Robust Adaptive Synchronisation of a Single-Master Multi-Slave Teleoperation System over Delayed Communication

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***Abstract*— Considering communication delays in networked multi-robot teleoperation systems, this paper proposes a new control strategy for synchronisation and stability purposes. A single-master and multi-slave (SMMS) networked robotic teleoperation system is considered. Based on a sliding surface combined with a smooth filtering and estimation methodology, a robust adaptive control is developed to guarantee the synchronisation and stability of the system in the presence of network-induced time-varying delays. Extensive simulation studies demonstrate the effectiveness of the developed control scheme.**

Keywords: Sliding mode, adaptive control, networked systems, teleoperation, time-varying delay.

I. INTRODUCTION

Providing the human beings with the ability to simultaneously command several tasks in separate locations, networked systems became one of the major achievements in automation science and engineering. Among the variety of utilisations, robotic teleoperation systems have relatively more interesting applications, like space-exploration and medical operations [1], [2].

A teleoperation system, generally consists of two main subsystems, including the master and the slave systems. From a scientific and technical perspective, there are a number of difficulties in control design for teleoperation systems; position-force synchronisation in dissimilar-slaves applications, maintaining stability of the system under communication disturbances, and performance deterioration due to uncertainties in the remote environment, for instance. Moreover, in cooperative applications utilising two or more robots in either sides of a teleoperation system, the analysis and design of a practical control methodology is more complicated. In the literature, several control solutions have been proposed for various types of cooperative multi-robot teleoperation systems [3]–[5], including predictive simulator [6], Petri-net techniques [7], central control methodology [8], adaptive nonlinear controls [9], [10], and discretisation methods [11]. However, there are some challenges, such as collision and kinematic uncertainties between the slave robots, that still needs more attention. Especially, when the communication network between different master and slave sites is faulty and introduces time-varying delays to the system.

Amongst the investigated control methods, those based on tool motion are interesting, but not applicable enough due to missing internal forces. The other appealing control technique is based on the leader-follower topology, in which one of the systems is chosen as a leader and communicates with the master system. Meanwhile, the other systems in slave site will follow the commands received from the leader system. This strategy is proper in terms of internal forces, however, causes off-balance control mechanism between the slave systems and thence, failure in tool positioning. Furthermore, researchers have dealt with the collaboration issues in multi-master teleoperation systems, but no uncertainty has been considered [12], [13]. A control strategy proposed in [14] for SMMS teleoperation systems does not cope with neither network uncertainties, nor kinematic constraints in the remote workspace. One of the major kinematic constraints that should be a mindset in control design for multi-slave systems, is to avoid possible collisions, either between the slave systems or the tools and environmental objects. This concern has been taken into account in [15]–[18], however, they did not consider time-delays and internal forces. Internal forces are dynamic constraints in multi-slave systems and do not affect the total motion in the remote environment. The predictive control method in [19], [20] to meet these dynamic constraints requires the human operator to have a vision from the remote environment, and the accurate information about the robots, environment, and the operator, which are difficult, and in some cases impossible to acquire. The control approach in [21] pairs every slave robot with a specified task. Dealing with time-varying delays and actuators uncertainties, the neural adaptive control developed in [22] assumes that the slave robots moving in a singularity-free regime, and a detachable configuration between the slave end-effectors and the remote object, which reduces the manipulability of the slave robots.

In this paper, first we describe the dynamic model of the studied SMMS teleoperation system in a general form. The slave robots are considered identical and are expressed in a uniform equation. Then, regarding the aforementioned challenges in the system, we develop a control strategy based on an adaptive algorithm to tackle the synchronisation and stability issues of the system in the presence of communication uncertainties and latencies. Finally, we examined

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the proposed controller by extensive simulations executed on precise model of an industrial robotic manipulator UR10.

The rest of this paper is organised as follows. Section II provides a full description of the SMMS teleoperation system in terms of dynamic models and properties. Introducing the developed adaptive control strategy for the considered teleoperation system, Section III presents the main result of this study. Simulation results are illustrated in Section IV, followed by conclusion remarks in Section V.

