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A Linear Output Feedback Controller for a 2-DOF Parallel Robot

Zongtao Lu and Xiaoping Liu

Abstract— **This paper studies the problem of output feedback control for a 2-DOF parallel robot. The dynamics of the parallel robots are characterized a set of ordinary differential equations(ODEs). Under the condition of bounded joint velocities, a linear output dynamic compensator is designed to guarantee the semi-global exponential stability of the closed-loop system. The bound of velocity can be made arbitrarily large by appropriately tuning the observer gain, which leads to semi-global stability. Simulation results are given to illustrate the proposed output feedback controller.**

I. INTRODUCTION

The mechanisms of parallel robots are also known as closed kinematic chains. Different from serial robots, parallel robots have the links connected in series as well as in parallel combinations forming one or more closed-link loops and typically not all the joints are actuated. The actuators are placed closer to the base or on the base itself. This makes parallel robots have lighter moving parts, which leads to greater efficiency and faster acceleration at the end-effector. Parallel robots also offer greater payload handling capability for the same number of actuators. Due to these advantages, parallel robots recently have been receiving growing attention from both academia and industries [10], [8], [9], [19], [20] and etc. Fig. 1 shows planar examples of a parallel robot and a serial robot.

The existing control schemes of parallel robots are all characterized by a state feedback control, such as proportional integral derivative (PID) control [1], artificial intelligence-based algorithms [3] and nonlinear control [15]. In [6], the mass and inertia of the links were neglected in the dynamic model in order to implement the computed-torque control. A PD plus simple gravity compensation control law was proposed in [10] for set point control for a planar 2-DOF parallel robot. In [13], the design for control approach was employed in the design stage of a parallel robot to find an appropriate mechanical structure with a simple dynamic model.

The implementation of the state feedback controllers require the measurements for all the state variables. The need for velocity feedback shows the drawback lying in two main reasons [5]. First, although robotic systems are equipped with the sensors for velocity measurements, the circumstance may reduce the dynamic performance of the robotic system because the approximated velocities are often contaminated by the presence of noise [11]. Second, velocity sensors are frequently omitted due to the savings in cost, volume and weight [12]. Using the derived velocity signal by first-order numerical differentiation of the position signal is one way to bypass the velocity feedback problem. However, such a simple approximation may be inadequate especially for relatively high or low velocities [4]. Moreover, with differentiation, even low levels of noise in position signal may generate unacceptable large velocity noise [7]. For this reason, a band-pass filter is necessary for the derived velocity signal but no systematic approach to the filter design is established yet. Therefore, there are some literature reported on the output feedback control design for robotic systems [14], [21], [2].

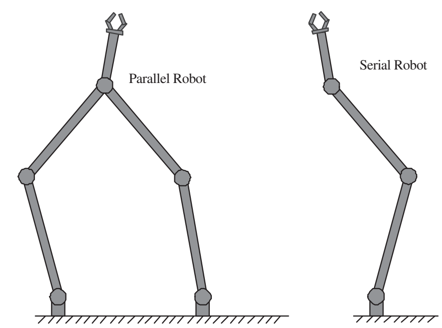

Fig. 1. A planar parallel robot and a serial robot

In this paper, we consider the output feedback control of a 2-DOF parallel robot without using the velocity information. The dynamic model of 2-DOF parallel robot are characterized by a set of differential algebraic equations (DAEs)

$$D'(q')\ddot{q}' + C'(q',\dot{q}')\dot{q}' + g'(q') = u' \qquad (1)$$

$$\phi(q') = 0 \qquad (2)$$

where $q' \in \mathcal{R}^4$ denotes the vector of generalized coordinates, $D'(q') \in \mathcal{R}^{4\times 4}$ is the symmetric positive define inertia matrix which is bounded for any q', $C'(q',\dot{q}')\dot{q}'$ represents the centrifugal and Coriolis terms, $g'(q') \in \mathcal{R}^4$ is the gravity vector and $\phi(q') \in \mathcal{R}^2$ is the constraint holonomic constraint. By eliminating the Lagrangian multipliers originating from the algebraic constraints, the set of DAEs end up with the following second order ODE with 2-DOF [10],

$$D(q')\ddot{q} + C(q',\dot{q}')\dot{q} + g(q') = u \qquad (3)$$

where $q \in \mathcal{R}^2$ denotes the independent generalized coordinates, $D(q') \in \mathcal{R}^{2\times 2}$, $C(q',\dot{q}')\dot{q} \in \mathcal{R}^{2\times 2}$ and $g(q') \in \mathcal{R}^2$.

