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Adaptive Robot Control for Human-dominant Interactions using a General Task Function

S. Lyu and C. C. Cheah

Abstract—When humans and a robot manipulator are sharing the same workspace, the robot is required to interact with the humans in addition to performing the standard robot tasks. Due to the different natures of the robot tasks and interaction tasks, different controllers are required when the task is switched from one to another. However, few results have been obtained in integrating the robot task and the interaction task using one general controller. In this paper, a general task function is employed so that different task requirements can be specified by changing certain task parameters instead of the controller. A simple active role allocation is developed such that when the human is outside the robots workspace, the robot performs the desired robot task and when the human enters the workspace, the robot interacts with human in a way or behaviour as specified by the human. The stability of overall system which integrates both the robot task and interaction task is shown by using Lyapunov like analysis. Experimental results are presented to illustrate the performance of proposed controller.

I. INTRODUCTION

Traditional applications of robots were mainly limited to factory automation where the robots were isolated and the environment was structured. Recent advances in sensing and robotics technologies have led to the new scenarios of robots operating in an uncertain environment with existence of human. Due to the lack of cognizance for machines, it is in general difficult for robots to operate in a less structured environment. With the development of artificial intelligence, it seems possible for robots to make some simple decisions by themselves. However, at current stage of research in artificial intelligence, it is still difficult for robots to deal with some complex problems or unexpected events. Besides, the cooperation and combination of human and robot can also dramatically improve the physical abilities of a person to achieve some tasks that are beyond the limits of the human body. All of these highlight the need to introduce human into the workspace or control loop to guide and also work cooperatively with the robots.

In order to combine strengths of both human and robot, human-robot interaction systems were developed and applied in many applications such as exoskeleton that can dramatically improve the physical abilities of a person [1]-[3]. Another rapidly developed application that involves physical contact interaction with human is the rehabilitation robots. To control the interaction between the robotic system and environment, impedance control which was first proposed in

[4], was widely adopted in human-robot interaction, especially in rehabilitative robotic system [5]. A variable impedance control method was used in an active foot ankle orthosis to assess its clinical effects [6]. A two-level controller was developed in [7] to achieve assist-as-needed control during rehabilitation. In [8], an adaptive controller with position dependant stiffness and desired trajectory was presented to resolve the possible conflicts in motions between the patients and robot in a stable manner.

Robotic manipulation has shown to be a key technology in factory automation. Traditionally, robot manipulators have been isolated from human workers for safety reason. The possibility of humans and robots working together in the same workspace would dramatically broaden the potential applications of robot manipulators. However, the sharing of workspace between humans and robots also introduces new research problems that are non-existence in the traditional robotic manipulation tasks such as interaction control and safety issues. In [9], a human-guided co-manipulation control problem was formulated to combine the abilities of human and robot in a stable and complementary way. An adaptive control method was proposed in [10] to update the impedance parameters so as to compensate the unmodelled uncertainty in environment. In [11], a frequency-shaped impedance control was developed based on disturbance observer to achieve shared control between reference tracking and human assistance. To ensure the safety of human in human-robot interaction, variable stiffness actuator (VSA) systems were employed [12]. A variable impedance actuation approach was also developed to control both the reference position and mechanical stiffness of the VSA so as to achieve the optimal performance while ensuring the safety of human during physical interaction [13]. By using the feedback linearization approach, VSA system was used to reduce injury risk while guaranteeing precisely tracking for high-speed tasks [14].

In this paper, we consider the interaction control problem when humans and robots co-exist in the same workspace. When human is outside the robot's workspace, the robot should perform its assigned tasks (robot tasks) but when human enters the workspace, the robot should stop and then react in a way as specified by human (interaction tasks). In this way, human plays a dominant role over the robot during interaction. Generally, when the task is switched from the robot task to interaction task, different controllers are required due to the different task requirements. To solve this problem, a general task function that can be used to define several tasks is employed so that a single controller can be used. By using the general task function, the task can

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be defined or specified according to different requirements through changing the task parameters instead of the controller. A simple active role allocation strategy is developed to resolve the conflicts between the robot task and human-robot interaction task. The stability of overall system which integrates both the robot task and interaction task is shown using Lyapunov-like analysis and experimental results are presented to illustrate the performance of proposed control strategy.

