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FUZZY HYSTERESIS COORDINATOR FOR NEURO-FUZZY POSITION CONTROLLED MANIPULATORS

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Abstract: A fuzzy coordination scheme for two neuro-fuzzy position controlled manipulators performing upper-limb rehabilitation is developed by maintaining certain kinematic relationship between robot manipulator's end-effectors. The basic idea of the new coordination strategy is to benefit from the use of the motion synchronization concept within acceptable tolerance for the vector connecting the two manipulator's end-effectors. In this scheme, each manipulator tracks its desired trajectory using its neuro-fuzzy Cartesian controller while synchronizing its motion with the other manipulator so that the position error computed for the vector connecting the two manipulator's end-effectors is reduced to zero or kept within acceptable tolerance. *Copyright © 2008 IFAC*

Keywords: Fuzzy logic, Neural networks, Robots manipulators, Adaptive fuzzy control, Tracking, Regulation.

1. INTRODUCTION

Coordination of multi-robot systems has received extensive studies in the past decade. This is due to applications that require more than one robot manipulator to perform tasks such as lifting heavy or awkwardly shaped objects where independent manipulator controllers cannot be trusted to fulfil the task. Coordination between robot manipulators can be achieved with and without interactions of forces between robots (Osumi and Arai, 1994). The first coordination scheme is the master/slave control where the motion of the master robot is pre-planned according to the desired motion of the manipulated object and the motion of the slave robot is to follow the master (Akella and Hutchinson, 2002). The hybrid position/force control (HPFC) method can also form part of a master/slave cooperative robotic system, where the master robot is position controlled and the slave robot is subject to compliant force control. HPFC scheme requires appropriate force measurement at the end-effector of the robot. This results in additional hardware in the control system. The second scheme is the centralized control, in which robots and the grasped payload are considered as a closed kinematic chain. The third scheme is the decentralized control, in which each robot is controlled separately by its own controller, while a compliance device, such as a spring or a free joint, is used to avoid excessive forces between the two robots (Tinos and Terra, 2002; Osumi, e*t al.*, 1997). In situations where the robots are not kinematically constrained but performing a common task together, coordination without interactions of forces is more realistic (Sun and Mills, 2002). Upper-limb rehabilitation, using two robot manipulators, can be viewed as an example of these systems (Culmer *et al.*, 2005; Pham and Fahmy, 2005b). Using the synchronization approach introduced in (Sun and Mills, 2002), the two robots are controlled in a way so that tracking errors and synchronization error converge to zero or to a small acceptable value. The consideration of synchronization error in the proposed control design aims to regulate robot trajectories in the transient stage. This complies with the nature of the rehabilitation application (Pham *et al.*, 2001) due to sudden change in patient arm muscular resistance despite of the slow motion nature of the application.

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The remainder of this paper is organized as follows. Section (2) reviews the definition of the synchronization function. Section (3) presents the detailed structure of the proposed position coordinator. Section (4) introduces the idea of fuzzy hysteresis coordinator. Section (5) introduces the experimental set-up of the proposed coordination system, while section (6) concludes the paper.

2. SYNCHRONIZATION FUNCTION

Consider a robotic cell formed by two manipulators. Denote $x_i(t)$ as the Cartesian coordinates vector of robot manipulator *i*, where *i*=1 or 2. The position tracking error vector of the manipulators in following a desired position trajectory vector, $x_i^d(t)$ is,

$$e_i(t) = x_i(t) - x_i^d(t) \tag{1}$$

For upper-limb rehabilitation application using two robot manipulators, the rehabilitation task required to be performed by the two robots can be approximated by the schematic diagram shown in fig. 1.

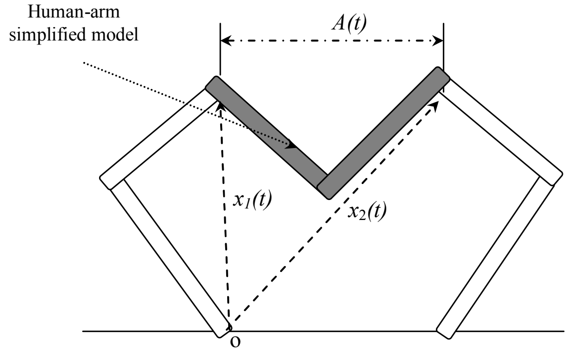

Fig. 1. Simplified representation of two robots manipulating human upper-limb.

