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Design and Implementation of Active Error Canceling in Hand-held Microsurgical Instrument

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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 37.2% in 3-D tests.

1 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 high 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 microsurgeons in their prime years, fatigue, caffeine consumption, and other factors affect manual stability.

The most familiar type of erroneous movement affecting microsurgery is tremor [3], which is 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].

One common procedure in vitreoretinal microsurgery involves removing membranes as thin as 20 μm from the front and back of the retina [2,6,7]. The measured tool tip oscillation during vitreoretinal microsurgery is often 50 μm peak-to-peak (p-p) or greater [8,9]. There is some degree of consensus among vitreoretinal microsurgeons that instrument-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 [9,10], where the unstable human hand is replaced by a robotic arm. 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 [11], 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

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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. This device should sense its own motion, estimate the undesired component of the sensed motion, and manipulate its own tip in real time to nullify the erroneous motion as shown in Figure 1. 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.

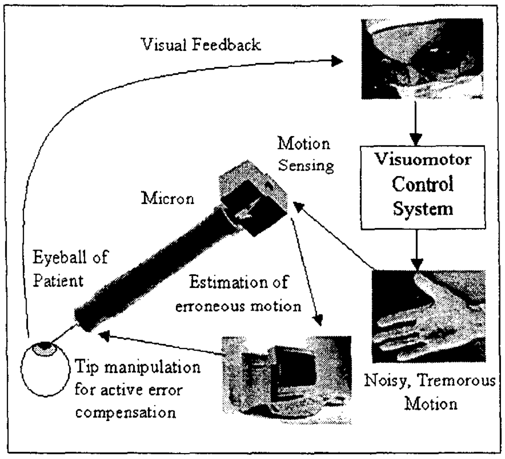


Figure 1. Active hand-held instrument for error compensation in microsurgery

2 System Overview

Micron, shown in Figure 2, 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. Our first prototype weighs 170 g, measures 210 mm in length (including the 30 mm intraocular shaft) and has an average diameter of 22 mm. The narrowed section of the handle near the tip is contoured as an aid to grasping.

Figure 2. Micron, the active error compensation microsurgical instrument

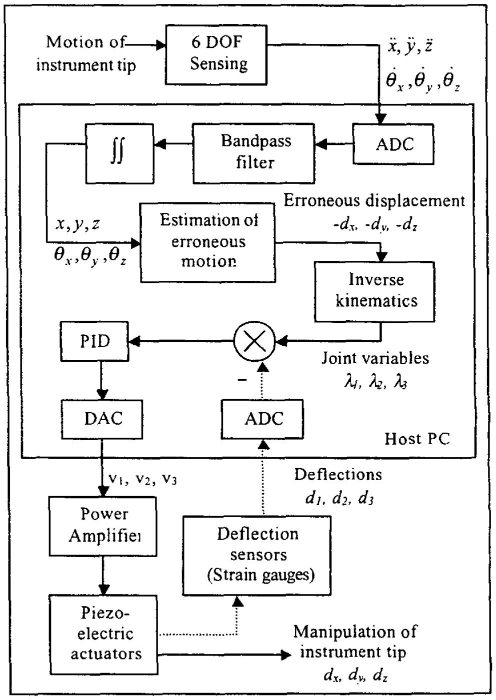


Figure 3. Block diagram of the Micron system

An overview of the complete system is presented in Figure 3. The current system controls the piezoelectric actuators in open loop. In the future, strain gauges will be added to sense the deflection of the actuators in order to provide closed-loop control as indicated by dotted arrows in Figure 3.

3 Sensing System

The motion-sensing module is mounted at the back end of the instrument handle, to detect translation and rotation in 6-dof [12]. 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 using an ADAC 5803HR data acquisition board.

Using the data from these sensors and the assumed knowledge of the instrument's instantaneous center of rotation, the three-dimensional (3-D) velocity of the instrument tip is obtained via appropriate kinematic calculations, and then integrated to obtain tip displacement [12].

4 Erroneous Motion Estimation

Estimation of tremor will be performed by a system based on the weighted-frequency Fourier linear combiner (WFLC) algorithm [13]. The WFLC 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 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 [13].

Additional ongoing 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 [15], with extended Kalman filtering being used for learning [16]. This technique has been tested in simulation on recordings of vitreoretinal instrument movement, yielding an average rms error reduction of 44% [14].

5 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 simplicity in design, as compared to a serial mechanism.

