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Automatica 37 (2001) 1845–1851

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Brief Paper

Nonlinear control of the Reaction Wheel Pendulum☆

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Received 9 November 1999; revised 26 January 2001; received in final form 12 May 2001

Abstract

In this paper we introduce the *Reaction Wheel Pendulum*, a novel mechanical system consisting of a physical pendulum with a rotating bob. This system has several attractive features both from a pedagogical standpoint and from a research standpoint. From a pedagogical standpoint, the dynamics are the simplest among the various pendulum experiments available so that the system can be introduced to students earlier in their education. At the same time, the system is nonlinear and underactuated so that it can be used as a benchmark experiment to study recent advanced methodologies in nonlinear control, such as feedback linearization, passivity methods, backstepping and hybrid control. In this paper we discuss two control approaches for the problems of swingup and balance, namely, feedback linearization and passivity based control. We first show that the system is locally feedback linearizable by a local diffeomorphism in state space and nonlinear feedback. We compare the feedback linearization control with a linear pole-placement control for the problem of balancing the pendulum about the inverted position. For the swingup problem we discuss an energy approach based on collocated partial feedback linearization, and passivity of the resulting zero dynamics. A hybrid/switching control strategy is used to switch between the swingup and the balance control. Experimental results are presented. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Nonlinear control; Mechanical systems; Passivity; Feedback linearization; Stabilization; Switching control

1. Introduction

The *Reaction Wheel Pendulum* is shown schematically in Fig. 1. It is a physical pendulum with a symmetric disk attached to the end which is free to spin about an axis parallel to the axis of rotation of the pendulum. The disk is actuated by a DC-motor and the coupling torque generated by the angular acceleration of the disk can be used to actively control the system. The control problems for the Reaction Wheel Pendulum are reminiscent of those for the *Acrobot* (Murray & Hauser, 1990) and *Pendubot* (Spong & Block, 1996), but are distinct enough to warrant a separate investigation. Because of the symmetric mass distribution of the disk, precise analytical statements are more readily obtainable for the Reaction Wheel Pendulum than for the Acrobot (Spong, 1995) or Pendubot (Spong & Block, 1996). From a pedagogical standpoint, the Reaction Wheel Pendulum is one of the simplest nonlinear systems that can be used to illustrate advanced control designs based on recently developed geometric methods. We consider the problem of swinging the pendulum up and balancing it about the inverted position. This is accomplished with a supervisory hybrid/switching control strategy which uses a passivity based nonlinear controller for swingup and a local controller for balance. The nonlinear swingup controllers are designed so that trajectories are guaranteed to eventually enter the basin of attraction of the balance controller, which is in turn designed to asymptotically stabilize the inverted equilibrium state. The supervisor determines when to switch between the swingup and balance controllers based on an estimate of the basin of attraction of the balance controller.

For the design of the balance controller we consider two approaches; a linear pole placement design based on the linearized approximation of the nonlinear dynamics about the inverted equilibrium, and a full state nonlinear

☆This paper was not presented at any IFAC meeting. This paper was recommended for publication in revised form by Associate Editor Henk Nijmeijer under the direction of Editor Hassan Khalil.

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PII: S0005-1098(01)00145-5

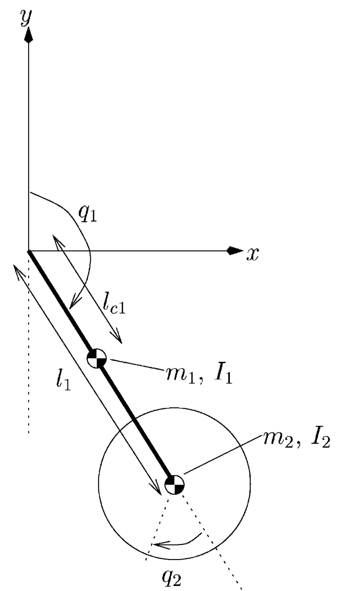

Fig. 1. Coordinate conventions for the reaction wheel pendulum.

feedback linearizing controller. The fact that the dynamics of the reaction wheel pendulum are feedback linearizable, the proof of which is a new contribution of the present paper, is interesting in its own right. Other underactuated nonlinear systems of this type, such as the Acrobot, Pendubot, and cart–pole system do not satisfy the conditions for feedback linearization.

