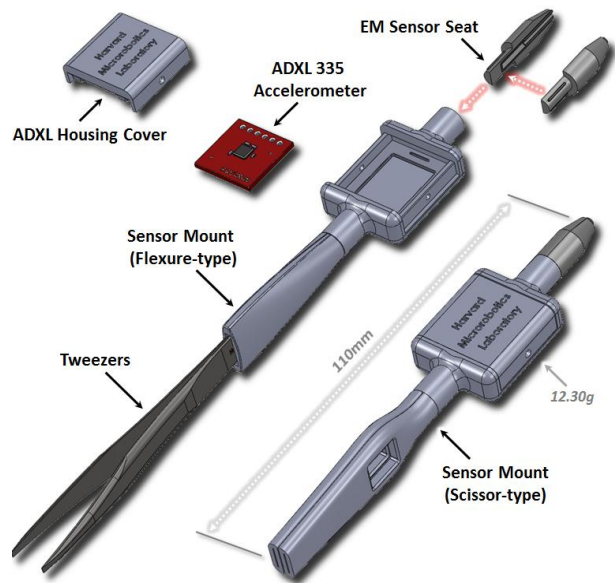


Figure 1. Electromagnetic sensor and accelerometer mounts for surgical instruments

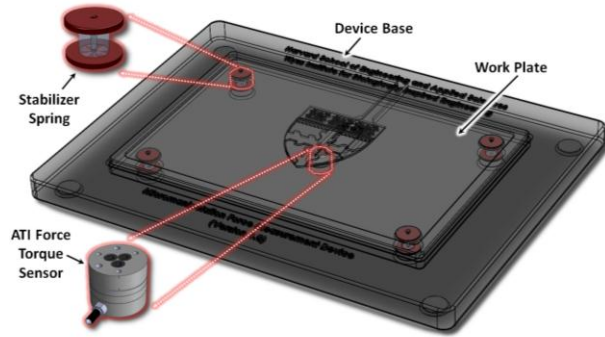


Figure 2. Proposed standalone force measurement device with embedded force-torque sensor

The experimental data from the instrument-mounted EM trackers, accelerometers, and force-torque sensor are recorded using LabVIEW NIDAQ software (National Instruments, Inc.) at rates of 50Hz, 500Hz, and 500Hz respectively. The data are post-processed to calculate the surgical workspace (EM tracker data), motion bandwidth (acceleration data) and required microsurgical forces. All procedures are performed on a non-metallic workbench to reduce EM interference caused by the presence of ferromagnetic materials. Kalman filter-based sensor fusion is used on the accelerometer and EM sensor and data sets to mitigate the effects of EM interference on tracking fidelity (by cross-validation). An initial validation of the system was done using standard surgical instruments (forceps, tweezers) to manipulate compliant lacrimal duct tubing which serves as a small blood vessel phantom. The validation task was to create four suture loops around the tube cusp. Only relevant motion and forces involved with phantom manipulation, were used for analysis.

3 Results

Spectral analysis of the instrument motion during the lacrimal duct tube micromanipulation experiment yielded a linear motion bandwidth of 0.0-2.18Hz and an angular motion bandwidth of 0.0-1.34Hz, both less than the 5-8Hz human hand tremor bandwidth measured in previous research [3]. Workspace dimensions were measured at 83.0mm, 196.3mm, 152.2mm in the X, Y, and Z axes of the EM transmitter, respectively. Angular motion ranges about the X (axial rotation), Y (elevation), and Z (lateral deviation) axes of the instrument shaft/sensor were measured at 110.5°, 33.0°, and 37.8°, respectively (Figure 3). The maximum forces detected by the force detection plate were 74.4mN, 82.9mN, and 30.5mN in X, Y, and Z axes of the force measurement device (ATI Nano 17 sensor) respectively.

4 Interpretation

Analysis of the initial surgical motion and force validation experiment showed that this new system significantly improves sensitivity to hand tremor (compared to previous work using only EM sensors). An accuracy experiment (placing an instrument tool tip into a precisely machined 500µm grid of holes) demonstrated a position measurement accuracy of ~120µm, which is adequate resolution for the structures of interest (small blood vessels). The force

measurement device, coupled with EM tracking of instrument position and orientation, enabled estimation of the magnitude and direction for forces applied at an instrument tip during microsurgery when uni-manual (i.e. single-instrument contact during tool changing, needle grasping or repositioning, or the passing of objects between instruments) dexterous manipulation occurs. During bi-manual manipulation (two or more instruments imparting force on the target object), the pinch force and net forces applied by each instrument cannot be resolved from the resultant force measured at the plate.

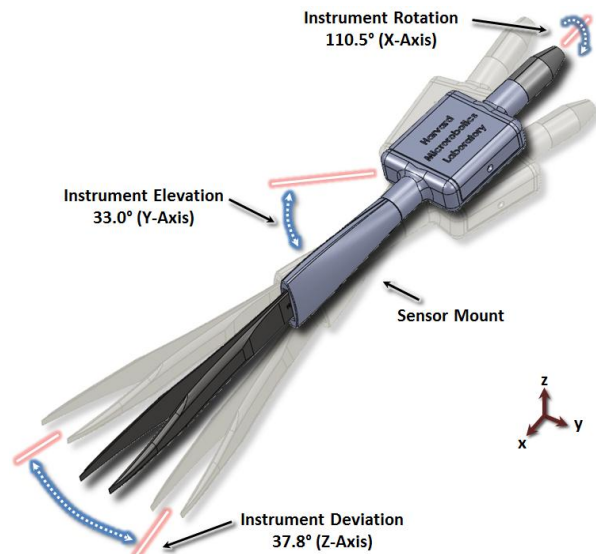


Figure 3. Angular motion convention and the motion ranges recorded during micromanipulation instrument tracking

Ongoing work involves further validation of the experimental setup by expert surgeons, as well as refinement of the manual microsurgery motion characterization pipeline, including data acquisition and post-processing. Preliminary motion characterization experiments will be comprised of six microanastomoses performed on sacrificed rat specimens: two each (left and right sides) on the major femoral arteries, veins, and nerves. These structures range in diameter from 0.3mm to 1.2mm and push the limits of manual microsurgery capabilities. Gathered force data will be used to inform the design novel soft tactile arrays and force sensors for microgrippers, and motion data will be used to design dexterous robotic wrists for bi-manual manipulation.

References

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