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The Mechatronics Control Kit for Education and Research

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Abstract— **In this paper we discuss the use of the *Mechatronics Control Kit* from *Mechatronic Systems, Inc.* for control education and research. The Mechatronics Control Kit can be configured with several distinct plants, including a simple DC-motor, an *Inertia Wheel Pendulum*[1] and a *Pendubot*. The digital electronics are fully integrated and include Texas Instruments DSP development system, the TMS320C6711 DSK Board (a DSP board with parallel port interface), a PWM Output/Optical Encoder Input Data Acquisition Daughter Board, a PWM amplifier, and power supplies. We discuss the hardware and software interface and outline a set of experiments that can be performed using this system.**

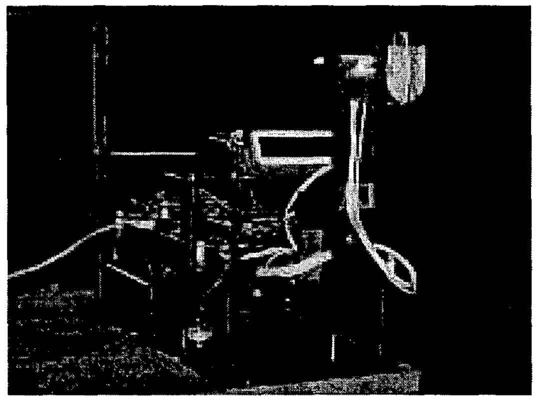

Fig. 1. Mechatronics Control Kit with Attached Inertia Wheel Pendulum

I. Introduction

In this paper we discuss the use of the *Mechatronics Control Kit* from *Mechatronic Systems, Inc.* for control education and research. The Mechatronics Control Kit can be configured for several distinct plants and control experiments, from simple DC-motor control for beginning students, to mid-level experiments using the *Inertia Wheel Pendulum* for more advanced students, up to advanced research projects using the *Pendubot.* The Mechatronics Control Kit is shown in Figure 1 with the Inertia Wheel Pendulum attached and in Figure 2 with a Pendubot attached. The base unit of the Mechatronics Control Kit, hereafter called the Kit, is lightweight and portable enough to be carried into the classroom. The digital electronics are fully integrated and include Texas Instruments newest DSP development system, the TMS320C6711 DSK Board (a DSP board with parallel port interface), a PWM/Optical Encoder Data Acquisition Daughter Board, a PWM amplifier, and power supplies. Additional hardware include a 24 Volt DC motor with 1000 counts/rev optical encoder, a second 1000 counts/rev optical encoder and aluminum links and mounts to construct the above experiments. The Kit can be operated without a PC as a stand alone system, or with a PC connected through a parallel port interface.

The software supplied with the Mechatronics Control Kit includes the Texas Instruments *Code Composer Studio* supplied with the DSK Board, the TI C6x Optimizing C-compiler, the

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[1]Also called a Reaction Wheel Pendulum.

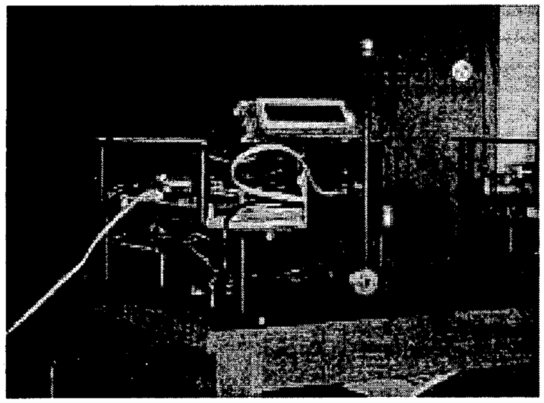

Fig. 2. Mechatronics Control Kit with Attached Pendubot

Code Composer Development/Debug IDE (integrated development environment), as well as DSP BIOS/RTDX realtime debugging/plotting capabilities. Example source files of different controllers for the plants and Visual Basic Interface software examples are also included as is all source code.