II. SMMS Teleoperation System Descriptions

In this section, we explain the dynamic model of the SMMS robotic teleoperation system in two separate parts: master subsystem and slave subsystem. The slave subsystem itself includes a number of robotic systems cooperating in a remote workspace.

A. Master Subsystem

Dynamics of the m-DOF master device handled by a human operator is expressed as [23], [24]:

$$M_m(q_m)\ddot{q}_m + C_m(q_m,\dot{q}_m)\dot{q}_m + g_m(q_m) = \tau_m - J_m^T f_h \tag{1}$$

where, $q_m \in \mathbb{R}^m$ is the mater's joint variables, $M_m \in \mathbb{R}^{m\times m}$ is the symmetric positive-definite inertia matrix, $C_m(q_m,\dot{q}_m) \in \mathbb{R}^{m\times m}$ is the Centripetal and Coriolis matrix, and $g_m(q_m) \in \mathbb{R}^m$ is the gradient of potential energy of the master device. $\tau_m \in \mathbb{R}^m$ is the controlled torque input, and $f_h \in \mathbb{R}^6$ is the Cartesian force imposed by the human operator, which is translated into joint-space by the master Jacobian matrix $J_m \in \mathbb{R}^{6\times m}$. Furthermore, the kinematics of the master device is presented by

$$\begin{aligned} x_m &= P_m(q_m) \\ \dot{x}_m &= \frac{\partial P_m}{\partial q_m}\dot{q}_m = J_m\dot{q}_m \\ \ddot{x}_m &= J_m\ddot{q}_m + \dot{J}_m\dot{q}_m \end{aligned} \tag{2}$$

and $P_m(q_m)$ is the forward kinematics of the master. Having said that, the inverse kinematics of the master is not always straightforward, and would be derived by pseudo-inverse of the Jacobian matrix J_m:

$$\begin{aligned} \dot{q}_m &= (J_m^T J_m)^{-1} J_m^T \dot{x}_m = J_m^\dagger \dot{x}_m \\ \ddot{q}_m &= J_m^\dagger(\ddot{x}_m - \dot{J}_m\dot{q}_m) \end{aligned} \tag{3}$$

Hence, the master dynamic equations in Cartesian space could be expressed as

$$\mathrm{M}_m\ddot{x}_m + \mathrm{C}_m\dot{x}_m + \mathrm{g}_m = u_m - f_h \tag{4}$$

in which,

$$\begin{aligned} \mathrm{M}_m &= J_m^{\dagger T} M_m J_m^\dagger \\ \mathrm{C}_m &= J_m^{\dagger T}(C - M_m J_m^\dagger \dot{J})J_m^\dagger \\ \mathrm{g}_m &= J_m^{\dagger T} g_m \\ u_m &= J_m^{\dagger T}\tau_m \end{aligned} \tag{5}$$

B. Slave Subsystem

A similar approach and definitions (1) to (5) apply for K slave systems with the subscripts $si,\ i \in \{1,2,\ldots,K\}$ for the ith slave system, i.e.

$$\begin{aligned} &\mathrm{M}_{s1}\ddot{x}_{s1} + \mathrm{C}_{s1}\dot{x}_{s1} + \mathrm{g}_{s1} = u_{s1} - f_{e1} \\ &\mathrm{M}_{s2}\ddot{x}_{s2} + \mathrm{C}_{s2}\dot{x}_{s2} + \mathrm{g}_{s2} = u_{s2} - f_{e2} \\ &\vdots \\ &\mathrm{M}_{sK}\ddot{x}_{sK} + \mathrm{C}_{sK}\dot{x}_{sK} + \mathrm{g}_{sK} = u_{sK} - f_{eK} \end{aligned} \tag{6}$$

while $f_{ei},\ i \in \{1,2,\ldots,K\}$ is the environmental force sensed on end-effector of the ith slave system.