It is a requirement that the difference between position vectors of the two end-effectors of the robots to a common coordinates system, $A(t)$ must equal to the pre-planned connection vector $A_o(t)$ (Pham *et al.*, 2001). Where $A_o(t)$ is a time-varying vector calculated from the pre-planned upper-limb motion in the teach-in stage (Pham and Fahmy, 2005b).So, the position coordinates of the two robot manipulator's end-effectors, denoted by $x_1(t)$ and $x_2(t)$, are subject to the synchronization function,

$$f(x_i) = f(x_1(t), x_2(t)) = x_1(t) - x_2(t) - A(t) = 0 \tag{2}$$

Using the same Taylor's expansion procedure as in (Sun and Mills, 2002), and eliminating the higher order derivatives, the above function is equivalent to causing position errors $e_1(t)$ and $e_2(t)$ to satisfy,

$$f(x_i) = \frac{\partial f(x_i)}{\partial x_1}\bigg|_{x_1^d}\big(e_1(t)\big) + \frac{\partial f(x_i)}{\partial x_2}\bigg|_{x_2^d}\big(e_2(t)\big) = 0 \tag{3}$$

$$\left|f(x_i)\right| = \left|\frac{\partial f(x_i)}{\partial x_1}\bigg|_{x_1^d}\big(e_1(t)\big) + \frac{\partial f(x_i)}{\partial x_2}\bigg|_{x_2^d}\big(e_2(t)\big)\right| \le \varepsilon \tag{4}$$

$$\left|e_1(t) - e_2(t)\right| \le \varepsilon \tag{5}$$

A tolerance value (ε) is introduced in the equation by the physiotherapist as the manipulated human-arm contains the elbow-joint which prevents excessive forces from being transmitted from one robot to the other and the flexibility nature of the human arm tissues allows certain amount of position error. The control of the synchronization error within this tolerance value aims to guarantee that no harmful twisting is applied to the human arm.

3. COORDINATOR STRUCTURE

The overall system can be regarded as comprising three main components. The first is the joint-based controllers (Pham *et al.*, 2008; Pham and Fahmy, 2005a); the second is the Cartesian internal model controllers (Pham and Fahmy, 2005b); while the third is the proposed fuzzy coordinator which synchronizes the motion of the two robots. Fig. 2 illustrates the structure of the joint-based controller reported in (Pham and Fahmy, 2005a); Fig. 3 illustrates the structure of the Cartesian internal model controller reported in (Pham and Fahmy, 2005b); while Fig. 4 illustrates the structure of the proposed fuzzy coordination system. The fuzzy hysteresis coordinator transforms the error in the connection vector into trajectory tracking compensation signal. Direct modification of the robots controllers' reference tracking command is an effective method which does not involve changing the controller configuration which is importance to maintain the internal model controller's structure (Verdonck and Swevers, 2002).

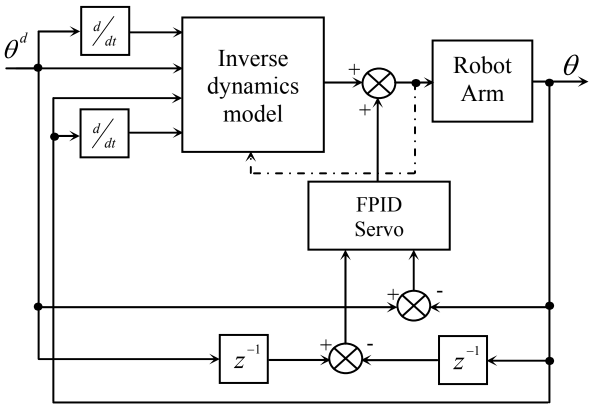

Fig. 2. Neuro-fuzzy joint-based controller.

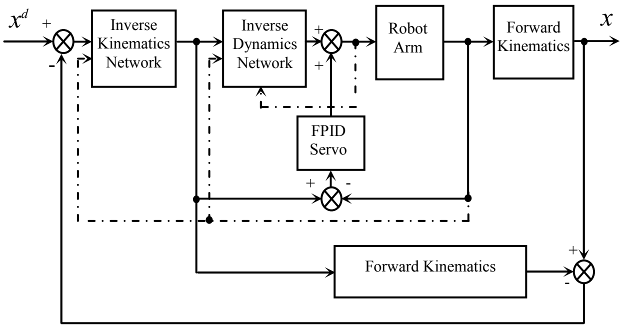

Fig. 3. Neuro-fuzzy Cartesian internal model controller.

