MASTER-SLAVE ROBOT POSITION COORDINATION BASED ON ESTIMATED VARIABLES

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Keywords: Master-slave, position coordination, Lyapunov stability, state feedback, observers.

Abstract

In this paper we present a controller that solves the problem of position coordination of two (or more) robotic systems, under a master-slave scheme, in the case when only position measurements are available. The controller consists of a feedback control law and two nonlinear observers. It is shown that the controller yields semi-global ultimate uniformly boundedness of the closed loop errors and a relation between the bound of the errors and the gains on the controller is established. Experimental results show, despite obvious model uncertainties, a good agreement with the predicted convergence.

1 Introduction

Nowadays the developments on technology and requirements on efficiency and quality in production processes have originated more complex and integrated systems. These integrated systems are a synergy of many different disciplines such as mechanics, electronics, control, etc.. The final goal of this synergy is to improve the performance, and in many cases to give rise to more flexible and robust systems.

In manufacturing processes, automotive applications and teleoperated systems there is a high requirement on flexibility and manoeuvrability of the involved systems. In most of these processes the use of mechanical systems, particularly robot manipulators, is widely spread, and their variety in uses is practically endless, e.g. ensembling, transporting, painting, welding, grasping. All the mentioned tasks require large manoeuvrability and manipulability from the robots, such that some of the tasks can not be carried out by a single robot. In those cases the use of multi robot systems, working under cooperative or coordinated schemes, has been considered as an option.

The cooperative schemes give flexibility and manoeuvrability that can not be achieved by an individual system, e.g. multi finger robot-hands, multi robot systems, multi-actuated platforms, [8], [10], vibro-machinery [1], tele-operated master-slave systems [7] and [3]. Typically robot coordination and cooperation of manipulators form important illustrations of the same goal, where it is desired that two or more mechanical systems, either identical or different, are asked to work in synchrony. In robot coordination the basic problem is to ascertain synchronous motion of two (or more) robotic systems. This is obviously a control problem that implies the design of suitable controllers to achieve the required coordinated motion.

This work addresses the problem of coordination of mechanical systems, particularly robotic systems, under master-slave schemes. Since the pioneering work of Goertz [2], most of the master-slave robotic systems – if not all – are based on full knowledge of the dynamic model and joint variables (position, velocity and acceleration) of the master and slave robots [5], [6]. However, in practice, robot manipulators are equipped with high precision position sensors, such as encoders, but very often the velocity measurements are obtained by means of tachometers, which are contaminated by noise.

In this paper we present a coordination controller that solves the problem of position coordination of two (or more) robot systems, under a master-slave scheme, in the case when only position measurements of both master and slave robots are available. The setup here considered is as follows. Consider two rigid joint robots, such that the movement of one of the robots is independent of the other one. This robot is the dominant one and will be referred to as the master robot. The master robot is driven by a control $\tau_m(\cdot)$, that in the ideal case, ensures convergence of the master robot joint positions and velocities $q_m, \dot{q}_m$ to a given desired trajectory $q_d, \dot{q}_d$. Then, the goal is to design interconnections and a feedback controller for the non dominant robot, hereafter referred to as slave, such that its position and velocity $q_s, \dot{q}_s$ coordinate (synchronize) to those of the master robot $q_m, \dot{q}_m$. However, the input torque τ_m, the dynamic model and parameters of the master robot, as well as the velocity and acceleration variables $\dot{q}_m, \ddot{q}_m$, are not available for the design of the slave control law $\tau_s(\cdot)$. Therefore for the design of the slave interconnections and controller only master and slave angular positions q_m, q_s are available by means of measurements.

Notice that the goal is to ensure coordination between the slave robot trajectories $q_s, \dot{q}_s$ and the master robot trajectories $q_m, \dot{q}_m$, and not to the master desired trajectories $q_d, \dot{q}_d$ which may not be realized due to model uncertainties or disturbances in the system, e.g. noise, unknown loads, friction.