We express the slave subsystems in one equation by:

$$\mathrm{M}_S\ddot{x}_S + \mathrm{C}_S\dot{x}_S + \mathrm{g}_S = u_S - f_{ES} \tag{7}$$

in which,

$$\begin{aligned} \mathrm{x}_S &= [\mathrm{x}_{s1}^T, \mathrm{x}_{s2}^T, \ldots, \mathrm{x}_{sK}^T]^T \\ \mathrm{M}_S &= \mathrm{diag}[\mathrm{M}_{s1}, \mathrm{M}_{s2}, \ldots, \mathrm{M}_{sK}] \\ \mathrm{C}_S &= \mathrm{diag}[\mathrm{C}_{s1}, \mathrm{C}_{s2}, \ldots, \mathrm{C}_{sK}] \\ \mathrm{g}_S &= [\mathrm{g}_{s1}^T, \mathrm{g}_{s2}^T, \ldots, \mathrm{g}_{sK}^T]^T \\ \mathrm{u}_S &= [\mathrm{u}_{s1}^T, \mathrm{u}_{s2}^T, \ldots, \mathrm{u}_{sK}^T]^T \\ \mathrm{f}_{ES} &= [\mathrm{f}_{e1}^T, \mathrm{f}_{e2}^T, \ldots, \mathrm{f}_{eK}^T]^T \end{aligned} \tag{8}$$

C. Remote Workspace

We also consider a dynamical model of the remote workspace in which the slave robots cooperating. Regarding the tool(s) and contacts that slave systems interact with, this model is in a similar form to (1), but in the Cartesian space:

$$M_e(x_e)\ddot{x}_e + C_e(x_e,\dot{x}_e)\dot{x}_e + g_m(x_e) = f_e + f_{ES} \tag{9}$$

where the subscript e is for the remote object that the slave robots commonly cooperating on. x_e is the motion in the remote Cartesian workspace, and f_e is the force profile from the environment. For synchronisation purpose, a Jacobian relation exists between every slave robot and the cooperative object:

$$\dot{x}_e = J_{ei}\dot{x}_{si}, \quad i = 1,2,\ldots,K \tag{10}$$

This Jacobian expression results in a kinematic constraint (chain) in the remote workspace defined as follow:

$$\begin{aligned} &\alpha_{s1}x_{s1} + \alpha_{s2}x_{s2} + \cdots + \alpha_{sK}x_{sK} + \alpha_e x_e = 0 \\ &\beta_{s1}\dot{x}_{s1} + \beta_{s2}\dot{x}_{s2} + \cdots + \beta_{sK}\dot{x}_{sK} + \beta_e\dot{x}_e = 0 \\ &\gamma_{s1}\ddot{x}_{s1} + \gamma_{s2}\ddot{x}_{s2} + \cdots + \gamma_{sK}\ddot{x}_{sK} + \gamma_e\ddot{x}_e = 0 \end{aligned} \tag{11}$$

in which, all the coefficients $\alpha_{\{si,e\}}$, $\beta_{\{si,e\}}$ and $\gamma_{\{si,e\}}$ are non-zero constants. In other words, these kinematic constraint implies that the position, velocity and acceleration of the slave end-effectors and the cooperative object should satisfy the linear dependencies (11).

Furthermore, from the equation (9) and the Jacobian relation (10) it is realised that the total force from the remote task space f_e is in a redundant relation with the slaves' end-effector forces f_{ES}, i.e.

$$f_{ES} = J_{ei}^\dagger f_e + (I - J_{ei}^\dagger J_{ei})\varepsilon \tag{12}$$

that presents the internal forces of the slave systems ε, which do not affect the desired motion in the remote task environment. These forces are utilised to control extra features of the cooperative task, such as tension, torsion, etc. To achieve this goal, the leader follower strategy is applied so that the follower systems produce the same force as that the leader receives from the master operator. Like [25]:

$$\varepsilon = [-\frac{1}{K-1}I_{s1}, -\frac{1}{K-1}I_{s2}, \ldots, -\frac{1}{K-1}I_{sK}]^T f_{leader} \quad (13)$$

in which, I_{si} is the identity matrix with the proper dimension, and f_{leader} is the end-effector force of the leader slave system.