Piezoelectric actuators were chosen for their high bandwidth. The TS18-H5-202 piezoelectric stack actuator (Piezo Systems, Inc., Cambridge, Ma.) measures 5 mm x 5 mm x 18 mm, and deflects to a maximum of about 14.5 μm with an applied voltage of +100VDC. It offers relatively good control linearity, response time of 50 μs and actuation force of up to 840 N. A range of motion of 100 μm or greater has been achieved in each of the three coordinate directions by stacking seven piezoelectric elements to form each actuator. The response time of the piezoelectric actuator ensures the velocities in the joint space are more than adequate to map out the trajectory of the instrument tip in the workspace at the speed needed for canceling of tremor.

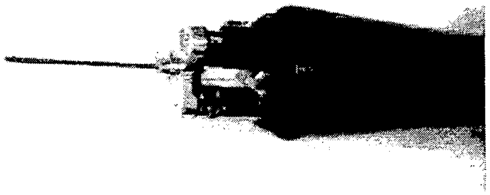


Figure 4. The 3 DOF intraocular shaft parallel manipulator.

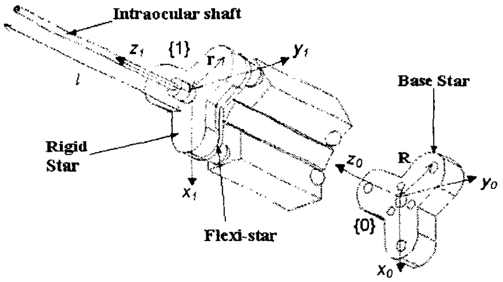


Figure 5. Kinematic frames of the intraocular shaft manipulator of Micron

Figure 4 depicts the intraocular shaft manipulator and Figure 5 shows the kinematic frames of Micron. The 30 mm stainless steel intraocular shaft is affixed to the center of the three-legged rigid star. The three legs of the rigid star form the vertices of an equilateral triangle. The rigid star is screwed onto the "flexi-star," which has the exact same shape, by a contact pin at each of its legs. The flexi-star is a thin plate made of ABS 780 thermoplastic. It is bolted to the triangular column by three bolts close to its center, constraining it in the three degrees of freedom that are not being driven, namely, axial rotation, and translation in the two coordinates transverse to the long axis of the instrument.

The stacked piezoelectric actuators are located on the three faces of the triangular column, and sandwiched between the base star and the contact pins. When voltage is applied to the piezoelectric stacks, they expand and push against the contact pins and the base star. This deflects the three overhanging legs of the flexi-star and in turn moves the intraocular shaft on the rigid star. There is a calibration screw at each of the three legs of the base star to compensate for the manufacturing inconsistencies in the length of the piezoelectric actuators. The manipulator system fits within the main housing of the instrument handle, with an interface to the sensor suite at the back end of the handle. The specifications of the manipulator are summarized in Table 1.

Table 1. Specifications of Micron Manipulator.

	Transverse x & y	*Axial* z
Max. tip displ. (μm)	560	100
Max. tip vel. (μm/μs)	11.2	2

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 [17]. Detailed inverse kinematics of the 3 DOF parallel manipulator can be found in [17] and [18].

6 Experimental Methods

The experimental setup consists of two separate systems, the testbed oscillator and the optical motion 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.

An optical motion tracking system, the Apparatus for Sensing Accuracy of Position (ASAP) [19], 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 involving one, two, or all three Cartesian coordinates (with respect to the instrument handle) can be performed by reorienting the direction of the testbed oscillation. The performance of the gyros is currently not tested as the experiment involves only translational motion. Figure 6 shows the experimental set up for a 3D motion-canceling test.

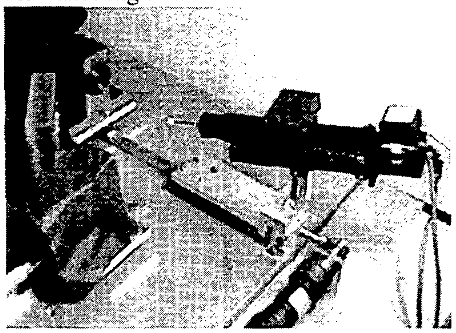


Figure 6. Experimental setup for motion canceling test.

