Development of a Human-Robot-Shared Controlled Teletweezing System

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***Abstract*—This brief proposes a process of implementing a teletweezing system using multiple slaves for deformable object manipulation such as bio tweezing tasks. The multiple slave feature is desirable to improve both the manipulation dexterity and stable grasping force control capability. A flexible multiple robot connection environment is assured in a very quick and easy manner using an RT-Middleware platform. In this brief, we propose the control strategy for a single-master multislave telemicrotweezer. Also, several simulations and experiments are performed to prove the validity of the proposed control scheme and the design methodology. These involve biomanipulation tasks such as Ikura (salmon roe) tweezing, which is a magnified version of a wide variety of bio-cell tweezing. To realize the Ikura remote tweezing using a single-master multislave system and a human's dexterous operation skill, we first decompose the dynamics of multiple slaves into two decoupled systems, which are the shape system describing cooperative tweezing aspect and the locked system that preserves energetic passivity. Scattering-based communication is used to passify the master-slave communication delay. Last, a preliminary pick-and-place experiment and some simulation results are provided to verify the validity of the proposed control method.**

***Index Terms*—Biological cell, cooperative system, delay effects, microassembly, telerobotics.**

I. Introduction

A HUMAN-FRIENDLY biomanipulation or tweezing assistance system is very necessary due to the conventional tool's complexity and low success rate caused by several problems in handling bio organisms. Slippery surfaces require a surface process to handle the task. Further, deformable membranes need the force applied to them to be controlled. An equal positioning accuracy in a wide workspace is also necessary.

Conventional micromanipulators for biomanipulation are very limited in workspace and target objects (e.g., cell scale). A flexible prototyping biotweezer requires a flexible system modification to account for different target objects.

In this brief, we present preliminary research into developing a human-friendly telebiotweezer based on a single-master multislave (SMMS) configuration. The scale of bio objects varies in a very wide range from nano- to micro- or mesoscale. There have been many biotweezing approaches in contact and noncontact types for specific purposes.

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In contact-type nanomanipulation, atomic force microscope (AFM) and scanning tunneling microscope (STM) probes are the most widely used [1]. Optical tweezers enable noncontact tweezing by applying loads in the order of pN on the samples [2]. It is well-featured for bionanomanipulation applications where the samples are very fragile. DNA, RNA, chromatin fiber, or other biomaterial can be manipulated in almost 3-D. However, all these available technologies are based on specifically limited scale ranges and not eligible for a wide range of biomanipulation, which is more realistic. Especially, most biomanipulation requires an aqueous environment, which makes tracking and manipulating in a wide workspace and brownian motion difficult. Even in the limited scale (nano-), unknown physical nonlinearity, limited depth-of-field, and the slow scanning rate of images such as the AFM, a scanning electro-microscope (SEM) prevents fully autonomous manipulation to be possible. Therefore, we propose a teleoperated biotweezing assistance system which is useful for multiscale biomanipulation with a high fidelity haptic feeling that delivers workspace physical interaction to a human operator.

II. SMMS Telemicromanipulation

A. Why SMMS?

Our proposed teletweezing system in a wide-scale range should have several of the following features.

- Human-friendly design: The proposed SMMS configuration improves human's operability by reducing the high operational burden (focusing the microscope, manipulation, and etc.).
- Flexible and reconfigurable design: A modular software architecture (RT-Middleware [3]) and hardware (micro- to nanoprecision manipulator) approach which reduces the reconfiguration time in a varying target objects.
- High fidelity force feedback: The communication or network delay caused by the modular approach such as RT-Middleware should be overcome. Human-induced delay caused by human's delayed reaction time is considered by the proposed force-feedback strategy.

Our system design concept is inspired by both the chopstick and the tweezer. Chopsticks are very well featured to position two sticks very accurately in a very wide range of workspace. This can be useful for multiscale biomanipulation. However, to use them proficiently, quite a long training time is necessary and performance highly depends on a person's operational skill. In our system, micromanipulators should be independent and multiple to have design flexibility on the tool tip. The independent tweezer tooltip design is achieved by modular hardware and software.