The design of the swingup controller is based on the notion of collocated partial feedback linearization of underactuated systems from (Spong, 1994). Passivity from acceleration of the disk to velocity of the pendulum of the resulting zero dynamics is used to design a Lyapunov function that is positive definite in the pendulum energy and the disk kinetic energy. The control then drives the pendulum energy and disk velocity to zero. The proof of convergence relies on LaSalle's Invariance Principle. We compare the performance of the swingup and balance controller on an experimental device constructed in our laboratory at the University of Illinois.

2. Dynamics

An easy way to derive the dynamic equations of the Reaction Wheel Pendulum is to notice that the system may be modeled as a two-degree-of-freedom robot, where the pendulum forms the first link and the rotating disk forms the second link. We assume that the center of mass of the disk is coincident with its axis of rotation and we measure the angle of the pendulum clockwise from the vertical. Under these assumptions the equations of motion can be taken from any standard text, for example (Spong & Vidyasagar, 1989), as

$$d_{11}\ddot{q}_1 + d_{12}\ddot{q}_2 + \phi(q_1) = 0, \tag{1}$$

$$d_{21}\ddot{q}_1 + d_{22}\ddot{q}_2 = \tau, \tag{2}$$

where q_1 is the pendulum angle, q_2 is the disk angle, τ is the motor torque input and

$$d_{11} = m_1\ell_{c1}^2 + m_2\ell_1^2 + I_1 + I_2, \tag{3}$$

$$d_{12} = d_{21} = d_{22} = I_2, \tag{4}$$

$$\phi(q_1) = -\bar{m}g\sin(q_1) \tag{5}$$

with the various parameters as shown in Fig. 1 and $\bar{m} := m_1\ell_{c1} + m_2\ell_1$.

2.1. Reduced order model

Since the disk angular position, q_2, is a cyclic variable, i.e., does not appear in the system Lagrangian, we shall ignore it in the sequel and define a reduced order model with states $x_1 = q_1$, $x_2 = \dot{q}_1$, and $x_3 = \dot{q}_2$. Our goal will thus be to control only the pendulum position, pendulum velocity and disk velocity and leave the disk position unspecified. In terms of the state vector $x = (x_1, x_2, x_3)^{\mathrm{T}}$ we can write the system as

$$\dot{x}_1 = x_2, \tag{6}$$

$$\dot{x}_2 = -\frac{d_{22}}{det\,D}\phi(x_1) - \frac{d_{12}}{det\,D}\tau, \tag{7}$$

$$\dot{x}_3 = \frac{d_{21}}{det\,D}\phi(x_1) + \frac{d_{11}}{det\,D}\tau, \tag{8}$$

where $det\,D = d_{11}d_{22} - d_{12}d_{21} > 0$. This can be written as

$$\dot{x} = f(x) + g(x)\tau \tag{9}$$

in terms of the vector fields

$$f(x) = \begin{bmatrix} x_2 \\ -\frac{d_{22}}{det\,D}\phi(x_1) \\ \frac{d_{21}}{det\,D}\phi(x_1) \end{bmatrix}, \quad g(x) = \begin{bmatrix} 0 \\ -\frac{d_{12}}{det\,D} \\ \frac{d_{11}}{det\,D} \end{bmatrix}. \tag{10}$$

We will assume that the pendulum angle is computed modulo 2π so that the system state trajectory evolves on the manifold $S^1 \times \Re^2$, where S^1 is the unit circle. Therefore, the state will be bounded whenever the velocities x_2 and x_3 are bounded. We will use this reduced order model (9) in the remainder of the paper.

3. Balancing control

3.1. Feedback linearization (FL)

To show feedback linearizability we will follow the approach of Isidori (1995) and seek an output function with respect to which the system relative degree equals the dimension of the state space, in this case, three. With the system defined as in (9), we define an output equation

$$y = h(x) = d_{11}x_2 + d_{12}x_3. \tag{11}$$

The function $h(x)$ is the first component of the generalized momentum. The derivative of the output function y satisfies

$$\dot{y} = L_f h + L_g h\tau, \tag{12}$$

where $L_f h$ and $L_g h$ denote the Lie derivatives of h with respect to f and g, respectively. In local coordinates, $L_f h$ and $L_g h$ are given as

$$L_f h = \begin{bmatrix} 0, & d_{11}, & d_{12} \end{bmatrix} \begin{bmatrix} x_2 \\ -\dfrac{d_{22}}{det\,D}\phi(x_1) \\ \dfrac{d_{21}}{det\,D}\phi(x_1) \end{bmatrix} = -\phi(x_1) = \bar{m}g\sin(x_1) \tag{13}$$

and

$$L_g h = \begin{bmatrix} 0, & d_{11}, & d_{12} \end{bmatrix} \begin{bmatrix} 0 \\ -\dfrac{d_{12}}{det\,D} \\ \dfrac{d_{11}}{det\,D} \end{bmatrix} = 0. \tag{14}$$

