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A Dual-user Teleoperation System with Adaptive Authority Adjustment for Haptic Training

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Abstract. This paper presents a shared control based dual-user teleoperation haptic training system. The main contribution is an Adaptive Authority Adjustment (AAA). The authority is determined online according to the trainee's behavior performance. An evaluation method is introduced based on an adaptive virtual boundary, which results into a time-varying dominance factor. An overruling function is set upstream to solve some specific cases. The system is modeled and controlled in port-Hamiltonian form for passivity preserving. Experiments are conducted for validation.

Key words: Dual-user Teleoperation, Port-Hamiltonian, Adaptive Authority Adjustment (AAA), Shared Control

1 Introduction

Medical robotics have received a great deal of attention for the past decades [18]. As an important part of this field, bilateral teleoperation systems which enable the execution of a remote task by providing haptic feedback, find useful applications such as Minimally Invasive Surgery (MIS) [17] and medical training systems [8]. Indeed, MIS requires skilled and trained staffs as it requires precision, dexterity and reliability for the surgeon who is penalized by a limited observation and operation field (shaking cameras, reduced field of view, visual interruptions, ...). Simulation based training is progressively extending the classical medical hands-on training [1] but for complex training cases, it is useful to work on a simulated with a mentor who can make demonstrations and to bring real-time corrections to the trainee's motions.

Dual-user teleoperation systems have been proposed to fulfill the purpose of supervised haptic training. This kind of system is an extension of the traditional bilateral teleoperation system, which features two users working collaboratively and simultaneously on a shared remote environment. A typical dual-user training system is shown in Fig. 1.

Several architectures have been proposed for the dual-user teleoperation system. The *Shared Control* based structure has been mostly developed in [2, 3, 7, 9]. The main idea of this architecture is to share the control authority of each user over the

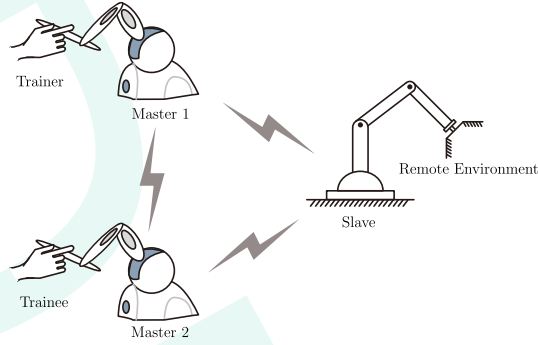


Fig. 1 A Dual-User Training System

slave robot according to a dominance factor ($\alpha \in [0, 1]$). When $\alpha = 1$ (resp. 0), the trainer (resp. trainee) has full authority on the trainee's (resp. trainer's) device and the slave. When $0 < \alpha < 1$, both users share the slave control with a dominance (over the other user) which is function of α . The control authority shared between the users is chosen according to their relative level of skills and experiences.

For the haptic training application, it is important to design a system enabling adaptive authority adjustment. During a given training task, the authority of the trainee over the slave should be adjusted adaptively according to his performances. This allows the trainer to focus on the task without having to manually manage the authority factor when the trainee deviates from the right motion. In any case, the trainer still holds the rights to reset the trainee's authority during the training progress, even when the trainee shows skillfulness.

This kind of system requires for Online Authority Adjustment (OAA) behaviors without disturbing the stability and performance. At the same time, an online motion measure of the trainee's skill level which adapts the control authority should be provided. We found that only a few papers are concerned with this issue. In [13], the control authority is adaptively adjusted according to the trainee's expertise. But it requires to specify a maximum desired level of authority of the trainee over the task at first. As a matter of fact, the trainer cannot alter this desired level during training progress. In [14], the shared control authority is managed using a time-varying dominance factor. However, the proposed method necessitates a bounded first-derivative for the dominance factor $\alpha(t)$. This involves that it should be pre-designed as a derivable function. Both of the two aforementioned methods constrains the cases of emergency when the authority needs to be changed suddenly.

