

AN INTELLIGENT HAND-HELD MICROSURGICAL INSTRUMENT FOR IMPROVED ACCURACY

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Abstract - This paper presents the development and initial experimental results of the first prototype of Micron, an active hand-held instrument to sense and compensate physiological tremor and other unwanted movement during vitreoretinal microsurgery. The instrument incorporates six inertial sensors, allowing the motion of the tip to be computed. The motion captured is processed to discriminate between desired and undesired components of motion. Tremor canceling is implemented via the weighted-frequency Fourier linear combiner (WFLC) algorithm, and compensation of non-tremorous error via a neural-network technique is being investigated. The instrument tip is attached to a three-degree-of-freedom parallel manipulator with piezoelectric actuation. The actuators move the tool tip in opposition to the tremor, thereby suppressing the erroneous motion. Motion canceling experiments with oscillatory motions in the frequency band of physiological tremor show that Micron is able to reduce error amplitude by 45.3% in 1-D tests and 34.3% in 3-D tests.

Keywords –Microsurgery, accuracy, tremor, robotics

I. INTRODUCTION

Humans have intrinsic limitations in manual positioning accuracy. These limitations resulting from small involuntary movements that are inherent in normal hand motion hinder micromanipulation. Microsurgery is one area in which performance is significantly hampered [1]. Manual imprecision complicates some surgical procedures, and makes certain delicate procedures impractical and sometimes impossible [2]. The level of manual accuracy demanded by microsurgery restricts the number of qualified surgeons. The fact that human hand stability deteriorates with age further exacerbates the situation. Even for microsurgions in their prime years, factors such as fatigue and caffeine consumption affect manual stability.

The most familiar type of erroneous movement affecting microsurgery is tremor [3], defined as any involuntary, approximately rhythmic, and roughly sinusoidal movement [4]. Physiological tremor is a type of tremor that is inherent in the movement of healthy subjects. In ophthalmological microsurgery, its significant component is found to be an oscillation at 8-12 Hz whose frequency is independent of the mechanical properties of the hand and arm [4]. Measurements of the hand motion

of surgeons have also shown the existence of other sources of non-tremorous erroneous motion such as jerk (i.e., normal myoclonus) and drift. These components are often larger than physiological tremor [5].

Vitreoretinal microsurgery often involves the need to remove membranes as thin as 20 μm without damaging the retina [2]. The measured tool tip oscillation during vitreoretinal microsurgery is often 50 μm peak-to-peak (p-p) or greater [5]. There is some degree of consensus among vitreoretinal microsurgions that tool-tip positioning accuracy of 10 μm is desired.

Efforts to provide solutions to the problem of increasing accuracy in microsurgery have included the use of telerobotic technology [6], in which a robotic arm is used in place of the unstable human hand. This approach allows filtering of erroneous motion between master and slave manipulators, and also allows motion scaling to be implemented. Taylor et al. have used a "steady hand" approach, in which a robot and a surgeon directly manipulate the same tool [7], with the robot having high stiffness, and moving along with only those components of the manual input force that are deemed desirable. While this system cannot scale input motion, it has advantages in terms of cost and likelihood of user acceptance. Moreover, it lends the surgeon a "third hand," holding a tool in position while the surgeon performs other tasks with his own two hands.

In order to further reduce cost, and to maximize ease of use, user acceptance, and compatibility with current surgical practice, the present authors are implementing accuracy enhancement within a completely hand-held tool, keeping the instrument size and weight as close as possible to those of existing passive instruments. The instrument senses its own movement, estimates the undesired components, and manipulates its own tip in real time to nullify the erroneous motion. This paper presents the design, implementation, and preliminary error-canceling results of the first prototype of Micron, an active hand-held instrument for error compensation in microsurgery. While the initial design is geared toward vitreoretinal microsurgery, the principles involved are general.

