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A Tracking Controller for Mechanical Systems with Only Position Measurements as Feedback

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Abstract: A dynamic feedback control law is presented to solve the tracking problem in completely actuated mechanical systems of n degrees of freedom, this is achieved without using velocity measurements nor observer/differentiator algorithms. Moreover viscous friction can be compensated by the algorithm. Only position measurements are available for feedback, by this way this new proposal do not require to measure or estimate another signal but the position of the mechanical system in order to achieve the control objective. It is proved that the equilibria set of the closed-loop system are globally asymptotically stable.

Keywords: Mechanical systems, friction, dynamic control, output feedback, asymptotic stability

1. INTRODUCTION

In many works related to tracking control design for mechanical systems, the velocity state must be available for feedback, this could be a disadvantage if there is not a velocity sensor available, this situation can be solved using a velocity observer or a differentiator, see Bartolini et al. (2016); Gutiérrez-Giles and Arteaga-Pérez (2014); Shtessel et al. (2014); Rosas et al. (2016) and references therein. Due to this situation, the tracking problem of a nonlinear dynamical system is more complex, since two algorithms must be designed; the observer/differentiator algorithm and the control law.

Many problems arise when an observer design is used, such the gain tuning, not suitable transient response, use of many computational resources, and they can be complicated to implement. Also, because observers form software control loops, they can become unstable under certain conditions, see Ellis (2002). Also, it is necessary to prove stability for the whole closed-loop system, including the plant, observer and controller as a whole system.

There are some previous works about tracking control in Lagrangian systems using only position feedback, see for example Loria (2016) where is proposed a tracking controller for Lagrangian systems with arbitrarily high relative degree; this includes underactuated systems, where instead of using velocity measurements they used the dirty derivative as a replacement of unavailable state measurements, hence obviating the use of observers. In Romero et al. (2015) a solution to the problem of global exponential tracking of mechanical systems without velocity measurements is presented, the proposed controller is obtained combining a redesign of the recently reported exponentially stable immersion and invariance velocity observer and a new state-feedback passivity-based controller, which assigns to the closed-loop a port-Hamiltonian structure with a desired energy function. In Zhao et al. (2015) investigates the distributed finite-time tracking problem of networked agents with multiple Euler—Lagrange dynamics, where a distributed finite-time protocol is first proposed on the basis of both relative position and relative velocity measurements, the control objective is achieved with the aid of second-order sliding-mode observer approach. Some other previous works of tracking control without using velocity measurements are given in Loria (1996); Lizarralde and Wen (1996); Do et al. (2003); Wang et al. (2010); Abdessameud and Tayebi (2010), all of these works obviate the need for the velocity using a filter, an observer or an estimator.

In this work, a dynamic feedback design is considered in order to use only position data to solve the tracking problem in mechanical systems, the result is extended to nDOF (degrees of freedom) Lagrangian systems. The main contribution of the present control approach is that no velocity measurements are needed, neither an observer design nor a differentiator in order to solve the tracking problem in mechanical systems, moreover the control algorithm has only three gain parameters which are very simple to tune, they only must meet certain conditions given in the document. Also, the controller can compensate viscous and Coulomb friction without any measurement or estimation of the velocity, although the friction magnitudes must be known with the purpose of achieving the control objective.

In applications for fully actuated mechanical systems the proposed control law provide the desired tracking performance. A strict Lyapunov function will be used to prove global asymptotic stability of the closed-loop system, for further information about Lyapunov tools see Orlov (2009).

The rest of the paper is organised as follows: In Section 2 is described the statement of the problem in second order dynamical systems, which can be applied in mechanical systems of one degree of freedom on either rotational or translational links, also it is proposed the general structure of the controller. The dynamic output feedback design is presented in Section 3. In Section 4 is proved the global asymptotic stability of the closed-loop system using a strict Lyapunov function. The Section 5 presents the controller extension to Lagrangian systems of nDOF and its stability proof. Section 6 presents an application in a X-Y translational mechanical system, where the tracking problem was addressed. In Section 7 are given some conclusions.

