SCIENCE CHINA
Information Sciences

• LETTER •

Special Focus on Human-Robot Hybrid Intelligence

May 2019, Vol. 62 050204:1–050204:3
https://doi.org/10.1007/s11432-018-9663-1

Human-micromanipulator cooperation using a variable admittance controller

Hsieh-Yu LI[1*], Theshani NURADHA[2], Sebaratnam Alex XAVIER[2] & U-Xuan TAN[1]

[1]*Pillar of Engineering Product Development, Singapore University of Technology and Design, Singapore* 487372*, Singapore;*
[2]*Department of Electronic and Telecommunication, Faculty of Engineering, University of Moratuwa, Moratuwa* 10400*, Sri Lanka*

Received 16 August 2018/Accepted 7 October 2018/Published online 28 March 2019

Citation Li H-Y, Nuradha T, Xavier S A, et al. Human-micromanipulator cooperation using a variable admittance controller. Sci China Inf Sci, 2019, 62(5): 050204, https://doi.org/10.1007/s11432-018-9663-1

Dear editor,
Micro-scale operations, such as microsurgery [1] and micro-devices assembly [2], have been gaining importance among different industries. However, it is challenging to execute these operations owing to the accuracy requirements of the operation which are close to the limit of the human hand accuracy. For example, microsurgery is a difficult and time-consuming procedure for the human operator as some of the anatomical structures of sizes (e.g., veins of the human retina ranges 40 to 350 μm [3]) are extremely small and fragile. Therefore, the performance of these operations is limited by physiological hand tremors.

To suppress the hand tremors and enhance the performance, a cooperative micromanipulator is a promising way to achieve it. A force/torque (F/T) sensor is typically appended in the end-effector of the robot to measure operational human forces. The measured hand tremor in program is filtered out by a low-pass filter. A controller is implemented to transfer the filtered human forces and yield the corresponding robot velocity [4–6]. If a cooperative micromanipulator with low controller gains consists of precise and accurate motors, the end-effector is stiff in response to human force and hence, the robot provides tremor-free, precise positional control for the human [3]. Steady-hand in [1] and a robot in [7] are examples of such a cooperative robot for retinal microsurgery.

However, the cooperation is stiff which is time-consuming for the human to execute the cooperative task. Precise operator's hand operation is achieved with tremor suppression but the compliance is compromised. Maneuvering the instrument with a stiff cooperation requires great efforts (such as large operational force is needed). Large acceleration is desired in some operational paths that involve large motion. A compliant cooperation is more beneficial for human in these large motion.

Hence, we address the issue of controlling the best trade-off between accurate and compliant cooperation for a cooperative micromanipulator. More specifically, we propose a variable admittance controller whose admittance between human force and robot velocity is varied based on human's intention. We have developed a micromanipulator in [8] for microsurgical suturing, and in this study, we extend our results by conducting more experiments. Our target (as shown in Figure 1(a)) is to ensure that the robot provides stiff and accurate cooperation in fine motion while also allowing compliant cooperation in large motion. With such a controller and developed robot, we hope to enhance the performance of the micro-scale tasks in terms of accuracy with minimal human's efforts.

Variable admittance control for microsurgical suturing. We use microsurgical suturing as an example owing to its complex operational gestures. We propose a variable admittance control defined as follows:

$$M_d(t)\ddot{x}_d + B_d(t)\dot{x}_d = F_{\text{ext}}, \qquad (1)$$

* Corresponding author (email: hsiehyu_li@sutd.edu.sg)