In this paper, our main contribution is to incorporate the Adaptive Authority Adjustment (AAA) into a Shared Control Based Dual-User Teleoperation system. The passivity of the system is ensured by port-Hamiltonian approach. The outline of this paper is as follows: next section introduces the dual-user architecture we based our work on. Part 3 defines the AAA while part 4 shows experimentation results before our conclusions.

2 Shared Control Based Dual-user Teleoperation

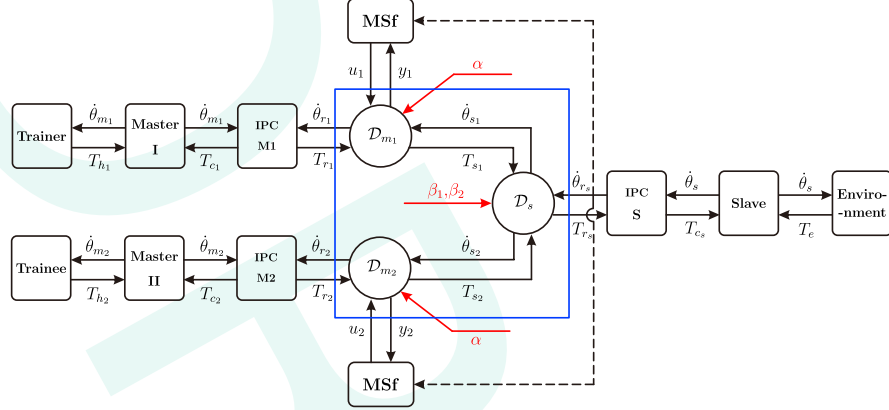


Fig. 2 The global scheme of shared control based dual-user teleoperation system. The structure inside the blue solid line is the shared control based architecture.

In this section, we introduce a shared control based teleoperation, as shown in Fig. 2. The system is modeled within port-Hamiltonian framework.

2.1 Port-Hamiltonian Approach

The port-Hamiltonian framework is an energetic based generalization of the standard Hamiltonian mechanics. The port-Hamiltonian approach allows to keep track of the energy flows in the dynamic behaviors with its energetic structure, which is favorable in the modeling process. From the view of control, one of the advantages of such approach is that the Hamiltonian function, which is usually formed as Lyapunov function explicitly appears in the dynamics of the system [5]. The most common representation of a port-Hamiltonian system is the following:

$$\begin{cases} \dot{x} = [J(x) - R(x)] \frac{\partial H}{\partial x} + g(x)u \\ y = g^T(x) \frac{\partial H}{\partial x} \end{cases} \quad (1)$$

where $x \in \mathbb{R}^n$ is the state and $H(x) : \mathbb{R}^n \rightarrow \mathbb{R}$ represents the Hamiltonian function; $J(x) = -J^T(x)$ is a skew-symmetric matrix representing Dirac structure, $R(x) = R^T(x) \geq 0$ specifies the energy dissipation, $g(x)$ is a matrix representing the way that the power is exchanged through the power ports formed by input-output pair (u, y) between the system and its environment.

Port-Hamiltonian approach has been applied for bilateral system modeling and controlling in [12, 16]. The intrinsically passive controller (IPC) is proposed, which is passive regardless the characteristics and parameters. This provides a natural robustness and leaves freedom to tune its parameters for performance. In our architecture, we reuse the IPC controllers as our local compliance controller.

2.2 Shared Control Based Architecture

In this study, a one degree of freedom (rotation) system is modeled. The main concept of shared control is to introduce a dominance factor. We use *Dirac* structure, which keeps the power balance (see [11]), for authority management. Three Dirac structures are inserted between the IPC controllers, named \mathcal{D}_{m_1} , \mathcal{D}_{m_2} and \mathcal{D}_s . In order to achieve our control goal, three dominance factors $\alpha, \beta_1, \beta_2 \in [0, 1]$ are adopted. As the efforts (forces) and flows (velocities) follow power-conserving interconnection (skew-symmetric representation, see [11]), the behavior of these Dirac structures is passive and lossless. The \mathcal{D}_{m_1} , \mathcal{D}_{m_2} and \mathcal{D}_s in input-output matrix are given by,

