Digital Pendulum Control Experiments

33-935/936-1V61

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Control in a MATLAB® Environment

Digital Pendulum

Control Experiments

33-935/936-1V61

(For 33-005, MATLAB 6.1 version and Windows 95, 98, NT, 2000)

Feedback
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Notes

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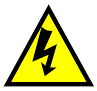

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ELECTROSTATIC
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Notes

1 Introduction

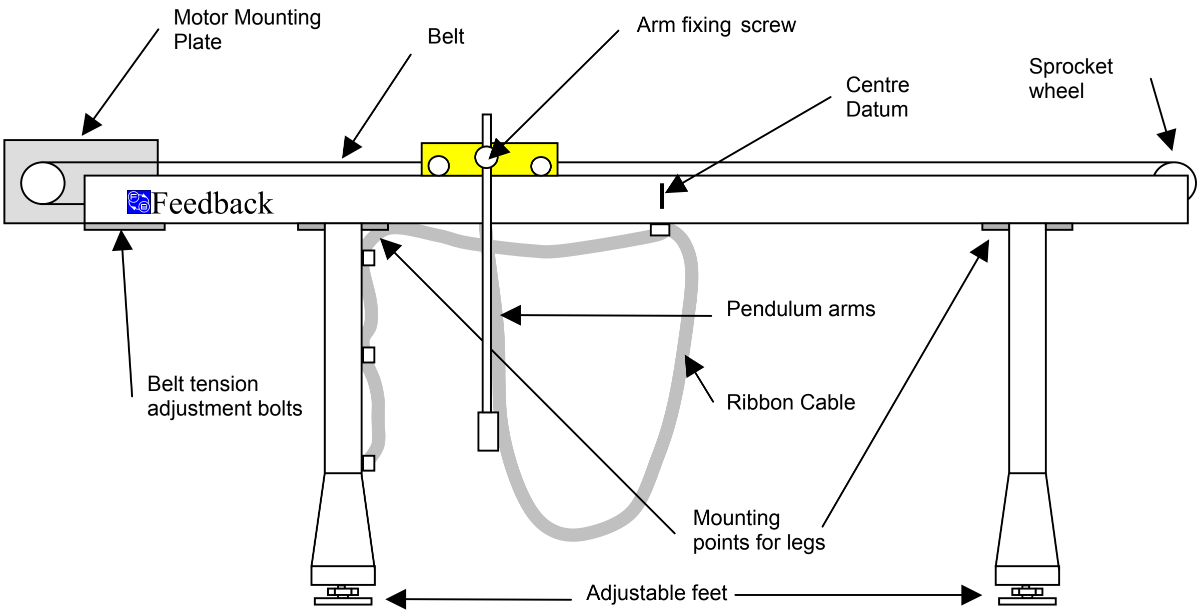

Fig 2.1: The pendulum system

The pendulum system consists of a rail and a cart which can move along it. Attached to the cart are two pendulums which are free to rotate around a horizontal axis attached to the cart

The control objective is to raise the pendulum from a down position to an upright position by moving the cart back and forth along the rail without touching the ends.

When the pendulums are in the upright position then the control objective is to keep them upright vertical and at the same time to be able to move the cart in a predetermined trajectory.

Swinging up the pole may result in over-reaching the upper unstable equilibrium point.

To achieve a “soft” landing in the vicinity of the upright position, a routine called the soft landing arbiter checks whether the kinetic energy of the pole, minus the energy loss due to friction, is sufficient to raise the centre of gravity of the pole to its upright position.

If the condition is satisfied then the control is set to zero and the "bang-bang" character of the control is finished. After the pole has entered the stabilisation zone, the system can be treated as linear and the control is switched to the stabilising algorithm.

As the rail is limited in length, part of the control algorithm requires that a prediction has to be made whether the cart is likely to hit the end stops (or the micro switches which cut power to the motor). If this is the case then sufficient power is applied to the motor in the opposite direction to ensure that the end points of the rail are not reached.

The pendulum is an example of a Multiple Input (pendulum angle and cart position) and Single Output (power to the motor) system.

2 Safety Instructions

Read these instructions carefully

Ensure you are acquainted with the safety Instructions in the Preface to this Manual

Do not enter the workspace of the Equipment whilst it is in operation.

In the event of an emergency. the control effort should immediately be discontinued by hitting the Red Stop button on the Pendulum Control Unit.

All users of this equipment should be familiar with and trained in good Laboratory Practice where electrical machinery is used.

When running any control experiment ensure that the Real Time control program is running before pressing the Start button on the equipment control unit

Notes

3 Experiment 1 – Double PID Crane Control

Theory and Model Description

The crane problem is illustrated in Figure 2-1 where the pendulum is hanging in the down (equilibrium) position from the cart. Swing is induced in the pendulum as the cart is moved back and forth by the dc motor. Generally, the goal of the crane control problem is to move the cart between positions; preferably as fast as possible, with few oscillations, and without letting the angle and velocity of the pendulum swing become too large or the duration of the swing too prolonged. This problem is named for the similarity to the problem of controlling overhead cranes used at shipping ports and construction sites to move cargo and supplies.

The PID control rule is very common in control systems. It is the basic tool for solving most process control problems. The PID controllers are usually standard building blocks for industrial automation. The most basic PID controller has the form

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt}(e(t))$$

where $u(t)$ is the control output

and the error, $e(t)$, is defined as

> $e(t)$ = desired value – measured value of quantity being controlled.

The control gains

> K_p, K_d, and K_i

determine the weight of the contribution of the error, the integral of the error, and the derivative of the error to the control output and will dictate the response of the closed-loop system to the initial conditions and inputs.

There are a number of tuning methods for PID controllers. Some of them are based on transient response experiments e.g., the Ziegler-Nichols step response tuning rule, other are based on relay feedback when the parameters of a PID controller are determined from features of the limit cycle of the closed-loop system, some others are based on frequency analysis. In the crane system under consideration, the candidate quantities for PID control are the cart position and pendulum angle.