Continuing in this fashion it is straightforward to compute the higher derivates of y as

$$\ddot{y} = L_f^2 h + L_g L_f \tau = L_f^2 h, \quad L_g L_f h = 0,$$

$$y^{(3)} = L_f^3 h + L_g L_f^2 h\tau, \quad L_g L_f^2 h \neq 0, \tag{15}$$

where

$$L_f^2 h = \bar{m}g\cos(x_1)x_2,$$

$$L_f^3 h = -\bar{m}g\sin(x_1)x_2^2 + (\bar{m}g)^2\frac{d_{22}}{det\,D}\cos(x_1)\sin(x_1),$$

$$L_g L_f^2 h = -\frac{d_{12}}{det\,D}\bar{m}g\cos(x_1).$$

Thus, the system has a well-defined relative degree of three with respect to the output $y = d_{11}x_2 + d_{12}x_3$ since $L_g L_f^2 h$ is nonzero in the region $-\pi/2 < q_1 < \pi/2$.

We can therefore define new state variables $\xi_1, \dots, \xi_3$ as

$$\xi_1 = h(x) = d_{11}x_2 + d_{12}x_3,$$

$$\xi_2 = L_f h(x) = \bar{m}g\sin(x_1),$$

$$\xi_3 = L_f^2 h(x) = \bar{m}g\cos(x_1)x_2. \tag{16}$$

It is easy to show that this state space transformation defines a local diffeomorphism $T: S^1 \times \Re^2 \to S^1 \times \Re^2$. In terms of these new state variables, the system becomes

$$\dot{\xi}_1 = \xi_2, \tag{17}$$

$$\dot{\xi}_2 = \xi_3, \tag{18}$$

$$\dot{\xi}_3 = L_f^3 h + LgL_f^2 h\tau. \tag{19}$$

We can now define the feedback transformation

$$\tau = \frac{1}{L_g L_f^2 h(x)}[u - L_f^3 h(x)], \tag{20}$$

so that the system becomes the linear chain of integrators

$$\dot{\xi}_1 = \xi_2, \tag{21}$$

$$\dot{\xi}_2 = \xi_3, \tag{22}$$

$$\dot{\xi}_3 = u. \tag{23}$$

The new control variable u can then be taken as

$$u = -k_1\xi_1 - k_2\xi_2 - k_3\xi_3, \tag{24}$$

to place the closed-loop poles (in the ξ-coordinates) arbitrarily. The state transformation and hence the feedback linearization control strategy is valid as long as $|x_1| < \pi/2$.

We have shown that the reaction wheel pendulum is feedback linearizable in the region $|x_1| < \pi/2$. Thus, as long as the pendulum angle, q_1, is above the horizontal, the feedback linearizing control strategy can balance it. In practice, of course, limitations on the available input torque will reduce the region in which the pendulum can be stabilized using this control.

We leave it to the reader to verify that the region $|x_1| < \pi/2$ is the largest possible region in which the system can be feedback linearizable and that the full fourth order system, including the disk angular position, is also locally feedback linearizable in the above fashion using the output equation

$$y = d_{11}q_1 + d_{12}q_2.$$

3.2. Approximate linearization (AL)

For later comparison in experiment we also present here the linear approximation about the origin of the nonlinear system (9). Since the Lagrangian equations of motion are linear apart from the gravity term, linearizing about $x_1 = 0$ gives the controllable linear system

$$\dot{x} = Ax + B\tau, \tag{25}$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{\bar{m}gd_{22}}{\det D} & 0 & 0 \\ \frac{-\bar{m}gd_{21}}{\det D} & 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ \frac{-d_{12}}{\det D} \\ \frac{d_{11}}{\det D} \end{bmatrix} \tag{26}$$

and a linear state feedback control, $\tau = Kx$, can be used to balance the pendulum in a neighborhood of the inverted equilibrium. In the later section on experimental results we will compare the performance of a linear control (AL) and the exact feedback linearization control (FL) for balance control using parameter values measured for our laboratory apparatus.