D. Communication network

Motion of the master device is the desired trajectory for the slave systems, while the contact force sensed at the slaves' end-effector should be felt by the human operator, simultaneously. The position and force information is transferred between the master site and the remote workspace through an Internet-based communication network. Consequently, latency and interruptions are unavoidable, which negatively affect the stability and performance of the system. The delayed signals are defined as:

$$\begin{aligned} x_S^* &= x_m(t - d_f(t)) \\ f_h^* &= f_e(t - d_b(t)) \end{aligned} \quad (14)$$

where $d_f(t)$ and $d_b(t)$ are the time-varying delays through the forward and backward communication channels, respectively. Without loss of generality, these delay functions are assumed to satisfy the features bellow:

1) $\lim_{t \to +\infty} \left(t - d_{\{f,b\}}(t)\right) = +\infty$,
2) differentiable with respect to time and $|\dot{d}_{\{f,b\}}(t)| \leq 1$ for all $t > 0$.

Shown in Figure 1, the time-varying delay between the master and slave sites has been implemented according to an experimentally measured network delay.

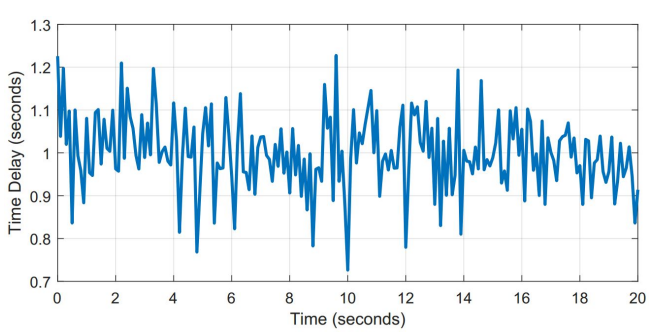

Fig. 1. The delay profile implemented in the simulation study, between each slave robot and the master system.

III. Adaptive Control for SMMS Teleoperation Systems

This section details the developed adaptive control algorithm for the prescribed SMMS teleoperation system. The structure of the control methodology is based on the hybrid adaptive sliding approach proposed in [26]. Combining with the estimation filter proposed in [27], we have developed an adaptive control strategy to deal with the time-delay consequences moreover than unstructured uncertainties degrading the teleoperation system stability and performance. To this end, we have profited the linear parametrisability of the equations (1) and (9) [28], i.e.

$$M_i\ddot{x}_i + C_i\dot{x}_i + g_i = \Psi_i(\ddot{x}_i, \dot{x}_i, \dot{q}_i, q_i)\Theta_i \ , \ i \in \{m, S\} \quad (15)$$

where Ψ_i is the parameters regressor, and Θ_i is the corresponding parameters vector.

A. Delay Compensation

To face the problem of delayed signals, we apply the smoothing filters (15) and (16) on both sides of the teleoperation system:

- on the master side:

$$\begin{aligned} \dot{\mathfrak{s}}_{m1} &= \mathfrak{s}_{m2} + m_m n_{m1}(f_h^* - \mathfrak{s}_{m1}) \\ \dot{\mathfrak{s}}_{m2} &= m_m^2 n_{m2}(f_h^* - \mathfrak{s}_{m1}) \end{aligned} \quad (16)$$

- on the slave side:

$$\begin{aligned} \dot{\mathfrak{s}}_{S1} &= \mathfrak{s}_{S2} + m_S n_{S1}(x_S^* - \mathfrak{s}_{S1}) \\ \dot{\mathfrak{s}}_{S2} &= m_S^2 n_{S2}(x_S^* - \mathfrak{s}_{S1}) \end{aligned} \quad (17)$$

in which, $m_{\{m,S\}}$ are positive constants, and $n_{\{i1,i2\}}$, $i \in \{m, S\}$ are positive coefficients so that making the polynomial $s^2 + n_{i1}s + n_{i2}$ Hurwitz.

B. Robust Adaptive Control Scheme

The procedure is identical for either sides of the teleoperation system. Hence, we only present the slave control development because of space reasons.