We shall consider the pendulum-cart control system containing two PID controllers. The first operates based on the angle of the pendulum and the second operates based on the position of the cart. The outputs of the PID controllers are added to produce the final control value for the D/A converter, and as a result the output motor torque.

A schematic of the proposed double PID control system for the pendulum-cart system is shown in Figure 1, constructed as a Simulink block diagram. It is used to control the pendulum system as described in the following text.

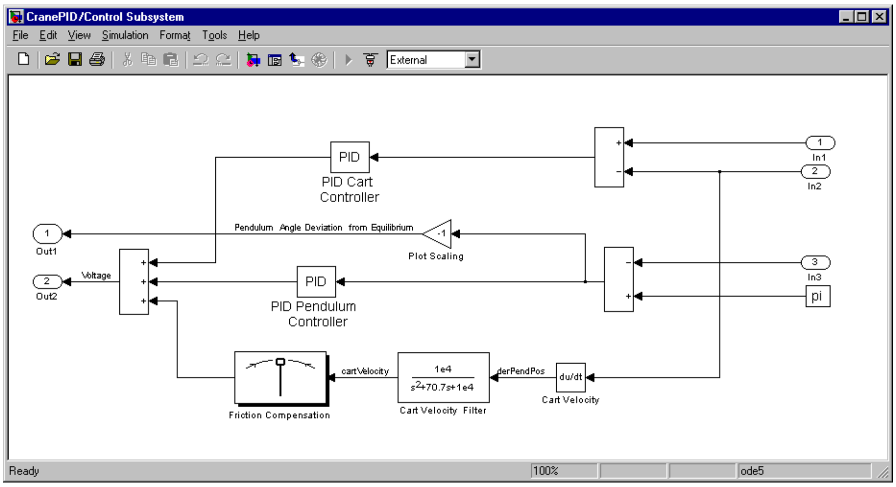

Figure 1: Block Diagram of Double Crane PID controller

Loading the RTWT Block Diagram

To load and execute the RTWT block diagram for the crane control, follow the procedure outlined below:

Start MATLAB

Type the following commands into the MATLAB command window

```
cd C:\Feedback\Pendulum

CranePID
```

The RTWT block diagram for the Crane PID, appears and is shown in Figure 2.

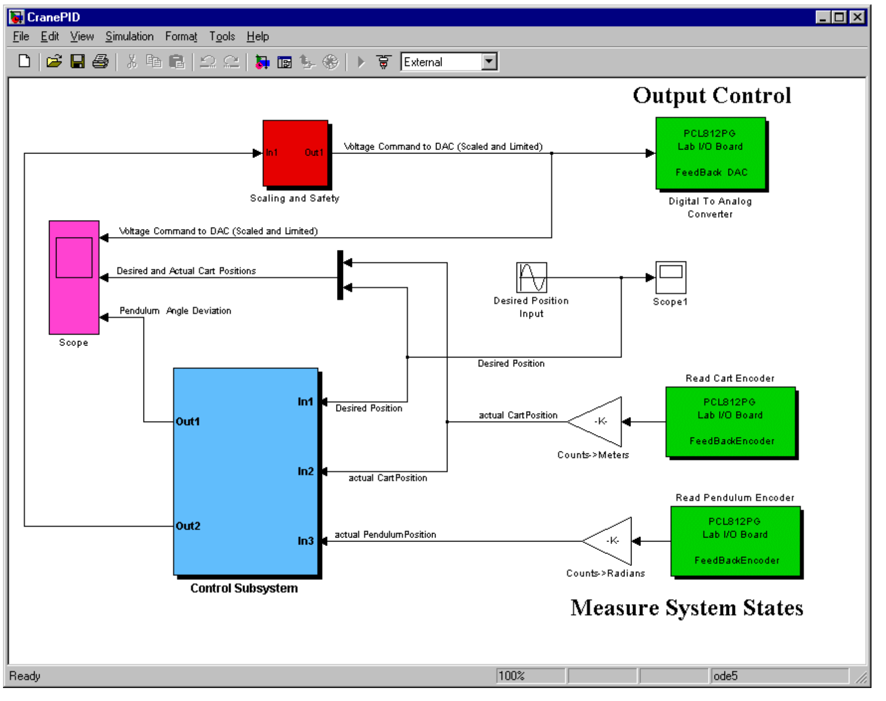

Figure 2: RTWT Block Diagram for Crane Control Experiment

Simulink Block Diagram - Description of Block Functions

In Figure 2, the green blocks denote input/output operations or hardware and the red block denotes the safety subsystem. The user has full access to the control algorithm and safety settings. The control gains should be changed only after their affect on the stability of closed-loop system is understood. The user must read the RTWT User’s Manual in great detail before modifying the hardware and safety blocks.

Input Output Setup

In Figure 2, the green blocks, labelled “Read Cart Encoder” and “Read Pendulum Encoder”, represent the input of the cart and pendulum positions as encoder counts from two incremental encoders.

Note

Prior to the start of a control experiment the system must be at the reference position. This may entail the user depressing the "STOP" button and manually moving the cart to the center of travel and manually stabilizing the pendulum in the down position.

These cart and pendulum positions will be referred to as 0 meter and π radian, respectively. Motion of the cart to the right from the reference position will be considered motion in the positive direction and clockwise rotation of the pendulum will be considered positive.

