

# Tracking Control of A Peddulum-driven Cart-pole Underactuated System

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**Abstract:** In this paper, we use an example – a pendulum-driven cart-pole system studied in [1] to investigate the tracking control of underactuated dynamic systems. In this paper, we propose a six-step motion strategy of the pendulum driven cart-pole system. We design a desired profile of the pendulum joint velocity based on the proposed six-step motion strategy. Based on the desired joint velocity profile, we can compute the desired joint position and acceleration. The desired joint trajectories will be used in the proposed control approach. We also propose a closed-loop control approach using the partial feedback linearization technique. Extensive simulation studies are conducted to demonstrate the proposed approaches.

## I. INTRODUCTION

In the past two decades, the analysis and control of the fully actuated robot manipulators have been extensively studied. Many control strategies based on passivity, Lyapunov theory, feedback linearization, adaptive, robust, learning etc. [4] have been developed for the fully-actuated case, i.e. systems with the same number of actuators as degrees of freedom. The techniques developed for fully actuated robot manipulators do not apply directly to the case of underactuated non-linear mechanical systems. Underactuated mechanical systems or underactuated vehicles are systems with fewer independent control actuators than degrees of freedom to be controlled. In recent years there has been a major interest in developing stabilizing algorithms for underactuated mechanical systems [5][6]. The need for analysis and control of underactuated mechanical systems arises in many practical applications. The interest comes from the need to stabilize systems like ships, underwater vehicles, helicopters, aircraft, satellites, mobile robots, space platforms, flexible joint robots, hyper-redundant and snake-like manipulator, walking robots, capsule robots, and hybrid machines, etc. which may be underactuated by design or become underactuated due to actuator failure.

The classical inverted pendulum mounted on a cart is a benchmark underactuated system that has been widely used in many control laboratories to demonstrate the effectiveness of different control approaches in analogy with the control of many real systems. The control issue requires not only stabilize the pendulum in the upward equilibrium position, but also have to consider the displacement of the cart and this will certainly increase the design complexity. There are many similar extended systems, such as Acrobot, Pendubot, double inverted pendulum, three-link gymnast robot, Furuta pendulum, reaction wheel pendulum, etc. which belong to the class of underactuated mechanical systems. For controlling nonlinear underactuated mechanical systems, many control strategies based on feedback linearization, energy shaping, passivity, Lyapunov theory, etc. have been

extensively studied. However, control of underactuated systems has been mainly along the line of stabilization of special examples of cascade nonlinear systems using linearization-based methods or energy-based methods [2][3].

In this paper, we describe a contrary experiment from the classical inverted pendulum cart (cart-pole) system [7]. Here we concern the pendulum-driven cart using torque on the pivot, instead of the force on the cart. The different between the classical cart-driven system and the pendulum-driven system is that the former is a stabilization problem and the later is a tracking problem. The aim of the cart-driven inverted pendulum is to rotate the pendulum to the upward position and stabilize it there by applying a control input force to the cart [7]. While the aim of the pendulum-driven inverted pendulum is to make the cart trajectory to track a desired (designed) trajectory by applying a control input torque to the pendulum.

In this paper, we use an example – pendulum-driven cart-pole system studied in [1] to investigate the tracking control of underactuated dynamic systems. A four-step motion, dynamic modelling and optimal open-loop control of the pendulum driven cart-pole system is investigated in [1]. In this paper, we propose a six-step motion strategy of the pendulum driven cart-pole system. We design a desired profile of the pendulum joint velocity based on the proposed six-step motion strategy. Based on the desired joint velocity profile, we can compute the desired joint position and acceleration. The desired joint trajectories will be used in the proposed control approach. An optimal parameter selection is also investigated. We also propose a closed-loop control approach using the partial feedback linearization technique [2][3]. Extensive simulation studies are conducted to demonstrate the proposed approaches.