Based on the resulting ODE model, one linear observer is built to estimate the joint velocities. Inspired by [17], we

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Zongtao Lu is with Dept. of Electrical Engineering and Computer Science, Case Western Reserve University, Cleveland, Ohio 44106, USA.

Xiaoping Liu is with the Department of Electrical Engineering, Lakehead University, Thunder Bay, ON, Canada.

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prove that the following linear output compensator

$$\begin{aligned} \dot{\xi} &= M\xi + Ny \\ v &= K\xi \end{aligned} \tag{4}$$

with $v = D^{-1}(q')\,[u - g(q')]$ guarantees that the corresponding closed-loop system is semi-globally exponentially stable, i.e., by appropriately tuning the designed observer gain, the attraction region of the velocity variables can be arbitrarily large.

The rest of the paper is organized as follows. The dynamic model of the planar 2-DOF parallel robot is presented in next section. In Section III, a linear output feedback controller is designed making the closed-loop system semi-globally exponentially stable. Simulation results are given in Section IV. Finally the conclusions are drawn in Section V.

II. ROBOT MODEL

A schematic of a planar 2-DOF parallel robot is shown in Fig. 2, where m_i, a_i, and l_i are the mass, length and distance to the center of mass from the lower joint of link i, respectively, for $i = 1, 2, 3, 4$. I_i denotes the mass moment of inertia of link i. Joints q_1 and q_2 are actuated while joints q_3 and q_4 are passive.

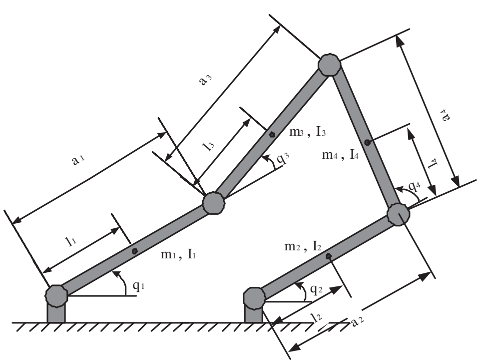

Fig. 2. A schematic of a planar 2-DOF parallel robot

Recall the dynamic model of DAEs (1)-(2). With the imposed constraint (2), it follows from the equation (1) that the resulting dynamic system has 2-DOF and there exist two independent generalized coordinates $q = \begin{bmatrix} q_1 & q_2 \end{bmatrix}^T$, such that the parallel robotic system can be written by a second-order ODE

$$D(q')\ddot{q} + C(q', \dot{q}')\dot{q} + g(q') = u \tag{5}$$

$$q' = \sigma(q) \tag{6}$$

$$\dot{q}' = \rho(q)\dot{q} \tag{7}$$

where q' and $\dot{q}'$ can be expressed analytically by the functions of q and $\dot{q}$ in (6) and (7) respectively, which can be found in [10].

Without the constraint (2), consider the dynamic equation of the serial robot in (1) , which is independent of constraints and has 4-DOF. It is well-known that (1) is characterized by the following properties.

Property 1: The inertia matrix, $D'(q')$, defined in (1) satisfies the following inequality [18]

$$d_1 \leq \|D'(q')\| \leq d_2 \tag{8}$$

where d_1 and d_2 are known positive scalar constants, $\|\cdot\|$ represents the Euclidean norm.

Property 2: The Euclidean norm of $C'(q', \dot{q}')$ satisfies the inequality [16]

$$\|C'(q', \dot{q}')\| \leq k_c \|\dot{q}'\| \tag{9}$$

where k_c is a known positive scalar constant.

In the following content of this section, we will present the parallel robotic system (5)-(7) has similar properties.