4. Swingup control

Since the control schemes discussed in the previous section are only valid locally around the inverted equilibrium, they cannot be used to swing the pendulum up from the vertically downward position, $x_1 = \pi$. In this section we derive a swingup control based on the notion of *Collocated Partial Feedback Linearization* (*PFLBC*) from Spong (1994) and passivity of the resulting zero dynamics. Interestingly enough, this swingup controller cannot be used to balance the pendulum, as we shall see, but it can swing the pendulum up to a neighborhood of the equilibrium starting from (almost) arbitrary initial conditions. This is the reason that our complete control strategy must switch between the swingup and the balance control.

The partial feedback linearization strategy proceeds, as in the previous section, by choosing an output function and its derivatives as new state variables. In this case we take the output equation as

$$\bar{y} = x_3, \tag{27}$$

the velocity of the disk, and compute from (8)

$$\dot{\bar{y}} = \dot{x}_3 = \frac{d_{21}}{\det D}\phi(x_1) + \frac{d_{11}}{\det D}\tau. \tag{28}$$

The system thus has relative degree one with respect to the output $\bar{y}$, resulting in two-dimensional zero dynamics which we compute below. Defining the control input

$$\tau = -\frac{d_{21}}{d_{11}}\phi(x_1) + \frac{\det D}{d_{11}}u, \tag{29}$$

we have, after some algebra,

$$\dot{x}_1 = x_2, \tag{30}$$

$$\dot{x}_2 = -\frac{1}{d_{11}}\phi(x_1) - \frac{d_{12}}{d_{11}}u, \tag{31}$$

$$\dot{x}_3 = u. \tag{32}$$

We note that, with $u = 0$, the system

$$\dot{x}_1 = x_2, \tag{33}$$

$$\dot{x}_2 = -\frac{1}{d_{11}}\phi(x_1), \tag{34}$$

defines the dynamics of the undamped pendulum. We shall define the additional control input u both to stabilize the disk angular velocity, x_3, and to render the homoclinic orbit of the pendulum attractive. To accomplish this we first set

$$E_0 = \tfrac{1}{2}d_{11}x_3^2 + \bar{m}g(1 - \cos(x_1)), \tag{35}$$

the energy of the free pendulum corresponding to $u = 0$ and compute

$$\dot{E}_0 = -d_{12}x_2u, \tag{36}$$

which is the passivity property of the pendulum with input $-d_{12}u$ and output x_2 that we computed previously. We then choose as a Lyapunov function V

$$V(x_1, x_2, x_3) = \tfrac{1}{2}k_eE_0^2 + \tfrac{1}{2}k_vx_3^2. \tag{37}$$

It is easy to show that V is positive definite and that

$$\dot{V} = -(d_{12}k_eE_0x_2 - k_vx_3)u. \tag{38}$$

If we therefore choose the control input u according to

$$u = d_{12}k_eE_0x_2 - k_vx_3, \tag{39}$$

we have that

$$\dot{V} = -u^2 \leqslant 0. \tag{40}$$

LaSalle's Invariance Principle (Khalil, 1996) can now be used to show that all solutions of the reaction wheel pendulum converge to the set $\mathscr{M} := \mathscr{C}_1 \cup \mathscr{C}_2$ where

$$\mathscr{C}_1 = \{(x_1, x_2, x_3) \,|\, E_0(x_1, x_2) = 0 \text{ and } x_3 = 0\},$$

$$\mathscr{C}_2 = \{(x_1, x_2, x_3) \,|\, x_1 = 0 \text{ or } \pi \text{ and } x_3 = 0\}.$$

Remark. (1) From Eq. (38) it is easy to show that LaSalle's Theorem gives exactly the same conclusion using the saturated control

$$u = sat(d_{12}k_eE_0x_2 - k_vx_3). \tag{41}$$

Thus, the practical problem of input constraints is easily handled with the energy/passivity approach here. This is an important feature of our technique. In contrast to the approach here, which relies on switching between separate swingup and balance controllers, it is also possible to show the existence of globally stabilizing controllers for this system that do not rely on switching (Olfati-Saber, 2000; Praly & Ortega, 2000; Ortega & Spong, 2000). Such controllers tend to aggressively stabilize the equilibrium and require extremely high torque input to accomplish. It is not clear whether these controllers can be made to work on the actual physical system considered.