The input blocks and the attached scaling blocks must be configured so that the startup initialises these positions and the feedback has the correct direction sense

Read Cart Encoder Block

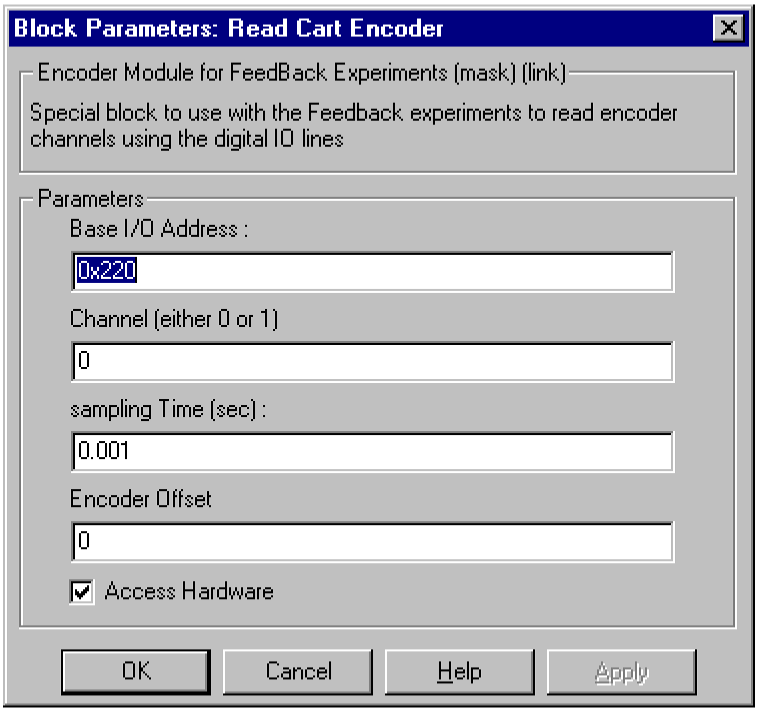

Figure 3: Cart encoder input configuration dialogue box

Double click on the “Read Cart Encoder” to open the dialog box shown in Figure 3.

There are four edit windows for entering

Base I/O Address

Channel

Sampling Time

Encoder Offset

You will notice that there are preset values already entered into the four edit windows. The Base I/O address is set when the Advantech PCL812 board is inserted into the PC by means of switches. The appropriate value should be entered into the edit window in Hex, and the model saved. It should not be necessary to then change this value unless another I/O interface board is used.

Note

The Advantech PCI1711 PCI I/O card has its base address automatically set by Windows, and it is therefore not necessary for the user to set it.

In the following experiments, the following values are set

Base I/O Address is set to 220 Hex or 544 Decimal

Encoder Channel is set to 0

Sampling Time is set to 0.001

Encoder Offset is set to 0 to initialize the cart encoder input to zero encoder counts at the start of the simulation, thus naming the start position zero.

Note that the **Access Hardware** is enabled.

The scaling block converts from counts of the incremental encoder turning with the motor, to units of meters for the movement of the cart along the rails.

Read Pendulum Encoder Block

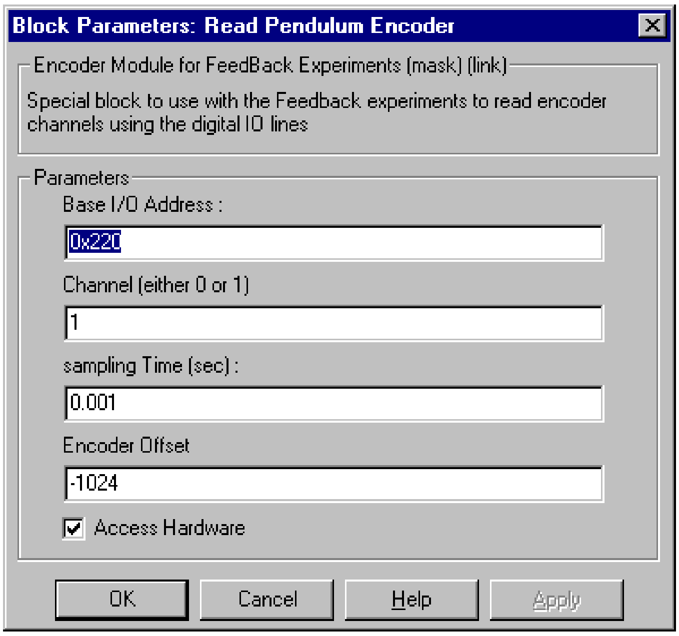

Figure 4: Pendulum encoder input configuration dialogue box

Double click on the "Read Pendulum Encoder" to open the dialog box shown in Figure 4.

In the following experiments the following values are set

Base I/O Address is set to 220 Hex or 544 Decimal

encoder **Channel** is set to 1

Sampling Time is set to 0.001

Encoder Offset is set to -1024. This sets the pendulum reference position to π according to the following calculation.

$$\text{Reference Position} = -1024 \text{ count} \times \frac{1 \text{ pendulum revolution}}{2048 \text{ count}} \times \frac{-2\pi \text{ radian}}{1 \text{ pendulum revolution}}$$

$$= \pi \text{ radian}$$

where the -2π term is contributed by the scaling block. The sign on the scaling blocks create the proper direction sense as described above.

Note that the **Access Hardware** is enabled.

Digital to Analogue Converter Block

The output command must match the capabilities of the hardware.

The Advantech board is capable of outputting a 0-5V signal. This signal is shifted in the amplifier to create a +/-2.5V capability required to command the drive motor in both directions. The shifting is transparent to the user at this level of use, so it is only necessary to ensure that the output command is in the range +/-2.5V.

The saturation block found in “Scaling and Safety” ensures that this constraint is met. Scaling is set to 1 so that a positive input creates motor torque that acts to move the cart in the positive direction.