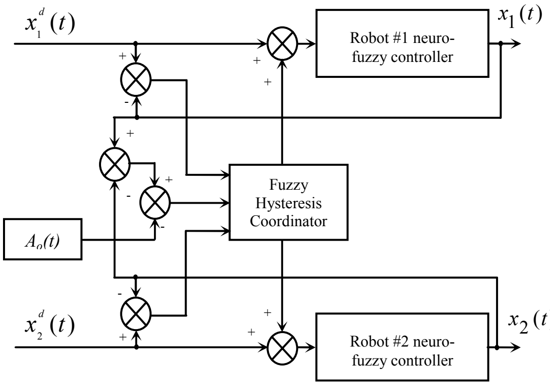

Fig. 4. Proposed fuzzy hysteresis coordinator.

3.1 Coordination System

The design issue here is how to map the measured connection vector error to the reference position tracking compensation vector of each robot. The mapping rules from connection vector error to corrective signals are constructed to force the connection vector error to lie within the acceptable tolerance. The first component is a sign generator for positive/negative connection vector error. The second component is the hysteresis controller which is used to monitor the connection vector error and generates a switching signal for the error mapping mechanism to calculate the required tracking command correction signals. The width of the hysteresis loop represents the acceptable tolerance in the coordination error. This is to be designed according to the safety limits provided by the physiotherapist for the patient upper-limb rehabilitation allowable torsion.

If the connection vector error is within this loop, then there is no need for the coordination system to interfere in any of the robot's controllers as the system overall performance will not be affected by this error. This method ensures that the coordination controller is operating only when any of the robots controllers fails to quickly compensate for its own generated error and that error is affecting the overall performance. The coordination controller in this case will be working to speed-up this compensation process. In this way, the proposed synchronization controller aims to improve the transient performance of the system when a sudden or large change in the patient arm resistance occurs.

3.2 Error Mapping Logic

This part of the coordinator is used to transferring the connection vector error into a tracking command compensating signal. The main strategy depends on the most significant error concept, which is defined as the error with the largest impact on the overall motion accuracy at a particular moment. The connection vector $A(t)$ is calculated online from the forward kinematics model used in the internal model controller structure of each robot as shown in equations (5) and (6).

$$A(t) = x_1(t) - x_2(t) \qquad (5)$$

$$e_A(t) = A(t) - A_o(t) \qquad (6)$$

The error mapping function is to detect the robot which affects the overall motion of the manipulated object. By monitoring the coordination error and both of the robots end-effectors position errors, a decision on which robot trajectory to be modified is taken according to table (1). Where $R_i(t)$ is the reference position tracking compensation signal. By examining the first row in table (1), it implies that, if the synchronization error is positive and exceeded the value (ε), and both of the robots errors are positive then, robot No.1 error forms the most significant error. In this case a negative torque or input reference compensation signal is to be applied to its controller. Also, by examining the last row in table (1), it implies that, if the synchronization error is negative and exceeded the value (ε), and robot No.1 error is negative, while robot No.2 error is positive then, it is not certain which robot forms the most significant error. A successful strategy for this case is to apply a positive torque or reference compensation signal to robot No.1 and a negative compensation signal to robot No.2.

Table 1. Error Mapping Logic

$e_A(t)$	$e_1(t)$	$e_2(t)$	$R_1(t)$	$R_2(t)$
+ve $>\varepsilon$	+ve	+ve	$-e_A(t)$	zero
+ve $>\varepsilon$	+ve	zero	$-e_A(t)$	zero
+ve $>\varepsilon$	-ve	-ve	zero	$e_A(t)$
+ve $>\varepsilon$	zero	-ve	zero	$e_A(t)$
-ve $<-\varepsilon$	+ve	+ve	zero	$-e_A(t)$
-ve $<-\varepsilon$	-ve	-ve	$e_A(t)$	zero
-ve $<-\varepsilon$	-ve	zero	$e_A(t)$	zero
-ve $<-\varepsilon$	zero	+ve	zero	$-e_A(t)$
+ve $>\varepsilon$	+ve	-ve	$-e_A(t)$	$e_A(t)$
-ve $<-\varepsilon$	-ve	+ve	$e_A(t)$	$-e_A(t)$

4. FUZZY HYSTERESIS COORDINATOR

The above proposed look-up table can be transformed to form a fuzzy hysteresis position coordination system by assigning specific shape membership functions (Moore and Chen, 1995). Fig. 5 illustrates the suggested input membership functions, while fig. 6 represents the output membership functions. As shown in fig. 5, and fig. 6, a decaying slope for the hysteresis loop of (ε) in the central membership functions is designed to allow smoother tracking compensation signals for both of the robot's controllers.

