Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Acousto-Optic Compensation of Tremor for Use in a Handheld Laser Microsurgical Instrument

R. Cernat[1], C. E. Matei[1], L. Olteanu[1], C. N. Riviere[2], D. C. Dumitraş[1]
[1]National Institute for Laser, Plasma, and Radiation Physics, Bucharest, Romania
[2]The Robotics Institute, Carnegie Mellon University, Pittsburgh, Pa., USA

Abstract—**Development of a handheld microsurgical manipulator that incorporates active cancellation of the hand tremor of the user is ongoing. Thus far, experiments with the instrument have involved mechanical tools or end-effectors. In considering the possibility of laser procedures with the instrument, it is conceivable that a laser version of the instrument could be developed with no moving parts, using acousto-optic deflection of the laser beam to compensate the tremor. The paper describes the application and presents a proof of concept in a single degree of freedom using a benchtop laser deflection system and recorded hand motion data. Operating with a hand motion input tremor amplitude of 4 microns rms, the average overall canceling error is 0.8 microns rms.**

I. Introduction

Physiological hand tremor is a widely-discussed problem in microsurgery [1]. This involuntary movement generates an undesirable vibration or noise at 20 Hz or less [2]. A variety of engineered accuracy-enhancement devices have been or are being developed in order to improve the manipulation accuracy of microsurgeons, including telerobotic systems [3,4] and the Johns Hopkins "steady-hand" system [5]. Another approach presently under investigation is a handheld micro-manipulator with active tremor canceling [6]. This instrument, known as "Micron," uses a six-degree-of-freedom (6-dof) inertial sensing module to detect its own rigid-body movement [7]. An adaptive filter then estimates in real time the tremulous component of the overall motion [8], and this tremor estimate is used to drive a set of three piezoelectric stack actuators, deflecting a 3-dof parallel manipulator at the instrument tip [9] with an equal but opposite motion, thus compensating the tremor in the movement of the tool tip.

To date, research efforts in this project have been focused toward instruments with a mechanical tool tip. However, there are also numerous types of laser microsurgery in which enhanced accuracy could be of significant benefit, including procedures in neurosurgery and otologic surgery [10,11]. In addition, laser microsurgical applications in cell and developmental biology could also benefit [12].

For laser procedures, an alternative approach to the operation of the instrument is possible: hypothetically, an instrument with no moving parts could be constructed by the use of an acousto-optic deflector to manipulate the laser beam for tremor compensation [13]. As an initial proof of this concept, demonstrating that the approach can be implemented with sufficient accuracy, this paper presents the results of an acousto-optic tremor canceling experiment conducted using a benchtop apparatus with one degree of freedom.

Funding provided by National Institutes of Health (grant no. R01 EB000526) and National Science Foundation (grant no. EEC-9731748).

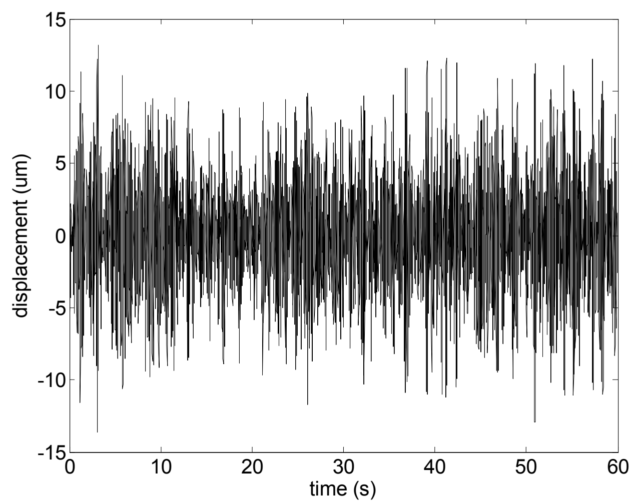

Fig. 1. Graph of the input to the system (the signal *s*), consisting of the hand tremor of a vitreoretinal surgeon recorded during a procedure in a rabbit model in vivo.

II. Methods

A recording of physiological tremor was acquired during vitreoretinal surgery in a rabbit model in vivo [14]. To facilitate evaluation of experimental results from the deflector, the tremor was isolated by bandpass filtering the data with a tenth-order Butterworth filter with corner frequencies at 7 and 13 Hz. Data were recorded in three dimensions, but only one dimension was used for the present experiment. A sampling rate of 100 Hz was used for data collection, and in all other portions of the experiment. A data segment 60 s in duration was used for this experiment. This yielded the input signal, *s*, shown in Fig. 1. The rms amplitude of the data segment is 4 μm.