7 Results

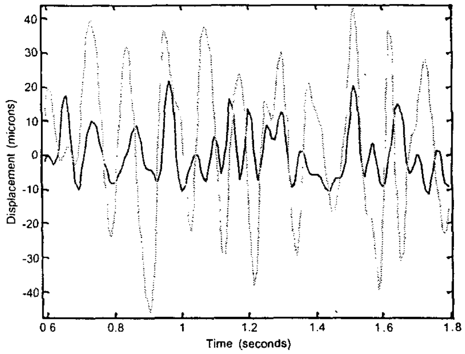
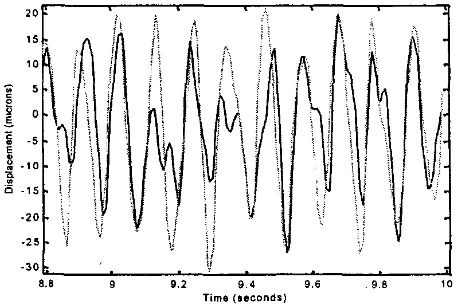
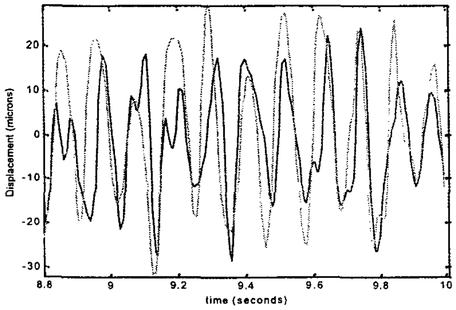


Figure 7. Performance of Micron in 1D motion canceling test. The dotted line depicts the uncompensated motion and the solid line depicts the compensation motion.

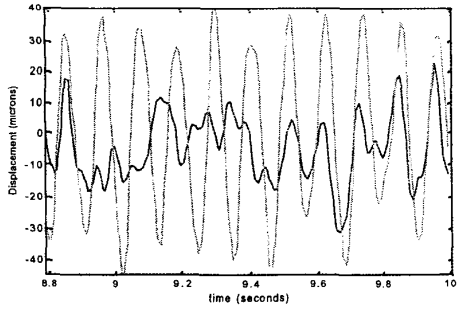
Figure 7 shows the result of a 1D motion canceling test in the axial direction or Z-axis over a period of around 1.2 second. The average pp amplitude of the tip's motion generated by the testbed oscillator is 50.6 μm at 9 Hz and the average p-p amplitude of an error compensated motion is 27.7 μm or a reduction of 45.3% over a set of 10 runs.



(a) Tip Displacement in X



(b) Tip Displacement in Y



(c) Tip Displacement in Z

Figure 8. Performance of Micron in 3D motion canceling test. The dotted line depicts the uncompensated motion and the solid line depicts the compensated motion.

Figures 8(a, b, c) show the typical results of a 3D motion canceling test over a period of 1.2 second. The average p-p amplitude of the tip's motion generated by the testbed oscillator is 90.8 μm at 9 Hz and the average p-p amplitude of an error compensated motion is 57.0 μm or a reduction of 37.2% over a set of 10 runs.

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

Table 2. Average Error Reduction Performance of Micron in each Axis over 10 runs.

	Uncompensated p-p amplitude (μm)	Compensated p-p amplitude (μm)	Error Reduction (%)
X	38.7	31.1	19.7
Y	43.3	34.8	19.6
Z	69.9	32.8	53.0

More reduction is achieved in Z-axis than the others because of the way Micron is oriented with respect to the oscillating direction for the 3D canceling test.

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

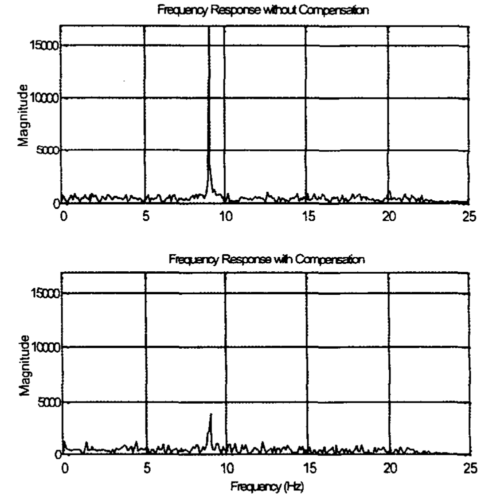


Figure 9. The frequency response plots show that most of the generated 9 Hz motion is being suppressed.

8 Conclusion

The design and implementation of the first prototype of Micron, an active hand-held microsurgical instrument for accuracy enhancement, has been presented. 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 37.2% in 3-D tests.

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