We testify to the feasibility of our tweezer design by the salmon roe (Ikura) tweezing experiment, which is representative of other scale biomanipulation. An operator should be

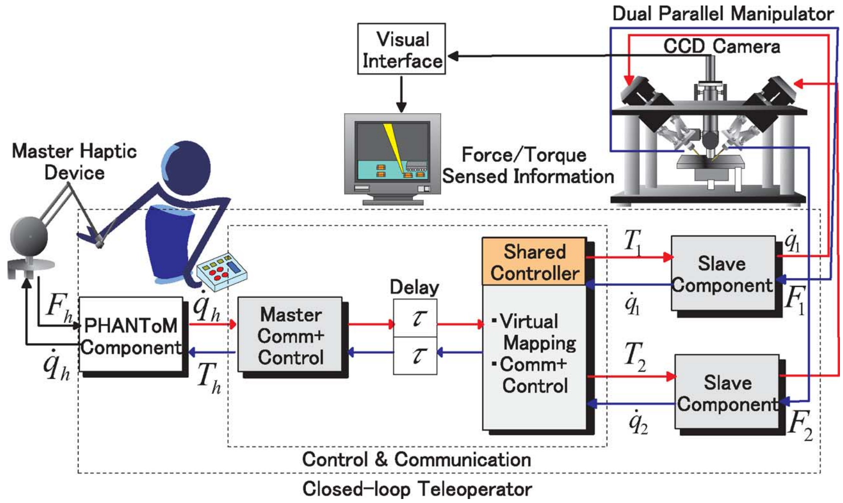


Fig. 1. SMMS telemicromanipulation system architecture based on an RT-Middleware network platform where both visual and haptic communication channels are applied to connect the micro/macro world. τ and τ_h depict communication delay and human induced delay, respectively.

very careful with internal grasping force control for successful tweezing of ikura cells which have fragile membranes and slippery surfaces. Therefore, SMMS configuration is highly featured for such a task by assuring more dexterity and less operational stress.

There are several advantages of the proposed SMMS systems for many applications where the required manipulation dexterity, mechanical strength, robustness to single-point failure, safety, and human's flexible intelligence is necessary for successful task completion. However, it is not possible to send a human to the micro- or nanoworld. Especially, an operator experiences difficulties in manipulating biocells or injection tasks from a limited operational capability and lots of required devices (i.e., microscopes, etc.) to be operated.

However, the desired Ikura tweezing task requires human–robot shared internal grasping force control more than depending only on a human operator's operational ability [14] or on autonomous force control in the sense of grasping security or credibility in an unstructured environment.

B. Related Works

Many successful single-master single-slave (SMSS) system implementations and control schemes have been proposed to be useful for even microscale teleoperation tasks. However, works related to control multiple slave robots are very rare.

In the teleoperated approach, Tanikawa *et al.* [7] developed a chopstick-like microtweezing system having a two-fingered microhand as a slave. The surgical system such as the Da Vinci System [8] is a good application since humans and robots collaborate with each other for the purpose of assuring high performance with safety. However, these direct teleoperation systems were not supporting force feedback to the operator and thus not assuring enough telepresence with the lack of dexterity.

In the meantime, an autonomous microtweezing system was also proposed by Fearing *et al.* [10]. This sensor-based automation approach had difficulties when expanded to dexterous micromanipulation tasks under unstructured environments. Also, several problems (e.g., lack of micromanipulation planning, unexpected dynamic effects, noisy sensing, etc.) exist which prevent fully autonomous manipulation with dextrous skills in microscale. Therefore, we are especially interested in the telemicromanipulation approach where the proposed SMMS system can be applied to enable human–robot cooperative control for dramatically improving the state of the art.

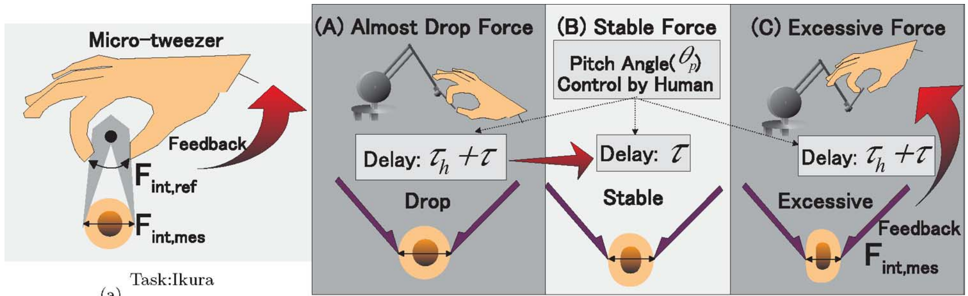
Compared to gripper-based manipulation, our approach is reconfigurable in design. Therefore, a networked but independent master-slave connectivity to build a human–robot-shared dexterous microtweezing system is necessary.