## II. DYNAMIC MODELLING OF PENDULUM-DRIVEN CART

### A. Generic Models of Underactuated Systems

A generic model of the dynamics of an n-DOF system [3][4][5][6] can be written as

$$D(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) + N = Bu \quad (1)$$

where  $q \in R^n$  is a vector of the generalized coordinates;  $D(q) \in R^{n \times n}$  is the inertia matrix,  $C(q, \dot{q}) \in R^n$  represents the centripetal, Coriolis forces;  $G(q)$  represents the gravitational forces;  $N \in R^n$  is the external disturbances,  $u \in R^m$  is the vector of control input, and  $B \in R^{n \times m}$ . If  $m = \text{rank}(B) = n$ , the system represented by (1) is called full-actuated system which has been investigated intensively during the past two decade. If  $m = \text{rank}(B) < n$ , the system represented by (1) is called an underactuated system. Without losing the generality, we let  $B = \begin{bmatrix} 0 & I_m \end{bmatrix}^T$ ,

and  $q = [q_1^T \quad q_2^T]^T$  where  $q_1 \in R^{n-m}$  and  $q_2 \in R^m$ . (1) can be written as

$$\begin{cases} D_{11}\ddot{q}_1 + D_{12}\ddot{q}_2 + h_1(q_1, \dot{q}_1, q_2, \dot{q}_2) = 0 \\ D_{21}\ddot{q}_1 + D_{22}\ddot{q}_2 + h_2(q_1, \dot{q}_1, q_2, \dot{q}_2) = u \end{cases} \quad (2)$$

where  $h_i$  includes terms of the centripetal, Coriolis forces, the gravitational forces and the external disturbances.

### B. Modelling of A Pedulum-driven Cart-pole system

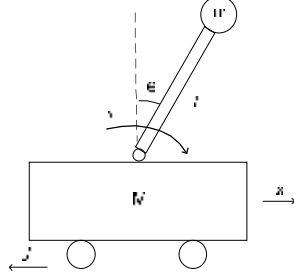


Figure.1. Pendulum-driven cart system

The pendulum-driven cart-pole system is shown in Fig.1. The inverted pendulum is mounted on the top of the cart. The cart has four passive wheels which make it move horizontally on the ground. A torque motor is directly attached to the pivot on the cart to swing the pendulum.  $M$  is the mass of the cart,  $m$  is the mass of the ball,  $l$  is the distance between the pivot and the mass center of the ball,  $\mu$  is the friction coefficient between the cart and the ground,  $q$  is the pendulum angle from vertical,  $x$  is the cart position coordinate, and  $t$  is the torque applied to the pivot by the motor.

Let the center of the cart be the origin of the coordinate. Thus the coordinate of the ball is  $[x_b \quad y_b]^T = [x + l \sin q \quad l \cos q]^T$ . Let  $F = [F_x \quad F_y]^T$  be the internal force applied to the pendulum by the torque. From the Newton's law, summing the forces applied on the ball in the horizontal direction gives  $F_x = m\ddot{x}_b$  and summing the forces applied on the ball in the vertical direction gives  $F_y - mg = m\ddot{y}_b$ . Combining the two equations gives

$$F = \begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} m\ddot{x} + ml\ddot{q} \cos q - ml\dot{q}^2 \sin q \\ mg - ml\ddot{q} \sin q - ml\dot{q}^2 \cos q \end{bmatrix}$$

Thus the torque can be calculated as

$t = [l \cos q \quad -l \sin q] \cdot F = ml\ddot{x} \cos q + ml^2\ddot{q} - mgl \sin q$   
Then summing the forces applied on the cart in the horizontal direction gives  $F_x + f = -M\ddot{x}$  where  $f = \mu N \operatorname{sgn}(\dot{x})$  is the friction force of the cart on the ground. Summing the forces applied on the cart in the vertical direction gives the normal force  $N = Mg + F_y = (M + m)g - ml\dot{q}^2 \sin q - ml\dot{q}^2 \cos q$ . Summarizing the above, we have the dynamical model as

$$\begin{aligned} (M + m)\ddot{x} + ml(\cos q - m \sin q \operatorname{sgn}(\dot{q}))\ddot{q} - ml(\sin q \\ + m \cos q \operatorname{sgn}(\dot{q}))\dot{q}^2 + m(M + m)g \operatorname{sgn}(\dot{x}) = 0 \end{aligned} \quad (3)$$