(2) The open-loop equilibrium point, $(x_1, x_2, x_3) = (\pi, 0, 0)$, is also an equilibrium of the closed-loop system. As is typical for energy/passivity-based controllers for these systems (Shiriaev, Pogromsky, Ludvigsen, & Egeland, 2000), there is a one-dimensional manifold of initial conditions (the stable manifold associated with this equilibrium) that will not converge to the inverted equilibrium. Since this set of initial conditions has measure zero, convergence to the local equilibrium will typically not be seen in practice due to noise, parameter uncertainty, computational round-off, and other effects.

5. Experimental results

In this section we present experimental results obtained on a hardware setup in the College of Engineering Control Systems Laboratory at the University of Illinois at Urbana-Champaign. The model parameters used are shown in Table 1.

The experimental apparatus is shown in Fig. 2. The apparatus has a high-resolution encoder fitted to each axis giving 4000 count/rev on q_1 and 2000 count/rev on q_2. A D/A converter provides a current demand voltage to an amplifier which drives the permanent magnet DC motor. The controller was implemented in Simulink using the WinCon real-time extension with a sample interval of 5 ms. This sample rate is sufficiently fast that the continuous time state-feedback gain matrices are used. Angular rates were estimated using a first-order difference with no filtering.

Table 1
Estimated parameters for the laboratory apparatus. K'_m is a lumped gain representing motor torque constant and amplifier transconductance

Parameter	Value	Units
l_1	0.125	m
l_{c1}	0.063	m
m_1	0.020	kg
m_2	0.300	kg
I_1	47×10^{-6}	kg m^2
I_2	32×10^{-6}	kg m^2
d_{11}	4.83×10^{-3}	kg m^2
d_{12}	32×10^{-6}	kg m^2
d_{21}	32×10^{-6}	kg m^2
d_{22}	32×10^{-6}	kg m^2
$det\ D$	155×10^{-9}	kg m^2
$\bar{m}$	38.7×10^{-3}	kg
K'_m	5.5×10^{-3}	Nm/V

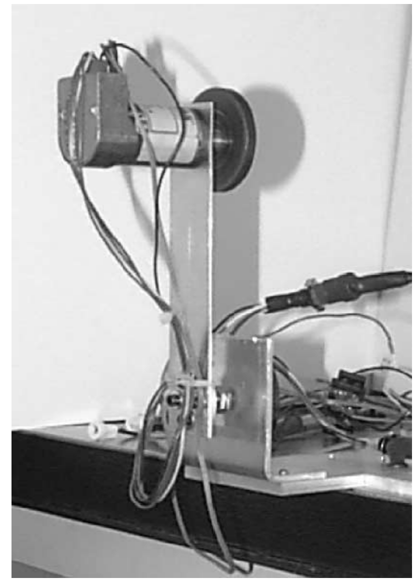

Fig. 2. Photograph of the experimental apparatus balancing at the unstable equilibrium point.

Since the stable equilibrium configuration of the open-loop system is also an equilibrium point for the closed-loop system, it is required that the arm be displaced in order to start the swingup motion. This displacement could be accomplished by a third ‘push off’ controller which is active at this point in state space. In fact, we were able to use the balancing controller for this purpose, since it is unstable at the downward equilibrium point. Taking the angle x_1 modulo π, instead of modulo 2π, maps both equilibrium points to $x_1 = 0$ where the linear controller is active. When the error is sufficiently large the swingup controller is activated.

Experimental results for the hybrid PFBLC + AL controller are shown in Fig. 3. The control was able to reach the inverted position in only 5 swings. The control parameters used were $k_e = 1000$ and $k_v = 0.1$. The switching function shown in Fig. 3 indicates which controller is active—the linear controller is active during both initial pushoff and the final balance phase. The closed-loop poles of the balancing controller were placed at $-4 \pm 2j$ and -8 rad/s.

We can see in the figure that there is a steady state error in $\dot{q}_2$ of nearly 200 rad/s. This is due to the disturbance torque exerted on the pendulum by the connecting wires. This disturbance torque results in $q_1 \neq 0$ and at steady-state $\tau = \dot{q}_1 = 0$ the state feedback control law

$$k_1 q_1 + k_3 \dot{q}_2 = 0,$$

relates q_1 error to disk velocity $\dot{q}_2$. We can also observe in Fig. 3 that neither the Lyapunov or energy functions