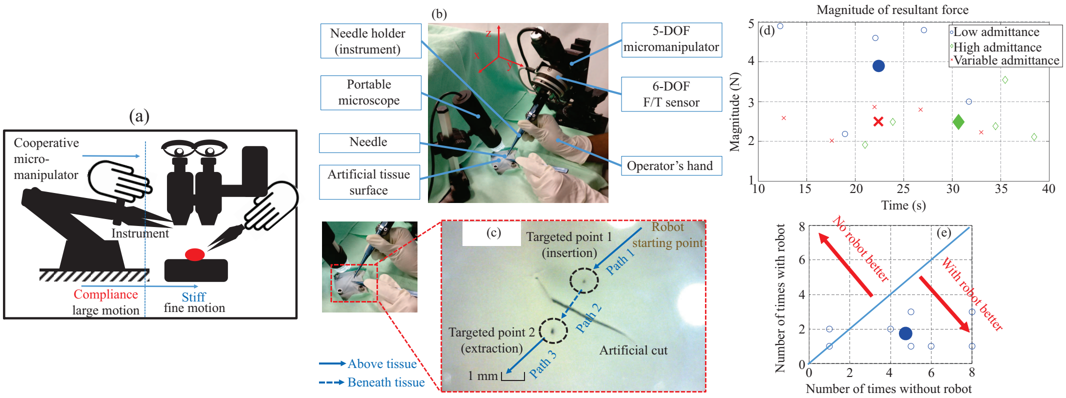

Figure 1 (Color online) (a) Overview of research objective; (b) the microsurgical robotics system; (c) the path of the needle from insertion (point 1) to extraction (point 2) under the microscope imaging; (d) first experiment result's path 1 to 3 (controller comparison); (e) second experiment result (with or without the robot comparison) – insertion only.

where $\dot{x}_d, \ddot{x}_d \in \mathbb{R}^n$ are the desired velocity and acceleration in the task space, and $M_d(t), B_d(t) \in \mathbb{R}^{n\times n}$ are the desired variable inertia and damping matrices, which are symmetric, diagonal, positive definite for all $\dot{x}_d \in \mathbb{R}^n$. The human force is the external force $F_{\rm ext}$. The objective of variable admittance control is to provide compliant or accurate cooperation in according with human's intentions with respect to different operational paths [4, 5]. In microsurgical suturing, two key moments are where the accuracy is most needed, namely, needle insertion and extraction. To target a precise insertion or extraction point is challenging and holding the needle until insertion easily causes hand-tremor. A robot with low admittance [4, 5] and stiff cooperation provides control with tremor suppression [1, 3]. Although the cooperation becomes stiff, it assists the operator to target a fine motion (where the insertion and extraction are normally carried out). However, when the needle is extracted and the operator makes a loop to tie knots, this hand motion involves large movement where fast acceleration is usually required. A compliant cooperation, which is achieved by high admittance, provides fast movement with minimal operational force that enables the operator to move the instrument with minimum efforts.

Hence, for every axis, the parameter adjustment of the admittance is proposed with respect to human force and defined as

$$B_{d,i}(t) = B_{0,j}(1 - \alpha_i \times |F_{{\rm ext},i}|) > 0, \tag{2}$$

$$M_{d,i}(t) = M_{0,j}(B_{d,i}(t)/B_{0,i}(t)) > 0, \tag{3}$$

where $M_{0,i}$, $B_{0,i}$ are the initial values of the desired inertia and damping in i-th axis when no external force is applied, $F_{{\rm ext},i}$ is the external force in the corresponding i-th axis for the admittance, and α_i is the updated gain for damping and $i = 1, \dots, n$. n is the degree of freedom (DOF). In (2) and (3), when there exists no external force, the admittance is maintained in the smallest value (largest $B_d(t)$ and $M_d(t)$). The cooperation starts with stiff cooperation which benefits the human to execute the fine movement. Conversely, if the human operator uses large hand motion, given $B_d(t)$ and $M_d(t)$ that are reduced, the admittance is increased for compliant cooperation. This shows our proposed control scheme (1)–(3) varies the admittance of robot with respect to $F_{\rm ext}$ to provide the corresponding cooperative interaction based on human's intention.

The passivity of the control scheme is next proved. The tracking error for such a collaborative robot is usually assumed to be [4, 5, 9], namely, $\dot{x}_d \cong \dot{x}$, where $\dot{x}$ is the robot velocity output. Eq. (1) becomes $M_d(t)\ddot{x} + B_d(t)\dot{x} = F_{\rm ext}$ with respect to the input-output pair $(F_{\rm ext}, \dot{x})$ and with a storage function

$$V(t) = \frac{1}{2}\dot{x}^{\rm T} M_d(t)\dot{x}. \tag{4}$$

Taking the derivative of $V(t)$ and integrating the input-output pair, we have

$$\int_0^t \dot{x}^{\rm T} F_{\rm ext} = V(t) - V(0) - \int_0^t W(\tau){\rm d}\tau, \tag{5}$$

where $W(\tau) = \frac{1}{2}\dot{x}^{\rm T}[\dot{M}_d(t) - 2B_d(t)]\dot{x}$. The passivity condition is defined as [4, 5, 9]

$$\int_0^t \dot{x}^{\rm T} F_{\rm ext} \geqslant V(t) - V(0) \geqslant -V(0). \tag{6}$$

Therefore, to ensure the dissipated energy

$$\int_0^t W(\tau){\rm d}\tau \leqslant 0, \tag{7}$$

the passivity is guaranteed as

$$\dot{M}_d(t) - 2B_d(t) \leqslant 0. \tag{8}$$

The closed-loop system (4) is always dissipative by condition (8), ensuring stable interaction within proposed-controlled robot and human operator.