$$(ml \cos q)\ddot{x} + (ml^2)\ddot{q} - mgl \sin q = t \quad (4)$$

Let  $q_1 = x$  and  $q_2 = \theta$ . Equations (3) and (4) can be written into a general compact form:

$$\begin{cases} D_{11}\ddot{q}_1 + D_{12}\ddot{q}_2 + h_1(q_1, \dot{q}_1, q_2, \dot{q}_2) = 0 \\ D_{21}\ddot{q}_1 + D_{22}\ddot{q}_2 + h_2(q_1, \dot{q}_1, q_2, \dot{q}_2) = u \end{cases}$$

where  $D_{11} = M + m$ ,  $D_{12} = ml(\cos q_2 - m \sin q_2 \operatorname{sgn} \dot{q}_2)$ ,  $D_{21} = ml \cos q_2$ ,  $D_{22} = ml^2$ ,  $h_1 = -ml(\sin q_2 + m \cos q_2 \operatorname{sgn} q_1)\dot{q}_2^2 + m(M + m)g \operatorname{sgn} \dot{q}_1$ ,  $h_2 = -mgl \sin q_2$

The control goal is to drive the cart move towards to one direction only by adjusting the control input  $t$ . It is noted that the control goal of the classical cart-pendulum system is to make the origin globally asymptotically stable [7].

### III. MOTION GENERATION ANALYSIS

To drive the cart move towards to one direction by using the joint torque only, we can divide the motion into two stages: 1) fast motion stage: moving the pendulum to one direction fast leads to  $F_x \gg f$ , thus this will lead the cart move and 2) slow motion stage: moving the pendulum to return it starting position slowly which makes  $|F_x| < f$ , this will maintain the cart still. By using this philosophy, we generate the desired joint velocity profile shown in Fig. 2. The detailed movements in each period are below:

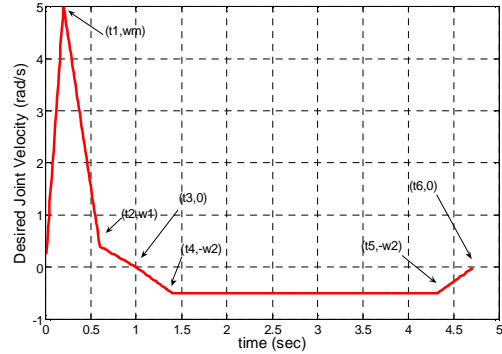


Figure 2 Desired pendulum angular velocity profile for one cycle

1)  $t \in [0, t_1]$ : The motion with a high angular acceleration of the pendulum ( $\ddot{q} \gg 0$ ,  $\dot{q} > 0$ ) leads to the forward accelerated motion of the cart ( $\ddot{x} > 0$ ,  $\dot{x} > 0$ ).

2)  $t \in [t_1, t_2]$ : The motion with an angular deceleration of the pendulum ( $\ddot{q} < 0$ ,  $\dot{q} > 0$ ) leads to the forward decelerated motion of the cart ( $\ddot{x} < 0$ ,  $\dot{x} > 0$ ).

3)  $t \in [t_2, t_3]$ : The motion with a low angular deceleration of the pendulum ( $0 > \ddot{q} > -e$ ,  $\dot{q} > 0$ ) and the cart remains stationary ( $\ddot{x} = 0$ ,  $\dot{x} = 0$ ).

4)  $t \in [t_3, t_4]$ : The motion with a low angular acceleration of the pendulum ( $0 > \ddot{q} > -e$ ,  $\dot{q} < 0$ ) in a

very short duration and the cart remains stationary ( $\ddot{x}=0, \dot{x}=0$ ).

5)  $t \in [t_4, t_5)$ : The motion with a zero acceleration and a low constant angular velocity of the pendulum ( $\ddot{\theta}=0, 0 > \dot{\theta} = -w_0$ ) and the cart remains stationary ( $\ddot{x}=0, \dot{x}=0$ ).

6)  $t \in [t_4, t_5)$ : The motion with a low angular deceleration of the pendulum ( $e > \ddot{\theta} > 0, 0 > \dot{\theta} > -w_0$ ) in a very short duration and the cart remains stationary ( $\ddot{x}=0, \dot{x}=0$ ).