Theorem: Regarding the equations (17), the sliding mode variable and the sliding surface given below:

$$\begin{aligned} \tilde{x}_S &= x_S - \mathfrak{s}_{S1} \\ \dot{\tilde{x}}_S &= \dot{x}_S - \mathfrak{s}_{S2} \\ S &= \dot{\tilde{x}}_S + P_S\tilde{x}_S \end{aligned} \quad (18)$$

the controller

$$\begin{aligned} u_S = M_S &\left(m_s^2 n_{S2}(x_S^* - \mathfrak{s}_{S1}) + Q_S(\dot{\mathfrak{s}}_{S1} - \dot{x}_S)\right) \\ &+ C_S\left(\mathfrak{s}_{S2} + Q_S(\mathfrak{s}_{S1} - x_S)\right) + g_S \\ &- P_S\left(\dot{x}_S - \mathfrak{s}_{S2} + Q_S(\mathfrak{s}_{S1} - x_S)\right) \\ &- K_S S - H_S \mathrm{sat}(S) + \Psi_S\hat{\Theta}_S + \hat{f}_{ES} \end{aligned} \quad (19)$$

with the symmetric positive-definite constant matrices P_S, Q_S, K_S, and H_S, and the saturation function sat(.), guarantees the convergence and stability of the SMMS teleoperation system (1)-(7).

Proof: Considering (15) and (18), and applying the controller (19) results in:

$$M_S\dot{S} + C_S S + (Q_S + K_S)S + H_S\mathrm{sat}(S) = \Psi_S\tilde{\Theta}_S - \tilde{f}_{ES} \quad (20)$$

where ˜ indicates the parameter estimation error. Now by defining the Lyapunov function

$$V_S = \frac{1}{2}\left(S^T M_S S + \tilde{\Theta}_S^T \Gamma_S \tilde{\Theta}_S + \tilde{f}_{ES}^T \Lambda_S \tilde{f}_{ES}\right) \tag{21}$$

with symmetric positive-definite and constant matrices Γ_S and Λ_S, and then differentiating along time by applying the skew-symmetry property of $\dot{M}_S - 2C_S$ [28],

$$\begin{aligned} \dot{V}_S = & -S^T(Q_S + K_S)S - S^T H_S \mathrm{sat}(S) \\ & + (S^T \Psi_S + \dot{\tilde{\Theta}}_S^T \Gamma_S)\tilde{\Theta}_S \\ & - (S^T - \dot{\tilde{f}}_{ES}^T \Lambda_S)\tilde{f}_{ES} \end{aligned} \tag{22}$$

it is concluded that the first term in (22) is negative-definite, the second term is always negative, and the third and fourth terms determine the adaptation laws:

$$\begin{aligned} \dot{\hat{\Theta}}_S &= -\Gamma_S^{-1}\Psi_S S \\ \dot{\hat{f}}_{ES} &= \Lambda_S^{-1} S \end{aligned} \tag{23}$$

Having said that, $\dot{V}_S$ is negative semi-definite implying all the system states and errors are stable and bounded. To examine the asymptotic convergence of the errors we shall apply the Barbalat Lemma [28]. As it comes from (20) to (23), V_S is lower-bounded, and $\dot{V}_S$ is uniformly continuous, thence

$$\lim_{t \to +\infty} \dot{V}_S = 0$$

and the proof is accomplished. ■

IV. Simulation Study

This section evaluates the performance of the developed adaptive controller for SMMS teleoperation systems. We carried out an extensive simulation on a single-master double-slave teleoperation system, consisting of one haptic model for the master, and two UR10 robotic manipulators modelled in SimMechanics and MATLAB SIMULINK for the slave systems. Shown in the figure 2, the considered slave workspace in the simulation environment consists of an object to be identically welded on both sides. In other words, the slave robots have to track the same circular trajectory on either sides of the object. The desired path is commanded by a human operator on the master site, which has been artificially simulated. For the UR10 manipulator models we used the manufacturer's simulation software and documentations to achieve more accuracy in our simulations.