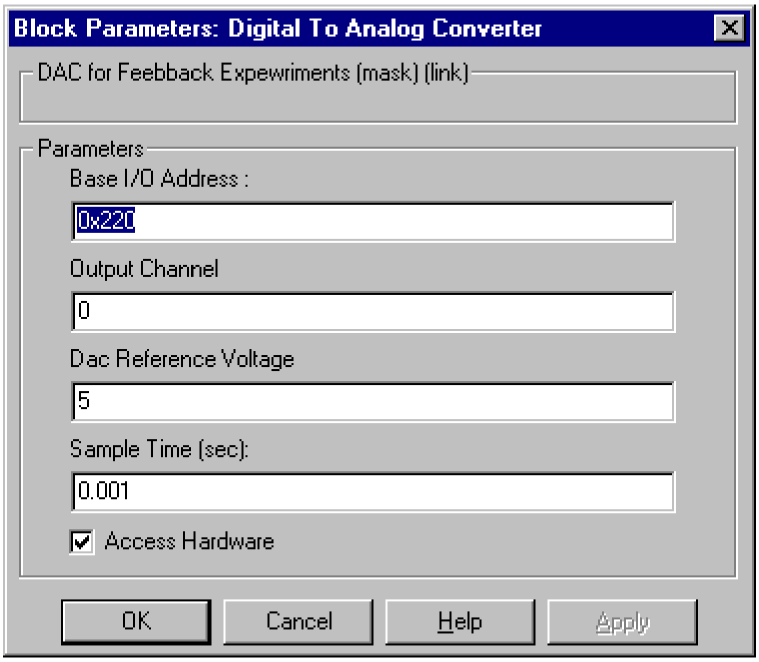

Figure 5: Digital to Analogue converter configuration dialogue box

Double click on the “Digital to Analogue Converter Block” to open the dialog box shown in Figure 5.

Base I/O Address is set to 220 Hex or 544 Decimal

Output Channel is set to 0 (i.e. the first D/A channel on the Advantech Board)

Dac Reference Voltage is set to 5

Sample Time is set to 0.001

Control Subsystem Block

The Control Subsystem is shown as a blue Block in the lower left section of Figure 2.

Double click on this block to open the PID control subsystem shown in Figure 6.

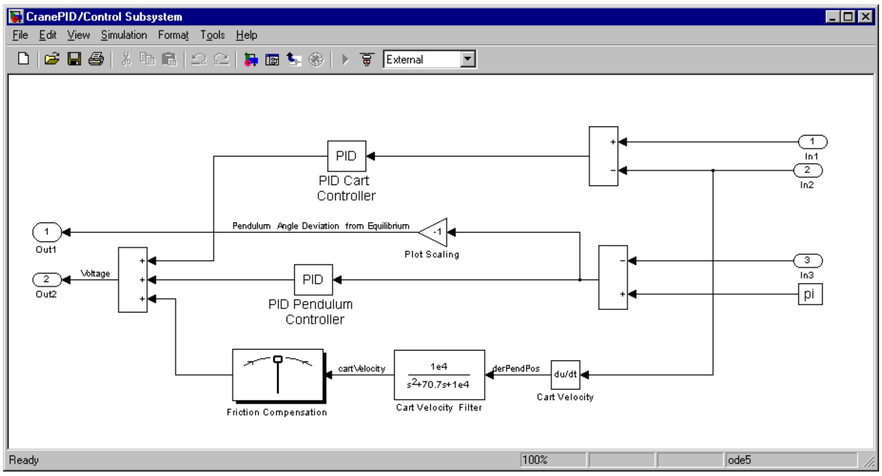

Figure 6: Crane mode PID subsystem

The “PID Cart Controller” and “PID Pendulum Controller” blocks are masked.

To reveal the structure either right click the mouse and select "`Look under mask`" or type (Ctrl+u) as shown in Figure 7 and Figure 8.

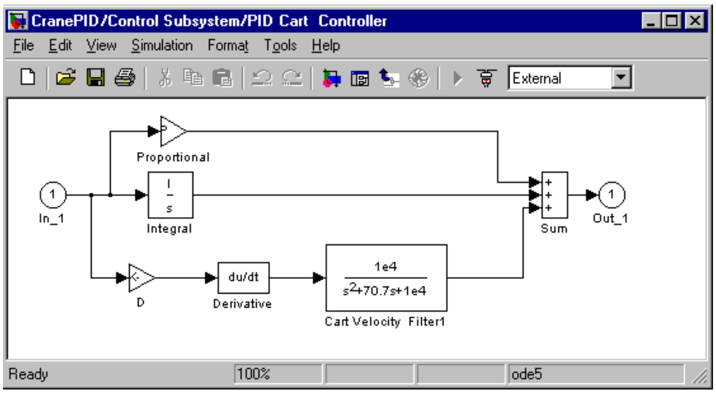

Figure 7: PID Cart Controller

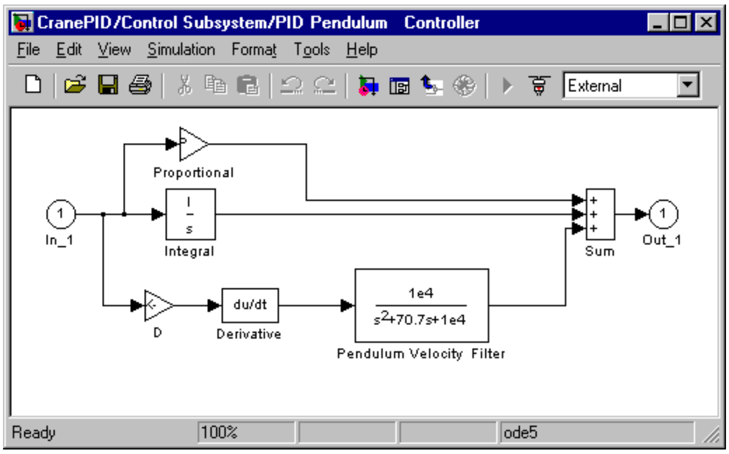

Figure 8: PID Pendulum Controller

Double click on these same blocks to reveal the changeable control gains as shown in Figure 9 and Figure 10.