The cycle time  $T=t_6$ . For one full cycle, the motion strategy includes two types: fast motion (steps 1 and 2), and slow motion (steps 3-6). Following the above, we have the formula for the desired joint velocity as

$$\dot{q}_d(t) = \begin{cases} \frac{t}{t_1} w_M & t \in [0, t_1) \\ w_M - \frac{t-t_1}{t_2-t_1} (w_M - w_1) & t \in [t_1, t_2) \\ \frac{t_3-t}{t_3-t_2} w_1 & t \in [t_2, t_3) \\ \frac{t_3-t}{t_4-t_3} w_2 & t \in [t_3, t_4) \\ -w_2 & t \in [t_4, t_5) \\ \frac{t_6-t}{t_5-t_6} w_2 & t \in [t_5, t_6) \end{cases} \quad (5)$$

Using the desired joint velocity from (5), we can compute the trajectories of the desired joint position and acceleration. To drive the cart move forward every cycle, we need to consider the several constraints the pendulum-driven cart-pole system should satisfy in next session.

#### IV. SYSTEM CONSTRAINTS AND OPEN-LOOP OPTIMAL CONTROL STRATEGY

##### A. System constraints

**Constraint for the whole motion:** In order to keep the cart on ground, the normal force of the cart on the ground has to be greater than zero, i.e.,

$$Mg + F_y = (M+m)g - ml\dot{q}^2 \sin q - ml\dot{q}^2 \cos q > 0$$

From the above equation, we have

$$\dot{q}^2 + \dot{q}^2 < \left( \frac{M+m}{ml} g \right)^2 = r_1 \quad (6)$$

**Constraint for the slow motion (step 3-6):** During the slow motion, in order to keep the cart in stationary, the internal force in the horizontal direction has to be lower than the maximal dry friction force, i.e.  $|F_x| \leq m(Mg + F_y)$ . Thus this constraint requires that

$$\dot{q}^2 + \dot{q}^2 < \left( \frac{M+m}{ml} g \right)^2 \frac{m}{1+m} = \frac{mr_1}{1+m}$$

We also have

$$\begin{aligned} & \frac{-m(M+m)gl + ml^2\dot{q}^2(\sin q + m\cos q)}{(\cos q - m\sin q)} \\ & \leq t + mgl \sin q \\ & \leq \frac{m(M+m)gl + ml^2\dot{q}^2(\sin q - m\cos q)}{(\cos q + m\sin q)} \end{aligned} \quad (7)$$

For a given friction coefficient  $m$ , we can choose  $\theta_0 \in (-\phi, \phi)$  to make both  $(\cos q - m\sin q)$  and  $(\cos q + m\sin q)$  are greater than zero, where  $f < \tan^{-1}(1/m)$ .

##### B. Open-loop control strategy:

From the discussion in session III, we know that for one full cycle, it can be classified into fast motion (step 1 and step 2) and slow motion (the rest steps). During the fast motion, the cart moves forward ( $\dot{x} > 0$ ) all the time. Because the durations for each step are fixed, using (3) and (4) we can compute the desired acceleration of the cart for steps 1 and 2 on each sampling time as below

$$\ddot{x}_d = \frac{ml\dot{q}_d^2(\cos q_d + m\sin q_d) - ml\dot{q}_d^2(\sin q_d - m\cos q_d)}{M+m} - mg$$

and the desired torque

$$t = -ml\ddot{x}_d \cos q_d + ml^2\dot{q}_d^2 - mgl \sin q_d \quad \text{for } t \in (0, t_2) \quad (8)$$

Using (5) and considering that  $\ddot{x}=0$  in (4) we can compute the desired torque for steps 3 and 4 as below:

$$t = \begin{cases} -\frac{w_1 ml^2}{t_3-t_2} - mgl \sin q_d & t \in [t_2, t_3) \\ -\frac{w_2 ml^2}{t_4-t_3} - mgl \sin q_d & t \in [t_3, t_4) \end{cases} \quad (9)$$

During step 5,  $\ddot{x}=0, \ddot{\theta}=0, \dot{q}^2=0$ , then

$$t = -mgl \sin q_d \quad t \in [t_4, t_5) \quad (10)$$

During step 6, the desired torque in step 6 is

$$t = \frac{w_2 ml^2}{t_6-t_5} - mgl \sin q_d \quad t \in [t_5, t_6) \quad (11)$$

The open-loop control law is given by (8)-(11). This has been adopted in [1].