Most of the master-slave robot systems are designed to interact with their environment, and thus force-position controllers are required [6], [5]. This paper is focused only on the position coordination problem. Nevertheless in case of a master-slave system interacting with its environment, passive compliance or end effector compliance models can be used in order to control the interaction forces between the slave robot and the environment.

The paper is organized as follows. Section 2 presents the dynamic model of the master and slave robots. The proposed coordination controller is presented in Section 3. Section 4 presents the theorem which supports the stability of the coordination system. In Section 5 experimental results are presented and discussed. Section 6 presents general conclusion and some further extensions of the proposed controller.

2 Dynamic model of the robot manipulators

Without loss of generality and considering that the friction phenomena can be compensated separately, it is assumed that the robots are frictionless. Consider a pair of fully actuated rigid robots, each one with the same number of joints, i.e. $q_i \in \mathbb{R}^n$, where $i = m, s$ identifies the master (m) and slave (s) robot; all the joints are rotational. This does not mean, however, that they are identical in their parameters (masses, inertias, etc.).

For each of the robots, the kinetic energy is given by $T_i(q_i, \dot{q}_i) = \frac{1}{2}\dot{q}_i^T M_i(q_i)\dot{q}_i$, $i = m, s$, with $M_i(q_i) \in \mathbb{R}^{n\times n}$ the symmetric, positive-definite inertia matrix, and the potential energy is denoted by $U_i(q_i)$. Hence, applying the Euler-Lagrange formalism the dynamic model of the robot is given by

$$M_i(q_i)\ddot{q}_i + C_i(q_i, \dot{q}_i)\dot{q}_i + g_i(q_i) = \tau_i \qquad i = m, s \quad (1)$$

where $g_i(q_i) = \frac{\partial}{\partial q_i}U_i(q_i) \in \mathbb{R}^n$ denotes the gravity forces, $C_i(q_i, \dot{q}_i)\dot{q}_i \in \mathbb{R}^n$ represents the Coriolis and centrifugal forces, and τ_i is the $[n \times 1]$ vector of input torques.

3 Coordination controller

If it is assumed that only angular joint positions q_m, q_s are measured, then the slave control τ_s can only depend position measurements q_m, q_s. Thus estimated values for the velocities $\dot{q}_m, \dot{q}_s$ and accelerations $\ddot{q}_m, \ddot{q}_s$ are required to implement controllers based on velocity and acceleration feedback.

3.1 Feedback control law

Under the assumption that the required estimated velocities and accelerations are available, and that the nonlinearities and parameters of the slave robot are known, the controller τ_s for the slave robot is proposed as

$$\tau_s = M_s(q_s)\widehat{\ddot{q}}_m + C_s(q_s, \widehat{\dot{q}}_s)\widehat{\dot{q}}_m + g_s(q_s) - K_d\widehat{\dot{e}} - K_p e \quad (2)$$

were $\widehat{\dot{q}}_s, \widehat{\dot{e}}, \widehat{\dot{q}}_m, \widehat{\ddot{q}}_m \in \mathbb{R}^n$ represent the estimates of $\dot{q}_s, \dot{e}, \dot{q}_m$ and $\ddot{q}_m$ respectively.

The coordination errors $e, \dot{e} \in \mathbb{R}^n$ are defined by

$$e := q_s - q_m, \qquad \dot{e} := \dot{q}_s - \dot{q}_m, \quad (3)$$

$M_s(q_s)$, $C_s(q_s, \widehat{\dot{q}}_s)$, $g_s(q_s)$ are defined as in equation (1), and $K_p, K_d \in \mathbb{R}^{n\times n}$ are positive definite gain matrices.