II. Hardware and Software

The Kit comes with the TI TMS320C6711 DSK Board, Texas Instrument's new development system kit for the 150MHz TMS320C6711 floating point DSP. Some features of this board are the following:

1. TMS320C7211 150 MHz Floating Point DSP
   (a) 64K bytes internal SRAM.
   (b) 2 32bit timers.
   (c) 2 high speed serial ports (one dedicated to the on board audio CODEC).
   (d) External interrupts.
2. 16M bytes external 100MHz SDRAM.
3. 128K bytes external bootable FLASH memory.
4. Audio CODEC, serial port interface, DMA data transfer.
5. Expansion connectors for daughter cards.

The Data Acquisition board supplied includes:

1. 2 Channels (upgradeable to 4) of 24 bit quadrature optical encoder input (upgradeable to 4).
2. 2 Channels of PWM output.
3. Parallel port interface to convert DSP system into a "dumb" data acquisition system. Could also be used as 8 lines of general-purpose digital input and 8 lines of digital output.
4. Can be upgraded to include 2 channels of 12bit +/-10V DAC output.
5. Standard 0.1 inch expansion headers provide access to DSP hardware interrupt pins and other DSP pins.

Also provided is a 40 character LCD panel display for monitoring and debugging.

Matlab/Simulink/Real-Time Workshop support as well as support for Wincon 3.0 from Quanser are also provided. Wincon 3.0 gives the user the capability of designing and implementing controllers within Simulink under Windows 9x/NT. Live updating of parameters and real-time data plotting are possible in Wincon 3.0.

Additional software support includes Windows Target from MathWorks. Windows Target gives the user the capability of designing and implementing controllers within Simulink under Windows 9x. Live updating of parameters and real-time data plotting are possible in Windows Target.

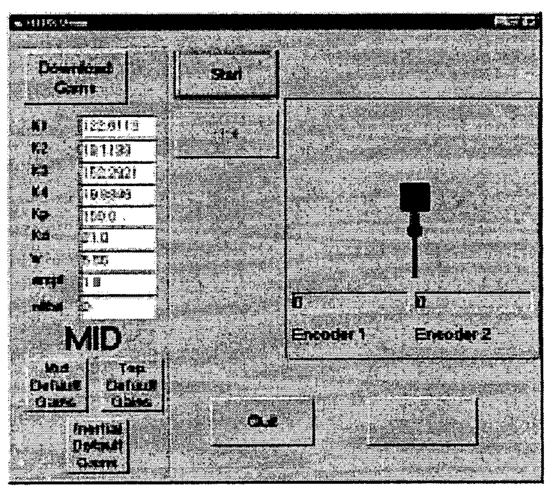

Fig. 3. Example Visual Basic GUI for Control Software

III. Experiments

We have developed a set of experiments, covering the range from modeling and identification to advanced nonlinear control, using the Kit in its various configurations. We are currently developing courseware (laboratory exercises and tutorials) based on these experiments to accompany the Kit. These experiments can be grouped as follows:

1. Modeling
   (a) Lagrangian dynamics
   (b) Equilibrium Points and Phase Portraits
   (c) Linearization of Nonlinear Systems
2. Parameter Identification
   (a) Identification from first principles
   (b) Identification from frequency response
   (c) Identification from time response
3. DC-motor Control
4. Adaptive Friction Compensation
5. Control of the Inertia Wheel Pendulum
   (a) Stabilization and Balance
   (b) Swingup Control
6. Control of the Pendubot
   (a) Stabilization and Balance
   (b) Swingup Control
7. Hybrid and Switching Control

IV. The Inertia Wheel Pendulum

For space reasons we will discuss only the control of the Inertia Wheel Pendulum. The Pendubot has been more extensively used and documented in the literature so it will not be discussed further.

