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An Output Controller based on dSPACE for Robot Manipulator in Tracking Following Tasks

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Abstract

The recent developments and studies in the framework of output tracking control in the field of robotics that has been studied in the Control Laboratory, are presented. An output controller based on "Hardware-In-the-Loop Simulation" (HILS) and "Rapid Control Prototyping" (RCP) concepts is developed using dSPACE. These new concepts are shown to be particularly beneficial for manipulator control tasks. In the Elbow manipulator design, there are two kinds of manipulators, namely the serial-drive type and the parallelogram-drive manipulator. The objective of this research is to model the two Elbow manipulators and to implement the proposed controller for manipulator applications. The control goal is to force the manipulator to follow a given trajectory in the given work space. Output controllers of the two elbow manipulators that are based on the model matching control approach have been implemented in two models that represent the robot equations of motion. To reduce the efforts in evaluating the proposed algorithm, a new system configuration method, based on HILS and RCP tools, was suggested to determine the parameters of the integrated dynamic system.

1. Introduction

In our research program in output tracking control, we have developed some widely-applicable output controller during our efforts to apply the proposed control algorithm to the elbow manipulators using dSPACE, which is one of the real time computer systems.

Various observer-based controllers have been considered for application in robotics, where the exact velocity measurement is replaced by an estimate obtained by the observer [1]. All other controllers assume the apriori knowledge of the reference trajectory that is also uniformly bounded [2]. However, in many applications, this is not the case, and the reference trajectory is an output of a reference model subjected to numerous input functions rather than a fixed function of time. The problem that then arises is to find a feedback compensator that guarantees for every reference model input the asymptotic convergence of the robot output to the corresponding model output. There is another important difference, namely in the present approach the dynamic model is linear time-varying system.

The concept of model matching considers the convergence of the controlled plant states to a suitable selected reference model (exosystem) which exists only in software. Different classes of tracking may be specified by the choice of the exosystem. It also allows to model the outside world by representing it by a dynamical model [3]. Various previous studies have been presented which are relevant examples to the problem of model matching. Among them is the standard real-time trajectory tracking [4], and the use of a first-order linear dynamic equation (reference model) that generates a field of trajectory [5]. However, few considerations have been made with respect to the industrial application and simulation of these controllers. Few aspects related to restrictions arising in real industrial applications have been considered in details. To the best of our knowledge, the issue of digital. controller and the relevant practical implementation problems have not been considered in the available literature[8]. The purpose of this paper is to examine some of the possible implementation problems that will occur in such real-time applications.

In section 2, the experimental equipment (robot) we have used in this research is described, and the design of the serial type and parallelogram type elbow manipulator we addressed is presented. The HILS and RCP concepts for control of the serial type and the parallelogram type manipulators present a truly new challenging topic for the output controller. In section 3, we present and set up the output controller that we have used in this research using MATLAB , which is an application program, that allows greater functionality. The evaluation and experimental validity of these methods has been verified on our elbow manipulators, as demonstrated in Section 4.

2. Modeling of the Elbow Manipulators

2.1 Serial-Type Manipulator

The serial type elbow manipulator used is shown in Figure 2-1.

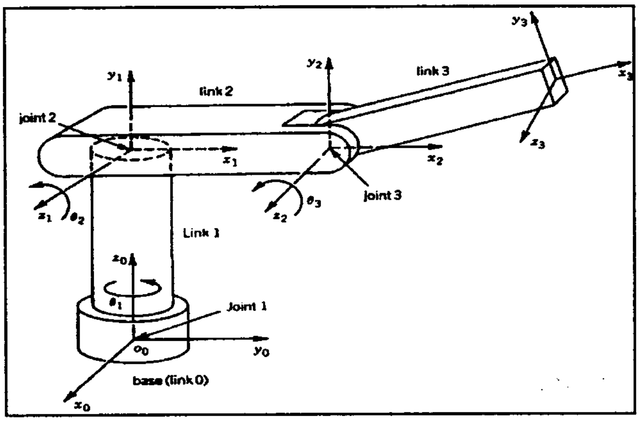

Figure 2-1. Serial Type elbow manipulator

The robot equation of motion is of the form

$$D(q(t))\ddot{q}(t) + C(q(t),\dot{q}(t))\dot{q}(t) + \phi(q(t)) = \tau(t), \quad t \geq 0.$$