3.2 An observer for the coordination errors $(e, \dot{e})$

Estimated values for the coordination errors $e, \dot{e}$ (3) are denoted by $\hat{e}, \widehat{\dot{e}}$; these estimated values are obtained by the full state nonlinear Luenberger observer

$$\begin{aligned} \frac{d}{dt}\hat{e} &= \widehat{\dot{e}} + \Lambda_1\tilde{e} \quad (4) \\ \frac{d}{dt}\widehat{\dot{e}} &= -M_s(q_s)^{-1}\left[C_s(q_s, \widehat{\dot{q}}_s)\widehat{\dot{e}} + K_d\widehat{\dot{e}} + K_p\hat{e}\right] + \Lambda_2\widetilde{\dot{e}} \end{aligned}$$

where the estimation position and velocity coordination errors $\tilde{e}, \widetilde{\dot{e}}$ are defined by

$$\tilde{e} := e - \hat{e}, \quad \widetilde{\dot{e}} := \dot{e} - \widehat{\dot{e}}, \quad (5)$$

and $\Lambda_1, \Lambda_2 \in \mathbb{R}^{n\times n}$ are positive definite gain matrices.

3.3 An observer for the slave joint state $(q_s, \dot{q}_s)$

Lets $\hat{q}_s, \widehat{\dot{q}}_s$ denote estimated values for $q_s, \dot{q}_s$, to compute these estimated values, we propose the full state nonlinear observer

$$\begin{aligned} \frac{d}{dt}\hat{q}_s &= \widehat{\dot{q}}_s + L_{p1}\tilde{e}_q \quad (6) \\ \frac{d}{dt}\widehat{\dot{q}}_s &= -M_s(q_s)^{-1}\left[C_s(q_s, \widehat{\dot{q}}_s)\widehat{\dot{e}} + K_d\widehat{\dot{e}} + K_p e\right] + L_{p2}\tilde{e}_q \end{aligned}$$

where the estimation position and velocity errors $\tilde{e}_q$ and $\widetilde{\dot{e}}_q$ are defined by

$$\tilde{e}_q := q_s - \hat{q}_s \qquad \widetilde{\dot{e}}_q := \dot{q}_s - \widehat{\dot{q}}_s, \quad (7)$$

and $L_{p1}, L_{p2} \in \mathbb{R}^{n\times n}$ are positive definite gain matrices.

3.4 Estimated values for $\dot{q}_m, \ddot{q}_m$

As stated, the master robot variables $\dot{q}_m, \ddot{q}_m$ are not available, therefore estimated values for $\dot{q}_m, \ddot{q}_m$ are used in τ_s (2). From

(3) and the definition of the estimated variables $\hat{e}, \widehat{\dot{e}}, \hat{q}_s, \widehat{\dot{q}}_s$, we can consider that estimated values for $q_m, \dot{q}_m, \ddot{q}_m$ are given by

$$\begin{array}{rcl} \hat{q}_m &=& \hat{q}_s - \hat{e} \\ \widehat{\dot{q}}_m &=& \widehat{\dot{q}}_s - \widehat{\dot{e}} \\ \widehat{\ddot{q}}_m &=& \frac{d}{dt}\left(\widehat{\dot{q}}_s - \widehat{\dot{e}}\right) \end{array} \quad (8)$$

from the definition of the observers (4), (6) it follows that

$$\widehat{\ddot{q}}_m = -(M_s(q_s))^{-1}K_p + \Lambda_2)\widetilde{e} + L_{p2}\widetilde{e}_q$$

which gives a clear insight of how $\widehat{\ddot{q}}_m$ is reconstructed and why by increasing some appropriate gains, specifically K_p, L_{p2}, the closed loop errors decrease in magnitude.

Remark 1 *Note that, in (4) and (5) the estimate for $\dot{e}$ is given by $\widehat{\dot{e}}$, not by $\dot{\hat{e}}$. This definition introduces an extra correcting term in $\dot{\widetilde{e}}$, as it follows from (4), (5) that*

$$\dot{\widetilde{e}} = \dot{e} - \dot{\hat{e}} = \widetilde{\dot{e}} - \Lambda_1\widetilde{e},$$

The term $\Lambda_1\widetilde{e}$ gives faster estimation performance, especially during transients, but it has some negative effects on noise sensitivity, since it amplifies noise measurements on $\widetilde{e}$.