Real-time estimation of tremor was performed just as it is performed in Micron [6]. The signal was filtered by a tremor estimation algorithm based on the Weighted-frequency Fourier Linear Combiner (WFLC), depicted in Fig. 2. This is a computationally simple time-domain algorithm, variants of which are frequently used for modeling and compensation of quasi-periodic biological signals or disturbances [6,15-17]. The raw motion signal, *s*, is bandpass filtered to the 7-14 Hz band to approximately isolate the tremor, producing the prefiltered input signal, $\tilde{s}$. The WFLC is an adaptive notch filter which also estimates the fundamental frequency of the incoming signal using a nonlinear phase-lock process. The time-varying frequency information is then used as the basis for a separate Fourier Linear Combiner which operates as an adaptive notch filter on the unfiltered signal, s, using the notch frequency information learned by the WFLC to suppress the tremor while avoiding the phase lag introduced by the bandpass prefilter. The equations of the system are [8]:

$$x_{r_k} = \begin{cases} \sin\left[r \sum_{t=0}^{k} w_{0_t} \right], & 1 \le r \le M \\ \cos\left[(r-M) \sum_{t=0}^{k} w_{0_t} \right], & M+1 \le r \le 2M \end{cases} \quad (1)$$

$$\varepsilon_k = \tilde{s}_k - \mathbf{w}_k^T \mathbf{x}_k \quad (2)$$

$$w_{0_{k+1}} = w_{0_k} + 2\mu_0 \varepsilon_k \sum_{r=1}^{M} r\left(w_{r_k} x_{M+r_k} - w_{M+r_k} x_{r_k} \right) \quad (3)$$

$$\mathbf{w}_{k+1} = \mathbf{w}_k + 2\mu \mathbf{x}_k \varepsilon_k \quad (4)$$

$$\hat{\varepsilon}_k = s_k - \hat{\mathbf{w}}_k^T \mathbf{x}_k \quad (5)$$

$$\hat{\mathbf{w}}_{k+1} = \hat{\mathbf{w}}_k + 2\hat{\mu} \mathbf{x}_k \hat{\varepsilon}_k \quad (6)$$

where k is the time index, and $\mathbf{w}$ and $\hat{\mathbf{w}}$ are vectors of adaptive weights, each having length $2M$. Equations (1)-(4) constitute the WFLC, and (5)-(6) are the FLC indicated in Fig. 2. The following parameter values were used: μ = 0.25, μ_0 = 0.000275, $\hat{\mu}$ = 0.3, M = 1, $\mathbf{w}_0 = \mathbf{0}$, and w_{0_0} = 0.6283 (10 Hz). This yielded the tremor estimate signal, $\acute{y}$.

Acousto-optic tremor canceling was demonstrated using an Isomet 1206C acousto-optic modulator controlled using an Isomet D302B tunable RF driver. A He-Ne laser was used. The signal $\acute{y}$ was used as input to the driver, after a prior transformation in order to place it within the usable input range of the driver. The modulating driver output was used in order to cause the modulator to deflect the laser beam. The position of the laser beam was sampled at 100 Hz using a DL100-7PCBA position-sensing photodiode (Pacific Silicon Sensor Inc., Westlake Village, CA). An optical bandpass filter (10LF10-633, Newport Corp., Irvine, CA) was used with the PSD in order to improve the quality of the measurements. The displacement, y, measured by the PSD was recorded and compared with the original motion signal, s, to obtain the overall canceling error, $\varepsilon = s - y$.

The tracking error of the laser deflection system alone, apart from the filtering, was quantified by comparing the measured output, y, with the driver input, $\acute{y}$, to obtain $\xi = \acute{y} - y$.

The tremor modeling error, $\zeta = \acute{y} - s$, was also calculated.

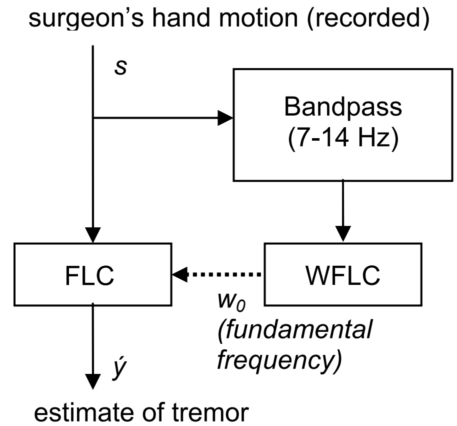

Fig. 2. WFLC-based tremor-canceling algorithm. The raw motion signal is bandpass filtered to the 7-14 Hz band to approximately isolate the tremor. The Weighted-frequency Fourier Linear Combiner is an adaptive notch filter which also estimates the fundamental frequency of the incoming signal using a nonlinear phase-lock process. The time-varying frequency information is then used as the basis for a separate Fourier Linear Combiner which operates as an adaptive notch filter on the unfiltered incoming signal, estimating the tremor while avoiding the phase lag introduced by the bandpass filter.

