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PASSIVE SLIDING-MODE SYNCHRONIZATION OF MULTI-ROBOTIC SYSTEMS WITH STRUCTURAL UNCERTAINTIES AND EXTERNAL DISTURBANCES

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Abstract: *In this paper a class of sliding-mode based controllers for passive synchronization of a multi-robotic system is proposed. The considered system is composed of a master robot which provides motion commands to the slave robot which performs the actual task. The conventional approach to synchronization of bilateral teleoperators is based on assumption that both robots have the same structure or regression matrix. Such an assumption allows applications of the conventional adaptive control approach for asymptotic tracking. The controller proposed in this paper provides asymptotic synchronization of master and slave robotic systems with different structural configurations. Simulation example with two robots with two revolute joints in horizontal and vertical plane demonstrates the effectiveness of the proposed control strategy.*
Key words: synchronization, telerobotics, passivity-based control, sliding-mode control

1. INTRODUCTION

A teleoperation system enables human operator to implement given tasks in a remote manner. A typical teleoperation system consists of a local master manipulator and a remotely located slave manipulator. The human operator controls the local master manipulator to drive the slave one to implement a given task remotely. More precisely, the human imposes a force on the master manipulator which in turn results in a displacement that is transmitted to the slave that mimics that movement. Various applications of telerobotics can be found in under-water operations, space explorations, telesurgery, nuclear reactors, etc. (Hokayem & Spong, 2006).

Many control methods have been applied to bilateral teleoperation like supervisory control, scattering approach, and H_∞ control (Hokayem & Spong, 2006). The mentioned methods are based on assumption that system dynamics model is known, and this model is entirely or partially included in control law. The adaptive control approach (Hung et al., 2003) overcomes this problem, but still structure of dynamic model in the form of regression matrix must be known. The sliding-mode control overcomes needs for regression matrix, but application in telerobotics is limited to linear 1-DOF mechanical systems, (Cho, et al., 2001).

Synchronization-based approaches to bilateral teleoperation have been developed relatively recently (Chopra, et al., 2008). Synchronization phenomena have been observed in mechanical and electrical systems, biological, chemical, physical and social systems (Nijmejier & Rodriguez-Angeles, 2003; Pikovsky, et al., 2001). Synchronization between master and slave robot is based on passivity properties of interconnected mechanical system, and parameter uncertainties are treated by adaptive control law (Chopra, et al., 2008).

In this paper we propose a synchronization-based sliding-mode approach to bilateral teleoperation avoiding needs for regression matrix and providing asymptotic synchronization between structurally different robot manipulators.

2. ROBOTS SYNCHRONIZATION

We consider the master and slave configuration of two robots with different structures. We suppose robot position and velocity measurement and short distance communication channel without time delays.

2.1 Master and slave robots dynamics

The Euler–Lagrange equations of motion for an n-link master and slave robot are given as (Chopra, et al., 2008)

$$\begin{aligned}\mathbf{M}_m(\mathbf{q}_m)\ddot{\mathbf{q}}_m+\mathbf{C}_m(\mathbf{q}_m,\dot{\mathbf{q}}_m)\dot{\mathbf{q}}_m+\mathbf{g}_m(\mathbf{q}_m)=\boldsymbol{\tau}_m+\mathbf{F}_h\\ \mathbf{M}_s(\mathbf{q}_s)\ddot{\mathbf{q}}_s+\mathbf{C}_s(\mathbf{q}_s,\dot{\mathbf{q}}_s)\dot{\mathbf{q}}_s+\mathbf{g}_s(\mathbf{q}_s)=\boldsymbol{\tau}_s+\mathbf{F}_e\end{aligned}, \qquad (1)$$

where $\mathbf{q}_m$, $\mathbf{q}_s$ are the n×1 vectors of joint positions, $\boldsymbol{\tau}_m$, $\boldsymbol{\tau}_s$ are the n×1 vector of applied torques, $\mathbf{M}(\mathbf{q})$ is the n×n symmetric positive definite manipulator inertia matrix, $\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}$ is the n×1 vector of centripetal and Coriolis torques and $\mathbf{g}(\mathbf{q})$ is the n×1 vector of gravitational torques. The human operator commands the master robot with force $\mathbf{F}_h$, and the remote force $\mathbf{F}_e$ appears when the slave robot contacts a remote environment.