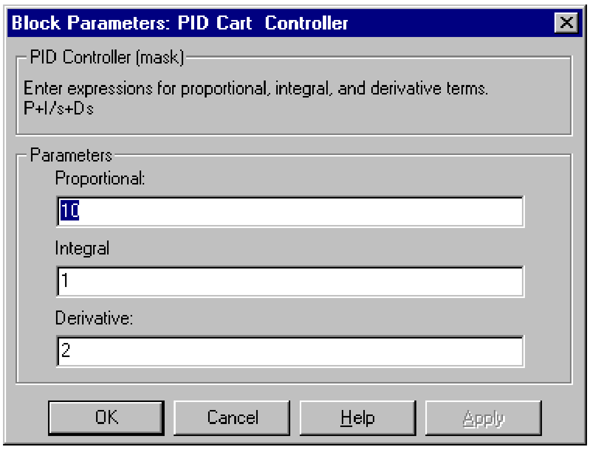

Figure 9: PID Cart Controller Parameters

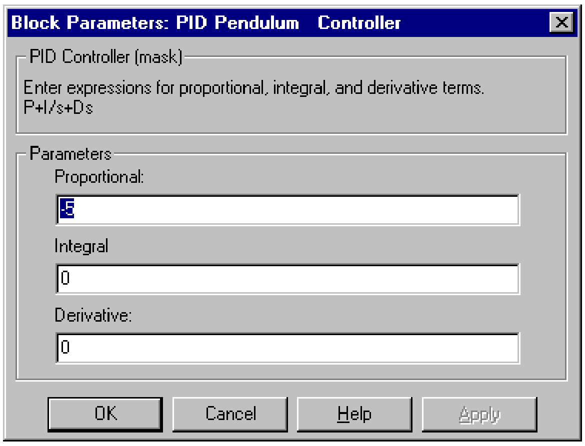

Figure 10: PID Pendulum Controller Parameters

Friction

An addition block “Friction Compensation” is used to compensate for the nonlinear static friction.

The diagram in Figure 11 represents the experimental relationship between cart friction and cart velocity.

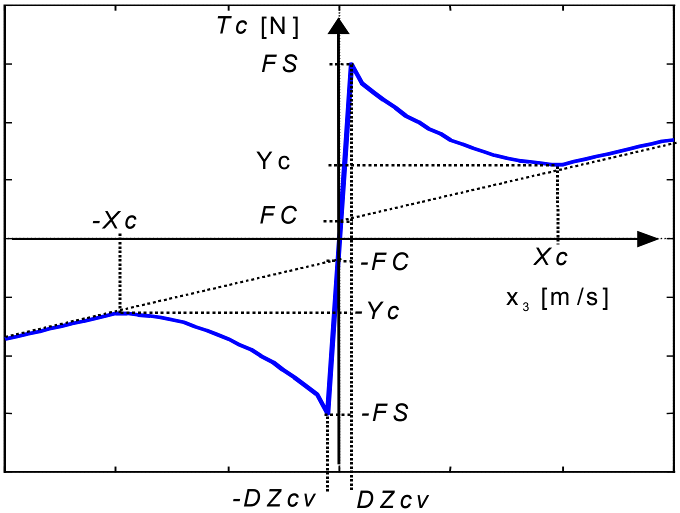

Figure 11: Typical cart friction T_C versus cart velocity x_3

Static friction exists in the dead zone of the cart, and this requires force to be applied on order to start movement (0< cart velocity <DZ cv).

Having overcome this initial friction, however, the static friction reduces, with an approximately quadratic relation to velocity, but the dynamic friction increases almost linearly with velocity.

The static friction eventually reaches a constant value of zero (at cart velocity = x_c), at which point the total friction becomes equal to the dynamic or Coulomb friction.

Since friction always acts in a direction opposite to the direction of motion, the function is mirrored for negative values of cart velocity with the friction force changed in sign.

The compensation used here represents a simplified approach in which the cart velocity is used to indicate the direction of a constant force offset.

The output of this function shown in Figure 13 produces a force in the direction of the sign of the velocity. It is clear that this can only partially compensate for the actual friction shown in Figure 11.

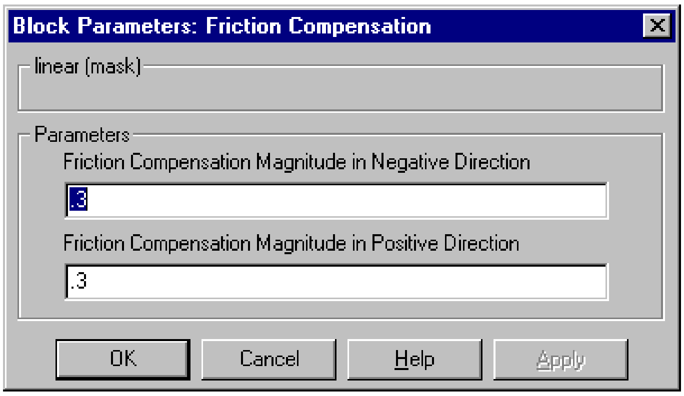

Figure 12: Friction Block parameters

The magnitude of the constant offset was obtained though applying the friction compensation as the only output (achieved by setting all PID gains for the cart and pendulum to zero) then varying the magnitude through trial and error until it feels that the cart glides freely. The user may adjust this magnitude slightly in order to better match the friction in a given system (Figure 12)

The user should continue through this manual and run the defined experiments before attempting to adjust the friction in this manner.

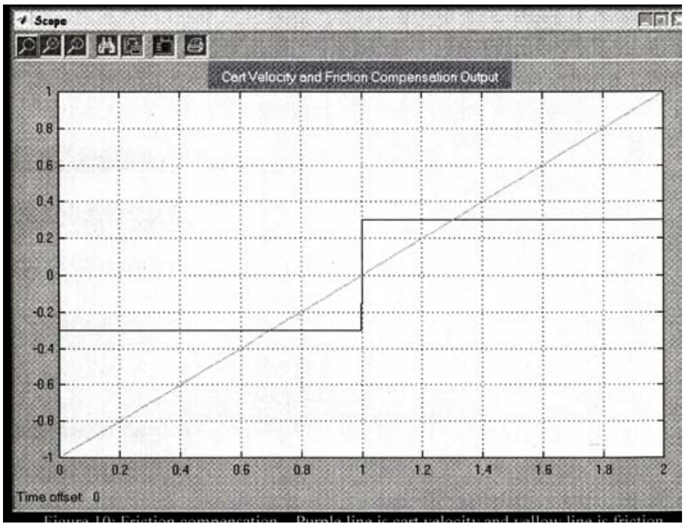

Figure 13: Friction Compensation

Display

The purple "Scope" block in Figure 2 provides the user with a record of the system states. This window can be opened, by double-clicking on the block *before* running the control, in order to see a live display. It can also be opened *after* the control has stopped in order to see a plot of systems states.