II. ROBOT DYNAMICS AND TASK FUNCTION

In this section, the robot dynamics and kinematics are briefly introduced and a general task function is presented.

A. Robot dynamics and kinematics

The dynamics of a robot manipulator with n degrees of freedom is given as [15]:

$$M(q)\ddot{q} + [\frac{1}{2}\dot{M}(q) + S(q, \dot{q})]\dot{q} + g(q) = \tau \quad (1)$$

where $q \in \mathbb{R}^n$ is the joint vector and $\dot{q}$ is the joint velocity vector; $M(q) \in \mathbb{R}^{n \times n}$ is the manipulator inertia matrix which is symmetric and positive definite; $[\frac{1}{2}\dot{M}(q) + S(q, \dot{q})]\dot{q} \in \mathbb{R}^n$ denotes the centripetal and Coriolis torques, where $S(q, \dot{q}) \in \mathbb{R}^{n \times n}$ is skew-symmetric; $g(q) \in \mathbb{R}^n$ represents the vector of gravitational torques, $\tau \in \mathbb{R}^n$ stands for the vector of control input. Let $x \in \mathbb{R}^p$ denotes the position of end effector in task space. The velocity of the end effector in task space is related to joint space velocity vector $\dot{q}$ as

$$\dot{x} = J(q)\dot{q} \quad (2)$$

where $J(q) \in \mathbb{R}^{p \times n}$ is the Jacobian matrix from joint space to task space.

B. General task function

We define a general task function as [16] :

$$y(z) = \max[0, K(1 - e^{-a_1(z^2 - d_1^2)})(1 - e^{-a_2(z^2 - d_2^2)})] \quad (3)$$

where $z \in \mathbb{R}$ is a feedback task variable, K, a_1, a_2, d_1, d_2 are task parameters. By using this function, a potential function is defined as

$$P = \max[0, K(1 - e^{-a_1(z^2 - d_1^2)})(1 - e^{-a_2(z^2 - d_2^2)})]^N \quad (4)$$

where N is greater than or equal to 3 so that the potential function is at least twice differentiable. The task parameters can be adjusted to define various tasks. The parameters K, a_1 and a_2 determine shape of the potential function and d_1 and d_2 specify the boundaries of the desired task. For example, if these parameters are specified so that $K < 0, a_1 > 0, a_2 < 0, d_1 = d_2 = 0$, then the task function and its corresponding potential function are shown in Fig. 1. This task function can therefore be used for setpoint or trajectory tracking control tasks if the variable z is defined as the error between desired position and actual position. It eventually drives the robot to an equivalent position where $z = 0$. Another example is when the parameters are chosen such that $K < 0, a_1 > 0, a_2 < 0, d_1 > 0, d_2 = \inf$. Then the task function and the

Fig. 1. Example of P when $K < 0, a_1 > 0, a_2 < 0, d_1 = 0, d_2 = 0$. This task function can be used to achieve trajectory tracking control.

Fig. 2. Example of P when $K < 0, a_1 > 0, a_2 < 0, d_1 > 0, d_2 = \inf$. This task function can be used to achieve collision or obstacle avoidance.

corresponding potential function are changed as shown in Fig. 2. This task function can be used for collision or obstacle avoidance between the robot and an object if the variable z is now defined as the distance between them.

By choosing appropriate parameters, this general task function can be used to define various different tasks. Some other possible tasks are shown in Fig. 3. The potential functions in Fig. 3(a),(b) are both unbounded but if the parameters K and a_2 are given as greater than 0, the potential functions can be saturated as specified to illustrate in Fig. 3(c),(d),(e). Since during human-robot interaction enormous position error may pose danger to human, the potential functions employed in this paper are therefore all specified to be bounded.