A few works on SMMS system and control are introduced here. Kosuge *et al.* [9] developed the SMMS system using the virtual internal model. However, their work was relying on the reference position distribution without considering the force feedback which made a comparative analysis with other systems. Lee *et al.* [11] focused on dealing with the communication delay in the SMMS system by decomposing the dynamics of multiple slaves and showing several simulated results. However, their work does not go further to the motion level strategy for the real task implementation.

C. SMMS System Architecture

To allow more dexterity in the slave while maintaining the human's operability with enough telepresence, an SMMS telemicrotweezing system [4], [17] is proposed in this brief (see Fig. 1). Our approach has a target goal to improve the intelligence of both human and robots resulting in the optimized human–robot-shared operation.

It is well known that micro-, nanointeraction is not reproducible enough to automate a procedure. Therefore, the VR simulation techniques of 3-D multibody systems would enhance the operator's skills by learning and feeling a realistic micro-, nanoworld in an offline user interaction mode. Fig. 1 illustrates the configuration of the SMMS teletweezing system and the 3-D VR simulator over delayed networks. We use a commercial PHANTOM haptic device as a haptic device and also the



(a) Task:Ikura tweezing

(b) Operation:SMMS Microtweezer

Fig. 2. Conceptual description of Ikura tweezing human friendly SMMS telemicrotweezer. (a) Task: Ikura tweezing. (b) Operation: SMMS microtweezer.

OpenHaptics toolkit (commercially available at SensAble technologies, Inc.) which enables software developers to add haptics and true 3-D navigation to a broad range of applications, including 3-D design and modeling, visualization, and simulation. The shared controller plays a major role in generating the multislave's reference position and internal force by human–robot cooperation. Each slave controller drives six link shafts to position the parallel mechanism end-effector within about 10-μm positioning accuracy. There are three RT components with position/force input/output (I/O) interface through the network. Both slave manipulators are controlled by a PC (Pentium III 500 MHz $\times$ 2). A real-time extension for Linux (ART-Linux) is used as the operating system to perform motion control at a 1-kHz sampling rate.

III. Shared Control With Time Delay

A. Task Model: Ikura (Salmon Roe) Tweezing

This section discusses our task model (Ikura Tweezing) and operational model of the SMMS microtweezer to complete the task (see Fig. 2). In the tweezing of fragile Ikura, operator should be very careful to maintain the most suitable internal grasping force for secure grasping. The microtweezer is a tool which is energetically passive. In the meantime, the teleoperated microtweezing tool based on SMMS configuration should be operated as similarly as the passive tweezing tool by compensating the communication network delay and assuring high fidelity of force feedback to the user.

B. Effect of Delayed Network

Fig. 2 shows delay effects to the controller. In the proposed human–robot-shared control framework, there exist two major delays: 1) human-induced delay (τ_h) and 2) network-induced delay (τ). τ_h is induced by a human's sensing and actuation delay. This can be more serious in smaller scale applications such as micro-, nanomanipulation which requires VR model-based interaction from the degraded sensing capability. Therefore, overall controller performance loses stability on dynamically varying grasp shape command when this delay occurs.

C. Improved Virtual Mapping Method

Since the SMMS system has very different kinematical structures between the master and the slave, the conventional direct mapping method (e.g., the joint-to-joint mapping) is impossible to be adopted in our system. Griffin *et al.* proposed the virtual mapping method [14] between a human's hand and nonanthrophormous slave device, where their feedback strategy was based on SMSS fingertip level force feedback. Our system applies a serial connected links type of a master device but a parallel connected link type of a slave device in what defines a new manipulation approach. A new approach is introduced in this brief to realize more dexterous control with the simplified master device to control multiple slave devices by decomposing grasp and group dynamics as discussed with the object-based angle control to adjust the grasp force control.