2. PROBLEM STATEMENT

The problem considered in this paper is to design a tracking controller for mechanical systems using output feedback, this is position measurements.

The dynamics of the second order mechanical systems considered in this section are governed by the following state space equations

$$\begin{aligned} \dot{x} &= y \\ \dot{y} &= f(x,t) - f_v y + g(x,t)u \end{aligned} \tag{1}$$

where $f(x,t)$ and $g(x,t)$ are nonlinear functions, being $g(x,t)$ invertible, f_v is the amplitude of the viscous friction. For system (1) the following control design is proposed

$$u = -g(x,t)^{-1}\left(f(x,t) - \tau - \ddot{x}_d\right) \tag{2}$$

where the first term is a compensation, τ is the proposed algorithm, and $\ddot{x}_d$ is the second derivative of the desired trajectory x_d which is C^k, for a sufficiently large k. Substituting (2) in (1) the remaining closed-loop system stands as follows

$$\begin{aligned} \dot{x} &= y \\ \dot{y} &= -f_v y + \tau + \ddot{x}_d. \end{aligned} \tag{3}$$

Let us rewrite system (3) in function of the errors $e_1 = x - x_d$ and $e_2 = y - \dot{x}_d$,

$$\begin{aligned} \dot{e}_1 &= e_2 \\ \dot{e}_2 &= -f_v(e_2 + \dot{x}_d) + \tau \end{aligned} \tag{4}$$

notice that the structure of (4) is a double integrator system with viscous friction.

3. DYNAMIC CONTROL ALGORITHM

The proposed dynamic algorithm to stabilise the system (4) is

$$\begin{aligned} \tau &= -k_1 e_1 + k_2 e_3 + f_v \dot{x}_d \\ \dot{e_3} &= -k_1 e_1 - k_2 e_3 \end{aligned} \tag{5}$$

considering the gain parameters $k_i > 0$, with $i = 1, 2$. Substituting (5) in (4) the closed-loop system is

$$\begin{aligned} \dot{e}_1 &= e_2 \\ \dot{e}_2 &= -k_1 e_1 + k_2 e_3 - f_v e_2 \\ \dot{e_3} &= -k_1 e_1 - k_2 e_3. \end{aligned} \tag{6}$$

The equilibria of the closed-loop system (6) are given by the set

$$(\bar{e}_1, \bar{e}_2, \bar{e}_3) = (0,\ 0,\ 0)\,. \tag{7}$$

4. STABILITY OF THE CLOSED-LOOP SYSTEM

The closed-loop system (6) is globally asymptotically stable around the equilibria set $\bar{e} = [\bar{e}_1, \bar{e}_2, \bar{e}_3]^T \in \mathbb{R}^3$ given by (7), as long as the roots of the polynomial

$$s^3 + (f_v + k_2)s^2 + (f_v + k_1 + k_2)s + 2k_1 k_2$$

have negative real part, notice that even in the absence of friction the closed-loop system can be asymptotically stable.

The above given polynomial is obtained from $det\,(sI - A_{cl})$, where $A_{cl} = [0\ 1\ 0; -k_1\ \ -f_v\ k_2; -k_1\ 0\ \ -k_2]$ is get it from (6).

5. EXTENSION TO NDOF LAGRANGIAN SYSTEMS

Consider a nDOF Lagrangian system described by

$$\mathbf{M}(q)\ddot{q} + \mathbf{C}(q,\dot{q})\dot{q} + \mathbf{G}(q) + \mathbf{F}_v\dot{q} = \tau_u \tag{8}$$

where $q \in \mathbb{R}^n$ is the generalised position vector, $\mathbf{M}(q)$ is the inertia matrix, $\mathbf{C}(q,\dot{q})$ is the centrifugal and Coriolis forces matrix, $\mathbf{G}(q)$ is the gravitational force vector, $\mathbf{F}_v$ is the matrix of viscous friction, and $\tau_u \in \mathbb{R}^n$ is the generalised force or torque input. Let us consider that the measured variable is the generalised position q.