Let $z_1 = q - q_d$ and $z_2 = \dot{q}$ where q_d denotes the desired set point and (5) is expressed as

$$\dot{z}_1 = z_2 \tag{10}$$

$$\dot{z}_2 = D^{-1}(q')\,[u - C(q', \dot{q}')\dot{q} - g(q')] \tag{11}$$

Define the new control input

$$v = D^{-1}(q')\,[u - g(q')] \tag{12}$$

and note that the equation (12) is independent of $\dot{q}$. Then (10)-(11) can be rewritten as

$$\dot{z}_1 = z_2 \tag{13}$$

$$\dot{z}_2 = v + \phi(z_1, z_2) \tag{14}$$

$$y = z_1 \tag{15}$$

where $\phi(z_1, z_2) = -D^{-1}(q')C(q', \dot{q}')\dot{q}$ and the output y represents the position difference to the set point.

From the relationship represented in [10], we have

$$D(q') = \rho^T(q')D'(q')\rho(q') \tag{16}$$

$$\begin{aligned} C(q', \dot{q}') &= \rho^T(q')C'(q', \dot{q}')\rho(q') \\ &\quad + \rho^T(q')D'(q')\dot{\rho}(q') \end{aligned} \tag{17}$$

$$g(q') = \rho^T(q')g'(q') \tag{18}$$

where

$$\rho(q^{'}) = \psi_{q'}^{-1}(q') \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^T \tag{19}$$

$$\dot{\rho}(q') = -\psi_{q'}^{-1}(q')\dot{\psi}_{q'}(q', \dot{q}')\rho(q') \tag{20}$$

$$\psi_{q'}(q^{'}) = \begin{bmatrix} \psi(1,1) & \psi(1,2) & \psi(1,3) & \psi(1,4) \\ \psi(2,1) & \psi(2,2) & \psi(2,3) & \psi(2,4) \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{21}$$

where $\psi(1,1) = -a_1 \sin(q_1) - a_3 \sin(q_1 + q_3)$, $\psi(1,2) = a_2 \sin(q_2) + a_4 \sin(q_2 + q_4)$, $\psi(1,3) = -a_3 \sin(q_1 + q_3)$, $\psi(1,4) = a_4 \sin(q_2 + q_4)$, $\psi(2,1) = a_1 \cos(q_1) + a_3 \cos(q_1 + q_3)$, $\psi(2,2) = -a_2 \cos(q_2) - a_4 \cos(q_2 + q_4)$, $\psi(2,3) = a_4 \cos(q_1 + q_3)$, $\psi(2,4) = -a_4 \cos(q_2 + q_4)$. For $i = 1, 2, 3, 4$, a_i are constant parameters.

It is not difficult to observe that the norm of $\psi_{q'}(q')$ is bounded by known constants and its time derivative of $\dot{\psi}_{q'}(q', \dot{q}')$ is bounded by the linear term of $\|\dot{q}'\|$. Hence, by (19) and (20), $\rho(q')$ and $\dot{\rho}(q')$ have the relationship as

$$c_{\rho 1} \leq \|\rho(q')\| \leq c_{\rho 2}$$

$$\|\dot{\rho}(q')\| \leq k_\rho \|\dot{q}'\|$$

where $c_{\rho 1}$, $c_{\rho 2}$ and k_ρ are known positive constants.

The dependent coordinates q_3 and q_4 are derived from the geometric relationships (6) and expressed as a function of q_1 and q_2. The function $\sigma(q)$ can be bounded by q's linear term, i.e.$\|\sigma(q)\| \leq c_\sigma \|q\|$.

With this in mind, recalling Property 1 and Property 2, (16)-(17) lead to

$$c_{D1} \leq \|D(q')\| \leq c_{D2} \tag{22}$$

$$\|C(q', \dot{q}')\| \leq k_C \|\dot{q}\| \tag{23}$$

with known constants c_{D1}, c_{D2} and k_C. Therefore, $\phi(z_1, z_2) = -D^{-1}(q')C(q', \dot{q}')\dot{q}$ is bounded by z_2's quadratic term, i.e.

$$\|\phi(z_1, z_2)\| \leq k_\phi \|z_2\|^2 \tag{24}$$

with k_ϕ being known constant.

III. OUTPUT FEEDBACK DESIGN

In this section, we are going to show that if the joint velocities can be bounded by a known constant number, then a linear output feedback controller can be designed for set point control of the parallel robot.

Assumption 1: We assume the velocity of the generalized coordinates $\dot{q}$ is bounded by a known positive constant number, i.e.

$$\|\dot{q}\| \leq k_v \tag{25}$$

Note that, under Assumption 1, the bounded condition in (24) leads to

$$\|\phi(z_1, z_2)\| \leq k \|z_2\| \tag{26}$$

with $k = k_v k_\phi$ being a known constant.