$$\begin{aligned} \mathcal{D}_{m_1} : \begin{pmatrix} \dot{\theta}_{r_1} \\ T_{s_1} \\ y_1 \end{pmatrix} &= \begin{pmatrix} 0 & \alpha & 1 - \alpha \\ -\alpha & 0 & 0 \\ \alpha - 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} T_{r_1} \\ \dot{\theta}_{s_1} \\ u_1 \end{pmatrix} \\ \mathcal{D}_{m_2} : \begin{pmatrix} \dot{\theta}_{r_2} \\ T_{s_2} \\ y_2 \end{pmatrix} &= \begin{pmatrix} 0 & 1 - \alpha & \alpha \\ \alpha - 1 & 0 & 0 \\ -\alpha & 0 & 0 \end{pmatrix} \begin{pmatrix} T_{r_2} \\ \dot{\theta}_{s_2} \\ u_2 \end{pmatrix} \\ \mathcal{D}_s : \begin{pmatrix} \dot{\theta}_{s_1} \\ \dot{\theta}_{s_2} \\ T_{rs} \end{pmatrix} &= \begin{pmatrix} 0 & 0 & \beta_1 \\ 0 & 0 & 1 - \beta_2 \\ -\beta_1 & \beta_2 - 1 & 0 \end{pmatrix} \begin{pmatrix} T_{s_1} \\ T_{s_2} \\ \dot{\theta}_{rs} \end{pmatrix} \end{aligned} \quad (2)$$

The relationship between α and β_1, β_2 are defined as,

$$\beta_1 = \begin{cases} \alpha, & \alpha = 1, 0 \\ 1, & 0 < \alpha < 1 \end{cases} \quad \beta_2 = \begin{cases} \alpha, & \alpha = 1, 0 \\ 0, & 0 < \alpha < 1 \end{cases} \quad (3)$$

Thus, we obtain three modes by changing the dominance factor α : training mode ($\alpha = 1$), guidance mode ($0 < \alpha < 1$) and evaluation mode ($\alpha = 0$). Notice that the modulated flow source **MSf** is associated with a velocity signal which is equal to $\dot{\theta}_{rs}$.

2.3 Passivity

As shown in Fig. 2, in order to analyze the close-loop passivity, the dual-user system can be divided into several parts. Both users and the environment could be considered with passive behaviors, which is a common assumption in the literature. The master and the slave robot are physically passive. The IPC controllers are intrinsically passive. The shared control based architecture is passive due to the power-conserving composition of three *Dirac* structures. As long as the modulated flow sources **MSf** keep passive behaviors, the passivity of close-loop dual-user teleoperation system is preserved.

Proposition 1 *The modulated flow sources **MSf** hold passive behaviors: i.e., \exists finite constant $d \in \mathbb{R}$ s.t.*

$$\int_0^t u_1^T y_1 + u_2^T y_2 dt \leq d^2 \quad \forall t \geq 0 \quad (4)$$

i.e., maximum generated energy from the **MSf** is bounded.

Proof. Let us first denote the generated energy at time t from **MSf** by integrating Eq. 2 as,

$$\begin{aligned} \int_0^t u_1^T y_1 + u_2^T y_2 dt &= \int_0^t (1 - \alpha) T_{r_1}^T \dot{\theta}_{r_s} + \alpha T_{r_2}^T \dot{\theta}_{r_s} dt \\ &= \int_0^t -T_{r_1}^T \dot{\theta}_{r_1} - T_{r_2}^T \dot{\theta}_{r_2} + T_{r_s}^T \dot{\theta}_{r_s} dt \end{aligned} \quad (5)$$

Considering the subsystem of masters (or slave) with the corresponding IPC controller, which is passive, there exists a finite constant $c_i \in \mathbb{R}$, s.t.

$$\begin{aligned} \int_0^t T_{h_1}^T \dot{\theta}_{m_1} + T_{r_1}^T \dot{\theta}_{r_1} dt &\geq -c_1^2 \quad \forall t \geq 0 \\ \int_0^t T_{h_2}^T \dot{\theta}_{m_2} + T_{r_2}^T \dot{\theta}_{r_2} dt &\geq -c_2^2 \quad \forall t \geq 0 \\ \int_0^t T_e^T \dot{\theta}_s - T_{r_s}^T \dot{\theta}_{r_s} dt &\geq -c_3^2 \quad \forall t \geq 0 \end{aligned} \quad (6)$$