The user is referred to Simulink help for the options to scale, zoom, and print using this standard scope block.

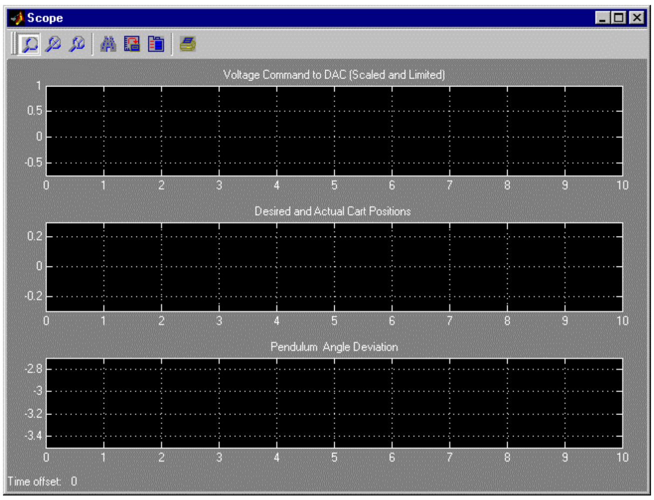

Figure 14: Scope Block

Building the Model

Build Options

Before initiating the subsequent automatic build process (that is using Real Time Workshop to generate, compile and link the actual C code to run the control model), it is necessary to ensure that the build options are set correctly.

To this end, select **Tools** from the Simulink model menu bar and then selecting **Real-Time Workshop** followed by **Options** from the pull-down menu. The **Simulation Parameters** window appears as shown in Figure 15.

From this window, click on the **Real-Time Workshop** tab as shown in Figure 15.

If you have followed the installation sequence described in both this manual and the introductory manual 33-000-1 the Simulation Parameters window should look exactly as in Figure 15.

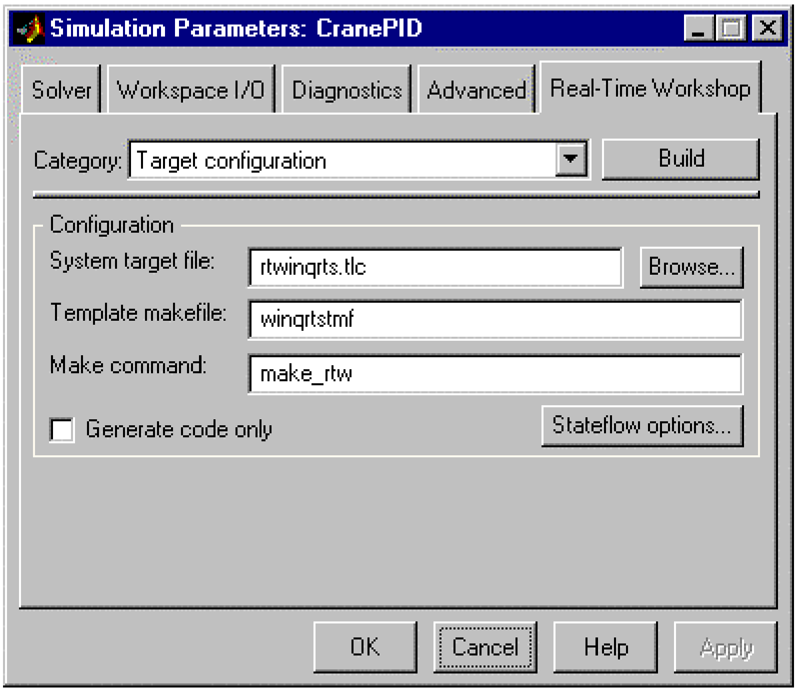

Figure 15: Simulation Parameter Options

Non standard Installations

If the text in the

```
System target file
Template makefile
Make command
```

edit boxes is not the same as shown in Figure 15 then follow the following sequence

Click on the **Browse** button.

From the resulting **System Target File Browser** window, select

```
rtwinqrts.tlc   Real-Time Windows Target with
                QRTS Extensions
```

as shown in Figure 16.

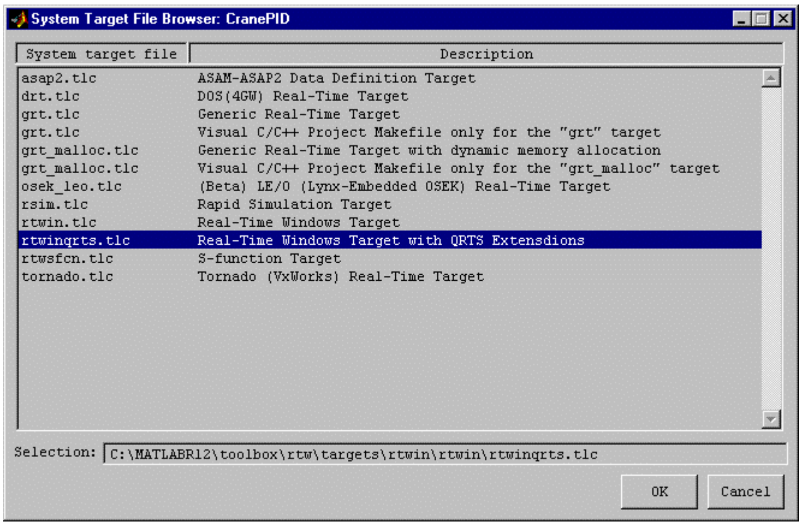

Figure 16: System Target File Browser

When the Simulation Parameters window is correctly set up, click the `Build` tab.

Real Time Workshop will now generate, compile and link the code necessary to run the model.