Since the robot dynamics are linearly parameterizable, system (1) can be written

$$\begin{aligned}\mathbf{Y}_m(\mathbf{q}_m,\dot{\mathbf{q}}_m,\ddot{\mathbf{q}}_m)\boldsymbol{\theta}_m=\boldsymbol{\tau}_m+\mathbf{F}_h\\ \mathbf{Y}_s(\mathbf{q}_s,\dot{\mathbf{q}}_s,\ddot{\mathbf{q}}_s)\boldsymbol{\theta}_s=\boldsymbol{\tau}_s+\mathbf{F}_e\end{aligned}, \qquad (2)$$

where $\mathbf{Y}_m(\cdot)$ and $\mathbf{Y}_s(\cdot)$ are n×p_m and n×p_s robots regression matrices, and $\boldsymbol{\theta}_m$ and $\boldsymbol{\theta}_s$ are p_m×1 and p_s×1 dimensional vectors of robots inertial parameters. The basic assumption of standard adaptive control-based robots synchronization is that the regression matrices are known and equal, what means that master and slave robots has the same structure.

2.2 Sliding mode synchronization control law

The proposed control law has the following form

$$\begin{aligned}\boldsymbol{\tau}_m=\mathbf{K}_1\tanh\left(\mathbf{r}_m-\mathbf{r}_s\right)+\mathbf{K}_2\mathrm{sign}\left(\mathbf{r}_m-\mathbf{r}_s\right)\\ \boldsymbol{\tau}_s=\mathbf{K}_1\tanh\left(\mathbf{r}_s-\mathbf{r}_m\right)+\mathbf{K}_2\mathrm{sign}\left(\mathbf{r}_s-\mathbf{r}_m\right)\end{aligned}, \qquad (3)$$

where $\mathbf{K}_1$ and $\mathbf{K}_2$ are positive definite symmetric gain matrices, and the vectors $\mathbf{r}_m$ and $\mathbf{r}_s$ are the outputs of the master and slave robots, respectively

$$\begin{aligned}\mathbf{r}_m=\dot{\mathbf{q}}_m+\lambda\mathbf{q}_m\\ \mathbf{r}_s=\dot{\mathbf{q}}_s+\lambda\mathbf{q}_s\end{aligned}, \qquad (4)$$

where λ is some positive parameter.

The saturation function tanh(·) is included to prevent control signals with magnitudes larger then saturation level of actuators. The control law (3) is completely model-free and doesn't include robots regression matrices what guarantee robustness to structural model uncertainties and external disturbances. In other words, independence of the control law on the regression matrices provides mutual synchronization of structurally different robots.

From the control law (3) follows that maximal values of control torques is equal to $\lambda_M\{\mathbf{K}_1\}+\lambda_M\{\mathbf{K}_2\}$, where $\lambda_M\{\cdot\}$ is maximal eigenvalue of the matrix.

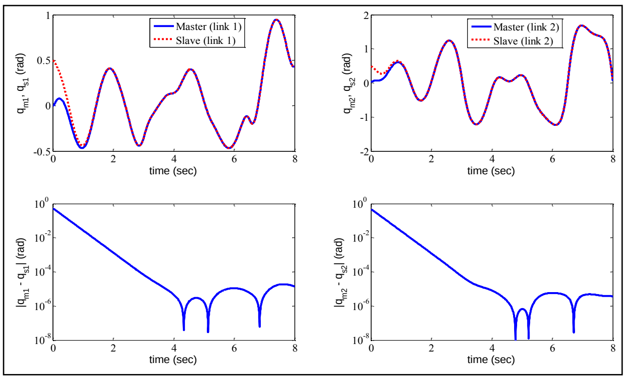

Fig. 1. Responses of the master and slave links positions in the case of external disturbances (upper subfigures); position errors between master and slave robots (bottom subfigures)

3. SIMULATION RESULTS

This section presents the results of simulation verification of proposed control strategy to synchronization of two robots with different structures. Both robots have two rotational degrees of freedom in a plane, but master robot is in horizontal plane (SCARA configuration) and slave robot is in vertical plane (planar elbow manipulator). The main structural difference between robots in horizontal and vertical plane is absence of gravitational force in the case of horizontal configuration.