Suppose that the operators and the environment define passive mappings, i.e., \exists finite constant $k_i \in \mathbb{R}$ s.t.

$$\begin{aligned} \int_0^t -T_{h_1}^T \dot{\theta}_{m_1} dt &\geq -k_1^2 \quad \forall t \geq 0 \\ \int_0^t -T_{h_2}^T \dot{\theta}_{m_2} dt &\geq -k_2^2 \quad \forall t \geq 0 \\ \int_0^t -T_e^T \dot{\theta}_s dt &\geq -k_3^2 \quad \forall t \geq 0 \end{aligned} \quad (7)$$

By combining Eq. 5, 6 and 7, we can straightforward prove the passive behavior of **MSf** in Eq. 4, that is:

$$\int_0^t u_1^T y_1 + u_2^T y_2 \, dt \leq c_1^2 + c_2^2 + c_3^2 + k_1^2 + k_2^2 + k_3^2 = d^2 \quad \forall t \geq 0 \quad (8)$$

Proposition 2 *The closed-loop system is passive regardless variation dominance factors $\alpha \in [0, 1]$.*

Proof. Firstly, we consider the shared control based architecture. The three Dirac structures form a lossless architecture which can be easily concluded. The energy stored inside them is always zero. Then, by denoting the Hamiltonian function of each subsystem at masters and slave sides (in Port-Hamiltonian framework) with H_{m_1}, H_{m_2}, H_s . Considering energy generated by **MSf** as internal stored part, we set the close-loop energy function as,

$$\begin{aligned} \frac{d}{dt} V(t) &= \frac{dH_{m_1}}{dt} + \frac{dH_{m_2}}{dt} + \frac{dH_s}{dt} + u_1^T y_1 + u_2^T y_2 + 0 \\ &= -T_{h_1}^T \dot{\theta}_{m_1} - T_{h_2}^T \dot{\theta}_{m_2} - T_e^T \dot{\theta}_s - P_{m_1} - P_{m_2} - P_s \end{aligned} \quad (9)$$

where P_{m_1}, P_{m_2}, P_s are the dissipated power at each subsystem.

Since the close-loop energy function has no relationship with the dominance factors α, β_1, β_2 , and according to the condition for passivity of a switched system given by [4], we confirm the conclusion of Proposition 2.

3 Adaptive Authority Adjustment

In this section, we introduce the Adaptive Authority Adjustment (AAA), which adapts in real-time the authority according to the behavior performances of the trainer.

3.1 Adaptive Virtual Boundary

The virtual boundary based is the maximum allowed distance between both master positions. It is used to guide the trainee through the right trajectory. The trainee can move his device freely inside the boundary. The virtual boundary is defined as:

$$d_{\theta_m} = (\theta_{m_1} - \theta_{m_2})^2 \leq B \quad (10)$$

where B defines the maximum allowed distance between the trainer and the trainee. We take the form of B specified in [13], as a function of the adaptive dominance factor (see the following section). That is,

$$B = B_0 - k_b \ln(\alpha_a + \epsilon) \quad (11)$$

where B_0 is the maximum allowed distance when the trainer gets full control, i.e. $\alpha_a = 1$. The $\ln(\cdot)$ function enables a non-linear behavior which results in the decreasing of the boundary as the trainee gets qualified (i.e. $\alpha = 0$). k_b is a tuning gain and ϵ is a very small value to avoid the zero argument case for $\ln(\cdot)$, i.e. when $\alpha_a = 0$.

As soon as the condition given in Eq. 10 is violated, a virtual torque will be generated, defined as follows:

$$T_v = -k_v(\theta_{m_1} - \theta_{m_2}) \quad (12)$$

where k_v acts as a virtual stiffness. Notice that in our architecture, this torque won't be transmitted back to the trainee (which is different from [13]), but used as a criterion for evaluation of the expertise of the trainee.