The Inertia Wheel Pendulum consists of a simple pendulum with a rotating disk at the end. A diagram of the system is shown in Figure 4. The disk is actuated by a DC-electric motor and the angular acceleration between the disk and pendulum serves as the control input to move the system. The system thus has two degrees of freedom and one control input. Optical encoders measure both the pendulum and disk angles. Introduce the following variables

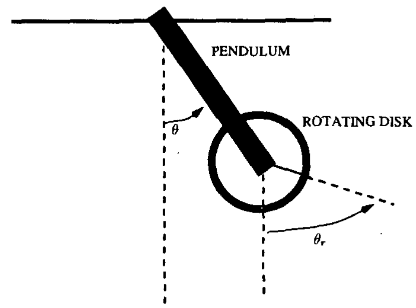

Fig. 4. Diagram of the Inertia Wheel Pendulum.

m_p mass of the pendulum
m_r mass of the rotor
m combined mass of rotor and pendulum
J_p moment of inertia of the pendulum about its center of mass
J_p moment of inertia of the rotor about its center of mass
ℓ_p distance from pivot to the center of mass of the pendulum
ℓ_p distance from pivot to the center of mass of the rotor
ℓ distance from pivot to the center of mass of pendulum and rotor

With

$$\begin{aligned} m &= m_p + m_r \\ m\ell &= m_p\ell_p + m_r\ell_r \\ J &= J_p + m_p\ell_p^2 + m_r\ell_r^2 \end{aligned}$$

the equations of motion of this system are

$$J\ddot{\theta} + mg\ell\sin\theta = -ku \quad (1)$$

$$J_r\ddot{\theta}_r = ku \quad (2)$$

where u is the control signal, in our case the input to the PWM amplifier in the range ± 10 and k is a proportionality constant scaling the input to the duty cycle range (0 - 500) of the PWM amplifier. This system thus has the simplest dynamic description among the various pendulum systems and can be introduced to students at virtually all stages of their education.

By measuring the dimensions of the components, weighing them and computing moments of inertial using simplified forumlas we find.

$$
\begin{aligned}
m_p &= 0.2164\,\mathrm{kg} \\
m_r &= 0.0850\,\mathrm{kg} \\
J_p &= 2.233\,10^{-4}\,\mathrm{kg\,m^2} \\
J_r &= 2.495\,10^{-5}\,\mathrm{kg\,m^2} \\
\ell_p &= 0.1173\,\mathrm{m} \\
\ell_r &= 0.1270\,\mathrm{m}
\end{aligned}
$$

From these values we obtain

$$
\begin{aligned}
J &= 4.572\,10^{-3}\,\mathrm{kg\,m^2} \\
m &= 0.3014\,\mathrm{kg} \\
\ell &= 0.1200\,\mathrm{m} \\
k &= 0.0049\,\mathrm{Nm/PWMunit}
\end{aligned}
$$

A. Friction Compensation

Once controllers for the rotor velocity are designed it is easy to determine the friction characteristics of the motor. To do this we simply use the velocity controllers to run the rotor at constant speed. The control signal required to to this is then equal to the friction torque. Figure 5 shows the results of such an experiment. The figure shows that the friction torque has a Coulomb friction component and a component with is linear in the velocity. Fitting straight lines to the data in the figure gives the following model for the friction.

$$
F = \begin{cases} 0.99 + 0.0116\omega, & \text{if}\,\omega > 0 \\ -0.97 + 0.0117\omega & \text{if}\,\omega < 0 \end{cases} \tag{3}
$$

Having obtained a reasonable friction model we can now attempt to compensate for the friction. This is done simply by measuring the velocity and adding a term given by the friction model (3) to the control signal. We can also implement an adaptive friction compensation scheme as the friction parameters will change with temperature of the motor and other factors.

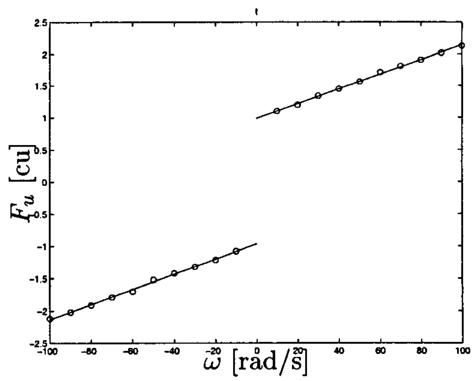

Fig. 5. Control signal u as a funtion of the angluar velociy of the rotor. With proper scaling this is the fricion curve of the rotor

B. Energy Control

We give here an example of passivity-based or energy-based control of the Inertia Wheel system, which can be used in for the problem of swingup control. In conjunction with hybrid/switching control the energy based control can be combined with a balance control to swing the pendulum up to the inverted position and catch it there.