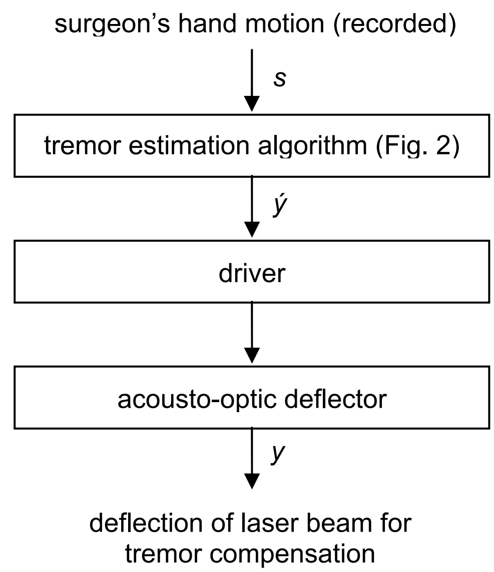

Fig. 3. Block diagram of acousto-optic tremor canceling system for laser instrument. The hand motion of the surgeon is filtered as depicted in Fig. 2. The resulting tremor estimate is then fed through the RF driver, which drives the acousto-optic deflector to displace the laser beam in order to compensate the signal.

III. RESULTS

The average overall canceling error, ε, over the 60 s duration of the experiment was 0.8 μm rms. A typical portion of the results is presented in Fig. 4.

The average tracking error, ξ, of the laser deflection system was found to be 0.6 μm rms. This is consistent with a result obtained separately when the recorded signal, s, was used directly as input to the driver, without passing through the WFLC tremor estimation algorithm; this trial also produced a tracking error of 0.6 μm rms.

The average tremor modeling error, ζ, was 0.5 μm rms.

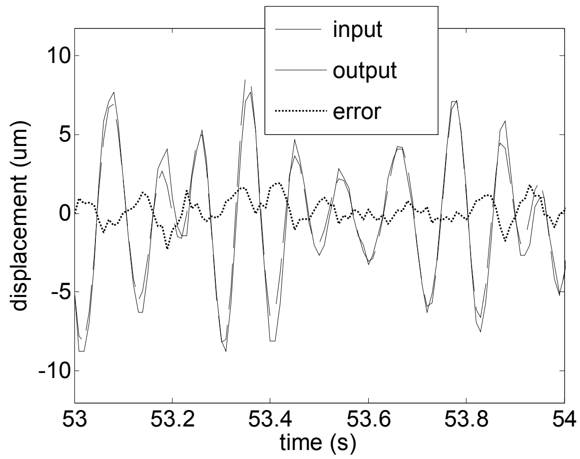

Fig. 4. Typical results from canceling experiment. The dashed line shows the input signal (Fig. 1). The solid line is the compensating displacement of the laser beam produced by the system. The dotted line shows the canceling error, ε, or the difference between the input and output.

IV. Discussion

The experimental apparatus used here, with the WFLC-based tremor filter [8] being used to provide the signal to drive an acousto-optic deflector, replicates the complete signal path from the proposed laser Micron. As such it represents a full offline test of the concept, albeit in a single degree of freedom. Since non-tremulous components were filtered out of s before the experiment, perfect operation would be indicated by a continuous output of zero, i.e., compensation of the entire input signal. The rms values of ε, ξ, and ζ obtained are consistent with the assumption that ξ and ζ are independent.

The results obtained for overall canceling error demonstrate the feasibility of the general concept of tremor cancellation via acousto-optic deflection of the laser beam. Future work would require extension of the technique to two degrees of freedom, as well as development of a miniature apparatus that can fit within the handle of an instrument such as Micron (approximately 15 mm in diameter).

In this experiment, the distance from the laser to the operating surface (or sensor, in this case) was known. In order for such an instrument to operate correctly in the field, the distance between the laser and the tissue must likewise be known. The most likely solution to this would be incorporation of an appropriate sensor into the instrument.

Acknowledgment

The authors thank Dr. V. Brajovic for helpful advice.

References

[1] R. C. Harwell and R. L. Ferguson, "Physiologic tremor and microsurgery," *Microsurgery*, vol. 4, pp. 187-192, 1983.