3.2 Adaptive Dominance Factor

The adaptive dominance factor refers to α_a , which determines the shared control authority based on the expertise of the trainee. The worse the trainee performs, the higher virtual torque T_v is generated. Therefore, we make use of T_v as an evaluation index. α_a is defined as follows:

$$\alpha_a = 1 - e^{-\frac{T_v^2}{2 \cdot (T_0)^2}} \quad (13)$$

where T_0 is a task based parameter. It is straightforward to conclude that α ranges from 0 to 1, which represents expertise of the trainee ranges from inexperienced to professional.

It is worth to note that the control authority can be switched to any expected value online by the trainer, denoted by α_o . We call this is the **overrule** function. The final decision of α is:

$$\alpha = \begin{cases} \alpha_a, & \text{overrule} = \text{False} \\ \alpha_o, & \text{overrule} = \text{True} \end{cases} \quad (14)$$

4 Experiment

In order to validate our proposed architecture with Adaptive Authority Adjustment method, we conducted the following experiments. The dual-user teleoperation platform is shown in Fig. 3.

Two Sensable® PHANTOM Omni devices (only their first joints) were employed as the two masters operated by the trainer and the trainee. The devices' kinematic

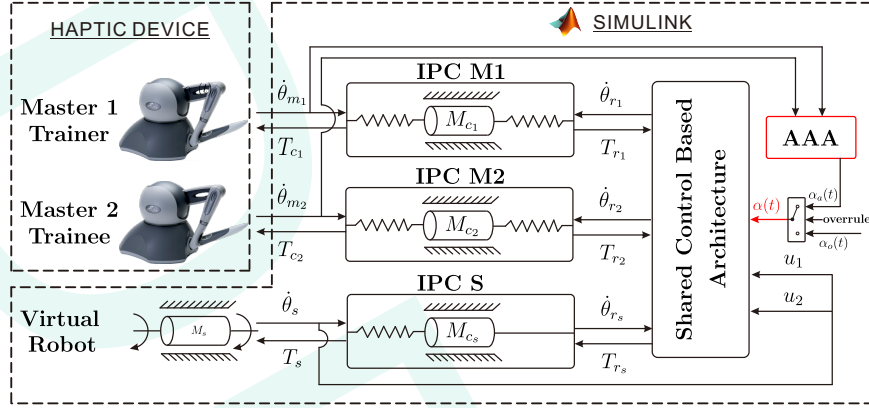


Fig. 3 The experiment setup

and dynamic parameters are available in [10]. The slave system and control software were implemented using Matlab Simulink. A simulated one d.o.f. joint robot (with mass M_s and f_s friction coefficient) was set up for the virtual slave. The master IPC controllers adopt the form proposed in [15]. Note that we applied a different form of IPC controller for the slave, for the purpose of fitting reverse causality interaction with two masters. The explicit equations of the master controllers can be found in [15]. The one of the slave IPC controller can be obtained in the same way. The AAA parameters are selected as:

$$B_0 = 0.05 \text{ rad}, \quad k_b = 0.01, \quad k_v = 10 \text{ N/m}, \quad T_0 = 0.707 \text{ Nm} \quad (15)$$

4.1 AAA Behavior

In the first experiment, we conducted an Adaptive Authority Adjustment. The training goal of this experiment was to move the slave device at target position located at angle 0.3 rad. A virtual obstacle (which may represent a human bone) was set at angle 0.5 rad. The obstacle model was:

$$T_w = \begin{cases} 0, & \theta_s < 0.5 \text{ rad} \\ -k_w(\theta_s - 0.5), & \theta_s \geq 0.5 \text{ rad} \end{cases} \quad (16)$$

where $k_w = 10 \text{ N} \cdot \text{m/rad}$ is the obstacle stiffness and θ_s is the slave robot's joint angle. The hand torques are estimated with a Nicosia observer described in [6]. The tracking of positions and hand/environment torques are shown in Fig. 4. The experiment time is separated into nine phases, i.e. A-I, given as Table 1.