The same can be said for observer (6) and the estimation position and velocity errors (7).

4 Main result

To simplify the stability analysis, we make the following assumptions.

Assumption 1 *Λ_1, Λ_2 and L_{p1}, L_{p2} satisfy*

$$\Lambda_1 = L_{p1}, \qquad \Lambda_2 = L_{p2}, \quad (9)$$

and K_p, K_d, L_{p1}, L_{p2} are symmetric $(n,n)-$matrices.

Assumption 2 *$\dot{q}_m(t)$ and $\ddot{q}_m(t)$ are bounded*

$$V_M = \sup_t \|\dot{q}_m(t)\|, \ \ A_M = \sup_t \|\ddot{q}_m(t)\|. \quad (10)$$

Theorem 1 *Consider the master and slave robots (1), in closed loop with (2), (4), and (6). Given scalar parameters $\varepsilon_o, \lambda_o, \mu_o, \gamma_o$,*

$$\varepsilon_o > \max\{0, \varepsilon_{q6}\}, \ \lambda_o > 0, \ \mu_o > 0, \ \gamma_o > 0, \quad (11)$$

and if the minimum eigenvalues of K_d, K_p, L_{p1}, L_{p2} satisfy

$$\begin{array}{r} L_{p2,m} > \max\left\{\mu_o^2, \ \gamma_o^2, L_{p2q4}, L_{p2q5}, L_{p2q6}\right\}, \\ L_{p1,m} > \max\left\{\mu_o, \gamma_o, L_{p1q5}\right\}, \\ K_{p,m} > \max\left\{K_{pq2}, K_{pq3}\right\}, \\ K_{d,m} > \max\left\{K_{dq1}, K_{dq3}, K_{dq5}, K_{dq6}\right\}, \end{array} \quad (12)$$

then, the closed loop errors $\dot{e}$, e, $\widetilde{\dot{e}}$, $\tilde{e}$, $\widetilde{\dot{e}}_q$, $\tilde{e}_q$ are semi-globally uniformly ultimately bounded. Moreover, this bound can be made small by a proper choice of $K_{p,m}$ and $L_{p1,M}$. The scalars ε_{q6}, L_{p2q4}, L_{p2q5}, L_{p2q6}, L_{p1q5}, K_{pq2}, K_{pq3}, K_{dq1}, K_{dq3}, K_{dq5}, K_{dq6} can be found in [9] and [10]. Also a gain tuning procedure whit guidelines to satisfy conditions (11) and (12) ig given in [9] and [10].

Proof: The proof in extend and the conditions on the gains K_d, K_p, L_{p1}, L_{p2} can be found in [9], [10].

5 Experimental case study

The proposed coordination controller has been implemented in a two CFT robot manipulators setup. The CFT robot is a Cartesian basic elbow configuration robot. It consists of a two links arm which is placed on a rotating and translational base, and it has a passively actuated tool connected at the end of the outer link, see Figure 1. The CFT robot is a pick and place industrial robot used for assembling. It has 4 degrees of freedom in the Cartesian space, denoted by x_{ci} ($i = 1, \dots, 4$), and 7 degrees of freedom in the joint space, denoted by q_j ($j = 1, \dots, 7$), and is actuated by 4 DC brushless servomotors. Although the robot has 7 degrees of freedom in the joint space, 3 of them are kinematically constrained, with the set of constrained joints given by $\{q_3, q_6, q_7\}$. Therefore the robot can be represented in the joint space by 4 degrees of freedom $\{q_1, q_2, q_4, q_5\}$ actuated by 4 servomotors. Although the shaft of the motors and the corresponding links are connected by means of belts, the servomotor-link pair proved to be stiff enough to be considered as a rigid joint.