Theorem 1: Under Assumption 1, there exists a linear output feedback controller making the system (13)-(15) semi-globally exponentially stable.

Proof. The proof consists of two parts. First of all, we design a linear high-gain observer motivated by [17] by the boundary condition but not using the information of the system nonlinearity, i.e $\phi(z_1, z_2)$. This results in an error dynamics producing a extra term. We then construct an output controller to take care of the extra term arising from the observer design. The design procedure is accomplished by choosing the gain parameters. At last, a linear output dynamic compensator is obtained, making the closed-loop system semi-globally exponentially stable.

A. Design of Linear High-Gain Observer

We begin with designing the following linear observer

$$\begin{aligned} \dot{\hat{z}}_1 &= \hat{z}_2 + La(z_1 - \hat{z}_1) \\ \dot{\hat{z}}_2 &= v + L^2 b(z_1 - \hat{z}_1) \end{aligned} \tag{27}$$

where $a > 0$, $b > 0$ and $L > 1$ is the gain parameter to be determined later.

Define $e_1 = z_1 - \hat{z}_1$ and $e_2 = (z_2 - \hat{z}_2)/L$. Then the error dynamics is given as

$$\begin{aligned} \dot{e}_1 &= -Lae_1 + Le_2 \\ \dot{e}_2 &= -Lbe_1 + \frac{1}{L}\phi(z_1, z_2) \end{aligned} \tag{28}$$

or, in a compact form

$$\dot{e} = LAe + \begin{bmatrix} 0 \\ \frac{1}{L}\phi(z_1, z_2) \end{bmatrix} \tag{29}$$

where

$$e = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} \text{ and } A = \begin{bmatrix} -a & 0 & 1 & 0 \\ 0 & -a & 0 & 1 \\ -b & 0 & 0 & 0 \\ 0 & -b & 0 & 0 \end{bmatrix}.$$

It is easy to see that A is a Hurwitz matrix. Hence, there is a positive definite matrix $P = P^T > 0$ such that

$$A^T P + PA = -I$$

Consider the Lyapunov function $V_0(e) = 3e^T Pe$. By Assumption 1, there is a positive constant number c_1, which is independent of L, such that

$$\begin{aligned} \dot{V}_0(e) &= 3Le^T(A^T P + PA)e + 6e^T P \begin{bmatrix} 0 \\ \frac{1}{L}\phi(\cdot) \end{bmatrix} \\ &\leq -3L\|e\|^2 + \frac{c_1}{L}\|e\|\|z_2\| \end{aligned}$$

Recall that $z_2 = \hat{z}_2 + Le_2$. Hence, $\|z_2\| \leq \|\hat{z}_2\| + L\|e_2\|$. With this in mind, it is not difficult to show that

$$\begin{aligned} \dot{V}_0(e) &\leq -(3L - c_1)\|e\|^2 + \frac{c_1}{L}\|e\|\|\hat{z}_2\| \\ &\leq -(3L - c_1)\|e\|^2 + \frac{c_1}{2}\left(\|e\|^2 + \frac{1}{L^2}\|\hat{z}_2\|^2\right) \\ &\leq -\left(3L - \frac{3}{2}c_1\right)\|e\|^2 + \frac{c_1}{2L^2}\|\hat{z}_2\|^2 \end{aligned}$$

B. Construction of an Output Feedback Controller

Step 1: Construct the Lyapunov function $V_1(e, z_1) = V_0(e) + \frac{1}{2}\hat{z}_1^T\hat{z}_1$. A straightforward calculation gives

$$\begin{aligned} \dot{V}_1 &\leq -\left(3L - \frac{3}{2}c_1\right)\|e\|^2 + \frac{c_1}{2L^2}\|\hat{z}_2\|^2 + \hat{z}_1^T(\hat{z}_2 \\ &\quad + Lae_1) \\ &\leq -\left(2L - \frac{3}{2}c_1\right)\|e\|^2 + \frac{c_1}{2L^2}\|\hat{z}_2\|^2 + \hat{z}_1^T\hat{z}_2 \\ &\quad + \frac{1}{4}La^2\|\widehat{z}_1\|^2 \end{aligned}$$