Thus, the state space representation of the serial type robot[7] is given by·

$$\dot{x} = f(x) + \hat{D}(x)u$$

$$y = Ex$$

where

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \in IR^{2n}, \quad f(x) = \begin{bmatrix} x_2 \\ D(x_1)^{-1}(-C(x_1,x_2)x_2 - \phi(x_1)) \end{bmatrix}$$

$$\hat{D}(x) = \begin{bmatrix} 0 \\ D(x_1)^{-1} \end{bmatrix}, \quad E = [I_n, 0]$$

and

$$x_1 = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} \quad x_2 = \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix}$$

Then we obtain

$$D(x_1) = \begin{bmatrix} \frac{81}{40}\cos(2x_{1,2}) + \frac{113}{40} + \frac{12}{5}\cos(x_{1,3} + 2x_{1,2}) + \frac{4}{5}\cos(2x_{1,3} + 2x_{1,2}) + \frac{12}{5}\cos(x_{1,3}) & 0 & 0 \\ 0 & \frac{19}{3} + \frac{24}{5}\cos(x_{1,3}) & \frac{32}{15} + \frac{12}{5}\cos(x_{1,3}) \\ 0 & \frac{32}{15} + \frac{12}{5}\cos(\dot{x}_{1,3}) & \frac{32}{15} \end{bmatrix}$$

$$D(x_1)^{-1} = \begin{bmatrix} \frac{40}{81\cos(2x_{1,2}) + 113 + 32\cos(2x_{1,3} + 2x_{1,2}) + 96\cos(x_{1,3} + 2x_{1,2}) + 96\cos(x_{1,2})} & 0 & 0 \\ 0 & \frac{10}{3}\frac{1}{-14 + 9\cos(x_{1,3})^2} & \frac{5}{12}\frac{8 + 9\cos(x_{1,3})}{-14 + 9\cos(x_{1,3})^2} \\ 0 & \frac{5}{12}\frac{8 + 9\cos(x_{1,3})}{-14 + 9\cos(x_{1,3})^2} & \frac{5}{48}\frac{95 + 72\cos(x_{1,3})}{-14 + 9\cos(x_{1,3})^2} \end{bmatrix}$$

$$\phi(x_1) = \begin{bmatrix} 0 \\ 73.5\cos(x_{1,2}) + 39.2\cos(x_{1,2} + x_{1,3}) \\ 39.2\cos(x_{1,2} + x_{1,3}) \end{bmatrix}$$

with the Christoffel symbols being

$$(c(x_1,x_2)x_2)_1 = \begin{bmatrix} [x_{2,2}[-\frac{81}{40}\sin(2x_{1,2}) - \frac{4}{5}\sin(2x_{1,3} + 2x_{1,2}) - \frac{12}{5}\sin(x_{1,3} + 2x_{1,2})] \\ + x_{2,3}[(-\frac{4}{5}\sin(2x_{1,3} + 2x_{1,2}) - \frac{6}{5}\sin(x_{1,3} + 2x_{1,2}) - \frac{6}{5}\sin(x_{1,3})]]x_{2,1} \\ + x_{2,1}[-\frac{81}{40}\sin(2x_{1,2}) - \frac{4}{5}\sin(2x_{1,3} + 2x_{1,2}) - \frac{12}{5}\sin(x_{1,3} + 2x_{1,2})]x_{2,2} \\ + x_{2,1}[-\frac{4}{5}\sin(2x_{1,3} + 2x_{1,2}) - \frac{6}{5}\sin(x_{1,3} + 2x_{1,2}) - \frac{6}{5}\sin(x_{1,3})]x_{2,3} \end{bmatrix}$$

$$(c(x_1,x_2)x_2)_2 = \begin{bmatrix} x_{2,1}^2[\frac{81}{40}\sin(2x_{1,2}) + \frac{4}{5}\sin(2x_{1,3} + 2x_{1,2}) + \frac{12}{5}\sin(x_{1,3} + 2x_{1,2})] \\ -\frac{12}{5}x_{2,3}\sin(x_{1,3})x_{2,2} + [-\frac{12}{5}x_{2,2}\sin(x_{1,3}) - \frac{12}{5}x_{2,3}\sin(x_{1,3})]x_{2,3} \end{bmatrix}$$

$$(c(x_1,x_2)x_2)_3 = \left[x_{2,1}^2[\frac{4}{5}\sin(2x_{1,3} + 2x_{1,2}) + \frac{6}{5}\sin(x_{1,3} + 2x_{1,2}) + \frac{6}{5}\sin(x_{1,3}) + \frac{12}{5}x_{2,2}^2\sin(x_{1,3})]\right]$$

2.2 Parallelogram Type Manipulator

The Parallelogram Type Elbow manipulator is shown in Figure 2-2.