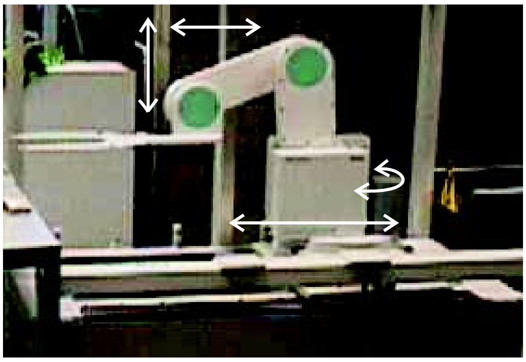

Figure 1: The CFT-transposer robot

The 4 Cartesian degrees of freedom are rotation, up and down, forward and backward of the arm, forward and backward of the whole robot, see Figure 1. The robot is equipped with encoders attached to the shaft of the motors with a resolution of 2000 PPR, which results in an accuracy of ± 0.5 [mm] in all motion directions. The tool connected at the end of the outer link is a kinematically constrained planar support. The tool is passively actuated and designed to remain horizontal at all time. A more detailed description of the structure of the robot can be found in [10].

For implementation of the controllers and communication to the robots, the experimental setup is equipped with a DS1005 dSPACE system, with a processor PPC750, a clock of 480 MHz and a bus clock of 80 MHz. Throughout the experiments the sampling frequency of the DS1005 dSPACE system was set to 2 kHz.

5.1 Joint space dynamics

The multi-robot system is formed by two structurally identical transposer robots, so that they have the same kinematic and dynamic model. However, the physical parameters of the robots, such as masses, inertias, friction coefficients are different for both robots.

Hereafter the notation q_i, for $i = m, s$ refers to the master or slave robot in the multi-composed system. According to [10] the dynamic model of the CFT-robot is given by

$$M(q_i)\ddot{q}_i + C(q_i, \dot{q}_i)\dot{q}_i + g(q_i) + f(\dot{q}_i) = \tau_i, \qquad i = m, s \quad (13)$$

where $f(\dot{q}_i)$ denotes the friction that is modelled as

$$f(\dot{q}_i) = B_{v,i}\dot{q}_i + B_{f1,i}\left(1 - \frac{2}{1 + e^{2w_{1,i}\dot{q}_i}}\right) + B_{f2,i}\left(1 - \frac{2}{1 + e^{2w_{2,i}\dot{q}_i}}\right) \quad (14)$$

with, $q_i = [\ q_{i,1} \quad q_{i,2} \quad q_{i,4} \quad q_{i,5}\ ]^T$ the vector of generalized coordinates of robot i, $M(q_i) \in \mathbb{R}^{4\times 4}$ the symmetric, positive definite inertia matrix, $g(q_i) \in \mathbb{R}^4$ denotes the gravity forces, $C(q_i, \dot{q}_i)\dot{q}_i \in \mathbb{R}^4$ represents the Coriolis and centrifugal forces, $f(\dot{q}_i) \in \mathbb{R}^4$ are the forces due to friction effects, and $\tau_i = [\ \tau_{i,1} \quad \tau_{i,2} \quad \tau_{i,4} \quad \tau_{i,5}\ ]^T$ is the vector of external torques.

The parameters in the matrices $M(q_i), C(q_i, \dot{q}_i)$ and the gravity vector $g(q_i)$ can be found in [10].