The simulation includes two parts; set-point positioning and task motion. First, we move the robots from their initial configuration to a set-point close to the object location. In this position, the slave robots come to a proper coordination to start the desired task on the object. In fact, the human operator keeps the master handle in a position until the slave robots reach that position in the task workspace. Then, the desired task, circular welding in this simulation example, begins. Notably, the desired set-point position for this example is depicted in the figure 2.

Figures 3 to 7 illustrate the Cartesian position, joints' angle, and input control torque of the slave robots for the first part of the simulation.

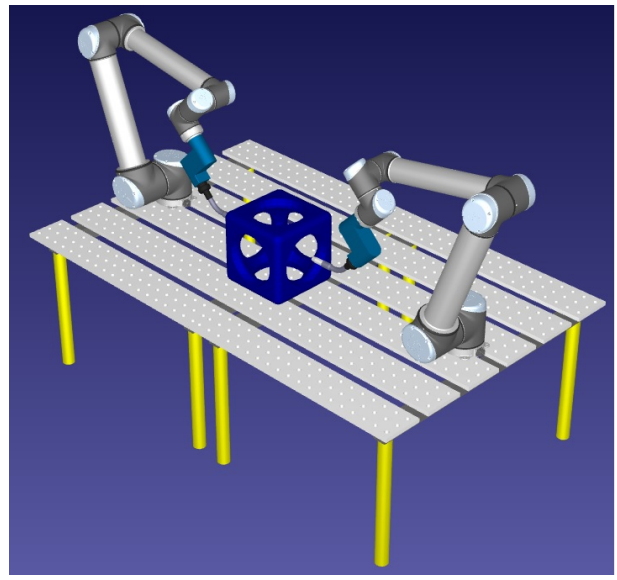

Fig. 2. Simulation model of the two UR10 robots cooperatively welding through a circular trajectory on an object.

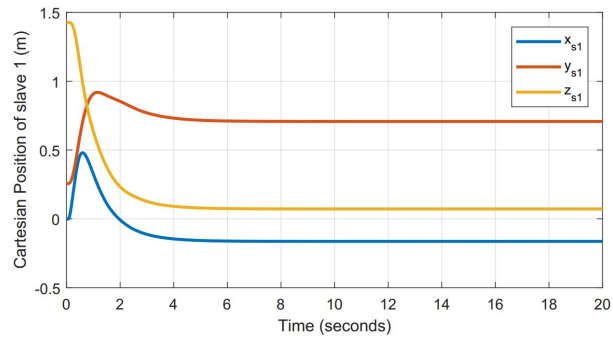

Fig. 3. Cartesian position of the slave 1 in set-point simulation.

In the second part of the simulation, the human operator starts to command the circular trajectory for welding task on both sides of the object. Figures 8 to 14 present the position and force information corresponding to the circular welding task in second part of the simulation.

Moreover, the controller gains K_i, Q_i, P_i, H_i, and Γ_i have been selected by trial and errors. Therefore, more practical gains could be obtained by more accurate tunings.

V. Conclusions

In this paper, we studied an SMMS teleoperation system, and developed an adaptive control strategy to cope with the stability and synchronisation problem under time-varying delays induced by communication networks. Based on a sliding surface combined with a smooth filtering methodology, a robust adaptive control algorithm is developed to guarantee the performance and stability of the SMMS teleoperation systems in the presence of network latencies. The leader-follower technique is applied for the slave robots, and simulation studies demonstrated the effectiveness of the developed control scheme.

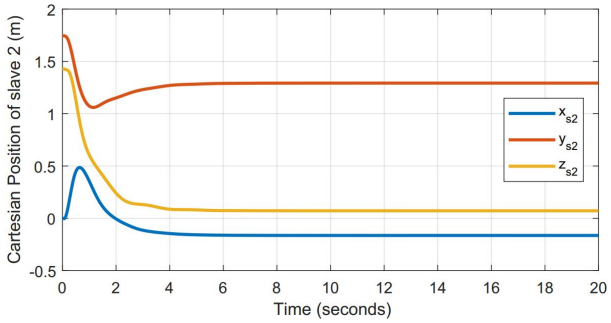

Fig. 4. Cartesian position of the slave 2 in set-point simulation.