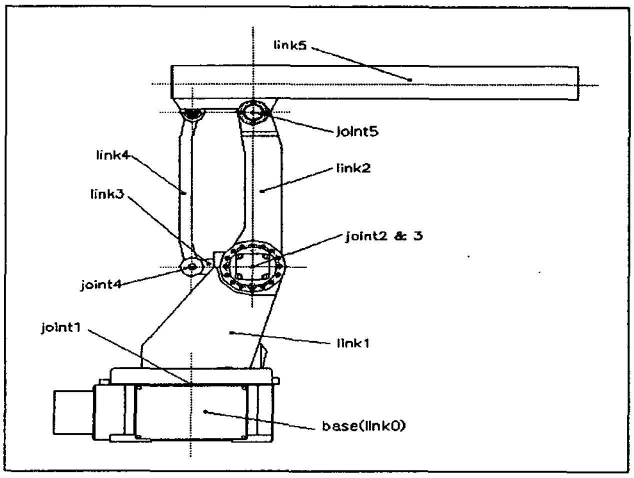

Figure 2-2. Parallelogram Type elbow manipulator

The variables q_i and their first derivatives were selected as the state variables with q_i representing the relative joint angle between two links[7].

The state space representation of the parallelogram robot is given by

$$\dot{x} = f(x) + \hat{D}(x)u$$

$$y = Ex$$

where

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \in \mathbb{R}^{2n}, \quad f(x) = \begin{bmatrix} x_2 \\ D(x_1)^{-1}(-C(x_1,x_2)x_2 - \phi(x_1)) \end{bmatrix}$$

$$\hat{D}(x) = \begin{bmatrix} 0 \\ D(x_1)^{-1} \end{bmatrix}, \quad E = [I_n, 0]$$

and

$$x_1 = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} \qquad x_2 = \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix}$$

Then the exact form of the matrix and vector coefficients for the parallel-drive 3-link manipulator is

$$D(x_1) = \begin{bmatrix} \frac{4}{5}\cos(2x_{1,2}) + \frac{111}{100} + \frac{31}{100}\cos(2x_{1,3}) & 0 & 0 \\ 0 & \frac{517}{300} + \frac{11}{300}\cos(2x_{1,2} - 2x_{1,1}) & 0 \\ 0 & 0 & \frac{31}{50} \end{bmatrix}$$

$$D(x_1)^{-1} = \begin{bmatrix} \frac{100}{80\cos(2x_{1,2}) + 111 + 31\cos(2x_{1,3})} & 0 & 0 \\ 0 & \frac{300}{571 + 119\cos(2x_{1,2} - 2x_{1,1})} & 0 \\ 0 & 0 & \frac{50}{31} \end{bmatrix}$$

$$\phi(x_1) = \begin{bmatrix} 0 \\ 58.92\cos(x_{1,2}) \\ 11.784\cos(x_{1,3}) \end{bmatrix}.$$

with the Christoffel symbols being

$$(c(x_1,x_2)x_2)_1 = \begin{bmatrix} x_{2,1}[-\frac{4}{5}x_{2,2}\sin(2x_{1,2}) - \frac{31}{100}x_{2,3}\sin(2x_{1,3})] \\ + x_{2,2}[-\frac{4}{5}x_{2,1}\sin(2x_{1,2}) - \frac{11}{300}x_{2,2}\sin(2x_{1,2} - 2x_{1,1})] \\ - x_{2,3}[\frac{31}{100}x_{2,1}\sin(2x_{1,3})] \end{bmatrix}$$

$$(c(x_1,x_2)x_2)_2 = \begin{bmatrix} x_{2,1}[\frac{4}{5}x_{2,1}\sin(2x_{1,2}) + \frac{11}{300}x_{2,2}\sin(2x_{1,2} - 2x_{1,1})] \\ + x_{2,2}[\frac{11}{300}x_{2,1}\sin(2x_{1,2} - 2x_{1,1}) - \frac{11}{300}x_{2,2}\sin(2x_{1,2} - 2x_{1,1})] \end{bmatrix}$$

$$(c(x_1,x_2)x_2)_3 = \begin{bmatrix} x_{2,1}^2[\frac{31}{1005}\sin(2x_{1,3})] \end{bmatrix}$$

