Visual Measurement of Microsurgical Motion with Application to Robotic Augmentation

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\textit{Abstract}—Hand tremor represents a significant problem in microsurgical applications, since high levels of accuracy are required for these procedures. Therefore various methods of tremor cancellation are an important area of study. The system investigated in this paper is the handheld tremor canceling system – Micron. An error analysis of the application of stereo vision based sensing for controlling the Micron instrument is presented.

I. INTRODUCTION

In microsurgery, involuntary hand motions limit the accuracy with which a surgeon can operate. This problem is especially significant in the fields of ophthalmological (applications such as retinal vein cannulation) and neurological surgery. The most familiar type of involuntary or erroneous movement affecting microsurgery is physiological tremor. Tremor is defined as any involuntary, approximately rhythmic, and roughly sinusoidal movement. Physiological tremor is a type of tremor that is inherent in the movement of healthy subjects. The component of physiological tremor that is generally evident in vitreoretinal microsurgery is the “neurogenic” component: an oscillation at 8-12 Hz whose frequency is independent of the mechanical properties of the hand and arm. The resulting tool tip oscillation during vitreoretinal microsurgery is typically 50 microns peak-to-peak (pp) or greater [3].

To overcome this problem, an intelligent active hand-held instrument - Micron - is being developed. This instrument senses its own motion, distinguishes between desired and undesired motion using advanced filtering techniques, and actively compensates for undesired motion by an equal but opposite deflection of its own tip. In this paper we analyze the accuracy of using a stereo vision system attached to a microscope as an external reference for controlling the Micron instrument.

II. THE MICRON INSTRUMENT

Micron is a complete hand-held robotic system that is made up of three distinct subsystems: the sensing system, the filtering system, and the manipulation system. Physiological hand tremor of trained surgeons during vitreoretinal microsurgery has been reported to be in the frequency band of 8-12 Hz and measures up to 50 microns pp in each principal direction. To effectively reduce the erroneous tremulous motion down to the accuracy level that the microsurgeon desires (approximately 10 microns), the sensing system would have to meet the required performance specifications. Based on an assumed sinusoidal tremor profile of 10 Hz and 50 microns the performance specifications are: sensing resolution of approximately 5 microns, sensing accuracy of approximately 5 microns rms, bandwidth greater than 13 Hz and a sampling rate greater than 500 Hz [1]. There are two types of motion sensors: externally referenced and internally referenced sensors. Externally referenced sensors require interactions between onboard components and external active sources or receivers, whereas internally referenced sensors are self-contained sensing modalities. Sensing modalities of externally referenced sensors include infrared, radio frequency, visible light, ultrasound, electromagnetic wave, etc. Internally referenced sensors sense the inertial quantities of a moving body, such as acceleration, angular velocity, and angular acceleration. The motion of a body in three dimensional euclidean space is measured by a six degrees-of-freedom (DOF) inertial measurement unit (IMU) consisting of three accelerometers and three rate gyroscopes. Internal motion sensing that meets the required performance specifications for cancellation of physiological tremor is beyond the limit of the current state of technology. Sensing accuracy of inertial sensors is greatly handicapped by integration drift that arises from the accumulation of integrated sensing errors. One solution to this problem is the use of external reference sensors, to bind the long term inertial sensor drift errors.
III. METHODS

The external reference system under consideration is a stereo vision system for tracking a tool held by Micron. The system would require a performance accuracy that is within the acceptable range of precision. The goal of this experiment therefore is to measure the accuracy of tracking a tool undergoing extremely small motions of 10 microns (which is the scale of tool motion tools in certain microsurgical applications). In order to develop this error budget, the following procedure was conducted: a surgical needle (size: 9-0, diameter: 6mm, type: N-2760) was imaged under a surgical microscope (Zeiss OPMI1-H) at 40x magnification with a textureless background. The needle was held by the JHU Steady-Hand robot which was moved in steps of 10 microns over 2mm of motion in depth (200 frames of video). The microscope was outfitted with digital video cameras (SONY DFW V-700). The robot motion, which has an accuracy of approximately 2 microns, was taken as the ground-truth motion. The position of the tool tip was computed via stereo video tracking (using SSD) [2]. (Fig 1 shows the setup of the JHU steady hand robot for vein cannulation.) The resulting position measurements were registered to the robot frame of reference, and the mean squared error in position between robot and video positions was computed.

IV. RESULTS

Fig 2 shows a plot of the actual motion of a needle held by the JHU Steady Hand Robot versus the motion estimated using stereo matching. The mean square error was found to be 7 microns RMS for individual measurements. Fig 3 shows a plot of the error in estimating motion for each frame from of a 200 frame sequence. We then simulated a Kalman filter assuming tip position data was supplied by video with a variance of 7 microns, and tip velocity data was supplied by inertial sensing with a variance of 0.009 mm² and a 30 micron RMS error. The data was assumed to be independent and identically distributed (iid). The steady-state variance parameter of the Kalman filter was computed to be 0.007 mm² RMS (approximately 7 microns). The motion error of the micron tip is approximately 30 microns RMS. Assuming independence, including this additional source of error yields a final expected position error of 34 microns RMS. If, in addition, the goal is to maintain standoff from a surface also measured using stereo depth estimation, then the corresponding RMS error is approximately 37 microns.

In order to determine the robustness of the system, stereo visual tracking was then applied to freehand needle videos with a background of a model eye. Fig 4 shows the depth plot of the tracked needle over a sequence of 39 images.

V. CONCLUSIONS

In this paper, we have presented an accuracy analysis of applying a stereo vision and tracking system for the control of the Micron instrument. The results obtained show that the system has a variance of 7 microns, which meets the performance accuracy specifications for hand tremor cancellation. Visual tracking can therefore be used as a fairly accurate external reference control for the Micron system. The use of this as an external reference however would have a few drawbacks in terms of implementation since it requires line of sight which may constrain the workspace of the surgeon.

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REFERENCES