II. MICRON DESIGN

Micron, shown in Fig. 1, is designed to resemble a typical vitreoretinal microsurgical instrument, which measures 75 to 150 mm long and 10 to 15 mm in diameter, with an intraocular shaft roughly 30 mm long and 1 mm in diameter. The first prototype weighs 170 g and is 210 mm in length (including the

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30 mm intraocular shaft), with an average diameter of 22 mm. The handle is contoured near the tip as an aid to grasping.



Fig. 1. Micron, the active error compensation microsurgical instrument

A. Sensing System

The motion-sensing module is mounted at the back end of the instrument handle, to detect translation and rotation in six degrees of freedom [8]. The sensor suite houses six inertial sensors: a CXL02LF3 tri-axial accelerometer (Crossbow Technology, Inc., San Jose, Ca.) and three CG-16D ceramic rate gyros (Tokin Corp., Tokyo). Data are sampled at 1000 Hz by an ADAC 5803HR data acquisition board.

Using the data from these sensors, and assuming the center of rotation to be at the fingertip grasping point, the three-dimensional (3-D) velocity of the instrument tip is obtained via kinematic calculations, and then integrated to obtain tip displacement [8].

B. Erroneous Motion Estimation

Estimation of tremor is performed by a system based on the weighted-frequency Fourier linear combiner (WFLC) algorithm [9]. This is an adaptive algorithm that estimates tremor using a dynamic sinusoidal model, estimating its time-varying frequency, amplitude, and phase online. Active canceling of physiological tremor using this algorithm was previously demonstrated using a one-degree-of-freedom (1-dof) instrument prototype. In 25 tests on hand motion recorded from eye surgeons, this technique yielded an average rms tremor amplitude reduction of 69% in the 6-16 Hz band, and average rms error reduction of 30% with respect to an off-line estimate of the tremor-free motion [9]. Other research within the Micron development effort involves a neural network technique for online estimation of non-tremorous erroneous movement, using the cascade-correlation learning architecture, with extended Kalman filtering being used for learning. This technique has been tested in simulation on recordings of vitreoretinal instrument movement, yielding an average rms error reduction of 44% [10].

C. Manipulator System

The tip of the intraocular shaft may be approximated as a point in Euclidean space. We may disregard changes in orientation of the intraocular shaft, since they will be small in any case, given the small workspace of the manipulator. This reduces the dimension of the configuration space of the manipulator to three, and simplifies the mechanical design and the online computation of inverse kinematics. A parallel manipulator design is best suited to this application because of its rigidity, compactness and design simplicity, as compared to a serial mechanism. The TS18-H5-202 piezoelectric stack actuator (Piezo Systems, Inc., Cambridge, Ma.) was chosen for its high bandwidth and miniature size. Fig. 2 shows the intraocular shaft manipulator and Fig. 3 depicts the design. Kinematic specifications of the manipulator are summarized in Table 1.

Experimental results show that the prototype is able to track 1D and 3D trajectories with rms error of 2.5 μm and 11.2 μm respectively [11]. Detailed design and inverse kinematics of the 3 DOF parallel manipulator can be found in [11,12].

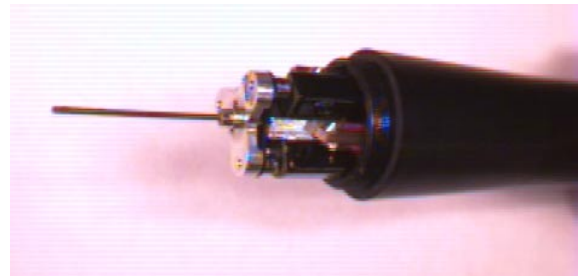


Fig. 2. The 3 DOF intraocular shaft parallel manipulator.