Defining the state variables $x_1 = q$, $x_2 = \dot{q}$, the state-space representation of system (8) is

$$\begin{aligned} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} &= \begin{bmatrix} \dot{x}_2 \\ \mathbf{M}^{-1}(x_1)\left[-\mathbf{C}(x_1,x_2)x_2 - \mathbf{G}(x_1) - \mathbf{F}_v x_2 + \tau_u\right] \end{bmatrix} \\ y &= x_1 \end{aligned} \tag{9}$$

where τ_u is the control input given by

$$\tau_u = \mathbf{G}(x_1) + \tau_c + \mathbf{M}(x_1)\ddot{x}^* \tag{10}$$

$x^* = [x_{d1}, \ldots, x_{dn}]^T \in \mathbb{R}^n$ is the vector of desired trajectories, also $\dot{x}^*, \ddot{x}^* \in \mathbb{R}^n$. Now defining $z_1 = x_1 - x^*$ and $z_2 = x_2 - \dot{x}^*$, the proposed controller that can be applied to nD**OF** is

$$\begin{aligned} \tau_c &= -\mathbf{K}_1 z_1 + \mathbf{K}_2 z_3 + \mathbf{C}(x_1, \dot{x}^*)\dot{x}^* \\ \dot{z_3} &= -\mathbf{K}_1 z_1 - \mathbf{K}_2 z_3 \end{aligned} \tag{11}$$

where $\mathbf{K}_1$, $\mathbf{K}_2 \in \mathbb{R}^{n\times n}$ are tunable gains matrices which are diagonal positive definite. The closed-loop system according to the variables $z = [z_1, z_2, z_3]^T$ stands as follows

$$
\begin{aligned}
\dot{z_1} &= z_2 \\
\dot{z_2} &= -\mathbf{M}^{-1}(x_1)\left[\mathbf{K}_1 z_1 - \mathbf{K}_2 z_3 + \mathbf{C}(x_1,x_2)x_2 \right. \\
&\quad \left. -\mathbf{C}(x_1,\dot{x}^*)\dot{x}^* + \mathbf{F}_v z_2\right] \\
\dot{z_3} &= -\mathbf{K}_1 z_1 - \mathbf{K}_2 z_3
\end{aligned} \tag{12}
$$

according to the properties of the centrifugal and Coriolis forces matrix presented in Section 4.2 of Kelly et al. (2006), the following equivalence is valid

$$
\begin{aligned}
\mathbf{C}(x_1,x_2)x_2 &= \mathbf{C}(x_1, z_2+\dot{x}^*)(z_2+\dot{x}^*) \\
&= \mathbf{C}(x_1,z_2)(z_2+\dot{x}^*) + \mathbf{C}(x_1,\dot{x}^*)(z_2+\dot{x}^*) \\
&= \mathbf{C}(x_1,z_2)z_2 + \mathbf{C}(x_1,z_2)\dot{x}^* + \\
&\quad \mathbf{C}(x_1,\dot{x}^*)z_2 + \mathbf{C}(x_1,\dot{x}^*)\dot{x}^* \\
&= \mathbf{C}(x_1,z_2)z_2 + 2\mathbf{C}(x_1,\dot{x}^*)z_2 + \mathbf{C}(x_1,\dot{x}^*)\dot{x}^*
\end{aligned} \tag{13}
$$

substituting (13) into (12) give us

$$
\begin{aligned}
\dot{z_1} &= z_2 \\
\dot{z_2} &= -\mathbf{M}^{-1}(x_1)\left[\mathbf{K}_1 z_1 - \mathbf{K}_2 z_3 + \mathbf{C}(x_1,z_2)z_2 + \right. \\
&\quad \left. 2\mathbf{C}(x_1,\dot{x}^*)z_2 + \mathbf{F}_v z_2\right] \\
\dot{z_3} &= -\mathbf{K}_1 z_1 - \mathbf{K}_2 z_3.
\end{aligned} \tag{14}
$$