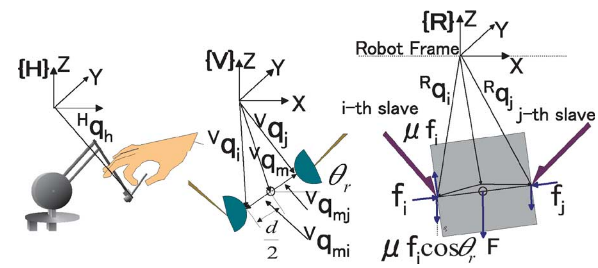


Fig. 3. (left) Coordinate system of human frame H, (middle) virtual object frame V, and (right) the robot frame R.

As shown in Fig. 3 an overall virtual mapping process can be summarized as the reference distribution (from user frame to virtual frame) and the scaling process (from virtual frame to robot frame).

The roll and yaw angle (θ_r, θ_y) of phantom haptic interface are measured and used to provide the orientation of the manipulated object. Then the reference grasping force is proportional to the measured pitch angle of phantom haptic interface. This reference object size is mapped into the width of both slave's tip positions.

The detailed reference contact position is calculated from the virtual mapping parameters denoted in Fig. 3, where d is the distance between two virtual tip positions which is calculated to assign virtual dynamics (spring constant: s_v) to the virtual object as follows:

$$F_g^r = s_v \frac{1}{d}, \quad d = \Delta\theta_p = \left| {}^V\boldsymbol{q}_i - {}^V\boldsymbol{q}_j \right| \tag{1}$$

where $\boldsymbol{q} = [\boldsymbol{q}_i \boldsymbol{q}_j] \in \Re^n$ denotes configuration of each slave end effector tip position.

Then, each slave's tip position based on the virtual object is

$${}^V\boldsymbol{q}_i = {}^V\boldsymbol{q}_m + {}^V\boldsymbol{q}_{mi}. \tag{2}$$

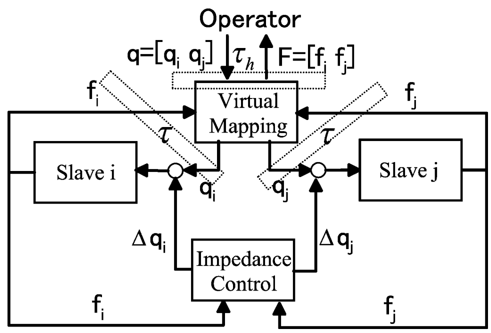


Fig. 4. Overview of shared control framework over delay.

D. Shared Control Framework

An overall control framework of the proposed system is shown in Fig. 4. A human operator generates the operational commands [six-degrees-of-freedom (6-DOF)] such as x, y, and z translational and roll, pitch, and yaw angular commands. The grasp force cooperative control mechanism over delay is summarized as follows. First, a human gives an internal grasp force command by generating grasp shape function as described in Section IV for delay compensation. The human recognizes his real-time grasping condition from the force sensors with only communication delay (τ). Then, the operator tries to modify the grasp shape function with a human's responsive actuation delay (τ_h). In our proposed control framework, human-induced delay τ_h is dealt with local semiautonomous control and the network induced delay τ is compensated with the scattering-based teleoperation control assuring energetic passivity.

Each slave's impedance control equation is derived as follows:

$$M_i \Delta\ddot{q}_i + D_i \Delta\dot{q}_i + K_i \Delta q_i = \boldsymbol{f}_i \tag{3}$$

where M_i, K_i, and D_i is each slave's inertia matrix, the damping coefficient matrix, and the spring coefficient matrix, respectively. Δq_i is the positional displacement of the end effector's tip position caused by the applied force while interacting with environment. $\boldsymbol{f}_i$ can be obtained from the force sensor located at the end effector. The same rule can be applied to the other slave micromanipulator.

Then the internal force displacement (ΔF_{int}) should be determined from each slave's interaction force $\boldsymbol{f}_i, \boldsymbol{f}_j$.