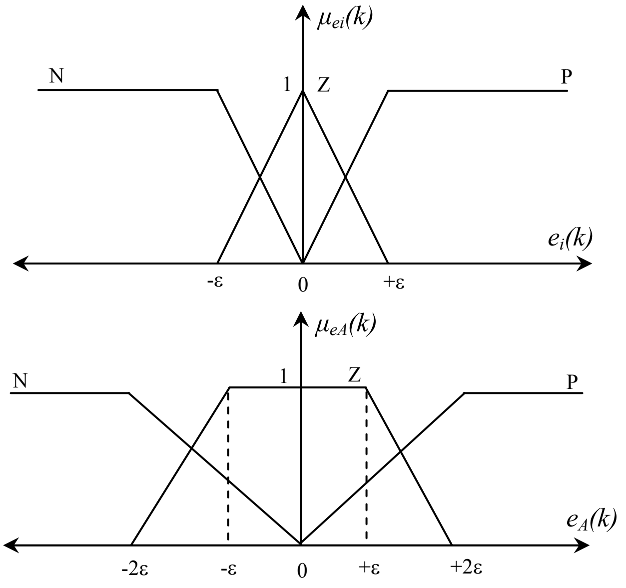

Fig. 5. Input membership functions.

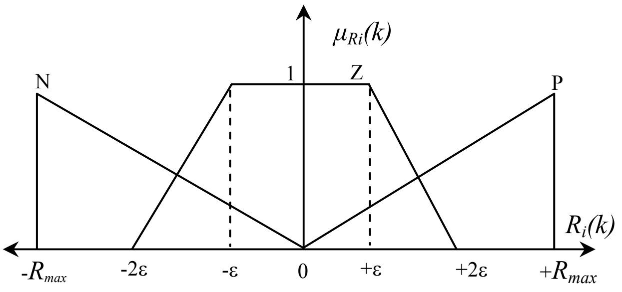

Fig. 6. Output membership function.

Where N, Z, and P, denotes negative, zero, and positive membership functions respectively. $\mu_{ei}(k)$, is the membership value for robot i position error, $\mu_A(k)$, is the membership value for connection vector error, $\mu_{Ri}(k)$, is the membership value for the compensation signal R_i, and R_{max} is the maximum compensation signal value. By assigning these membership functions, table (1) can be transformed to fuzzy coordinator rules as listed in table (2). Note that an additional rule at the end of table (2) is added to cover the fuzzy coordinator output when the connection vector error lies inside the tolerance band.

Table 2. Fuzzy Coordinator Rules

$e_s(t)$	$e_1(t)$	$e_2(t)$	$R_1(t)$	$R_2(t)$
P	P	P	N	Z
P	P	Z	N	Z
P	N	N	Z	P
P	Z	N	Z	P
N	P	P	Z	N
N	N	N	P	Z
N	N	Z	P	Z
N	Z	P	Z	N
P	P	N	N	P
N	N	P	P	N
Z	-	-	-	Z

The centre of area defuzzification method (COA) method (Runkler, 1997) is used to generate the crisp tracking modification signals for each robot reference tracking input command from the fuzzy output.

5. EXPERIMENTAL WORK

To test the proposed control and coordination strategy, a simplified test-bench representing the upper-limb rehabilitation cell was constructed. The cell is composed of two dual-links SCARA® type robots attached to a simple upper-limb model. Each robot link is then fitted with suitable bearing and powered by a high-torque compact frame D.C. motor with planetary reduction gear head by which high torque to weight ratio and virtually zero backlashes were achieved. Two different gear head ratio of 224 and 111 were used for link (1) and link (2) drive motors in each robot respectively. The angular displacement of each joint is measured by a high accuracy potentiometer. The system is controlled by an ADLINK® DAQ/PXI-2501 PC general purpose interface card plugged in the host computer. Figure (7) shows the schematic view of the overall system control architecture.