The equilibria of the closed-loop system (14) are given by

$$
(\bar{z}_1, \bar{z}_2, \bar{z}_3) = (0,\ 0,\ 0)\,. \tag{15}
$$

Now, for stability purposes let us use the following candidate Lyapunov function

$$
\begin{aligned}
V(z_1,z_2,z_3) &= \frac{1}{2}z_1^T\mathbf{K}_1 z_1 - z_1^T\mathbf{K}_2 z_3 + \frac{1}{2}z_2^T\mathbf{M}(x_1)z_2 + \\
&\quad + \frac{1}{2}z_3^T\mathbf{I}z_3.
\end{aligned} \tag{16}
$$

To show that the function defined in (16) is a positive-definite function, and radially unbounded, let us proceed to obtain the lower-bound of the function (16) as follows

$$
V(z_1,z_2,z_3) \geq
$$

$$
\frac{1}{2}\begin{bmatrix} ||z_1|| \\ ||z_2|| \\ ||z_3|| \end{bmatrix}^T \begin{bmatrix} \lambda_{min}\{\mathbf{K}_1\} & 0 & -\lambda_{max}\{\mathbf{K}_2\} \\ 0 & \lambda_{min}\{\mathbf{M}\} & 0 \\ -\lambda_{max}\{\mathbf{K}_2\} & 0 & 1 \end{bmatrix} \begin{bmatrix} ||z_1|| \\ ||z_2|| \\ ||z_3|| \end{bmatrix} \tag{17}
$$

the condition to keep $V(z_1,z_2,z_3) > 0$ is

(1) $\lambda_{min}\{\mathbf{K}_1\} > \lambda_{max}\{\mathbf{K}_2\}^2$.

Following similar steps as the developed above, it is possible to show that the Lyapunov candidate function $V(z_1,z_2,z_3)$ given in (16) is upper bounded by the following expression:

$$
V(z_1,z_2,z_3) \leq
$$

$$
\frac{1}{2}\begin{bmatrix} ||z_1|| \\ ||z_2|| \\ ||z_3|| \end{bmatrix}^T \begin{bmatrix} \lambda_{max}\{\mathbf{K}_1\} & 0 & -\lambda_{min}\{\mathbf{K}_2\} \\ 0 & \lambda_{max}\{\mathbf{M}\} & 0 \\ -\lambda_{min}\{\mathbf{K}_2\} & 0 & 1 \end{bmatrix} \begin{bmatrix} ||z_1|| \\ ||z_2|| \\ ||z_3|| \end{bmatrix} \tag{18}
$$

which is positive-definite and radially unbounded since the condition

(1) $\lambda_{max}\{\mathbf{K}_1\} > \lambda_{min}\{\mathbf{K}_2\}^2$.

is trivially satisfied, this means that $V(z_1,z_2,z_3) > 0$ is a positive definite and decrescent function. The derivative of (16) along the solutions of (14) is given by

$$
\begin{aligned}
\dot{V}(z_1,z_2,z_3) &= z_1^T\mathbf{K}_1 z_2 + z_2^T\mathbf{M}(x_1)\dot{z}_2 + \frac{1}{2}z_2^T\dot{\mathbf{M}}(x_1)z_2 \\
&\quad + z_3^T\mathbf{I}\dot{z}_3 - z_2^T\mathbf{K}_2 z_3 - z_1^T\mathbf{K}_2\dot{z}_3
\end{aligned} \tag{19}
$$