The entries of the inertia matrix are given by (Kelly, et al., 2005)

$$\begin{aligned} m_{11} &= m_1 l_1^2 + m_2(l_1^2 + l_2^2 + 2l_1 l_2 + 2l_1 l_2 c_2) + I_1 + I_2 \\ m_{12} &= m_{21} = m_2(l_2^2 + l_1 l_2 c_2) + I_2 \\ m_{22} &= m_2 l_2^2 + I_2 \end{aligned}, \qquad (5)$$

the vector of Centripetal and Coriolis torques is

$$\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} = \begin{bmatrix} -m_2 l_1 l_2 \dot{q}_2 (2\dot{q}_1 + \dot{q}_2) s_2 \\ m_2 l_1 l_2 \dot{q}_1{}^2 s_2 \end{bmatrix}, \qquad (6)$$

and, the gravitational torque vector is

$$\mathbf{g}(\mathbf{q}) = \begin{bmatrix} (m_1 l_1 + m_2 l_2) g c_1 + m_2 l_2 g c_{12} \\ m_2 l_2 g c_{12} \end{bmatrix}, \qquad (7)$$

where m_1 and m_2 are masses of the first and second links, l_1 and l_2 are lengths of the first and second links, I_1 and I_2 are inertias of the first and second links, and g=9.81m/s^2 is gravity acceleration, and $s_i = \sin(q_i)$, $c_i = \cos(q_i)$, $s_{ij} = \sin(q_i + q_j)$, $c_{ij} = \cos(q_i + q_j)$.

Parameters of the master robot in horizontal plane (g = 0 m/s^2) are: m_1 = 1.8 kg, m_2 = 2.2 kg, l_1 = 0.3 m, l_2 = 0.2 m, I_1 = 0.004 Nms^2, I_2 = 0.002 Nms^2. Parameters of the slave robot in vertical plane (g = 9.81 m/s^2) are: m_1 = 0.6 kg, m_2 = 0.7 kg, l_1 = 0.7 m, l_2 = 0.5 m, I_1 = 0.002 Nms^2, I_2 = 0.002 Nms^2.

Command forces are F_{h1} = sin(t) + sin(2t), F_{h2} = sin(t) + sin(3t), and environmental disturbances are F_{e1} = 0.4 sin(2t) + 0.2 sin(5t), F_{e2} = 0.4 sin(2t) + 0.2 sin(6t).

Further, a continuous approximation of signum function in (3) is introduced to prevent control variable chattering. The function sign(x) is replaced by tanh(μx), where μ is a parameter with large value (μ=1000).

In Fig. 1. we can see response of master and slave links positions in the case of external disturbances. After short transient time, the position error between links of master and slave robots asymptotically converges to zero. A small stationary-state position error shown in bottom subfigures is consequence of continuous approximation of the signum function. In Fig. 2. we can see master and slave control torques.

Simulation results for other choices of initial conditions show similar behavior. Also, controller shows high robustness to changes in system parameters.

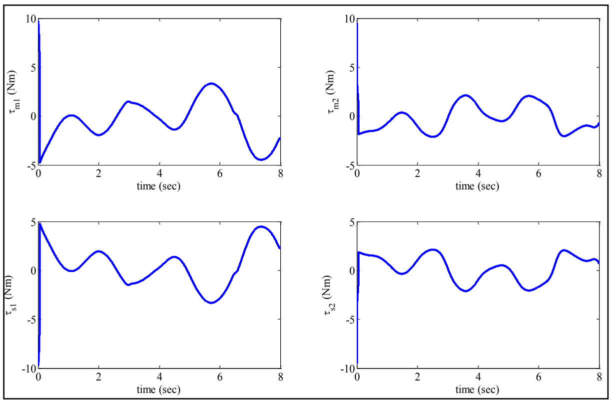

Fig. 2. The master and slave control torques in the case of external disturbances

4. CONCLUSION

In this paper a sliding-mode approach to asymptotic synchronization of multi-robotic systems with structural uncertainties and unknown external disturbances is presented. The proposed approach avoids limitations of standard adaptive control approach which requires knowledge of robot system dynamics, and it is not limited to robots with the same configuration. The future research will extend the proposed control approach including assumption of time delays in communication channel. Also, the Lyapunov-based stability analysis will be applied with aim to provide exact controller tuning rules.

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