5.2 Experimental results

The desired trajectory for the master robot $q_d(t)$ is obtained by transformation of a desired trajectory given in Cartesian coordinates $x_{cj,d}(t)$, $j = 1, \ldots, 4$, that is given by

$$\begin{aligned} x_{cj,d}(t) &= a_{0,j} + a_{1,j}\sin(2s_{f,j}\pi\omega t) + a_{2,j}\sin(4s_{f,j}\pi\omega t) \\ &\quad + a_{3,j}\sin(6s_{f,j}\pi\omega t) + a_{4,j}\sin(8s_{f,j}\pi\omega t) \end{aligned} \quad (15)$$

with the coefficients $a_{i,j}$, $i = 0, \ldots, 4$, $j = 1, \ldots, 4$ given in Table 1. The coefficients $a_{0,j}$ have been chosen as the middle value of the allowed displacements in the robots, while $a_{i,j}$, $i = 1, \ldots, 4$ were chosen to achieve the combination of maximum displacement and velocity allowed by the robots. This is done to generate a trajectory in amplitude that can be executed by the multi-robot system. The coefficients $s_{f,j}$, $j = 1, \ldots, 4$ have been chosen as to change the frequency of the desired trajectories, their values are $s_{f,1} = s_{f,2} = s_{f,3} = 1$ and $s_{f,4} = 0.25$.

The fundamental frequency of the master robot's desired trajectory $x_{cj,d}(t)$, given by (15), is set as $\omega = 0.4$ Hz. The joint space desired trajectory $q_d(t)$ is obtained by transformation of the desired Cartesian trajectories $x_{cj,d}(t)$, $j = 1, \ldots, 4$ using the inverse kinematics [10].

$a_{i,j}$	$i=0$	$i=1$	$i=2$	$i=3$	$i=4$
$j=1$ [m]	-0.1343	-0.05	-0.015	-0.005	-0.01
$j=2$ [m]	0.2766	0.05	0.03	-0.03	0.02
$j=3$ [rad]	2.4	0.15	0.05	-0.03	0.02
$j=4$ [m]	-0.265	0.2	0.1	-0.05	0.05

Table 1: Coefficients of the desired trajectory $x_{cj,d}(t)$, $j = 1, \ldots, 4$.

The master robot is driven by PID controllers with control gains listed as in Table 2. After a series of experiments to decrease the coordination position error $e = q_s - q_m$, the gains on the slave robot controller (2) were set as listed in Table 3.

	K_P	K_D	K_I
joint q_1	11000	50	2000
joint q_2	10000	50	1000
joint q_4	40000	600	1000
joint q_5	40000	600	1000

Table 2: Control gains in the master robot PID controllers.

	K_p	K_d	L_{p1}	L_{p2}
joint q_1	10000	1200	500	100000
joint q_2	8000	100	500	100000
joint q_4	8000	100	500	100000
joint q_5	8000	100	500	100000

Table 3: Control gains in the slave robot.

The initial joint position on the master robot were set as in Table 4.

The initial joint position of the slave robot and the initial conditions in the observers (4), (6) were chosen as in Table 5. The master and slave robot start from a steady state, therefore the joint velocity $\dot{q}(0)$, the estimated joint velocity $\widehat{\dot{q}}(0)$, and the estimated coordination error $\widehat{\dot{e}}(0)$ are all equal to zero. The initial condition for the estimated coordination error $\widehat{e}(0)$ in observer (4) was set equal to zero.

Figure 2 shows the master $q_{m,1}$ (dashed) and slave $q_{s,1}$ (solid) joint position trajectories for the joint $j = 1$. The coordination error $e = q_s - q_m$ for joint $j = 1$ after the transient period has finished is shown in Figure 3.

From Figures 2 and 3 it is evident that joint position coordination between the master and slave robot is achieved in the joint $j = 1$, such that bounded coordination errors are obtained. Further experiments showed that the coordination errors can be decreased by increasing the gains K_p, which agrees with the result stated in Theorem 1.

Similar results are obtained for the remaining 3 joints of the robots $j = 2, 4, 5$. The results for joints $j = 2, 4, 5$ are shown in Figures 4 - 9.

$q_1(0)$ [m]	$q_2(0)$ [rad]	$q_4(0)$ [rad]	$q_5(0)$ [rad]
-0.095	-0.4	-0.9615	2.1473

Table 4: Initial conditions for master robot.