using the skew-symmetric property $\frac{1}{2}\dot{\mathbf{M}} - \mathbf{C} = 0$ shown in Section 4.2 of Kelly et al. (2006), the time derivative of the Lyapunov candidate function yields

$$
\begin{aligned}
\dot{V}(z_1,z_2,z_3) &= -2z_2^T\mathbf{C}(x_1,\dot{x}^*)z_2 - z_2^T\mathbf{F}_v z_2 - z_3^T\mathbf{K}_2 z_3 \\
&\quad - z_1^T\mathbf{K}_2\mathbf{K}_1 z_1 + z_1^T\mathbf{K}_2^2 z_3 + z_3^T\mathbf{K}_1 z_1.
\end{aligned} \tag{20}
$$

Now, let us proceed to upper-bound $\dot{V}(z_1,z_2,z_3)$ by a negative definite function in terms of the states z_1, z_2, and z_3. To that end, it is convenient to find upperbounds for each term of (20). The first two terms of (20) may be trivially bounded by

$$
\begin{aligned}
&-2z_2^T\mathbf{C}(x_1,\dot{x}^*)z_2 - z_2^T\mathbf{F}_v z_2 \leq \\
&2k_{c1}||\dot{x}^*||\,||z_2||^2 - \lambda_{min}\{\mathbf{F}_v\}||z_2||^2
\end{aligned} \tag{21}
$$

where the property of the centrifugal and coriolis matrix $||\mathbf{C}(x_1,\dot{x}^*)z_2|| \leq k_{c1}||\dot{x}^*||\,||z_2||$ was used (for more properties see chapter 4 in Kelly et al. (2006)), the terms containing just z_3 in (20) satisfies

$$
-z_3^T\mathbf{K}_2 z_3 \leq -\lambda_{min}\{\mathbf{K}_2\}||z_3||^2 \tag{22}
$$

the term $-z_1^T\mathbf{K}_2\mathbf{K}_1 z_1$ is upper bounded by

$$
-z_1^T\mathbf{K}_2\mathbf{K}_1 z_1 \leq -\lambda_{min}\{\mathbf{K}_2\mathbf{K}_1\}||z_1||^2 \tag{23}
$$

now, let us upper bound the cross terms

$$
z_1^T\mathbf{K}_2^2 z_3 + z_3^T\mathbf{K}_1 z_1 \leq \left(\lambda_{max}\{\mathbf{K}_2^2\} + \lambda_{max}\{\mathbf{K}_1\}\right)||z_1||||z_3||. \tag{24}
$$

The bounds (21)—(24) yield that the time derivative $\dot{V}(z_1,z_2,z_3)$ in (20), satisfies

$$
\dot{V}(z_1,z_2,z_3) \leq -\begin{bmatrix} ||z_1|| \\ ||z_2|| \\ ||z_3|| \end{bmatrix}^T \mathbf{R} \begin{bmatrix} ||z_1|| \\ ||z_2|| \\ ||z_3|| \end{bmatrix} \tag{25}
$$

where

- $R_{11} = \lambda_{min}\{\mathbf{K}_2\mathbf{K}_1\}$
- $R_{12} = R_{21} = 0$
- $R_{22} = \lambda_{min}\{\mathbf{F}_v\} - 2k_{c1}||\dot{x}^*||$
- $R_{13} = R_{31} = -\frac{1}{2}\left(\lambda_{max}\{\mathbf{K}_2^2\} + \lambda_{max}\{\mathbf{K}_1\}\right)$
- $R_{23} = R_{32} = 0$
- $R_{33} = \lambda_{min}\{\mathbf{K}_2\}$

with an adequate $\mathbf{K}_1$ and $\mathbf{K}_2$ gain tune criteria and keeping true $\lambda_{min}\{\mathbf{F}_v\} > 2k_{c1}||\dot{x}^*||$ from R_{22}, the matrix $\mathbf{R} > 0$ can be kept positive definite. By this way, global asymptotic stability is ensured.

