Velocity-Limiting Control of an Active Handheld Micromanipulator¹

Shohin Mukherjee

The Robotics Institute,
Carnegie Mellon University,
Pittsburgh, PA 15213

Robert MacLachlan

The Robotics Institute,
Carnegie Mellon University,
Pittsburgh, PA 15213

Cameron Riviere

The Robotics Institute,
Carnegie Mellon University,
Pittsburgh, PA 15213

1 Background

Fine manipulation and precise movements are essential in any type of microsurgery. In manipulation of delicate tissue such as nerves, strain rate has been shown to be a factor in the extent of damage to tissue [1]. Hence, there is a need to limit the maximum permitted velocity of the tool tip.

Such a limitation can be enforced without losing the benefits of direct manual manipulation (e.g., tactile feedback, intuitive control, and low cost) by using an actuated handheld instrument. One such instrument is Micron, originally developed for active compensation of hand tremor during microsurgery. The current version of Micron is a six-degree-of-freedom system, with a Gough–Stewart platform manipulator for its tip [2]. The mechanism is shown in Fig. 1. The actuators are ultrasonic linear motors (SQL-1.8-RV Squiggle motor, New Scale Technologies, Inc., Victor, NY). The device has two sets of infrared light-emitting diodes (LEDs): three on the moving platform and three fixed to the handle. The LEDs are optically tracked by a custom-built tracking system, which uses two position-sensitive detectors to triangulate each LED's position in 3D.

2 Methods

2.1 Design. The velocity limiter is a part of the cancellation filter of Micron (Fig. 2), and it adjusts the goal position in order to ensure that the tool tip velocity does not exceed a preset value.

There are two parameters of concern: velocity limit (V_l) and lag limit (d). The velocity limit is the maximum velocity at which the tool tip should be allowed to move. The lag limit defines the maximum permitted lag of the tool tip. The velocity limiter functions in the following manner:

- The previous output of velocity limiter ($\mathbf{x}'_{t-1}$) is subtracted from the input goal position ($\mathbf{x}_t$).
- If the magnitude of this difference exceeds the maximum amount that the tool tip can be allowed to move in one cycle, the tool tip should move in the direction of the new goal, but at the limiting speed. Maximum increment $\Delta \mathbf{x} = V_l / f_s$, where f_s is the sampling frequency of the control loop. The new goal position that is used as a reference to the position controller is given by

$$\mathbf{x}'_t = \mathbf{x}'_{t-1} + \Delta \mathbf{x} \frac{\mathbf{x}_t - \mathbf{x}'_{t-1}}{|\mathbf{x}_t - \mathbf{x}'_{t-1}|}$$

Fig. 1 Exploded view of Micron

Fig. 2 Location (a) and structure (b) of the cancellation filter with velocity limiting included

- Once the system is in the limiting velocity region, there is a lag between the desired goal position and the tool tip position. This lag should not be allowed to exceed a reasonable value so that it does not take too long to recover. If the lag distance exceeds the lag limit, the tip trails the goal position by that distance, temporarily superseding the velocity limiting.

2.2 Experiment. In order to demonstrate the velocity limiter, retinal membrane peeling is simulated. The model used is a layer of sorbothane with a thin plastic film on top (Fig. 3). Ten peeling tasks are performed by a novice user in random order under each of two conditions, with and without the velocity limiter, under a board-approved protocol. A microscope is used for precise

¹Accepted and presented at The Design of Medical Devices Conference (DMD2016), April 11–14, 2016 Minneapolis, MN, USA.
DOI: 10.1115/1.4033806

Manuscript received March 1, 2016; final manuscript received March 17, 2016; published online August 1, 2016. Editor: William Durfee.

Fig. 3 Micron during a peeling task

Table 1 Mean and maximum velocities

Test number	Velocity limiter OFF		Velocity limiter ON	
	Average velocity (mm/s)	Max. velocity (mm/s)	Average velocity (mm/s)	Max. velocity (mm/s)
1	1.195	4.982	0.423	1.439
2	1.231	5.907	0.358	1.330
3	0.995	2.729	0.482	2.113
4	1.197	4.792	0.288	0.910
5	0.969	3.218	0.272	1.069
6	0.782	2.528	0.367	1.334
7	0.873	2.469	0.345	1.444
8	0.739	2.514	0.457	2.517
9	0.898	3.092	0.420	1.655
10	1.164	3.785	0.262	0.818
Mean	0.995	3.490	0.408	1.842

Fig. 4 Plot of tool tip velocity with time

Fig. 5 Plot of tool tip x-coordinate with time

manipulation. The position of the manipulator is tracked over time. The position data are then filtered to reduce noise, and the velocity is obtained by numerical differentiation. The velocity limit (V_l) was set to 0.5 mm/s, and the lag limit (d) was set to 2 mm.

Fig. 6 Plot of tool tip y-coordinate with time

Fig. 7 Plot of tool tip z-coordinate with time

3 Results

The average and maximum velocity magnitudes of the tool tip for both cases have been listed in Table 1. Typical velocity results for the two cases are shown in Fig. 4. Figures 5–7 show x-, y-, and z-coordinates of displacement for typical data.

A reduction of 59% was obtained in the mean magnitude of velocity. A reduction of 47% was obtained in the peak velocity. Reductions in both average and maximum velocity were significant ($p < 0.05$).

The velocity limiter greatly reduced the average and maximum velocity. The velocity exceeds the limit of 0.5 mm/s sometimes, since the controller does not permit a lag of more than 2 mm. Once the lag exceeds 2 mm, the velocity increases to more than 0.5 mm/s in order to recover.

4 Interpretation

In this experiment, velocity limiting led to a significantly lower tool tip velocity. This technology may be useful in limiting damage in manipulation of delicate tissues, such as in dissection near nerves or retinal membrane peeling [3].

Acknowledgment

This work was supported in part by the National Institutes of Health (Grant No. R01 EB000526).

References

- [1] Wall, E. J., Massie, J. B., Kwan, M. K., Rydevik, B. L., Myers, R. R., and Garfin, S. R., 1992, "Experimental Stretch Neuropathy. Changes in Nerve Conduction Under Tension," *J. Bone Jt. Surg. Br.*, **74**(1), pp. 126–129.
- [2] Yang, S., MacLachlan, R. A., and Riviere, C. N., 2015, "Manipulator Design and Operation of a Six-Degree-of-Freedom Handheld Tremor-Canceling Microsurgical Instrument," *IEEE/ASME Trans. Mechatronics*, **20**(2), pp. 761–772.
- [3] Balicki, M., Uneri, A., Iordachita, I., Handa, J., Gehlbach, P., and Taylor, R., 2010, "Micro-Force Sensing in Robot Assisted Membrane Peeling for Vitreoretinal Surgery," *Medical Image Computing and Computer-Assisted Intervention* (Lecture Notes in Computer Science, Vol. 6363), Springer, Berlin, pp. 303–310.