III. HUMAN DOMINANT INTERACTION

Due to the difference natures of the robot tasks and human-robot interaction tasks and the various possibilities of the robot tasks and interaction tasks as shown in Fig. 3, it is difficult to use a single task variable such as position error to represent all the robot tasks or human-robot interaction tasks. In order to resolve this problem, we introduce two general potential functions as follows:

1) for robot task:

$$P_r(\Delta x_d) = \frac{K_{r1}}{N} (\max(0, y(\Delta x_d)))^N \quad (5)$$

$$y(\Delta x_d) = K_{r2}(1 - e^{-a_{r1}(\|\Delta x_d\|^2 - d_{r1}^2)})(1 - e^{-a_{r2}(\|\Delta x_d\|^2 - d_{r2}^2)}) \quad (6)$$

$$\frac{\partial P_r(\Delta x_d)}{\partial \Delta x_d} = \varepsilon_r \quad (7)$$

where $\varepsilon_r \in \mathbb{R}^n$ is a task variable for the robot task which is nonzero until the desired task is achieved, $\Delta x_d = x(t) - x_d(t)$, $x(t) \in \mathbb{R}^p$ is the position of end effector and $x_d(t) \in \mathbb{R}^p$ is the desired trajectory of robot task.

2) for human-robot interaction task:

$$P_h(\Delta x_h) = \frac{K_{h1}}{N} (\max(0, y(\Delta x_h)))^N \quad (8)$$

Fig. 3. Different shapes of task function with different parameters. (a) For region tracking control. (b) For following control while keeping certain distance between robot and target. (c) For trajectory tracking control and its corresponding potential function is bounded. (d) For region tracking control and its corresponding potential function is bounded. (e) For following control while keeping certain distance between robot and target and its corresponding potential function is bounded.

$$y(\Delta x_h) = K_{h2}(1 - e^{-a_{h1}(\|\Delta x_h\|^2 - d_{h1}^2)})(1 - e^{-a_{h2}(\|\Delta x_h\|^2 - d_{h2}^2)}) \quad (9)$$

$$\frac{\partial P_h(\Delta x_h)}{\partial \Delta x_h} = \varepsilon_h \quad (10)$$

where $\varepsilon_h \in \mathbb{R}^n$ is task variable for human-robot interaction task, $\Delta x_h = x(t) - x_h(t)$, $x(t) \in \mathbb{R}^p$ is the position of end effector and $x_h(t) \in \mathbb{R}^p$ is the position of human.

As mentioned in section II.B, both potential functions P_r and P_h are chosen as bounded (such as the cases in figure 3.(c), (d) and (e)). That is

$$P_r(\Delta x_d) \leq N_r, \quad P_h(\Delta x_h) \leq N_h \quad (11)$$

where N_r and N_h are positive constant value.

Therefore, we define the overall potential function as:

$$P(x) = a_r(t)P_r(\Delta x_d) + a_h(t)[P_h(\Delta x_h) - C] \quad (12)$$

where $P(x)$ is the overall potential function, $a_r(t)$ and $a_h(t)$ are variables to allocate the active role between robot task and human-robot interaction task, C is a constant value.

The overall potential function works in such a way that when human is outside the robot's workspace, the potential function for human-robot interaction task P_h is disabled, that is, $a_h(t) = 0$, robot performs the robot task; when human enters the workspace, P_h is activated, that is, $a_h(t) = 1$, then robot reacts in the way as specified by human. Assume that the position of human can be detected by sensors. Let us suppose that human enters the robot's workspace at $t = t_{ei}$, (i represents the i^{th} time that human enters the workspace), then $a_h(t)$ is defined as:

$$a_h(t) = \begin{cases} 0, & x_{rh} \geq R \\ f_{in}(t, t_{ei}), & x_{rh} < R, t_{ei} \leq t \leq t_{ei} + T \\ 1, & x_{rh} < R, t_{ei} + T < t \end{cases} \quad (13)$$

where x_{rh} denotes the horizontal distance between human and robot base, R denotes the minimum distance to activate the human-robot interaction task and is slightly within the robot's workspace as illustrated in Fig. 6, T represents the transition time where $a_h(t)$ changing from 0 to 1 and $f_{in}(t, t_{ei})$ is a increasing function from 0 to 1 which is detailed in appendix. If human leaves the robot's workspace at $t = t_{li}$, (i represents the i^{th} time that human enters the workspace), then