A human operator's reference input $(\boldsymbol{q})$ is transformed to the reference position of each slave manipulator by the reference mapper. Then, the generated force $(\boldsymbol{f}_i, \boldsymbol{f}_j)$ by interacting with environment is fed into the mapper. A position-based object impedance controller generates the displacement of each slave manipulator by the interacting force. Without considering the impedance displacement factor here, the reference mapper and each slave manipulator construct the bilateral control for teleoperation.

Each slave manipulator is controlled by the impedance controller which is driven by the positional reference generated by the virtual mapping method.

IV. Delay Compensation

A. System Model

We can consider the m-DOF master robot dynamics

$$M_h(q_h)\ddot{q}_h + C\left(q_h, \dot{(q_h)}\right)\dot{(q_h)} = T_h + F_h \tag{4}$$

where q_h, T_h, and $F_h \in \Re^m$ are the configuration, the control command to the master haptic interface, and the human force, respectively. Also, $M_h(q_h) \in \Re^{m\times m}$ are the inertia and Coriolis matrics s.t. $M_h(q_h)$ is positive-definite and symmetric and $\dot{M}_h(q_h) - 2C_h(q_h, \dot{q}_h)$ is skew-symmetric.

Each slave manipulator is controlled by the impedance controller which is driven by the positional reference generated by the virtual mapping method.

We define the grasping shape function $q_E : \Re^n \rightarrow \Re^{n-m}$ on the configuration space of the slaves. Then a desired grasping shape generated by a human's command can be achieved by enforcing the following condition:

$$q_E\left(q(t)\right) \rightarrow q_E^d \tag{5}$$

where $q_E^d \in \Re^{n-m}$ is a target grasping shape generated by human operator.

B. Passive Decomposition

From the theoretical derivation in [11], we use the passive decomposition, and the dynamics of the multiple slaves is partially decomposed

$$M_L(q)\dot{v}_L + C_L(q,\dot{q})v_L + C_{LE}(q,\dot{q})\dot{q}_E = T_L + F_L \tag{6}$$
$$M_E(q)\ddot{q}_E + C_E(q,\dot{q})\dot{q}_E + C_{EL}(q,\dot{q})v_L = T_E + F_E \tag{7}$$

where F_L and F_E are the environmental forces affecting the overall slaves motion, and the internal grasping force, respectively, while T_L and T_E are the transformed controls designed below.

C. Control Design

The locked and shape controls T_L and T_E are designed such as

$$\begin{pmatrix} T_L \\ T_E \end{pmatrix} := \begin{pmatrix} C_{LE}(q,\dot{q})\dot{q}_E \\ C_{EL}(q,\dot{q})v_L \end{pmatrix} + \begin{pmatrix} T_L' \\ T_E' \end{pmatrix}. \tag{8}$$

The local grasping control T_E' is designed as

$$T_E'(t) := -K_v^E \dot{q}_E - K_p^E\left(q_E(t) - q_E^d\right) - \hat{F}_E(t) \tag{9}$$

where $\hat{F}_E(t)$ is the estimate of $F_E(t)$, q_E^d is the desired constant grasping shape, and K_v^E, K_p^E are the PD-gain matrices. We choose the symmetric teleoperation where local impedance controls are given by the following PI-control with damping injections:

$$T_*'(t) := -K_d^* v_*(t) - K_v^*\left(v_e^*\right) - K_p^* \int v_e^*(\theta)d\theta. \tag{10}$$

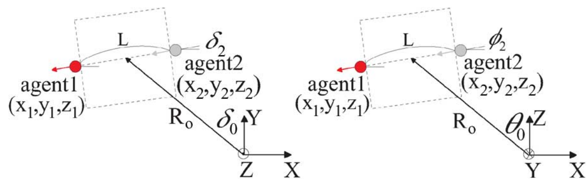


Fig. 5. Slave micromanipulators on XYZ frame.

To passify the communication delay, we use scattering-based communication [11].