##### C. Optimal Open-loop control strategy:

The aim of the optimization is to maximize the average speed of the cart by choosing the desired pendulum angular velocity profile. Here we need to choose the parameters, such as  $t_1-t_6, w_M, w_1$  and  $w_2$  in the motion profile shown in Fig 2. We can obtain the following boundary conditions:

$$q(0) = -q(t_2) = -q_0, \dot{q}(0) = 0, \dot{x}(0) = \dot{x}(t_2) = 0$$

Integrating (3) and using the above boundary conditions, we have the following two equations

$$(M+m)\ddot{x} - ml\ddot{q}\cos q - mml\dot{q}^2\sin q \quad (12)$$

$$= -m(M+m)gt$$

$$(M+m)x - ml\sin q + mml\cos q \quad (13)$$

$$= -ml(\sin q_0 - m_k \cos q_0) - \frac{1}{2}m(M+m)gt^2$$

Using (12) and considering that  $ml(\cos q_0 + m\sin q_0) \neq 0$  (we can choose  $q_0$  to avoid this), at time  $t_2$  we can compute  $w_1$  as below

$$w_1 = \dot{q}(t_2) = \frac{m(M+m)gt_2}{ml(\cos q_0 + m\sin q_0)} \quad (14)$$

From Fig 2, we have the following relations

$$\frac{1}{2}w_M t_1 + \frac{1}{2}(w_M + w_1)(t_2 - t_1) = 2q_0$$

$$\frac{1}{2}[(t_6 - t_3) + (t_5 - t_4)]w_2 = 2q_0 + \frac{1}{2}w_1(t_3 - t_2)$$

Thus, we have

$$w_M = \frac{4q_0 + w_1(t_1 - t_2)}{t_2} \quad (15)$$

$$w_2 = \frac{4q_0 + w_1(t_3 - t_2)}{t_6 + t_5 - t_4 - t_3} \quad (16)$$

Using (5) we can compute the desired joint position and acceleration. It is noted that

$$w_M t_2 + w_1(t_3 - t_1) = w_2(t_5 + t_6 - t_3 - t_4)$$

We can use the above equation to select the distance between  $t_4$  and  $t_5$ , i.e.  $t_5 - t_4$  as below

$$t_5 - t_4 = \frac{1}{w_2}[w_M t_2 + w_2(t_3 - t_6) + w_1(t_3 - t_1)] \quad (17)$$

Using (13) and considering the boundary condition, at time  $t_2$ , we have

$$x(t_2) = \frac{2m}{M+m}l\sin q_0 - \frac{1}{2}mgt_2^2 \quad (18)$$

We can find that if the duration of the fast motion (i.e.  $t_2$  is smaller) is shorter, the cart will move further (i.e.  $x(t_2)$  is larger). We can calculate the desired torque for such velocity profile using equations (8)-(11). The average velocity of the cart is

$$\bar{x} = \frac{x(t_2)}{T} = \left(\frac{2m}{M+m}l\sin q_0 - \frac{1}{2}mgt_2^2\right)/t_6$$

Thus if  $t_1 = 0.1s$ ,  $t_2 = 0.4s$ ,  $t_3 = 0.6s$ ,  $t_4 = 1.4s$ ,  $t_6 - t_5 = 0.8s$  are given, we can compute  $w_1$ ,  $w_2$ ,  $w_0$ , and  $t_5 - t_4$  using equations (14)-(17). This will generate a significant difference in terms of the distance that the cart can travel in the same length of time. This has demonstrated by the simulation study.