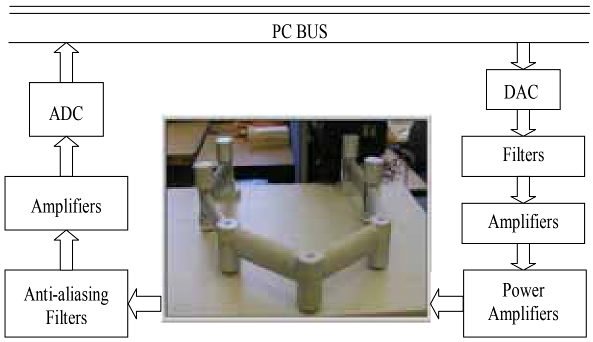

Fig. 7. Experimental system.

The neuro-fuzzy Cartesian control system presented in (Pham and Fahmy, 2005b) was used to control each robot manipulator individually in addition to imposing the proposed coordination system in order to imitate the upper-limb rehabilitation application. The two robot manipulators representation working together while holding the human-arm model was used to imitate the two hands of the physiotherapist while performing simple planner rehabilitation exercise (Pham *et al.*, 2001). The task implemented in the experiment was to move the two robots along desired trajectories while carrying the human arm simplified model and causing the connection vector position error to be within the band ($\varepsilon = 3\,\mathrm{mm}$) for Cartesian coordinates. The sudden load change is imitated by introducing suitable torsion springs in the arm joints scaled to the rating of the test model. The test carried out in the experiment was to move the system with the independent individual adaptive Cartesian controllers without coordination first, and then the two robots were coordinated using the developed fuzzy hysteresis coordinator. Fig. 8 through fig. 11 illustrates the trajectory tracking errors for robot 1 with and without coordination. Fig. 12 through fig. 15 illustrates the trajectory tracking errors for robot 2 with and without coordination. The major difference between each two consecutive results obtained lies in the involvement of the connection vector error in the control system in the form of the fuzzy hysteresis coordinator. It can be seen that although the independent control without coordination could achieve satisfactory performance in each robot trajectory tracking, it exhibits large errors especially at the instant of sudden load change. In contrast, the proposed coordination controller exhibits smaller errors in these instants and therefore better coordination ability.

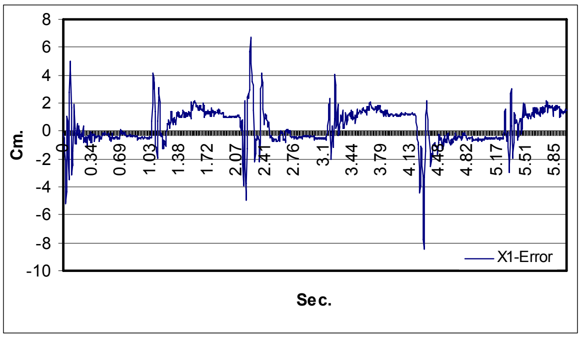

Fig. 8. Robot 1 X-coordinate trajectory error without coordination.

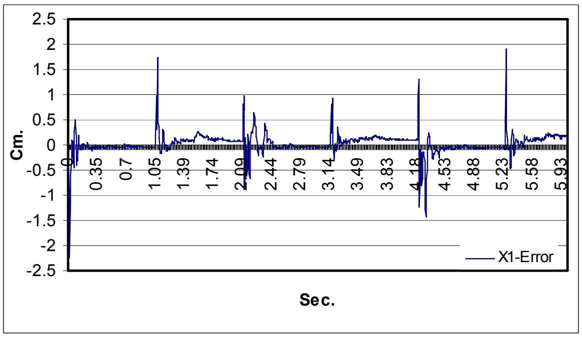

Fig. 9. Robot 1 X-coordinate trajectory error with coordination.

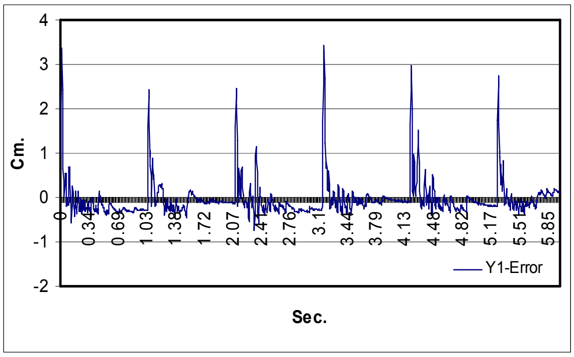

Fig. 10. Robot 1 Y-coordinate trajectory error without coordination.