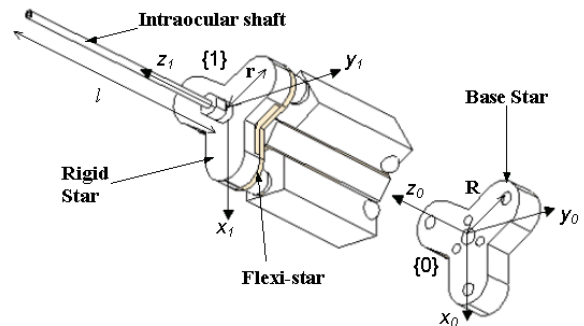


Fig. 3. Design of the intraocular shaft manipulator of Micron

TABLE I
SPECIFICATIONS OF MICRON MANIPULATOR

	Transverse (x, y)	Axial (z)
Max. tip displacement (μm)	560	100
Max. tip velocity ($\mu\text{m/s}$)	11.2	2

III. EXPERIMENTAL METHODS

The experimental setup consists of two separate systems: the testbed oscillator and the optical tracking system. The testbed generates oscillatory motion, simulating the hand tremor of the surgeon. The oscillating plate where Micron is mounted rests on a bearing-loaded linear slide. A spring-loaded driving shaft is attached to the back end of the plate. The shaft is driven by

a DC servomotor at 8-12 Hz, with selectable amplitude of either 50 μm or 90 μm p-p. Canceling tests involving one, two, or all three Cartesian coordinates (with respect to the instrument handle) can be performed by reorienting the direction of testbed oscillation.

An optical motion tracking system, the Apparatus for Sensing Accuracy of Position (ASAP) [13], is used to measure the motion of the instrument tip. ASAP uses light-emitting diodes to illuminate the workspace. It measures instrument tip position in 3D using two 2D position sensitive detectors to sense the reflected light from a marker ball at the instrument tip.

Motion canceling tests were performed in 1-D (along the long axis of the instrument) and 3-D. The frequency of oscillation was 9 Hz. In each case 10 trials were performed, and the results were compared to those of an uncompensated trial.

IV. RESULTS

Fig. 4 shows a sample result of a 1-D motion-canceling test in the axial direction or Z-axis. The average amplitude of the tip's motion generated by the testbed oscillator is 50.6 μm p-p. The average amplitude of error-compensated motion is 27.7 μm p-p, representing a reduction of 45.3%.

Fig. 5 shows the results of a 3-D motion-canceling test. The average amplitude of the tip motion generated by the testbed oscillator is 90.8 μm p-p, and the average amplitude of compensated motion is 59.7 μm p-p, for a reduction of 34.3%.

Table 2 shows the average amplitude and the average error reduction in each of the three axes.

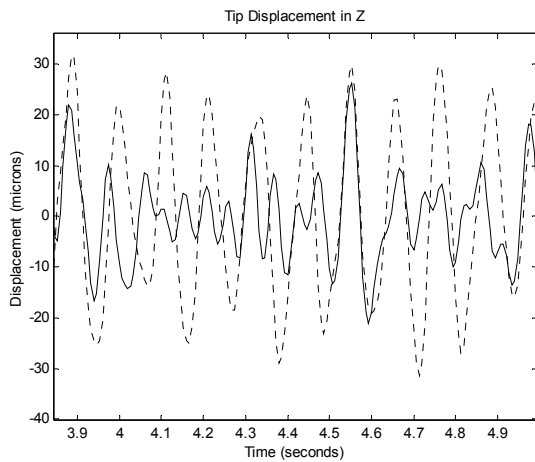
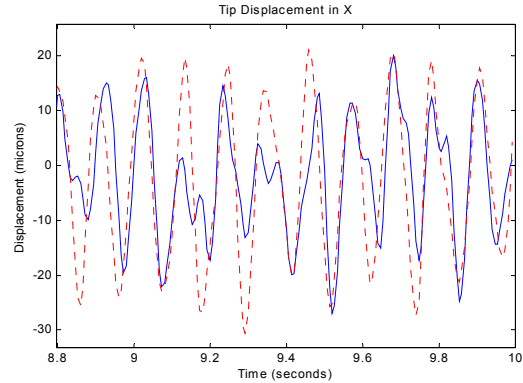
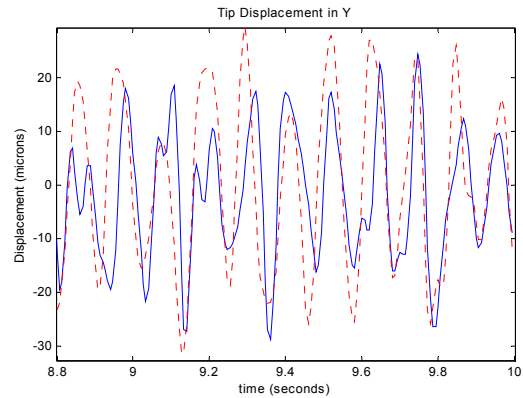