## V. CLOSED-LOOP CONTROL USING PARTIAL FEEDBACK LINEARISATION

From (3), we have

$$\ddot{q} = \frac{-1}{M+m}[ml(\cos q - m\sin q \operatorname{sgn}(\dot{q}))\dot{q}^2 - ml(\sin q + m\cos q \operatorname{sgn}(\dot{q}))\dot{q}^2 + m(M+m)g \operatorname{sgn}(\dot{q})]$$

We select the control law using the partial feedback linearization as

$$t = au + b \quad (19)$$

where  $a = ml^2 - \frac{m^2 l^2}{M+m} \cos q (\cos q - m\sin q \operatorname{sgn}(\dot{q}))$ ,

$b = \frac{ml}{M+m} \cos q [ml(\sin q + m\sin q \operatorname{sgn}(\dot{q}))\dot{q}^2 - m(M+m)g \operatorname{sgn}(\dot{q}) - mgl \sin q]$ . Letting  $\tilde{q} = q - q_d$ ,

choosing  $u = \ddot{q}_d - K_v \dot{\tilde{q}} - K_p \tilde{q}$  and applying control law (6) to (4) give the error equation as

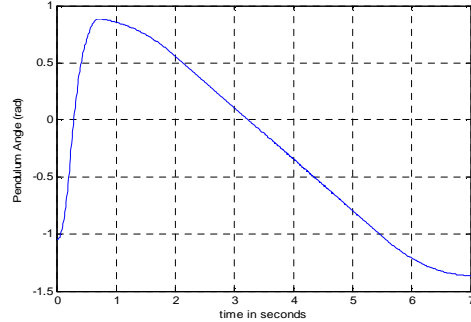
$$\ddot{\tilde{q}} + K_v \dot{\tilde{q}} + K_p \tilde{q} = 0 \quad (20)$$

We can easily select the suitable values of  $K_v$  and  $K_p$  to make the pendulum joint to follow the desired joint.

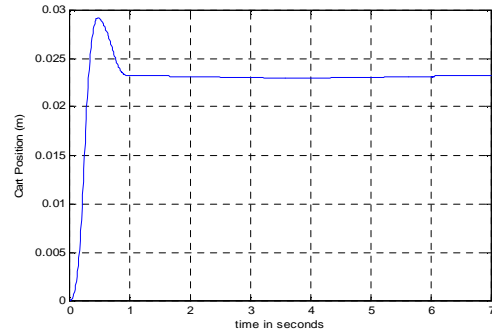
## VI. SIMULATION STUDY

The simulation was carried out by using MATLAB/SIMULINK. All of the relative parameters are given as  $M = 0.5kg$ ,  $m = 0.05kg$ ,  $L = 0.3m$ ,  $m = 0.02$ ,  $g = 9.81m/s^2$ . To avoid the problem generated by  $\dot{x} = 0$  in

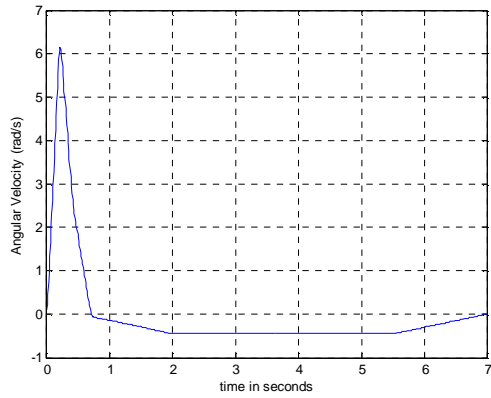
the simulation study, we use  $f = \begin{cases} mV \operatorname{sgn}(\dot{x}) & \dot{x} \neq 0 \\ mV \operatorname{sgn}(F_x) & \dot{x} = 0 \end{cases}$ .