We see from the equations of motion (1)-(2) that the Inertia Wheel Pendulum can be thought of as a parallel interconnection of a simple pendulum subsystem and a disk subsystem (double integrator), both with input u. We can therefore write this system as shown in Figure 6, where the

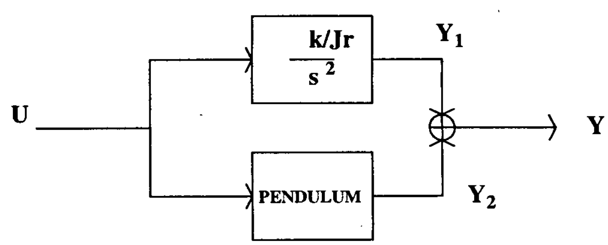

Fig. 6. Inertia Wheel System as a Parallel Interconnection

output functions y_1 and y_2 have not yet been specified. One attractive approach to controller design, especially for the problem of swingup control, is to determine these outputs so that the respective blocks are passive. Since parallel combinations of passive systems are themselves passive, we would then have a passive system from u to y.

For the double integrator subsystem we can choose as output $y_1 = k\dot{\theta}_r$ and storage function $S_1 = \frac{1}{2}J_r\dot{\theta}_r^2$. We note that the disk subsystem cannot be passive from input u to output θ_r since the double integrator system has relative degree two.

In order to define y_2 so that the pendulum subsystem is passive we consider the energy for the pendulum

$$E = \frac{1}{2}J\dot{\theta}^2 + mg\ell(1 - \cos(\theta)) \tag{4}$$

A simple calculation shows that

$$\dot{E} = -ku\dot{\theta} \tag{5}$$

and, hence, the pendulum subsystem is passive from $-ku$ to $\dot{\theta}$ with the energy E as storage function. However, instead of taking the energy E as the storage function, it turns out to be more useful to take as storage function

$$S_2 = \frac{1}{2}(E - E_{ref})^2$$

where E_{ref} represents a (constant) reference energy. Then

$$\begin{aligned} \dot{S}_2 &= (E - E_{ref})\dot{E} = -k\dot{\theta}(E - E_{ref})u && (6) \\ &= y_2 u && (7) \end{aligned}$$

where we have defined the output function $y_2 = -k\dot{\theta}(E - E_{ref})$. It follows that the parallel interconnection is passive with output

$$y = k_v y_1 + k_e y_2$$

and storage function

$$\begin{aligned} S &= k_v J_r S_1 + k_e S_2 \\ &= \frac{1}{2}k_v\dot{\theta}_r^2 + \frac{1}{2}k_e(E - E_{ref})^2 \end{aligned}$$

We have chosen a linear combination of the storage function S_1 and S_2 with weights k_v and k_e, respectively, to allow extra design freedom in the controller. As we shall see, the constants k_v and k_e play the role of adjustable gains that can be designed to influence the transient response of the system.

Computing $\dot{S}$ along trajectories of the system yields

$$\dot{S} = (k_v\dot{\theta}_r - k_e(E - E_{ref})\dot{\theta})u = yu$$

Therefore choose the control input u as

$$u = -k_u y = -k_u(k_v\dot{\theta}_r - k_e(E - E_{ref})\dot{\theta})$$

and we have

$$\dot{S} = -k_u y^2 \leq 0$$

Therefore, the system is stable and LaSalle's Invariance Principle can now be used to determine the asymptotic behavior of the system. Setting $y \equiv 0$ yields

$$u = k_u(k_e k(E - E_{ref})\dot{\theta} - k_v\dot{\theta}_r) \equiv 0$$

It follows that the derivative $\dot{u} \equiv 0$ from which we get

$$k_u(k_e k\dot{E}\dot{\theta} + k_e k(E - E_{ref})\ddot{\theta} - k_v\ddot{\theta}_r) = 0$$