Experiment. A 5-DOF robotic systemwith a 6-DOF F/T sensor for micro-suturing is developed as shown in Figure 1(b). The resolution of each joint (stepper motor) is 1.25 μm per full step and 5 mm/s for max speed in translation and $0.01°$ per full step and 8 rpm for max speed in rotation. In terms of controller parameters, to ensure the parameters are updated without the violation of (8), minimal values of the admittance (2), (3) are chosen and set empirically. (The rest of the specification and parameters of the controller can be found in [8].)

Three needle paths of the artificial tissue surface under microscope imaging are shown in Figure 1(c). This surface consists of a cut and two targeted points, namely insertion and extraction. In the first experiment, which is conducted by 5 subjects and 3 sets of controller, the operator grasps the needle holder and guides the robot from starting point to the targeted point 1 (path 1), crosses beneath the first point to the second one for extraction (path 2), and then pulls the needle out by non-dominant hand (path 3). The paths are designed to evaluate the compliant or accurate cooperation of the robot because they involve (a) large movement when the needle is approaching the insertion point or being pulled out from extraction, and (b) fine movement when two of the points are being inserted or extracted. As shown in Figure 1(d), the proposed controller (red) achieves similar execution time with low admittance (33.48% less than constant high admittance) and operational force with high admittance (35.82% less than constant low admittance). Hence, the results conclude that the proposed controller guarantees a decent trade-off between compliance and accuracy based on the operator's intentions.

The second experiment is to test the accurate of the robot. The subjects are asked to only execute insertion, but for three times at three different precise points. If three points are inserted under two conditions, it is considered success, otherwise failure. Two conditions are (1) the needle has to be inserted into the center of the points, and (2) the needle is allowed to touch only the insertion points (if it touches other part of the tissues, it is a failure). Two sets of experiment are designed, namely, with the developed robot and with free hand. Eight subjects try till success and numbers of the trials with and without robot are recorded in Figure 1(e). Six of the experiments show that the performance is better with the developed robot. Without the robot, the performance is limited by hand tremor and it is hard to insert into the correct positions and hence, more numbers of trials are needed. Some subjects have less hand tremors and it explains why the result of one of the subjects is not successful. Though the operation varies with different individuals, the performance appears to improve with the robot as the average of number of trials without robot (4.75) is almost three times higher than that with robot (1.75). The subjects also claim the tremor suppression provides an easier and more stable motion to target the points. The experimental results show that our robot enhances the performance significantly and improve the operational quality.

References

1 Taylor R, Jensen P, Whitcomb L, et al. A steady-hand robotic system for microsurgical augmentation. Int J Robotics Res, 1999, 18: 1201–1210

2 Cecil J, Kumar M B B R, Lu Y, et al. A review of micro-devices assembly techniques and technology. Int J Adv Manuf Technol, 2016, 83: 1569–1581

3 Mitchell B, Koo J, Iordachita I, et al. Development and application of a new steady-hand manipulator for retinal surgery. In: Proceedings of IEEE International Conference on Robotics and Automation, 2007. 623–629

4 Lecours A, Mayer-St-Onge B, Gosselin C. Variable admittance control of a four-degree-of-freedom intelligent assist device. In: Proceedings of International Conference on Robotics and Automation, 2012. 3903–3908

5 Ficuciello F, Villani L, Siciliano B. Variable impedance control of redundant manipulators for intuitive human-robot physical interaction. IEEE Trans Robot, 2015, 31: 850–863

6 Li H Y, Paranawithana I, Yang L, et al. Stable and compliant motion of physical human-robot interaction coupled with a moving environment using variable admittance and adaptive control. IEEE Robot Autom Lett, 2018, 3: 2493–2500

7 Degirmenci A, Hammond F L, Gafford J B, et al. Design and control of a parallel linkage wrist for robotic microsurgery. In: Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2015. 222–228

8 Li H Y, Nuradha T, Xavier A, et al. Towards a compliant and accurate cooperative micromanipulator using variable admittance control. In: Proceedings of IEEE International Conference on Advanced Robotics and Mechatronics (ICARM), 2018

9 Landi C T, Ferraguti F, Sabattini L, et al. Admittance control parameter adaptation for physical human-robot interaction. In: Proceedings of IEEE International Conference on Robotics and Automation (ICRA), 2017. 2911–2916