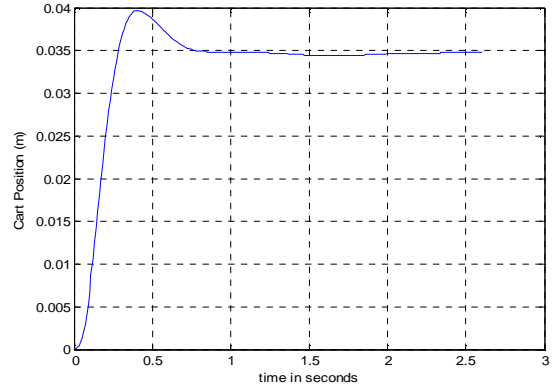
(a)



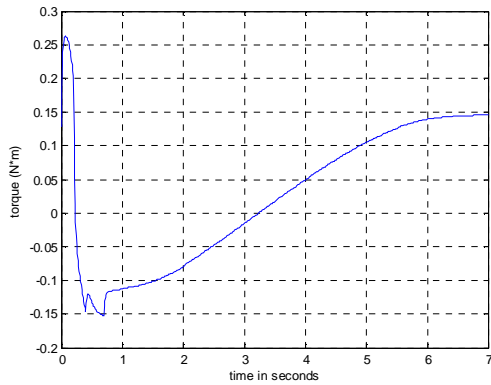
(b)



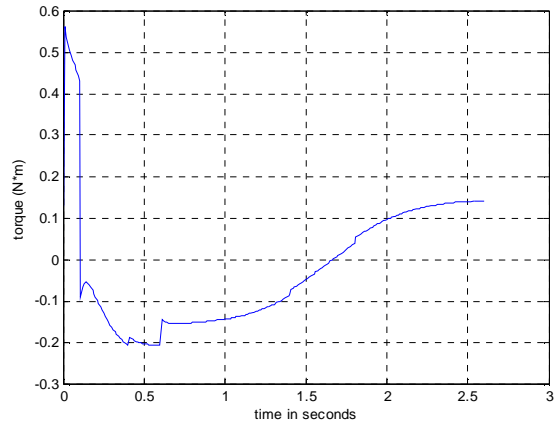
(c)



(a)



(d)



(b)

Figure 3 One full cycle of the pendulum-driven cart system

Figure 5 The results of the pendulum-driven cart system with optimal configuration in a full cycle

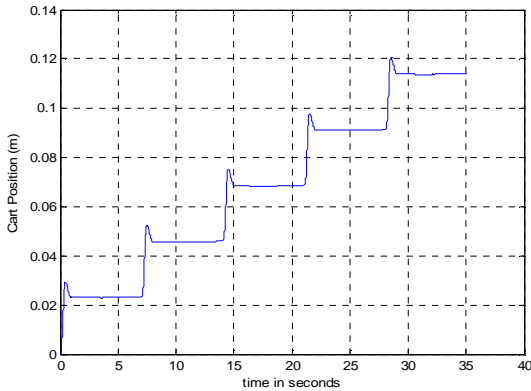


Figure 4 Cart trajectory in five cycles

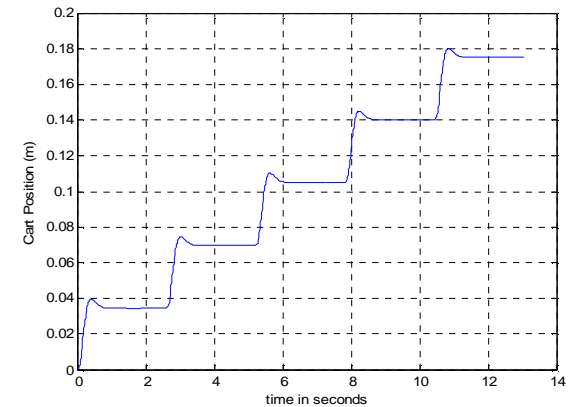


Figure 6 Cart trajectory with optimal configuration in five cycles

Figure 3 shows the results of the open-loop control strategy presented in IV.B. in a full cycle. From Figure 4(c), we can see that the joint velocity of the pendulum almost the same as the designed desired joint velocity under the idea case. Figure 4 shows the cart movement in 5 cycles.

Figures 5 and 6 show the simulation results when the optimal parameters are adopted. Comparing Figures 4 and 6, we can see the cart travels nearly 0.18 meters in less than 14 seconds under the optimal control, while it takes about 35 minutes to travel less than 0.12 meters under the none optimal control. To make a fair comparison, we also show the control inputs for both cases in Figures 3(d) and 5(b). It dose require slightly more energy for the optimal control.