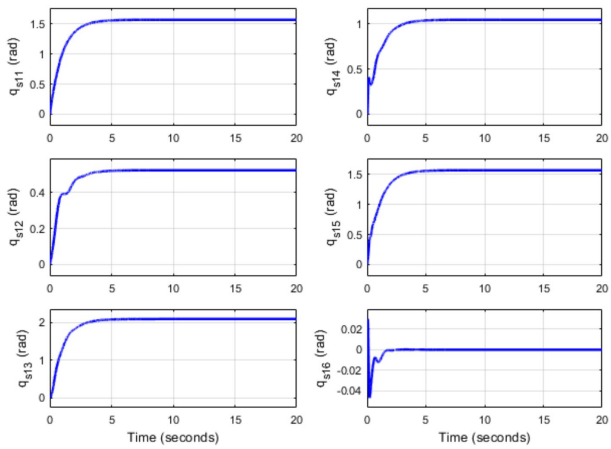

Fig. 5. Joints' angle of the slave 1 in set-point simulation.

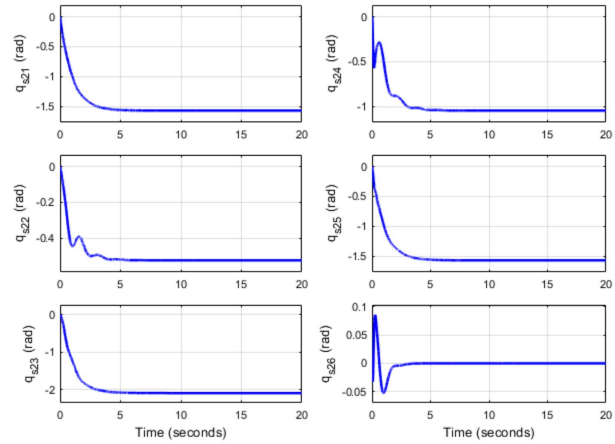

Fig. 6. Joints' angle of the slave 2 in set-point simulation.

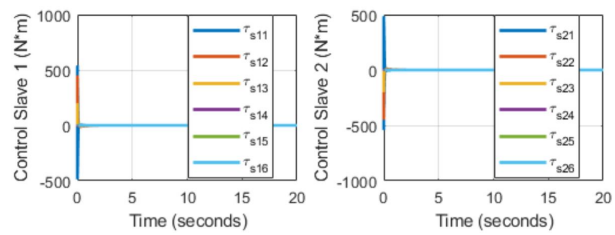

Fig. 7. Control input torques of the slaves 1 and 2 in set-point simulation.

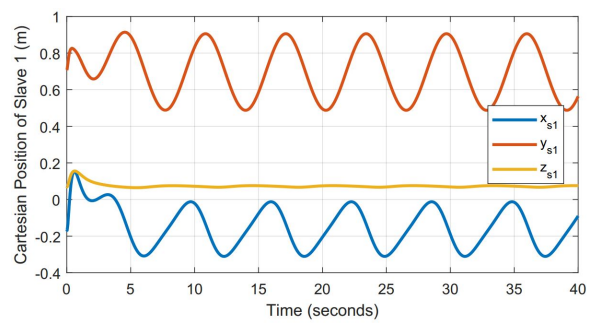

Fig. 8. Cartesian position of the slave 1 in circular welding simulation.

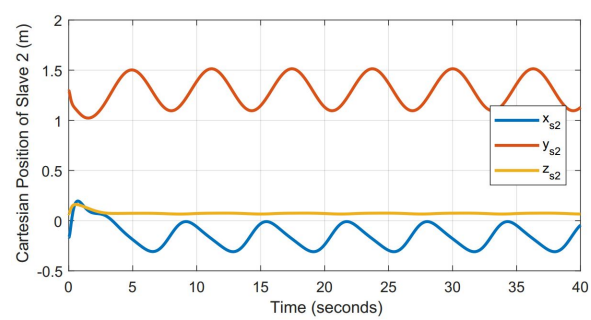

Fig. 9. Cartesian position of the slave 2 in circular welding simulation.