After selecting **Real-Time Workshop / Build** for *feedbackCraneDPID.mdl*, the following files will be automatically generated and saved in the directory c:\Feedback\Pendulum\

feedbackCraneDPID.bat, feedbackCraneDPID.c, feedbackCraneDPID.dt,

feedbackCraneDPID.h, feedbackCraneDPID.mk, feedbackCraneDPID.obj,

feedbackCraneDPID.prm, feedbackCraneDPID.reg, feedbackCraneDPID.rwd.

To connect to the target and execute the control program, follow the following sequence

Select `Tools` from the Simulink model menu bar.

Select `External Mode Control Panel` from the pull-down menu. The window shown in Figure 17 appears.

Click on the `Connect` button.

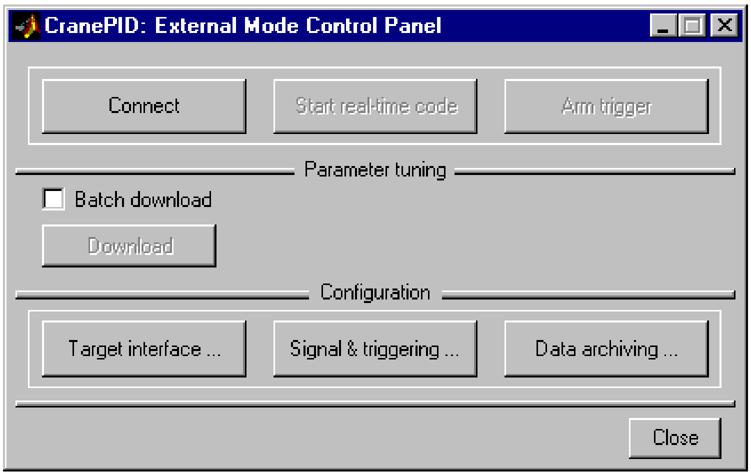

Figure 17: External Mode Control Panel

The `Connect` Button changes to `Disconnect` and the `Start real-time code` button is made available.

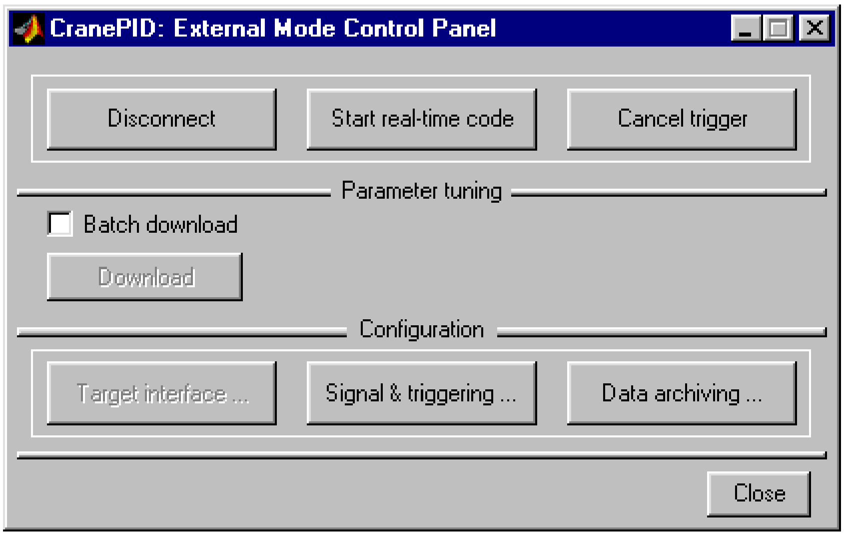

Figure 18: External Mode Control Panel

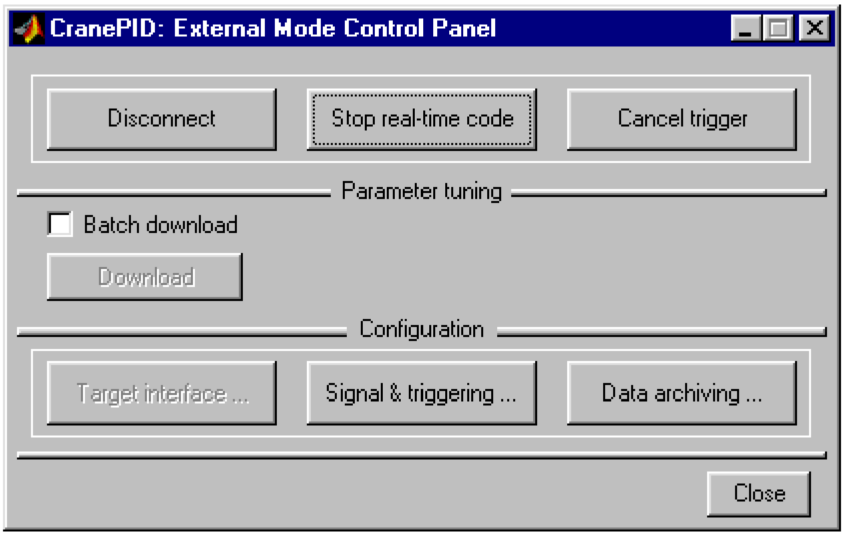

Figure 19: External Mode Control Panel

Note

The reference position is established during `connection` to the real-time target; thus the system must be moved to the reference position *before* the `Connect` button is activated.

If the system is not at the reference position, indicated by a vertical bar label on the cart track, click on the `Disconnect button`, move the cart to the reference position, and click on the `Connect` button.

Control Program Execution

Starting

To **begin** execution of the real time Control Program, click the

`Start real-time code` button

The control software is now active (the Advantech hardware adapter has been started)

Press the Green Start button on the pendulum control unit

Stopping

To **stop** execution of the real-time target click either the

`Stop real-time code` button or the
`Disconnect` button shown in Figure 19.

Press the Red Stop button on the pendulum control unit

In the `External Mode Control Panel`, the check box

`batch download`

under the

`Parameter tuning`

group title, controls the behaviour of the parameter tuning. If the

`batch download`

check box is enabled, then the new parameters will not be downloaded automatically to the real-time target until you click the

`Download`

button .