$$a_h(t) = \begin{cases} 1, & x_{rh} < R \\ f_{out}(t, t_{li}), & x_{rh} \geq R, t_{li} \leq t \leq t_{li} + T \\ 0, & x_{rh} \geq R, t_{li} + T < t \end{cases} \quad (14)$$

where $f_{out}(t, t_{li})$ is a decreasing function from 1 to 0 which is detailed in appendix. Based on this strategy, when human moves into the workspace such that $x_{rh} < R$, $a_h(t)$ increases to 1 and P_h is activated and when human leaves workspace such that $x_{rh} \geq R$, $a_h(t)$ decreases to 0 and P_h is disabled.

To define $a_r(t)$, we first introduce an activation zone and an inactivation zone of human-robot interaction task. The activation zones are defined as the regions where the gradient of interaction task potential function ε_h defined in Eq.(10) is not equal to 0. When the robot is inside the activation zone of interaction task, the robot task is disabled. The inactivation zones defined as the regions where the gradient ε_h is equal to 0. This corresponds to two cases: 1) the interaction task function has not yet been activated to control the robot as the human, though in the workspace, is still maintaining a safe distance from the robot. Therefore, the robot task is still activated to improve efficiency. 2) the interaction task has been completed but robot is still close to human and thus the robot task should be disabled.

In order to differentiate these two cases, a deactivation region $\Omega(x)$ to disable the robot task is defined as follows:

$$\Omega(x) = \{a_h(t)[(\|\Delta x_h\| - d_{hj})^2 - d^2] < 0\}, (j = 1, 2) \quad (15)$$

where d is a positive constant value and denotes the radius of deactivation region. The deactivation region is defined around the boundaries of desired region of interaction task. When the robot stays inside the deactivation region, the robot task is disabled. When human is outside the workspace, then $a_h(t) = 0$, deactivate region does not exist anymore.

For example, if the potential function P_h is defined as in Fig.4(a), then the first inactivation zone accords to the saturated part of the potential function and the second inactivation zone accords to the desired region of potential function in the middle. The deactivation region is thus defined around the desired region of interaction task as shown in Fig.4(b).

Therefore, based on the activation zone, inactivation zone and deactivation region, $a_r(t)$ is defined as follows:

$$a_r(t) = \begin{cases} 1, & \|a_h(t)\varepsilon_h\| = 0 \text{ and } x(t) \notin \Omega(x) \\ f_{out}(t, t_{ai}), & \|a_h(t)\varepsilon_h\| \neq 0 \text{ or } x(t) \in \Omega(x), t_{ai} \leq t \leq t_{ai} + T \\ 0, & \|a_h(t)\varepsilon_h\| \neq 0 \text{ or } x(t) \in \Omega(x), t_{ai} + T < t \end{cases} \quad (16)$$

where t_{di} represents the i^{th} time that robot enters the activation zone of interaction task or the deactivation region.

Therefore, if the potential function P_h is activated and robot is inside the activation zone of interaction task or inside the deactivation region, then the robot task is disabled, that is, $a_r(t) = 0$ as shown in Fig.5. If the potential function P_h is not activated or it is activated but robot is inside the inactivation zone of interaction task while outside the deactivation region, then robot task is activated, that is, $a_r(t) = 1$ as shown in Fig.5.