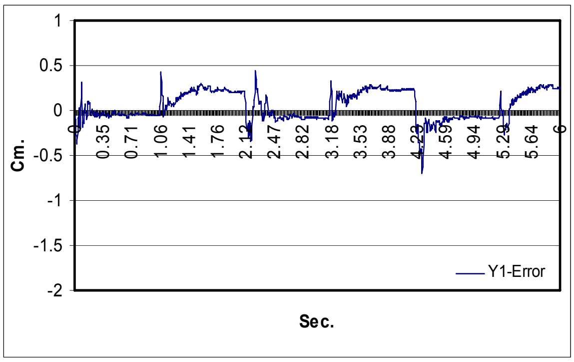

Fig. 11. Robot 1 Y-coordinate trajectory error with coordination.

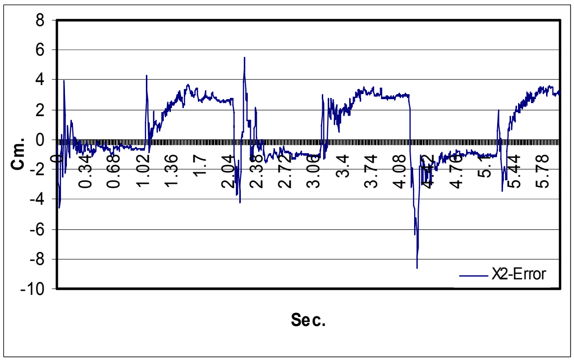

Fig. 12. Robot 2 X-coordinate trajectory error without coordination.

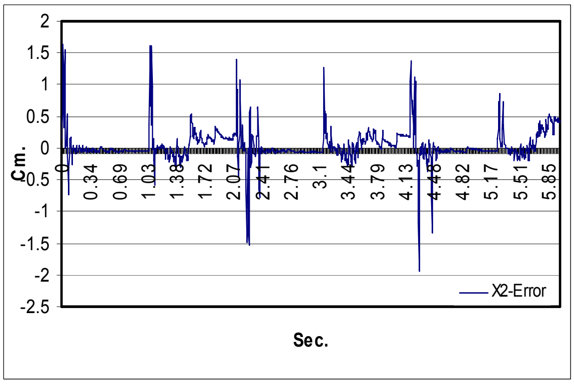

Fig. 13. Robot 2 X-coordinate trajectory error with coordination.

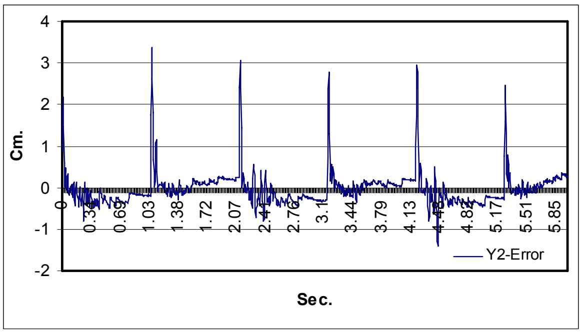

Fig. 14. Robot 2 Y-coordinate trajectory with coordination.

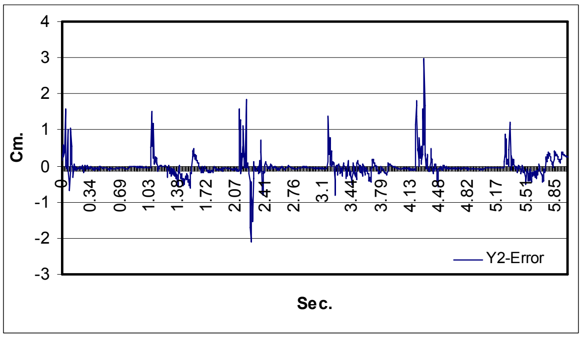

Fig. 15. Robot 2 Y-coordinate trajectory with coordination.

6. CONCLUSION

In this paper, a simple coordination scheme is proposed for coordinating two neuro-fuzzy position controlled manipulators. Each robot is supposed to track its desired position trajectory through its own neuro-fuzzy internal model controller, while coordinating its motion with the other robot to maintain a certain kinematic relationship with the other robot. Failure to maintain this relationship in tracking may cause failure of the task. The proposed coordination strategy is to stabilize position tracking of each manipulator while synchronizing its motion with the other manipulator by causing position connection vector error between the two robots to converge to zero or a small acceptable tolerance value. In the control design, the cross-coupling technology is incorporated into a supervisory structure for intelligent adaptive controllers. It has been shown that the proposed coordination system helps to reduce trajectory errors for the robots and hence better synchronization is achieved. Experimental investigation on coordinating two SCARA® type manipulators demonstrated the effectiveness of the proposed approach.

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