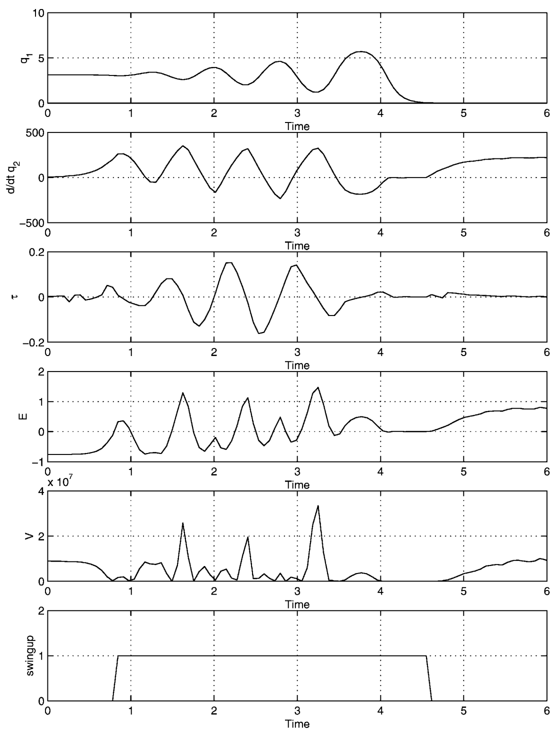

Fig. 3. Experimental trajectories for the hybrid controller PFBLC + AL. $k_e = 5 \times 10^5$, $k_v = 0.1$.

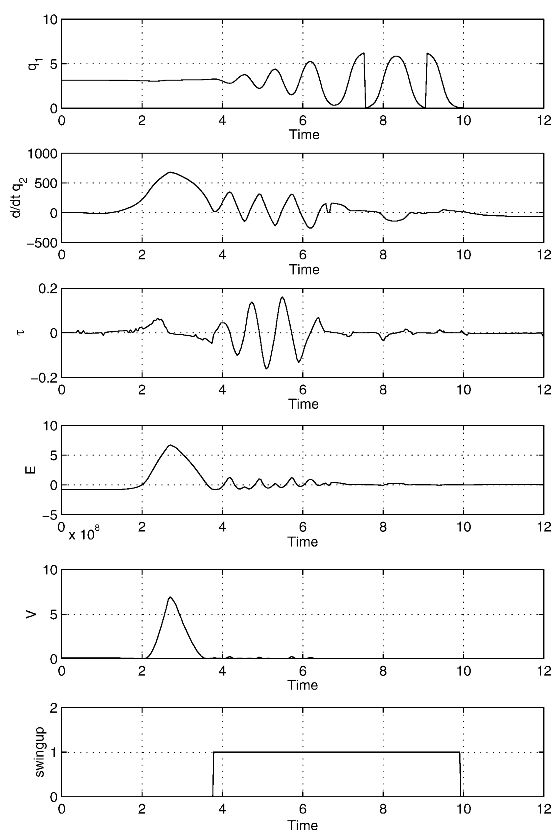

Fig. 4. Experimental trajectories for the hybrid controller PFBLC + FL. $k_e = 5 \times 10^5$, $k_v = 0.1$.

exhibit the expected monotonic characteristic, and which we postulate is due to model error.

Experimental results for the hybrid PFBLC + FL controller are shown in Fig. 4 and are not significantly different to the PFBLC + AL case. Qualitative investigations showed that both balancing controllers exhibited similar robustness to external disturbances, which is ultimately limited by the finite torque capability of the motor. The FL controller performs differently in the pushoff phase, taking longer to enter the operating region of the swingup controller, and doing so with a much higher disk velocity.

6. Conclusion

This paper has discussed hybrid nonlinear control of a Reaction Wheel Pendulum to achieve both swingup and balancing. We investigate several different control strategies based on feedback linearization, partial feedback linearization, and energy/passivity methods. We have shown that the system is locally feedback linearizable by a local diffeomorphism in state space and nonlinear feedback. In practice the performance of feedback linearization control is comparable to approximate linearization and pole placement control—the performance being limited by finite actuator torque capability. The swingup control was based on collocated partial feedback linearization, and passivity of the resulting zero dynamics (PFBLC).

Acknowledgements

This research was partially supported by the National Science Foundation under grants CMS-9712170 and ECS-9812591 and by a CNRS/UIUC Collaborative Research Agreement. We would also like to thank Dan Block, Manager of the College of Engineering Control Systems Laboratory at the University of Illinois for valuable assistance in constructing the Reaction Wheel Pendulum and implementing the control algorithms derived in this paper.

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