Since $u = 0$, $\ddot{\theta}_r = ku$, $\dot{E} = -ku\dot{\theta}$, and $\ddot{\theta} = -\frac{mgl}{J}\sin\theta - ku$, we obtain

$$(E - E_{ref})\sin\theta = 0$$

This equation says, in effect, that the closed loop system trajectories will converge to either $E = E_{ref}$ or $\sin\theta = 0$. In the first case $E = E_{ref}$ it follows, in addition, that $\dot{\theta}_r = 0$. In the second case, it follows that $\theta = n\pi$ and $\dot{\theta}_r = constant$.

We can use the previous analysis to design a controller to swing up the pendulum to the inverted configuration and simultaneously drive the disk velocity to zero by setting E_{ref} equal to the rest energy of the system in the inverted configuration. From the expression for the energy, we see that this corresponds to $E_{ref} = 2mg\ell$. With this value for E_{ref} the response of the system is shown below. The gains, k_e, k_v and k_u were chosen as $k_e = 1e5 \quad k_v = 12 \quad k_i = 0.01$.

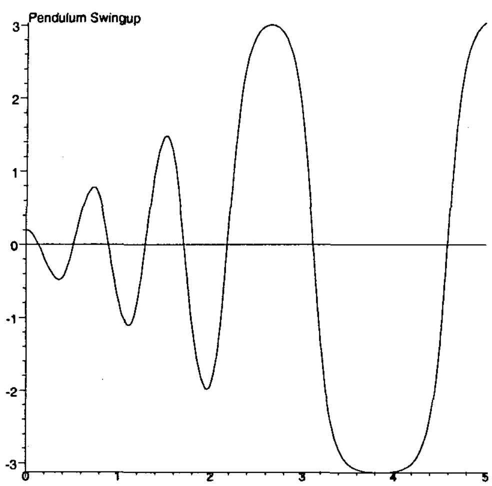

Fig. 7. Pendulum Response

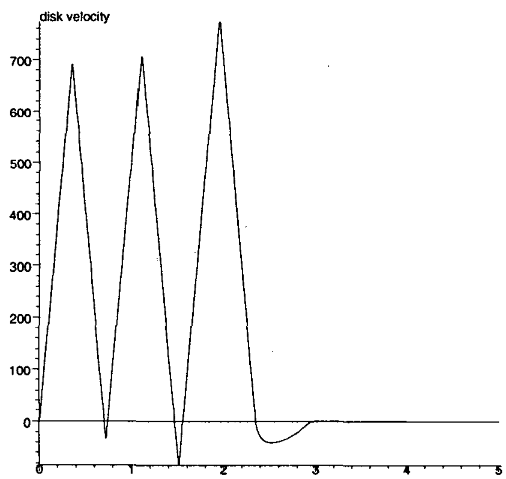

Fig. 8. Disk Velocity

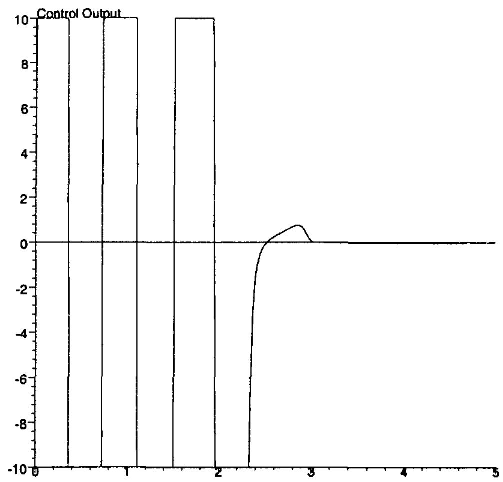

Fig. 9. Control Effort

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