[2] M. Patkin, "Ergonomics applied to the practice of microsurgery," *Aust. N. Z. J. Surg*., vol. 47, no. 3, pp. 320-329, 1977.

[3] H. Das, H. Zak, J. Johnson, J. Crouch, and D. Frambach, "Evaluation of a telerobotic system to assist surgeons in microsurgery," *Computer Aided Surg*., vol. 4, pp. 15-25, 1999.

[4] I. W. Hunter, T. D. Doukoglou, S. R. Lafontaine, P. G. Charette, L. A. Jones, M. A. Sagar, G. D. Mallinson, and P. J. Hunter, "A teleoperated microsurgical robot and associated virtual environment for eye surgery," *Presence*, vol. 2, pp. 265-280, 1993.

[5] R. Taylor, P. Jensen, L. Whitcomb, A. Barnes, R. Kumar, D. Stoianovici, P. Gupta, Z. Wang, E. de Juan, Jr., and L. Kavoussi, "A steady-hand robotic system for microsurgical augmentation," *Int. J. Robot. Res*., vol. 18, pp. 1201-1210, 1999.

[6] C. N. Riviere, W. T. Ang, and P. K. Khosla, "Toward active tremor canceling in handheld microsurgical instruments," *IEEE Trans. Robot. Autom*., vol. 19, pp. 793-800, 2003.

[7] W. T. Ang, P. K. Khosla, and C. N. Riviere, "Kalman filtering for real-time orientation tracking of handheld microsurgical instrument," Proc. IEEE/RSJ Intl. Conf. Intell. Robots Syst. (IROS), Sept. 28-Oct. 2, 2004, vol. 3, pp. 2574-2580.

[8] C. N. Riviere, R. S. Rader, and N. V. Thakor, "Adaptive canceling of physiological tremor for improved precision in microsurgery," *IEEE Trans. Biomed. Eng*., vol. 45, pp. 839-846, 1998.

[9] D. Y. Choi and C. N. Riviere, "Flexure-based manipulator for active handheld microsurgical instrument," 27th Annu. Intl. Conf. IEEE Eng. Med. Biol. Soc., Shanghai, China, Sept. 1-4, 2005, pp. 5085-5088.

[10] T. Goto, K. Hongo, J. Koyama, S. Kobayashi, "Feasibility of using the potassium titanyl phosphate laser with micromanipulators in robotic neurosurgery: a preliminary study in the rat," *J. Neurosurg*., vol. 98, pp. 131–135, 2003.

[11] S. Jovanovic, U. Schönfeld, H. Scherer, "New developments in CO_2 laser stapedotomy," *Med. Laser Appl*., vol. 17, pp. 202-213, 2002.

[12] M.W. Berns, J. Aist, J. Edwards, K. Strahs, J. Girton, P. McNeill, J.B. Rattner, M. Kitzes, M. Hammer-Wilson, L.H. Liaw, A. Siemens, M. Koonce, S. Peterson, S. Brenner, J. Burt, R. Walter, P.J. Bryant, D. van Dyk, J. Coulombe, T. Cahill, G.S. Berns, "Laser microsurgery in cell and developmental biology," *Science*, vol. 213, pp. 505-513, 1981.

[13] I.C. Chang, "I. Acoustooptic devices and applications," *IEEE Trans. Son. Ultrason.*, vol. 23, no. 1, pp. 2-21, 1976.

[14] D. Ortega Ibáñez, F. Perez Baquerín, D. Y. Choi, and C. N. Riviere, "Performance envelope and physiological tremor in microsurgery," Proc. 32nd IEEE Northeast Bioeng. Conf., 2006, pp. 121-122.

[15] R. Ginhoux, J. Gangloff, M. de Mathelin, L. Soler, M. M. Arenas Sanchez, and J. Marescaux, "Active filtering of physiological motion in robotized surgery using predictive control," *IEEE Trans. Rob*., vol. 21, no. 1, pp. 67-79.

[16] A. Thakral, J. Wallace, D. Tomlin, N. Seth, and N. V. Thakor, "Surgical motion adaptive robotic technology (S.M.A.R.T.): Taking the motion out of physiological motion," in Proc. 4th Int. Conf. Med. Image Comput. Comput.-Assist. Intervention (MICCAI), Utrecht, The Netherlands, Oct. 2001, pp. 317–325.

[17] C. Vaz, X. Kong, and N. Thakor, "An adaptive estimation of periodic signals using a Fourier linear combiner," *IEEE Trans. Signal Process*., vol. 42, pp. 1–10, Jan. 1994.