$q_1(0)$ [m]	$q_2(0)$ [rad]	$q_4(0)$ [rad]	$q_5(0)$ [rad]
-0.079	0.0	-1.0355	2.1165
$\widehat{q}_1(0)$ [m]	$\widehat{q}_2(0)$ [rad]	$\widehat{q}_4(0)$ [rad]	$\widehat{q}_5(0)$ [rad]
-0.07	0.1	-1.0	2.0

Table 5: Initial conditions for master and slave robot.

Remark 2 *The master-slave synchronization control goal is to synchronize joint coordinates. So, Cartesian space synchronization depends on the kinematics of the robots, particularly on the Jacobian of the robots. This means that the joint coordination errors will change accordingly to the Jacobian of the kinematic relation between Cartesian and joint spaces, see [4].*

Remark 3 *The conditions mentioned in Theorem 1 are very conservative. However, even without knowledge of the required physical bounds, the closed loop system can be made uniformly ultimately bounded. This may be achieved by selecting the control gains large enough. However, such high gain implementations may amplify unavoidable noise.*

6 Conclusions and further extensions

A position coordination controller for multi-robot systems working in master-slave schemes has been presented. The proposed controller is independent of the master robot dynamics and its physical parameters, and only requires position measurements. The coordination controller yields semi-global ultimate boundedness of the closed loop errors. The bound of the errors can be decreased by a proper tuning on the controller gains.

Further extensions of the proposed coordination controller are the case of flexible joint and mixed rigid-flexible joint robots.

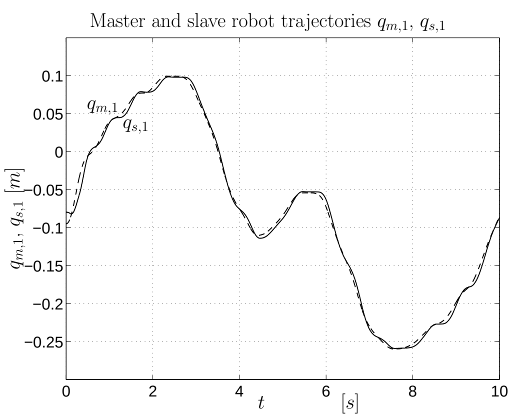

Figure 2: Master q_m (dashed) and slave q_s (solid) positions, joint q_1

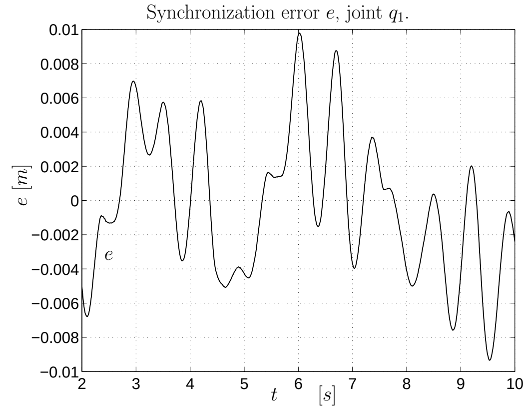

Figure 3: Coordination error e, joint q_1.

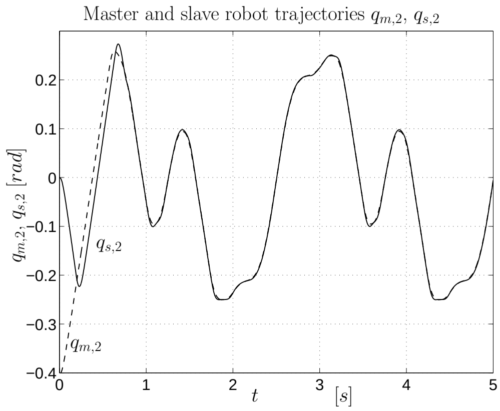

Figure 4: Master q_m (dashed) and slave q_s (solid) positions, joint q_2

Acknowledgments

The work was partly done when the second author was with the Department of Mechanical Engineering, Eindhoven University of Technology. The second author acknowledges support from the CONACYT (National Council for Science and Technology), Mexico, Scholarship No. 72368.