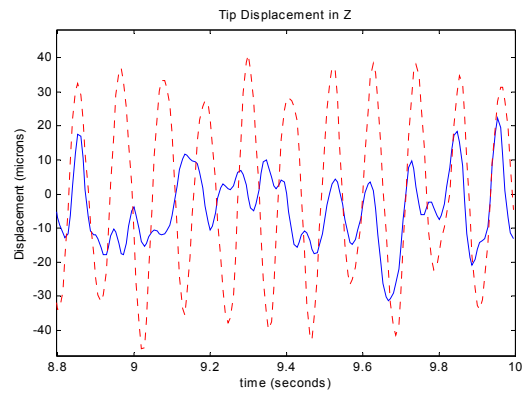
Figure 4. Performance of Micron in 1D motion canceling test. The dotted line depicts the uncompensated motion and the solid line the compensated motion.



(a)



(b)



(c)

Figure 5. Performance of Micron in 3D motion canceling test. The dotted line depicts the uncompensated motion and the solid line the compensated motion.

TABLE 2
Error Reduction Performance of Micron in each Axis.

	Uncompensated p-p amplitude (μm)	Compensated p-p amplitude (μm)	Error Reduction (%)
X	13.7	11.0	19.7
Y	15.3	12.3	19.6
Z	24.7	11.6	53.0

Figure 6 shows the frequency response plot of a 1-D motion canceling test with and without error compensation. The plots clearly manifest that most of the 9 Hz oscillatory motion has been attenuated by Micron.

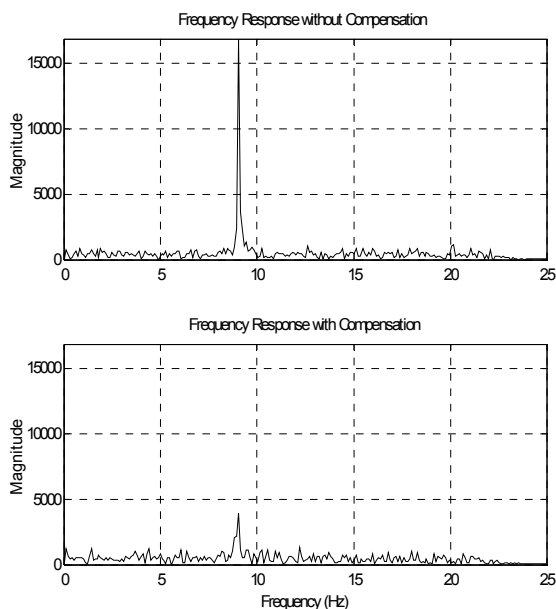


Figure 6. The frequency response plots show that most of the generated 9 Hz motion is being suppressed.

V. DISCUSSION

The results show the capability of Micron to cancel tremor-like periodic oscillations and thus improve positioning accuracy at the instrument tip. At present the system succeeds in suppressing such oscillations to the level of approximately $12\ \mu\text{m}$ p-p. In the tests, the original oscillation was largest along the Z axis. Because it exceeded the effective noise floor by a greater amount, the percentage reduction in the oscillation was larger along this axis.

Future work includes redesign of the instrument for closed-loop control and decreased weight and size. Upcoming experiments will involve recorded tremor instead of artificial oscillations.

VI. CONCLUSION

The design and implementation of the first prototype of Micron, an active hand-held microsurgical instrument for accuracy enhancement, has been presented. Canceling experiments with oscillatory disturbances in the frequency band of physiological tremor show that Micron is able to reduce error amplitude by 45.3% in 1-D tests and 34.3% in 3-D tests.

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