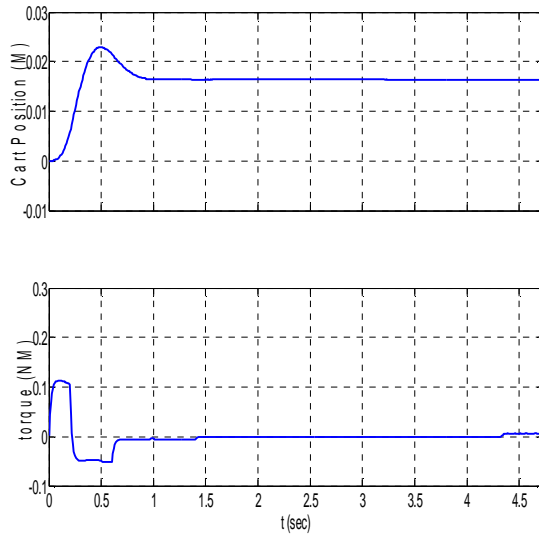


Figure 7 Trajectories of the cart position and control input for one cycle of the closed-loop control

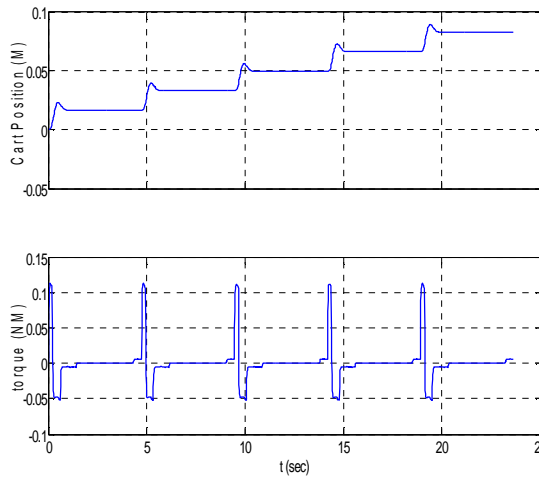


Figure 8 Trajectories of the cart position and control input for five cycles of the closed-loop control

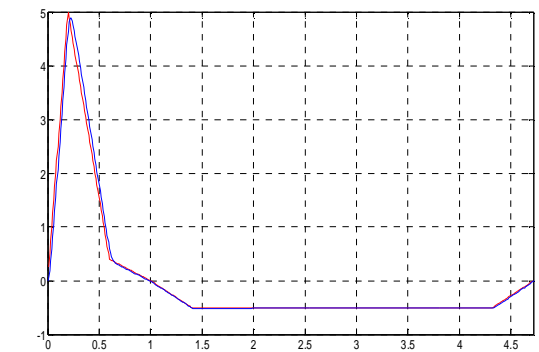


Figure 9 Tracking performance of the joint velocity (red line: desired joint velocity; blue line: joint velocity) of the closed-loop control  
 Figure 7 shows the cart position and control input for one full stroke (one cycle) within 0.01 second sampling

interval. The cart moves about 0.016 meters in one cycle. Figure 8 shows the cart position and control input for five full stroke. The cart moves about 0.8 meters in five cycles which takes less than 25 seconds. To look at the pendulum joint tracking performance, we show the pendulum joint velocity and the desired joint velocity in Fig. 9.

VII. CONCLUSIONS

The paper has investigated the tracking issue of underactuated dynamic systems. A special example, a pendulum-driven cart-pole system, has been considered to demonstrate the proposed concepts. The paper has three contributions: 1) a six-step motion profile; 2) an optimal parameter selection; 3) a close-loop control law. Extensive simulations conducted have demonstrated the proposed approaches. The Lab based experimental implementation is under development.

Our research aim is to develop an active driven capsule robot which is small enough that people can swallow, and use the idea developed here on the capsule robot to control its locomotion. The novel propulsion mechanism gives extensive applications on the micro-robot, such as medical inspection robot [8], rescuing robot[9], etc. Briefly, the mechanism can be used as an autonomous mobile robot to inspect the field that is inaccessible for human being. The further work along this direction is under way and the research findings will be reported in due course.

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