6. EXPERIMENTAL RESULTS

This section presents the experimental results for trajectory tracking using the controller (10), (11) for nDO**F** mechanical systems. The goal of the experiments is to validate the afore developed controller and its stability analysis in a closed loop system. The experiments were performed in a XY system of two degrees of freedom. The parameters of both mechanical systems are shown in Table 1.

Table 1. Nominal parameters

XY system			
mass	m_x	0.45	kg
viscous friction	f_{vx}	11	kg/s
mass	m_y	0.25	kg
viscous friction	f_{vy}	8	kg/s

6.1 XY mechanism

Let us consider the XY mechanism in Figure 7, whose schematic is presented in Figure 2.

Fig. 1. XY mechanism.

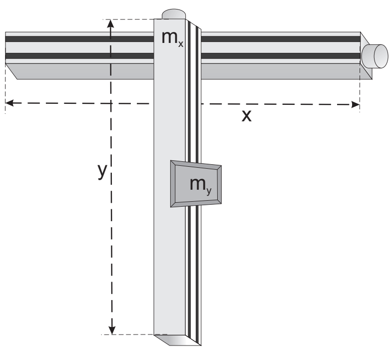

Fig. 2. XY table system.

The XY system model according to the representation of Lagrangian systems in (8) is

$$\frac{d}{dt}\begin{bmatrix} q \\ \dot{q} \end{bmatrix} = \begin{bmatrix} q \\ \mathbf{M}^{-1}(q)\left[-\mathbf{F}_v\dot{q} + \tau_u\right] \end{bmatrix} \tag{26}$$

where

$$\mathbf{M}(q) = \begin{bmatrix} m_x & 0 \\ 0 & m_y \end{bmatrix},\ \mathbf{F}_v = \begin{bmatrix} f_{vx} & 0 \\ 0 & f_{vy} \end{bmatrix},$$

considering $q = [x\ y]^T \in \mathbb{R}^2$, the system (28) can be rewritten as follows

$$\frac{d}{dt}\begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ -\frac{f_{vx}}{m_x}\dot{x} + \frac{1}{m_x}\tau_{ux} \\ -\frac{f_{vy}}{m_y}\dot{y} + \frac{1}{m_y}\tau_{uy} \end{bmatrix} \tag{27}$$

and substituting the parameters from Table 1 in the dynamical model (27) let us have

$$\frac{d}{dt}\begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ -24.44\dot{x} + 2.22\tau_{ux} \\ -32\dot{y} + 4\tau_{uy} \end{bmatrix}. \tag{28}$$

The proposed control scheme $\tau_u = [\tau_{ux}, \tau_{uy}]^T$ to solve the trajectory-tracking problem is as in (10), (11) using the following controller gains

$$k_1 = \begin{bmatrix} 50 & 0 \\ 0 & 35 \end{bmatrix},\ k_2 = \begin{bmatrix} 50 & 0 \\ 0 & 50 \end{bmatrix}.$$

The reference signal proposed for both links is $x^* = [0.01\sin(t), 0.01\sin(t)]^T$, where the amplitude is 0.01 m and the frequency is 1 $\frac{rad}{sec}$.

The control signal is activated after the first 2.5 seconds of being initialized the experiment, this is made in order to have a more detailed appreciation of the transient stage, in Figure 3 and Figure 4 it can be seen the position of the link on x and y axis respectively, in Figure 5 and Figure 6 is shown the position error on x and y axis, finally, the control signal from x axis can be seen on Figure 7 as well for y axis in Figure 8.

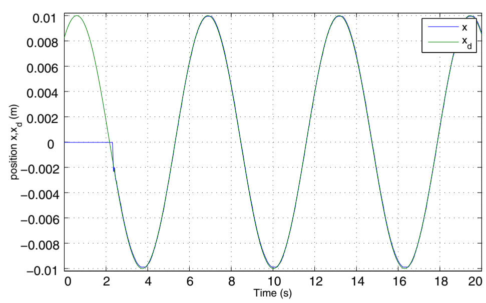

Fig. 3. Position on x axis.