3. Controller Design

3.1 Problem Formulation

The following problem is to be solved. Given the robot dynamic model, and the linear reference model (exosystem), find an output feedback control law such that the resulting robot output converges asymptotically to the corresponding model output y_R, i.e.,

$$\lim_{t\to\infty} e_R(t) = \lim_{t\to\infty}(y(T) - y_R(t)) = 0. \quad (3.1)$$

In addition, the control objective of the output controller is to observer ensure internal stability namely, the combined system comprising the plant and controller (excluding the reference model) must be stable, so that the corresponding state error vector tends to zero when no tracking is present.

The following notation is used

$$x_1^* := C\zeta = y_R,\quad x_2^* := CN\zeta = \dot{y}_R,\quad u^* := CN^2\zeta + CNSw = \ddot{y}_R \qquad (3.2)$$

It may be seen that, for every admissible w, the state components

$$\begin{aligned} \dot{x}_1^* &= x_2^*, \\ \dot{x}_2^* &= u^* \end{aligned} \qquad (3.3).$$

with $x_1^*(0) = y_R(0) = C\zeta(0), \quad x_2^*(0) = CN\zeta(0) = \dot{y}_R$

If a controller-observer is synthesized, such that the resulting state trajectory $x(t)$ of the robot dynamic model converges asymptotically to the state

$$x^*(t) = \begin{bmatrix} x_1^*(t) \\ x_2^*(t) \end{bmatrix}$$

of the linear reference model, then it guarantee that the output $y(t)$ of the robot converges asymptotically to the output $y_R(t)$.

Finally, it should be noticed that the synthesis approach is based on the assumption that an upper bound on the robot initial velocity norm is apriori available.

3.2 Structure of the Controller

The following observer-based controller, which is based on [6] is proposed:

$$\begin{aligned} \dot{\hat{x}}_1 &= \hat{x}_2 + F^*(t)y - R(\hat{x}_1 - y), \\ \dot{\hat{x}}_2 &= u^* - L(\hat{x}_1 - x_1^*) - F^*(t)(\hat{x}_2 + F^*(t)y) - A(\hat{x}_2 + F^*(t)y - x_2^*) - 2(x_2^{*T} u^*)Gy, \end{aligned} \qquad (3.4)$$

with the output

$$\hat{y} = \begin{bmatrix} \hat{x}_1 \\ \hat{x}_1 + F^*(t)y \end{bmatrix} \qquad (3.5)$$

where the $n \times n$ time-dependent matrix $F^*(t)$ is defined as

$$F^*(t) := B + (x_2^{*T}(t)x_2^*(t))G. \qquad (3.6)$$

Therefore, the input to the robot (the vector of the torques) is given by

$$\begin{aligned} u = g(y) + C(y,\hat{y}_2)\hat{y}_2 + D(y)[u^* - L(\hat{x}_1 - x_1^*) \\ - K(y - \hat{x}_1) - A(\hat{x}_2 + F^*(t)y - x_2^*)]. \end{aligned} \qquad (3.7)$$

The structure of the proposed controller is shown in Figure 3-1.

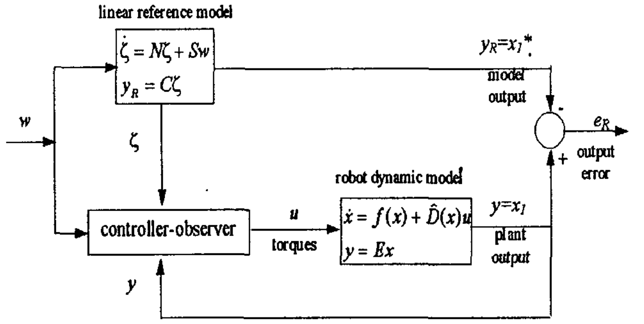

Figure 3-1: Structure of the controller for robot model matching

While the controller is nonlinear, by noting that the functions $x^*(\cdot)$ and $u^*(\cdot)$ are obtained from the linear reference model, it appears that its dynamic part is a linear time-varying system with continuous coefficients and piecewise continuous input function.

A constructive proof for the performance of the proposed controller as well as a detailed description of its parameters will not be discussed. Generally, the theoretical proof deals with the concepts of exponential and semi-global stability.