D. Grasping Shape Function for SMMS System

To be able to implement the algorithm to SMMS system, we define the grasp shape function q_E to be the desired one q_E^d

$$q_E\left(q(t)\right) \rightarrow q_E^d \tag{11}$$

$$q_E := \begin{pmatrix} x_2 - x_1 - L\cos\delta_1 \\ y_2 - y_1 - L\sin\delta_1 \\ z_2 - z_1 - L\cos\phi_1 \\ \phi_1 - \phi_2 \\ \theta_1 - \theta_2 \\ \delta_1 - \delta_2 \end{pmatrix}. \tag{12}$$

As shown in Fig. 5, $(x_{1,2}, y_{1,2}, z_{1,2}, \phi_{1,2}, \theta_{1,2}, \delta_{1,2}) \in \Re^6$ describe slave agent 1 and 2's coordinates. L is the distance between both agents to describe the grasp shape distance.

Decomposition of group behavior and shape system is able to be earned by

$$\dot{q} = [\alpha(q) \quad \beta(q)] \begin{pmatrix} v_L \\ v_E \end{pmatrix}. \tag{13}$$

Decomposition matrix $(\alpha(q), \beta(q))$ can be derived following the derivation in [11].

We can obtain the group and grasp shape velocity as v_L and v_E, respectively. Each slave's inertia is assumed to be the same as M_1

$$v_L = \frac{1}{4M_1} \begin{pmatrix} \dot{x}_1 + \dot{x}_2 \\ \dot{y}_1 + \dot{y}_2 \\ \dot{z}_1 + \dot{z}_2 \\ \dot{\phi}_1 + \dot{\phi}_2 \\ \dot{\theta}_1 + \dot{\theta}_2 \\ \dot{\delta}_1 + \dot{\delta}_2 \end{pmatrix} \tag{14}$$

$$v_E = \begin{pmatrix} -\dot{x}_1 + \dot{x}_2 \\ -\dot{y}_1 + \dot{y}_2 \\ -\dot{z}_1 + \dot{z}_2 + \frac{L}{2}\sin\phi_1(\dot{\phi}_1 + \dot{\phi}_2) \\ -\dot{\phi}_1 + \dot{\phi}_2 \\ -\dot{\theta}_1 + \dot{\theta}_2 \\ -\dot{\delta}_1 + \dot{\delta}_2 \end{pmatrix}. \tag{15}$$

E. Mode Transition

Passive decomposition-based SMMS bilateral control helps to avoid unstable force at the end effector over some delay. However, in Fig. 6, the simulation result shows the instability caused by dynamic change of reference command in uniform control mode. So, we should separate two different control modes to avoid this problem in real implementation. Normally, coarse or dynamic reference command change is created by a human operator before the stable grasping is assured. In this stage, we can apply the nonpassivity shared control with the reduced necessity of stable grasp. However, once an object is grasped stably, we can then transfer to the passive control mode using the rigid reference grasp force given by a human operator to assure the stability over the delay. For the easier implementation, we chose a manual triggering method by the use of a switch. The reason why we did it is that the sensor-based triggering was not giving enough robustness at this moment. However, we are currently working on HMM-based human intention recognition by several times of trial manipulation parallel on this project. Some of the simulation results can segment several different task modes such as approaching, grasping, lifting, moving, releasing, etc.

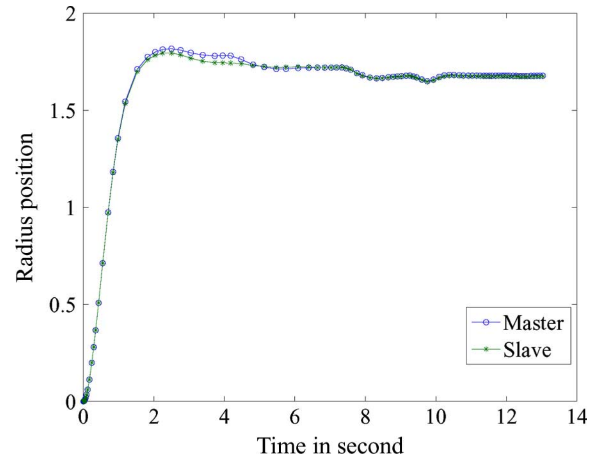


Fig. 6. 1-DOF simulation result of bilateral teleoperation over delayed networks.