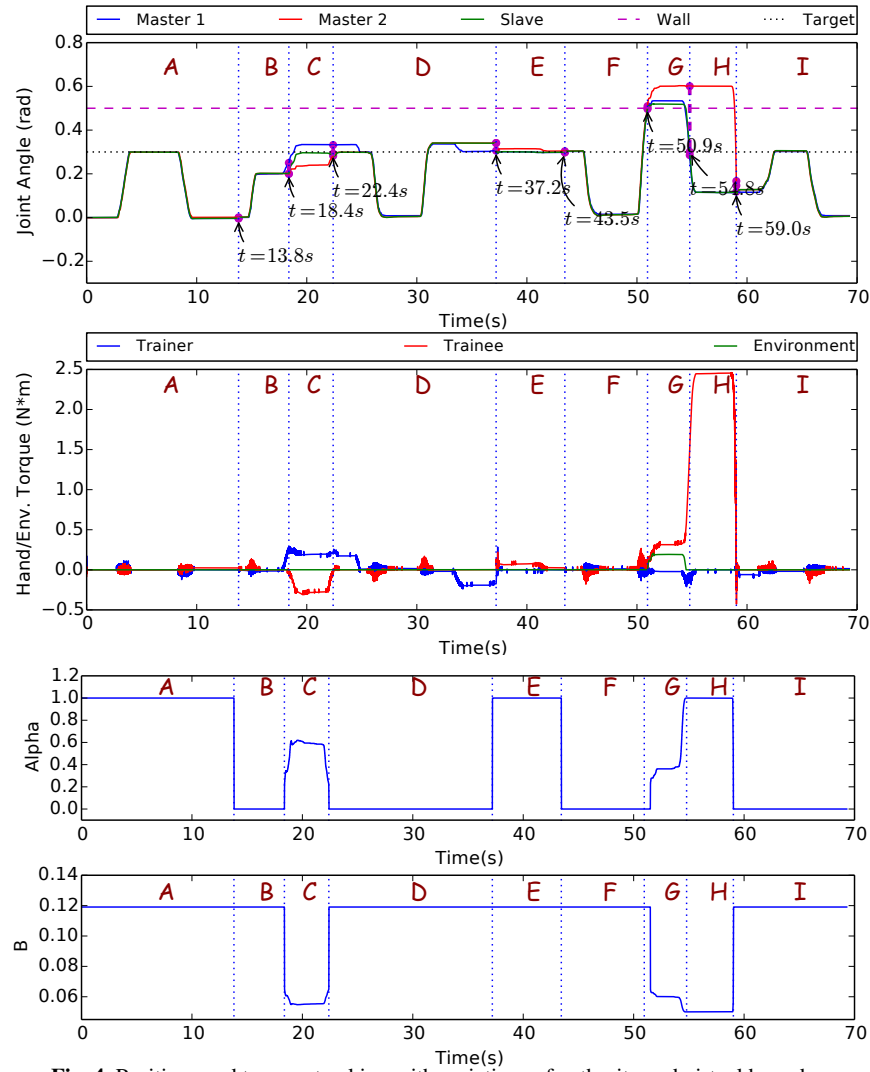
In figure 4, we can check that the phase A corresponds to the training mode. The authority is overruled by the trainer with $\alpha_o = 1$. The trainer guides the trainee

Table 1 The experiment phases

Phase	A	B	C	D	E	F	G	H	I
α	1	0	[0,1]	0	1	0	[0,1]	≈ 1	0
β_1	1	0	1	0	1	0	1	1	0
β_2	1	0	0	0	1	0	0	0	0
α_a	0	0	[0,1]	0	1	0	[0,1]	≈ 1	0
α_o	1	0	0	0	1	0	0	0	0
Mode	T	E	G	E	T	E	G	G	E
Wall Contact	N	N	N	N	N	N	Y	N	N
Override	Y	N	N	N	Y	N	N	N	N