Firstly, for the reference model, such matrices C, N and S are used so that finally, the reference input w is exactly the *acceleration* whereas the reference model is a double integrator thus producing in addition to the reference *acceleration* ($u^* = \ddot{y}_R = w$). The reference *position* is $x_1^* = y_R$ and the *velocity* is $x_2^* = \dot{y}_R$.

The matrices A, B, G, K, L, R are symmetric constant matrices defined as

$$K := I_n, \quad R := rI_n, \quad G := gI_n, \quad B := R + \beta G \qquad (3.8)$$

and, A and L are selected arbitrarily, though the convergence behavior is greatly dependent on this selection. The coefficients r, g, and β are determined by the robot parameters and the upper bound of the reference input w.

Finally, it should be outlined again that the initial conditions of the controller $\hat{z}_1(0)$, $\hat{z}_2(0)$, $\hat{x}_1(0)$ and $\hat{x}_2(0)$ are selected arbitrarily, whereas x_1 is a measurable signal. Also the initial conditions for the reference model should be known.

4. Simulations and Evaluation

Experiments were performed on the elbow manipulators described in Section 3 to verify the applicability of the proposed control algorithm. The proposed control algorithm is implemented on the on-board Alpha processor based on dSPACE system, which is a single computer system. Tables 4-1, 4-2 show the parameters of the serial and parallelogram type elbow manipulators used in this research.

The arms' masses			The arms' lengths		
m_1	m_2	m_3	l_1	l_2	l_3
10kg	5kg	10kg	1m	0.6m	0.8m

Table 4-1. The Physical Parameters of the Serial Type Elbow Manipulator

The arms' masses					The arms' lengths				
m_1	m_2	m_3	m_4	m_5	l_1	l_2	l_3	l_4	l_5
10kg	10kg	2kg	10kg	5kg	0.1m	0.4m	0.2m	0.4m	0.4m

Table 4-2. The Physical Parameters of the Parallelogram Type Elbow Manipulator

The tuned parameters of the controller that used are shown in Table 4-3.

Factor	Values	Comments
η	4.069	Inertia Matrix
Kc	3.841	Coriolis and Centrifugal
γ	31.270	$2\,\eta\,Kc$
g	32.000	$g > \gamma$
δ	10.000	$\delta = \nu$
ν	10.000	
μ	40.900	
σ	15.500	
r_e	2.000	Closed ball
φ	2.000	Any $\varphi > 1$
β	182.000	
r	6254.000	

Table 4-3. The Parameters of the Controller

The selected initial conditions are as follows

$$x_1(0)=x_2(0)=\begin{bmatrix}1\\2\\3\end{bmatrix},\quad \dot{x}_1(0)=\dot{x}_2(0)=\begin{bmatrix}0\\0\\0\end{bmatrix},$$

$$z_1(0)\doteq z_2(0)=\begin{bmatrix}0\\0\\0\end{bmatrix},\quad \hat{x}_1(0)=\begin{bmatrix}0\\0\\0\end{bmatrix},\quad \hat{x}_2(0)=\begin{bmatrix}-0.7008\\-1.4016\\-2.1024\end{bmatrix}$$

and the linear model reference input is

$$w(t)=\begin{bmatrix}2\sin(5t)\\4\sin(10t)\\8\sin(15t)\end{bmatrix}u_s(t)$$

where $u_s(t)$ is the unit step function.

4.1 Serial Type Manipulator

The general block diagram of the controller for the serial type elbow manipulator is shown is shown in Figure 4-1.

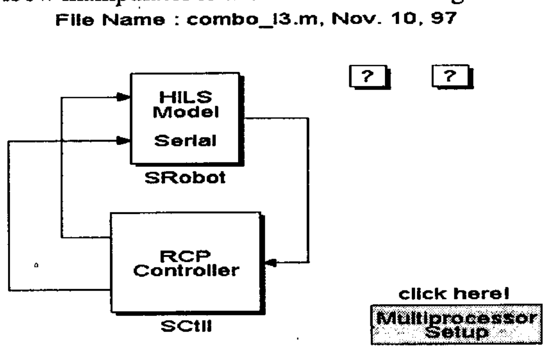

Figure 4-1. Real-time Evaluation Model

The three signals of the desired and actual trajectories are shown in Figure 4-2 to 4-3 with the tuned control parameters. The convergence of the output error function to zero in the manipulator is demonstrated.