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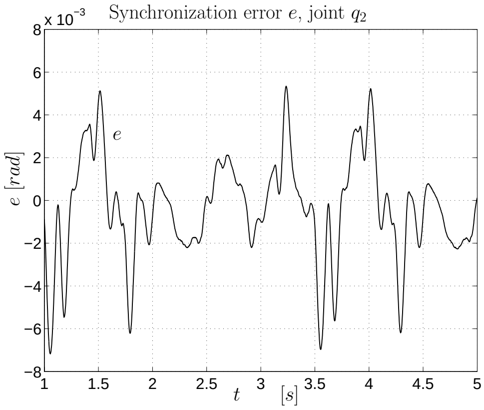

Figure 5: Coordination error e, joint q_2.

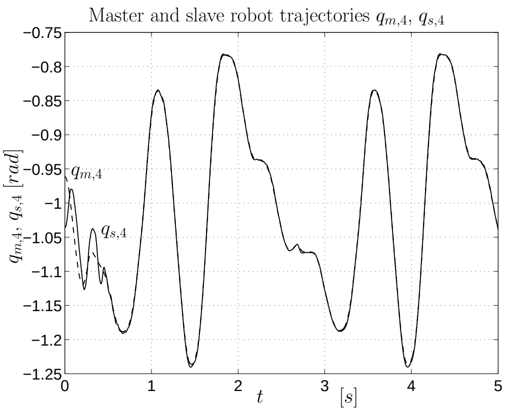

Figure 6: Master q_m (dashed) and slave q_s (solid) positions, joint q_4

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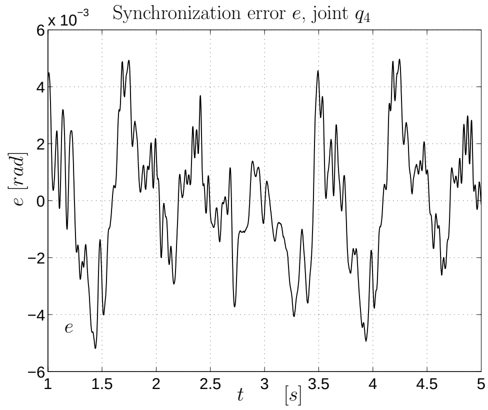

Figure 7: Coordination error e, joint q_4.

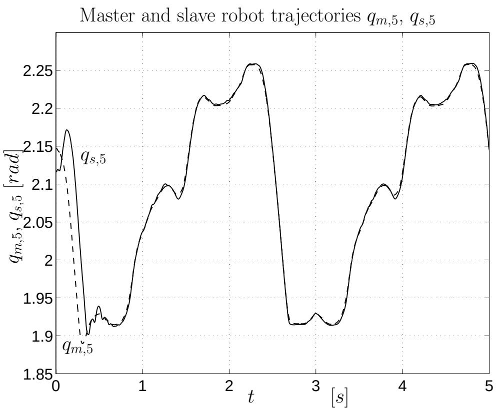

Figure 8: Master q_m (dashed) and slave q_s (solid) positions, joint q_5

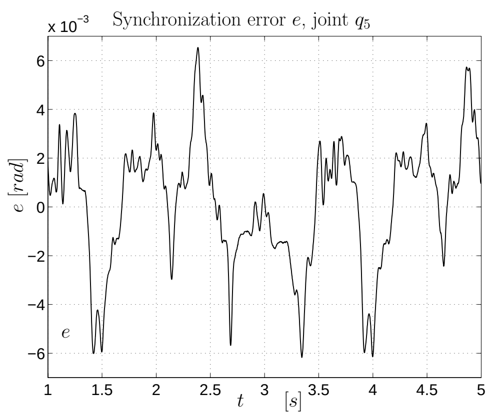

Figure 9: Coordination error e, joint q_5.