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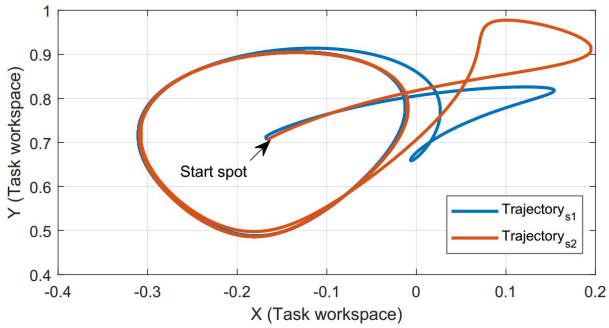

Fig. 10. Cartesian trajectory of both robots in circular welding simulation.

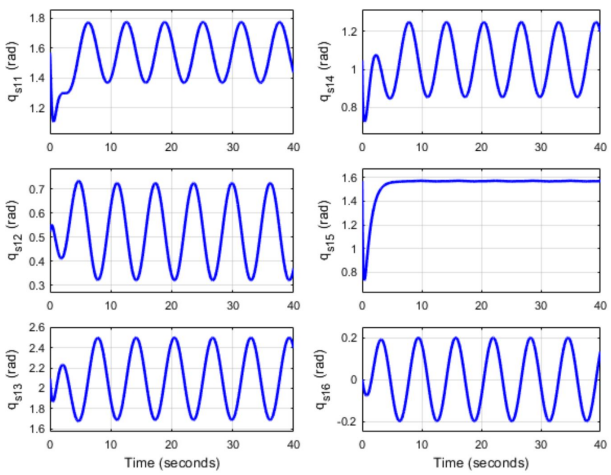

Fig. 11. Joints' angle of the slave 1 in circular welding simulation.

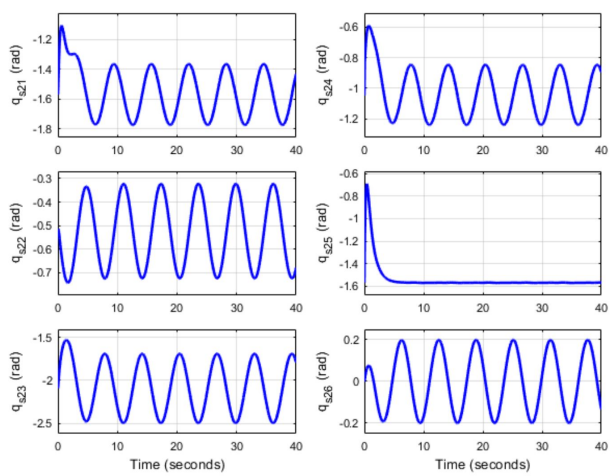

Fig. 12. Joints' angle of the slave 2 in circular welding simulation.

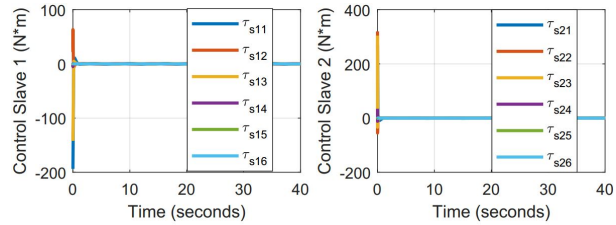

Fig. 13. Control input torques of the slaves 1 and 2 in circular welding simulation.

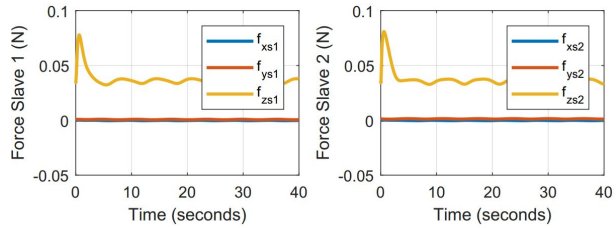

Fig. 14. Contact force of the slaves 1 and 2 in circular welding simulation.

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