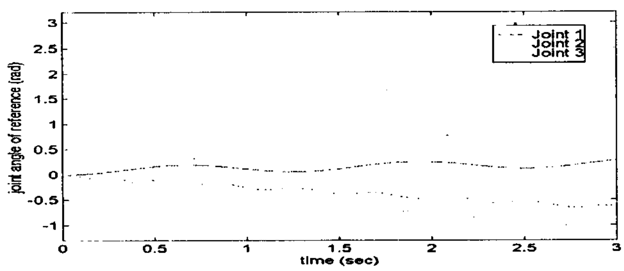

Figure 4-2. Desired Trajectories of the manipulator

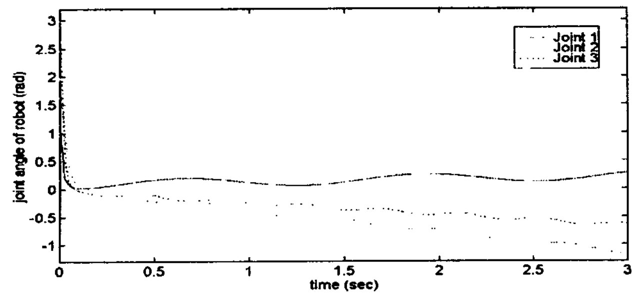

Figure 4-3. Actual Trajectories of the Joint of the Robot

4.2 Comparison of Two Type Manipulator

The upper side of Figure 4-4 shows the bigger execution time of the serial type elbow manipulator running on dSPACE. This unwanted result is caused from the complexity of the model. The total executing time for the serial type elbow is 25us at average ; the parallelogram is 15us.

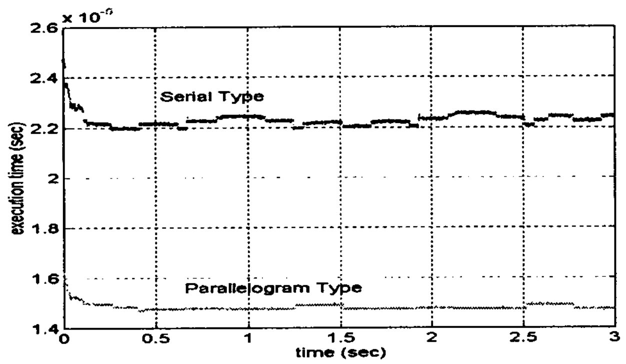

Figure 4-4. The comparison of the execution time of two manipulates

The over-all torques required to get the desired trajectory of two manipulators is shown in Figure 4-5.

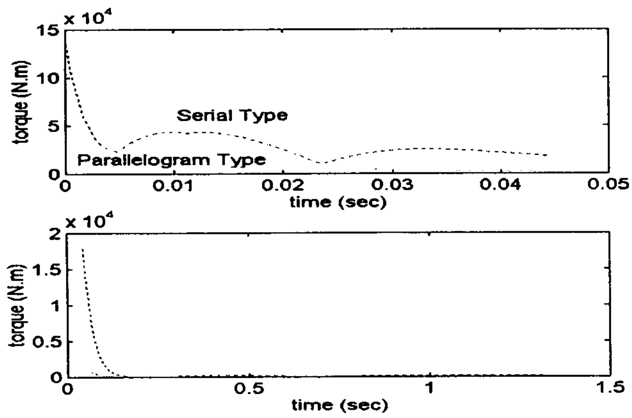

Figure 4-5. The comparison of the total torque between 0.0-1.5sec

5. Summary and Conclusion

The goal of the work described in this paper is to show recent developments and studies in the framework of practical realization of output tracking control in the field of robotics, specifically two elbow manipulators. In this paper we present how to apply HILS and RCP concepts to two different well-known robot manipulators, namely the serial type and the parallelogram drive type manipulator. Two different types of models and output controllers of manipulator are presented and the detailed results based on dSPACE are derived. Experimental results demonstrated that the total execution time of the implemented system and the torques required to get the desired position and velocity of the parallelogram type manipulator are smaller than that of the serial type manipulator.

As shown in this paper, the concepts mentioned are very useful for the analysis of robot dynamics and evaluating of the designed model and controller taking into account not only set-point control, but also output tracking control case. An experimental consideration of implementing the proposed control architecture on a RLFJ manipulator is of course a subject for further study

6. Reference

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