Next, if at $t = t_{di}$, (i represents the i^{th} time that interaction task is disabled or it is activated but robot enters the inactivation zone of interaction task while moves out the deactivation region), then $a_r(t)$ is defined as:

$$a_r(t) = \begin{cases} 0, & \|a_h(t)\epsilon_h\| \neq 0 \text{ or } x(t) \in \Omega(x) \\ f_{in}(t, t_{di}), & \|a_h(t)\epsilon_h\| = 0 \text{ and } x(t) \notin \Omega(x), t_{di} \leq t \leq t_{di} + T \\ 1, & \|a_h(t)\epsilon_h\| = 0 \text{ and } x(t) \notin \Omega(x), t_{di} + T < t \end{cases}$$

For the overall potential function, there exist three cases:

- 1) case 1: $P(x) = P_r(\Delta x_d)$ which represents the situation that only the robot task is activated.
- 2) case 2: $P(x) = P_h(\Delta x_h) - C$ which represents the situation that only the human-robot interaction task is activated.
- 3) case 3: $P(x) = P_r(\Delta x_d) + P_h(\Delta x_h) - C$, and $\epsilon_h = 0$ which represents the situation that robot is inside the inactivation zone of interaction task.

Based on the definition of $a_h(t)$ and $a_r(t)$, efficient interaction can be achieved. For example, if the human-robot interaction task is defined to maintain a safe distance with human so as to ensure safety of human. When human enters the workspace but still keeps a safe distance with robot as shown in Fig.6, then robot continues to do the robot task. When human approaches and robot is inside the deactivation

region, the robot task is disabled and robot stops. If human gets closer, interaction task is activated and robot moves away and if human stays there, robot stops there and if human moves away, the robot task is activated and robot performs the robot task.

IV. ADAPTIVE CONTROLLER FOR INTEGRATING ROBOT TASKS AND INTERACTION TASKS

First, the desired velocity $\dot{x}_{des}$ is defined as:

$$\dot{x}_{des} = a_r(t)\dot{x}_d + (1 - a_r(t))\dot{x}_h \quad (18)$$

Therefore, when robot is performing the robot task, $a_r(t) = 1$, the desired velocity is given as $\dot{x}_d$ and when robot task is disabled, $a_r(t) = 0$, the desired velocity is equal to $\dot{x}_h$.

Next, a reference joint velocity $\dot{q}_r$ is defined as:

$$\dot{q}_r = J^+(q)\dot{x}_{des} - a_r(t)J^+(q)\epsilon_r - a_h(t)J^+(q)\epsilon_h \quad (19)$$

Then, a sliding vector can be formulated as:

$$s = \dot{q} - \dot{q}_r = \dot{q} - J^+(q)\dot{x}_{des} + J^+(q)[a_r(t)\epsilon_r + a_h(t)\epsilon_h] \quad (20)$$

where $J^+(q)$ is the pseudoinverse of the Jacobian matrix. Based on the sliding vector and the task variables, a controller is proposed as follows:

$$\tau = -k_p J^T(q)[a_r(t)\epsilon_r + a_h(t)\epsilon_h] - K_s s + Y_d(q, \dot{q}, \dot{q}_r, \ddot{q}_r)\hat{\theta}_d \quad (21)$$

where k_p is the proportional gain, K_s is the sliding control gain, $Y_d(q, \dot{q}, \dot{q}_r, \ddot{q}_r)$ is the regressor matrix and $\hat{\theta}_d$ is estimated dynamic parameters.

The regressor matrix in Eq.(21) is defined as [19]:

$$M(q)\ddot{q}_r + [\frac{1}{2}\dot{M}(q) + S(q, \dot{q})]\dot{q}_r + g(q) = Y_d(q, \dot{q}, \dot{q}_r, \ddot{q}_r)\theta \quad (22)$$

and $\hat{\theta}_d$ is updated by using the following updated law:

$$\dot{\hat{\theta}}_d = -L_d Y_d^T(q, \dot{q}, \dot{q}_r, \ddot{q}_r)s \quad (23)$$

where L_d is a symmetric and positive definite matrix.

Using Eq.(20),(21),(22)into Eq.(1) yields the following closed-loop equation:

$$M(q)\dot{s} + [\frac{1}{2}\dot{M}(q) + S(q, \dot{q})]s + K_s s + Y_d(q, \dot{q}, \dot{q}_r, \ddot{q}_r)\Delta\theta_d + k_p J^T(q)[a_r(t)\epsilon_r + a_h(t)\epsilon_h] = 0 \quad (24)$$

where $\Delta\theta_d = \theta_d - \hat{\theta}_d$.

Fig. 4. Illustration of inactivation zone, activation zone and deactivation region.