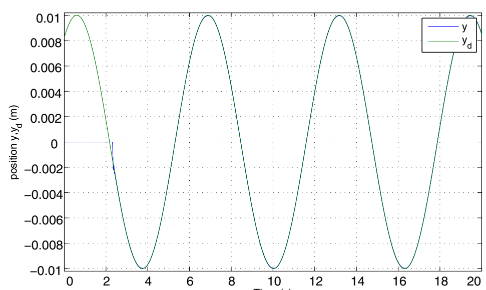

Fig. 4. Position on y axis.

The experiments results have illustrated the effectiveness of the proposed controller in a mechanical system, it can be observed the good performance of the closed-loop system where the position errors are kept bounded around 0.0002 m for the XY mechanism.

7. CONCLUSION

A control synthesis has been proposed to solve the tracking problem in mechanical systems using only position measurements and without the need to implement an

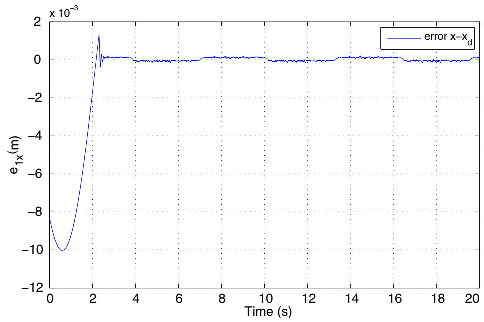

Fig. 5. Error measurement on x axis.

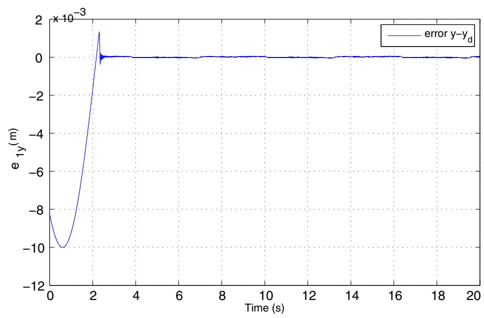

Fig. 6. Error measurement on y axis.

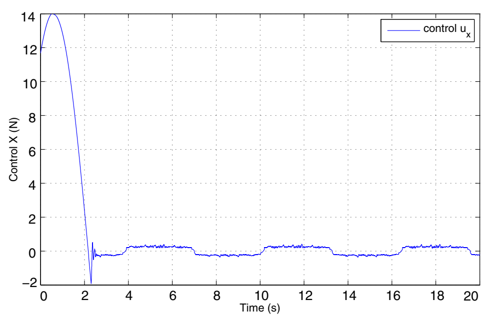

Fig. 7. Signal control on x axis.

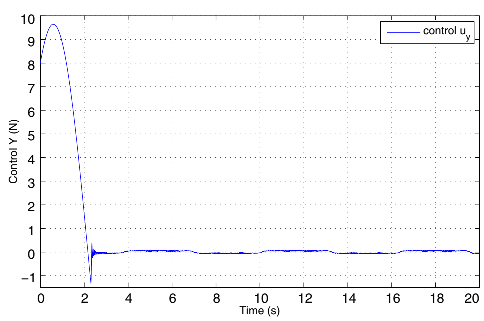

Fig. 8. Signal control on y axis.

observer/differentiator. The proposed approach consists of a nonlinear dynamic controller for Lagrangian systems, which ensures an asymptotic convergence to the reference using only two gain parameters, some criteria is given in order to tune the parameters. Also, viscous friction is considered. The proposed control algorithm achieves a zero position error during the nominal stage when only viscous friction is considered. The lack of need of velocity measurements in the control algorithm to achieve the tracking objective and the closed-loop stability proof using Lyapunov tools constitutes the main contribution of the present approach.

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