Define $\xi_2 = \hat{z}_2 - \hat{z}_2^*$ with $\hat{z}_2^*$ being a virtual controller and observe that

$$\frac{c_1}{2L^2}\|\hat{z}_2\|^2 \leq \frac{c_1}{L^2}\|\xi_2\|^2 + \frac{c_1}{L^2}\|\hat{z}_2^*\|^2$$

With this in mind, it follows that

$$\begin{aligned} \dot{V}_1 &\leq -\left(2L - \frac{3}{2}c_1\right)\|e\|^2 + \hat{z}_1^T\hat{z}_2 + \frac{1}{4}La^2\|\hat{z}_1\|^2 \\ &\quad + \frac{c_1}{L^2}\|\xi_2\|^2 + \frac{c_1}{L^2}\|\hat{z}_2^*\|^2 \end{aligned}$$

By choosing the virtual controller

$$\hat{z}_2^* = -Ld_1\hat{z}_1 \text{ with } d_1 := 2 + \frac{1}{4}a^2 \tag{30}$$

the time derivative $\dot{V}_1$ leads to

$$\begin{aligned}\dot{V}_1 \quad &\leq \quad -\left(2L - \frac{3}{2}c_1\right)\|e\|^2 - \left(2L - c_1 d_1^2\right)\|\hat{z}_1\|^2 \\ &\quad +\hat{z}_1^T\xi_2 + \frac{c_1}{L^2}\|\xi_2\|^2\end{aligned}$$

Step 2: Construct the Lyapunov function $V_2(e, z_1, z_2) = V_1(e, z_1) + \frac{1}{2L^2}\xi_2^T\xi_2$. Calculating its time derivative gives

$$\begin{aligned}\dot{V}_2 \quad &\leq \quad -\left(2L - \frac{3}{2}c_1\right)\|e\|^2 - \left(2L - c_1 d_1^2\right)\|\hat{z}_1\|^2 + \hat{z}_1^T\xi_2 \\ &\quad +\frac{1}{L^2}\xi_2^T\left[v + L^2 b e_1 - \frac{\partial \hat{z}_2^*}{\partial \hat{z}_1}(\hat{z}_2 + Lae_1)\right] \\ &\quad +\frac{c_1}{L^2}\|\xi_2\|^2\end{aligned}$$

Note that

$$\begin{aligned}&\frac{1}{L^2}\xi_2^T\left(L^2 b e_1 - \frac{\partial \hat{z}_2^*}{\partial \hat{z}_1}Lae_1\right) \\ \leq \quad &\frac{1}{L}(b + ad_1)^2\|\xi_2\|^2 + L\|e\|^2\end{aligned}$$

and

$$\hat{z}_1^T\xi_2 \leq L\|\hat{z}_1\|^2 + \frac{1}{4L}\|\xi_2\|^2$$

Then, we have

$$\begin{aligned}\dot{V}_2 \quad &\leq \quad -\left(L - \frac{3}{2}c_1\right)\|e\|^2 - \left(L - c_1 d_1^2\right)\|\hat{z}_1\|^2 \\ &\quad +\left[\frac{1}{L}\left((b + ad_1)^2 + \frac{1}{4}\right) + \frac{c_1}{L^2}\right]\|\xi_2\|^2 \\ &\quad +\frac{1}{L^2}\xi_2^T\left[v + Ld_1\xi_2 - L^2 d_1^2\hat{z}_1)\right]\end{aligned}$$

It is easy to see that one can design the linear controller

$$\begin{aligned}v \quad &= \quad L^2 d_1^2\hat{z}_1 - (L^2 + Ld_2 + c_1)\xi_2 \\ &= \quad Ld_1(Ld_1 - 1)\hat{z}_1 - (L^2 + Ld_2 + c_1)\hat{z}_2\end{aligned} \tag{31}$$

with $d_2 := (b + ad_1)^2 + d_1 + \frac{1}{4}$, such that

$$\dot{V}_2 \leq -\left(L - \frac{3}{2}c_1\right)\|e\|^2 - \left(L - c_1 d_1^2\right)\|\hat{z}_1\|^2 - \|\xi_2\|^2 \tag{32}$$