Fig. 5. Illustration of activation zone of $a_r(t)$

Fig. 6. Illustrative example of keeping a safe distance with human.

To prove the stability of system, a Lyapunov-like function based on the overall potential function obtained in Eq.(12) is proposed as follows:

$$\begin{aligned} V &= \frac{1}{2} s^T M(q) s + P(x) + \frac{1}{2} \Delta \theta_d^T L_d^{-1} \Delta \theta_d \\ &= \frac{1}{2} s^T M(q) s + a_r(t) P_r(\Delta x_d) + a_h(t) [P_h(\Delta x_h) - C] \\ &\quad + \frac{1}{2} \Delta \theta_d^T L_d^{-1} \Delta \theta_d \quad (25) \end{aligned}$$

Differentiating Eq.(25) and using Eq.(22) and (24), yields:

$$\begin{aligned} \dot{V} &= -s^T K_s s + \dot{a}_r(t) P_r(\Delta x_d) + \dot{a}_h(t) (P_h(\Delta x_h) - C) \\ &\quad - k_p [a_r(t) \varepsilon_r + a_h(t) \varepsilon_h]^T [a_r(t) \varepsilon_r + a_h(t) \varepsilon_h] \quad (26) \end{aligned}$$

As mentioned in the end of section III, there exist three cases, which corresponds to three different situations. Then we can prove that when robot task or interaction task is activated, robot is able to move to corresponding desired regions and when the transition phase from one task to another, system can remain stable.

V. EXPERIMENT

The proposed control scheme was implemented on the first two joints of a SCARA robot (Sony SRX-4CH).

A. Collision avoidance

The first experiment was to illustrate the scenario that when a human approached the robot while it was performing a robot task, then the robot moved away to maintain a safe distance with the human but when the human moved away from the robot, robot moved back. The robot task was specified as a region reaching task as shown in Fig3.(d) and the human-robot interaction task was defined as keeping a safe distance with human as shown in Fig.2.

The parameters of potential function for robot task were specified as: $K_{r1} = 9, N = 3, K_{r2} = 2, a_{r1} = 5, a_{r2} = 0.002, d_{r1} = 0 \text{ cm}, d_{r2} = 5 \text{ cm}$ and it was specified as two directions x axis and y axis, that is, $P_r = P_{rx} + P_{ry}$. The parameters of potential function for human-robot interaction task were specified as: $K_{h1} = 9, N = 3, K_{h2} = -12, a_{h1} = 0.168, a_{h2} = -0.168, d_{h1} = 0.5 \text{ m}, d_{h2} = 1000 \text{ m}$. The control parameters in Eq.(22) were set as: $k_p = 10, K_s = \text{diag}\{0.5, 0.5\}$. The desired position x_d of the robot task was specified as a square region in the plane as: $-0.35 \text{ m} < x < -0.45 \text{ m}, 0.15 \text{ m} < y < 0.25 \text{ m}$ and the desired position of human-robot interaction task was specified as the region where $\Delta x_h \geq 0.5 \text{ m}$. The desired velocity $\dot{x}_d$ and $\dot{x}_h$ were both set as 0 and transition region radius was set as $d = 0.2 \text{ m}$.

The experimental process are shown in Fig.7. As seen in Fig.7, when human entered the workspace, robot first remained stationary and when human moved nearer, robot moved away to keep a safe distance and when human moved out the workspace, robot moved back to the desired region of the robot task. Fig.8 shows the position errors are within the desired regional error.

B. Following human's motion

The second experiment aimed to illustrate the situation that when robot was performing the robot task and human entered workspace, robot then followed human's motion and when human moved out, then robot moved back to do the task region. Therefore, the robot task was still specified as the region reaching task and human-robot interaction task was specified as following human's motion with a safe distance kept as shown in Fig.3(e).