V. Simulations and Experiments

A. Time Delay Compensation Simulation

We consider bilateral teleoperation between a single master and multiple slave robots over the communication delay using passive decomposition [11]. The dynamics of multiple slave nanorobots is decomposed into two decoupled systems while enforcing the energetic passivity: shape system describing cooperative grasping aspect and locked system abstracting overall motion of the multiple slave nanorobots. We had made a MATLAB simulation of this powerful method against a constant time delay of 1 s; the simulation result is shown in Fig. 6. It efficiently shows a good tracking system between the position of the master robot and slave robots against the time delay.

The simulation condition is given as follows.

Master and slave robots are assumed to have 2 kg mass and 2 kgm^2 inertia on each. Communication delay (τ) is set as 1 s and a scattering-based method is used to passify the delay. It testifies the validity of the delay compensation controller. So, the center position of multiple slaves is compared with the master reference position.

Fig. 6 depicts 1-DOF simulation result. Before 3 s, controller experiences the highly varying control input from the master

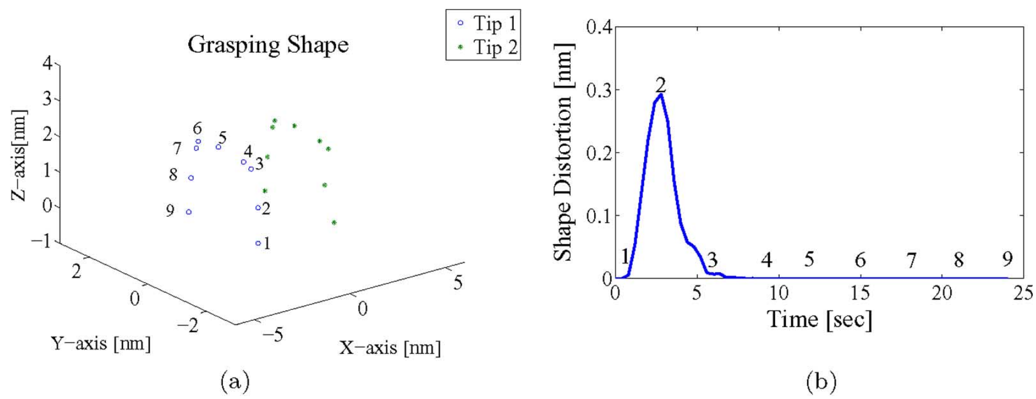


Fig. 7. Grasping shape error $\|q_E\|$ of two probe tips (1 picking a deformable object, 2–3 lifting, 4–6 moving, 7–8 lowering, and 9 releasing tasks: each step time interval is 3 s). (a) 3-D trajectory of probe tips. (b) Grasp shape error.

robot. This causes a slight unstable region around 3 to 4 s, but overall stability is soon recovered and maintained in almost all regions without the highly varying reference commands. This highly varying reference stability is overcome by the real implementation with the real-time force sensing-based local force control to compensate it.

We can verify the proposed controller is valid for the communication delay within the range from 300 ms to 1 s. From this result, it is known that rough force control should go to the stable region as quickly as possible and a small range of force control (stable force region) works well to compensate the delay very delicately.

Fig. 7 shows the cooperative movement of two probe tips. Two slave robots move following the movement of the master's position movement. The task is performed in 24 s. First, the task begins at position number 1 when two manipulators start to grasp the sample object then lift, move, lower, and finally place the sample object at position number 9. Since the grasping shape error is also shown, it can then be seen that the rigidity of the grasping shape is perturbed at the beginning but as time increases the error is suppressed closely to zero. It can also be observed that, as time increases, grasping shape error becomes smaller and steady after position number 4, which shows that the desired grasping shape (rigid grasping shape) is formed. We can see that the desired grasping shape can be maintained regardless of commands from the master robot and the delay. Deformation of the sample during grasping at position number 2, which is an error in grasping shape, can clearly be estimated and displayed CAD grasp sample model. The right probe tip is approximately 0.1 nm slipped from the center of the cell and both probe tips also indent the sample by about 0.1 nm. However, the indentation will not harm the sample because the pressure force applied into the probe tips is controlled by the force limitation according to the probe tip and sample model, which are beyond the scope of this brief. The contact force between sample and probe tip can also be estimated following the sample and probe tip model and displayed, where the magnitude of contact forces of both probe tips are the same but opposite in direction. It can be seen that as grasping shape error goes closely to zero, the contact force also becomes steady. Note that the force that exists after position number 4 is required force to hold the sample and finally becomes zero at position number 9 as the two tips release the sample.