If we choose the gain constant $L > L^* := \max\{c_1 d_1^2, \frac{3}{2}c_1\}$, then the right side of the inequality (32) becomes negative definite. Note that $V_2(e, z_1, z_2)$ is a positive definite and proper function which is defined by

$$V_2(e, z_1, z_2) = 3e^T Pe + \frac{1}{2}\hat{z}_1^T\hat{z}_1 + \frac{1}{2L^2}\xi_2^T\xi_2$$

Therefore, the closed-loop system is semi-globally exponentially stable. Recall the definition of v in (12), the designed control input u is

$$u = D(q')v + g(q') \tag{33}$$

∎

TABLE I

LINK PARAMETERS

Link i	m_i (kg)	a_i (m)	l_i (m)	I_i (kg·m^2)
1	0.1950	0.4600	0.3367	4.567×10^{-3}
2	0.1950	0.4600	0.3367	4.567×10^{-3}
3	0.2538	0.4600	0.2400	8.626×10^{-3}
4	0.2538	0.4600	0.2400	8.626×10^{-3}

Remark 1: With the bound condition (26), c_1 is expressed as $c_1 = 6\|P\| k_v k_\phi$. Hence, the upper bound k_v is

$$k_v = \frac{c_1}{6\|P\| k_\phi}$$

It is obvious that no matter how large is the upper bound of $\dot{q}$, we can always choose the gain

$$L > L^* := \max\{6\|P\| k_\phi k_v d_1^2, 9\|P\| k_\phi k_v\}$$

such that (32) is negative definite, in other words, the attraction region can be arbitrarily large. Therefore, the designed linear output feedback controller guarantees a semi-global exponential stability.

IV. SIMULATION RESULTS

We now discuss the simulation results for the output feedback controller in this section. The link parameters values of the parallel robot are given in Table 1. The distance between the shafts of the two motors is $c = 0.4240$ m.

We conduct two sets of simulations to move the parallel robot between the initial configuration q^i to the final configuration q^f with

$$q^i = \begin{bmatrix} 90^0 \\ 100^0 \end{bmatrix} \text{ and } q^f = \begin{bmatrix} 150^0 \\ 160^0 \end{bmatrix}.$$

The first set and the second set simulations are the set point control from q^i to q^f and from q^f to q^i respectively. The simulation results are shown in Fig. 3 for the first set simulation and Fig. 4 for the second set respectively.

In the simulations, the observer gain is chosen as $L = 800$. Because there is no prior knowledge about the velocities, the gain might be firstly chosen as a relatively large number to guarantee $L > L^*$. The simulation results show that the robot completes the motion in one second and achieves the desired configuration within reasonable tolerances. The performances of the output feedback controller are satisfactory.

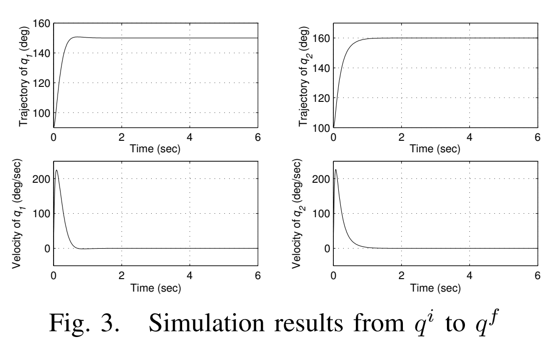

Fig. 3. Simulation results from q^i to q^f

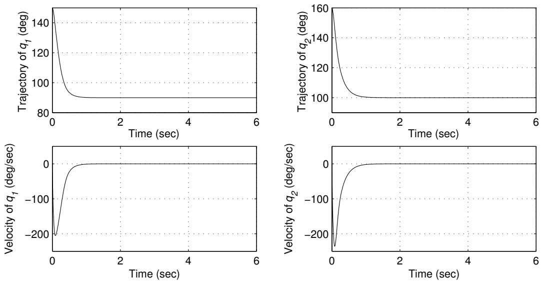

Fig. 4. Simulation results from q^f to q^i

V. CONCLUSIONS AND FUTURE WORKS

We have presented a new output feedback control scheme for set point control of a planar 2-DOF parallel robot. The proposed output dynamic compensator is linear and guarantees the semi-global exponential stability of the closed-loop system. The conducted simulations show the proposed control scheme work well and the results are satisfactory. It is believed that the similar output feedback control scheme can also be applied to the tracking control of the parallel robot.

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