The control parameters and the task parameters of potential function for robot task were still the same. The parameters of potential function for human-robot interaction task were specified as: $K_{h1} = 9, N = 3, K_{h2} = 0.6, a_{h1} = 16.8, a_{h2} = 8, d_{h1} = 0.2 \text{ m}, d_{h2} = 0.3 \text{ m}$. The desired position x_d of the robot task was specified as a square region in the plane as: $-0.35 \text{ m} < x < -0.45 \text{ m}, 0.15 \text{ m} < y < 0.25 \text{ m}$ and the desired position of human-robot interaction task was specified as the region where $0.2 \text{ m} \leq \Delta x_h \leq 0.3 \text{ m}$. The desired velocity $\dot{x}_d$ and $\dot{x}_h$ were both set as 0 and transition region radius was set as $d = 0.2 \text{ m}$.

The experimental process are shown in Fig.9. As seen in Fig.9, when human entered the workspace, the robot task was disabled and human-robot interaction task was activated and robot moved toward human. Once human moved and robot started to follow the human's motion. Fig.10 shows that the position errors are within the desired region.

VI. CONCLUSIONS

In this paper, the interaction control problem involving co-existence of human and robot in the same workspace has been formulated and solved. With the employment of general task function, various tasks during the interaction can be achieved with a single controller by changing only its parameters. The active role allocation strategy has been shown that effective interaction can be achieved in a stable manner. Experimental results have been presented to illustrate the performance of proposed controller.

Fig. 7. Path of end effector for the collision-avoidance experiment. (a) $t=2\text{s}$, robot moved towards the desired region. (b) $t=13\text{s}$, human entered the workspace but still kept a safe distance. Robot remained stationary. (c) $t=24\text{s}$, human moved nearer and robot moved away to maintain a safe distance. (d) $t=27\text{s}$, human moved away and robot moved back and finally reached the desired region again.

Fig. 8. Collision avoidance experimental results

Fig. 9. Path of end effector for human-following or leader-following experiment. (a) $t=2s$, robot moved towards the desired region and stopped there. (b) $t=11s$, human entered the workspace. The robot task was disabled and the robot moved towards human. (c) $t=12.5s$, human moved forward and robot followed but maintained the specified distance. (d) $t=13.4s$, human moved backward and robot followed at the specified distance. (e) $t=17s$, human moved out of the workspace and the robot task was activated again. (f) $t=25s$, robot moved back to the robot tasks desired region.

APPENDIX

The increasing function is defined as:

$$f_{in}(t, t_{in}) = \begin{cases} a_1(t - t_{in})^5 + b_1(t - t_{in})^4 + c_1(t - t_{in})^3 + \frac{\ddot{m}}{2}(t - t_{in})^2 + \dot{m}(t - t_{in}) + m, & t_{in} \leq t \leq t_{in} + T \\ 1, & t_{in} + T < t \end{cases} \quad (27)$$

where $c_1 = -\frac{3\ddot{m}T^2 + 12\dot{m}T + 20(m-1)}{2T^3}$, $b_1 = -\frac{4\ddot{m} + 3\dot{m}T + 6c_1T^2}{4T^3}$, $a_1 = -\frac{\ddot{m} + 6c_1T + 12b_1T^2}{20T^3}$, T is the transition time and $m, \dot{m}, \ddot{m}$ are preset based on the value at $t = t_{in}$. Similarly, the decreasing function is defined as:

$$f_{out}(t, t_{out}) = \begin{cases} a_2(t - t_{out})^5 + b_2(t - t_{out})^4 + c_2(t - t_{out})^3 + \frac{\ddot{n}}{2}(t - t_{out})^2 + \dot{n}(t - t_{out}) + n, & t_{out} \leq t \leq t_{out} + T \\ 0, & t_{out} + T < t \end{cases} \quad (28)$$

where $c_2 = -\frac{3\ddot{n}T^2 + 12\dot{n}T + 20n}{2T^3}$, $b_2 = -\frac{4\ddot{n} + 3\dot{n}T + 6c_2T^2}{4T^3}$, $a_2 = -\frac{\ddot{n} + 6c_2T + 12b_2T^2}{20T^3}$ and $n, \dot{n}, \ddot{n}$ are preset based on the value at $t = t_{out}$.

Fig. 10. Following human's motion experimental results

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