Mode: T=Training, G=Guidance, E=Evaluation

Wall Contact: Y=Yes, N=No Override: Y=Yes, N=No

**Fig. 4** Positions and torques tracking with variations of authority and virtual boundary

and the slave to the target position. The authority is set to the trainee during phase B. But due to unskilled behavior of the trainee, the slave does not reach the target position. Then, the trainer tries to lead the slave to the right position in phase C. The virtual boundary narrows down. There is a variation of authority during this period. The authority of the trainee over the slave reduced to around 0.4 based on the adaptive distance evaluation method, i.e. Eq. 13. Both the trainer and the trainee feel a torque on their hands during this period. In phase D, the full authority is given back to the trainee again. But he leads the slave beyond the target position. The trainer tries to revise the position by moving his device back a little. But it takes no effect since the trainee is still inside the virtual boundary. Under such cases, the overrule behavior could be adopted to set an expected authority. In this experiment, the overrule authority is set to 1 in phase E. The trainer guides the slave to the right position. In phase F, the trainee gets another chance to perform the task, but this time he leads his device to the virtual obstacle. The slave contacts the obstacle at time 50.9s. Afterwards, the trainer pulls the slave to the opposite direction, to get a certain level of authority. He almost gets full control at time 54.8s. The slave mainly follows the trainer. The trainee feels a bigger resistance torque, that informs him the wrong behavior. After releasing his device, he gets full authority again. At last, he leads the slave to the target position and finishes the task in phase I.

4.2 Transparency

It is worth to explore the force details during the wall contact cases. The transparency is an important issue in teleoperation problems, which indicates whether the user feels the environment properly. In our last experiment, both of the trainer and the trainee experienced a weighted torque (due to shared value of α) compared with the one generated by the obstacle (i.e., T_w) in phase G.

In this experiment, all the configurations keep the same as previously. The result is shown in Fig. 5

The experiment is divided into two phases A and B. During the first phase A, the trainee guides the slave to the obstacle, and gets into contact with it at time 3.3s. Then, the trainee continues his motion in depth until 0.6 rad. From the torque tracking, we could conclude the trainee experiences full obstacle feedback torque. But the trainer doesn't feel it. Afterwards, the trainer tries to move his device towards the same position as the trainee. Then, both the trainer and the trainee feel a full reaction torque generated by the environment, which indicates good transparency.

5 Conclusions

In this paper, we designed a shared control based dual-user teleoperation system with Adaptive Authority Adjustment (AAA). The adaptive virtual boundary and

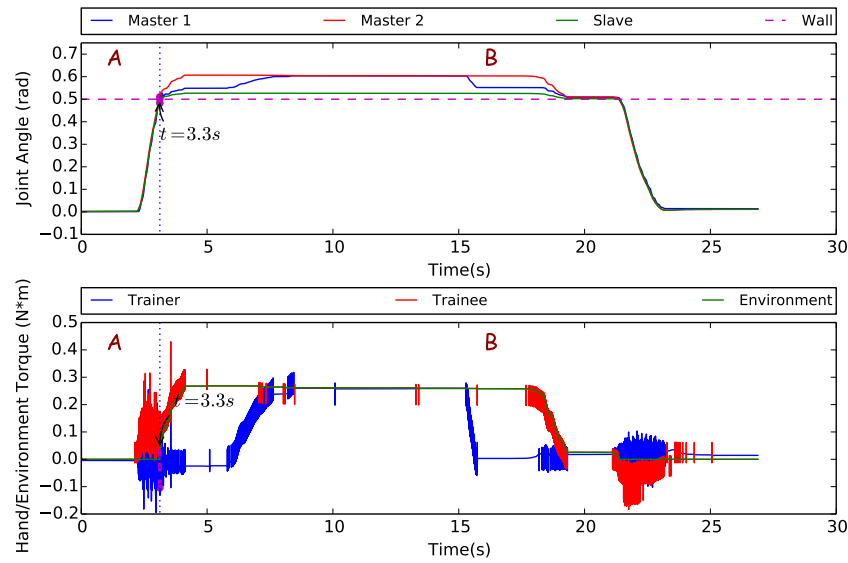


Fig. 5 Positions and torques tracking

adaptive dominance factor are introduced for evaluation of the trainee's behavior performance. The authority is adaptively determined base on this evaluation. An overrule function is brought forward to respond some specific cases. The stability of the system is ensured by an energetic modeling which guarantees the passivity of the system while the authority parameters evolve in time. The experiments revealed a good performance and transparency. Future work will extend the number of degrees of freedom and involve time delays.

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