TABLE I
IKURA GRASPING EXPERIMENT: MEAN AND S.D OF RECOGNITION TIME AND INTERNAL FORCE

	Drop	Stable	Excessive
S.D (T_{rec}[s])	0.11	0.09	0.09
Mean (T_{rec}[s])	0.80	0.67	0.37
S.D (F_{int}[mN])	0.21	0.23	0 (Destroyed)
Mean (F_{int}[mN])	0.75	4.48	0 (Destroyed)

B. Human-Induced Delay Compensation

It is very important to let a human operator know about the robot intervention time during human–robot shared internal force control. Thus, we conducted another experiment on Ikura grasping with the force feedback strategy to verify how fast human operators recognize the robot intervention to control. In our pick-and-place experiment, we assume three different modes, which are excessive force region, stable grasping region, and almost drop region. In each different mode, the human operator adaptively changes the τ_h based on real-time sensing information.

Three different cases (excessive, stable, drop) are assumed to be accelerated in a designated time constant (1 s) while the overall task time is set as 4 s. We set our hypothesis of this experimental setting, as more adaptive recognition speed is necessary for very fragile object manipulation such as Ikura or biocells.

Table I shows the results in drop, stable, and excessive grasping force conditions. The human operator informs the time when he or she recognized the robot intervention and the $T_{\rm rec}$ is calculated as the time interval between the actual contact time. Excessive grasp force condition provides quicker recognition time than the almost drop condition, which proves the proposed hypothesis on adaptivity to different operator's skill of operation. If the operator knows in advance about the classified information, then it is easy to operate because a human responds based on his/her real-time observation of the current grasping condition. So, a human can control the

TABLE II
SUCCESS RATE EVALUATION: (A), (B), (C) SUBJECTS

	Proposed	Normal	Chopstick	Tweezer
(A)	3/7	3/9	3/5	3/3
(B)	3/6	3/8	3/3	3/3
(C)	3/7	3/9	3/5	3/4
Total	9/20	9/27	9/13	9/10

reaction speed following the grasping status. Drop, stable, and excessive regions are showing the dynamically varying shape function to generate an intended varying delay. T_{rec} reduces according to increasing speed of grasp force (Drop, Stable: mid; Excessive: high).

Table II shows the summarized success rate for three subjects which are compared with the normal internal force feedback or chopstick manipulation (steel, ideal case) by each subject. The results show that Ikura grasping is a hard task even with chopsticks, so the simple information delivered to a human operator helps to increase his/her human's manipulation capability and dexterity. A human operator is considered to be not sensitive to high frequency internal force feedback, which is continuous, but more sensitive to classified force feedback such as "almost dropping," "stable," "excessive force," etc.

The improved force feedback to the human operator is evaluated here to verify the validity of the proposed force feedback strategy.

Finally, we have found that the proposed force feedback strategy lets a human operator know about the information on a robot's intervention to control. Therefore, this strategy improves human's operability during the human–robot-shared control with the SMMS system environment. Our hypothesis of Ikura grasping experiment is proved by showing the adaptivity to different operator's skill levels.

VI. CONCLUSION

First, a proposed SMMS system is introduced with a shared control framework. To realize the shared control on the SMMS system, a virtual mapping method is adopted to generate multi-slaves' reference tip positions from a single reference input. At the same time, impedance controlled parallel mechanism manipulators are shared with the human operator's control input based on the proposed shared control framework with virtual mapping method to regulate the internal force while grasping an object with safety.

Our target goal is to realize the SMMS teletweezing system over delays affecting operation. We developed the SMMS microtweezer for bio-operation based on a passivity-based SMMS bilateral teleoperation scheme to compensate for the communication delay in a stable force region and novel force feedback strategy, and shared control to converge to the stable region from the excessive or weak force region.

We are currently working to apply the controller to nanoscale manipulation by developing higher resolution Nanoelectromechanical sensors and actuators. In the meantime, a hidden Markov model based on a human's intention recognition algorithm is being simulated to give the virtual fixture based on haptic guidance to an operator. It is expected to give more support to human operators with improved operability and performance in unonstructed micro-, nano manipulation environments.

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