This feature is useful in a situation where you need to change *multiple* parameters and desire that all of these changes take effect instantaneously. Note, however, that there are some limitations to this capability.

Changing Real Time Parameters

To change parameters follow the following sequence;

Double Click the Simulink Block containing the parameters, make the changes, and then click the `Apply` Button followed by `OK`.

Note

Some of the parameters can be changed during program execution, others dealing with *changes* to the model will necessitate a new system build and new c code generation.

Real Time Workshop will inform you if a new build is necessary.

For example, the P I and D coefficients values can be changed in real time without re-compilation as they are simply constants read by the real time program, whereas a change of the exciting waveform from square to sinusoidal, will require a new-build.

System Operation

Before starting any experiments, perform the following steps:

Make sure that the green *Start* button on the controller box is in its **off** position. (not lit)

Switch-on the *power* switch on the controller box

Bring the cart to the centre of the rail and stop oscillations of the pole.

Start the controlling software as described above (e.g. the Simulink simulation) for an experiment.

Press the green button motor start switch on the controller box

Typical results

Figure 20 shows the graph of the cart velocity and friction compensation output. The line with the step function is the friction compensation added to the control based on the velocity, and the continuous line represents the cart velocity.

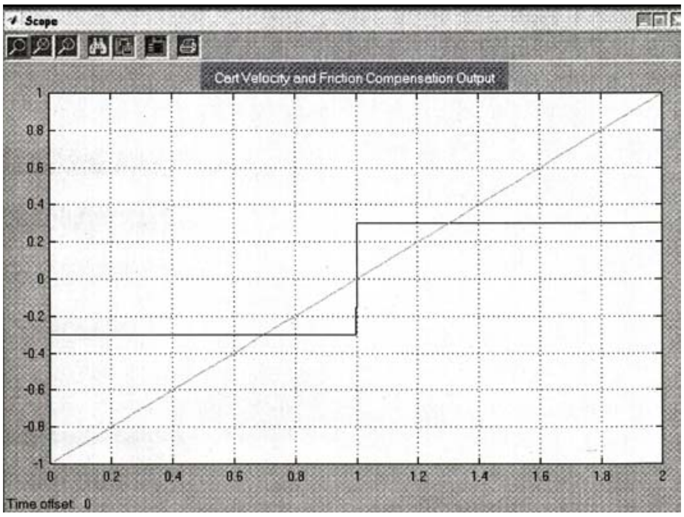

Figure 20: Cart friction versus velocity chart

Note that if the friction compensation parameters are set too high, then the cart velocity will be higher than expected leading to possible oscillations of the cart about the desired position.

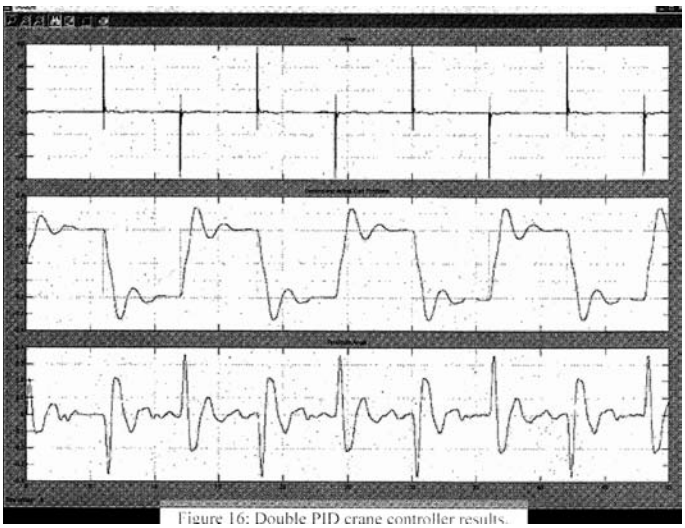

Figure 21:

The first trial, plotted in Figure 21, moves the cart between two points and attempts to reduce the swing of the pendulum at these points.

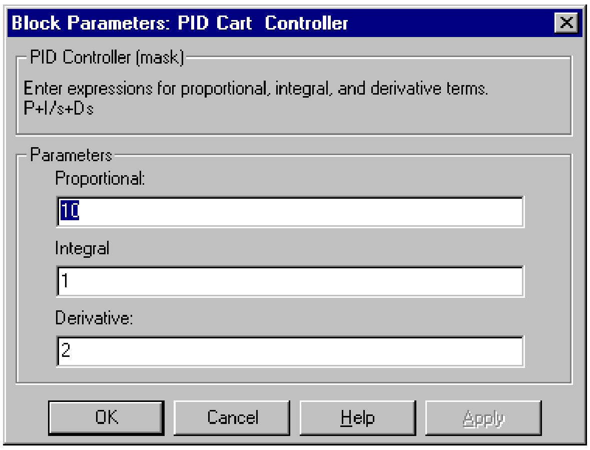

Figure 22: PID Cart Controller Gains

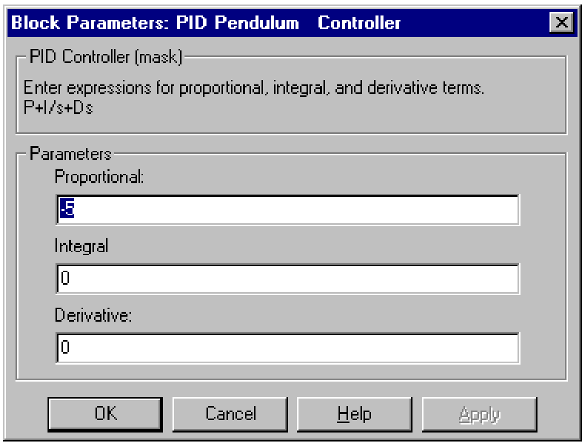

Figure 23: PID Pendulum Controller Gains

The gains are shown in Figure 22 and Figure 23. The effectiveness of the control is highlighted by setting all gains shown in Figure 23 to zero in the PID Pendulum Controller” to yield the results shown in Figure 24.

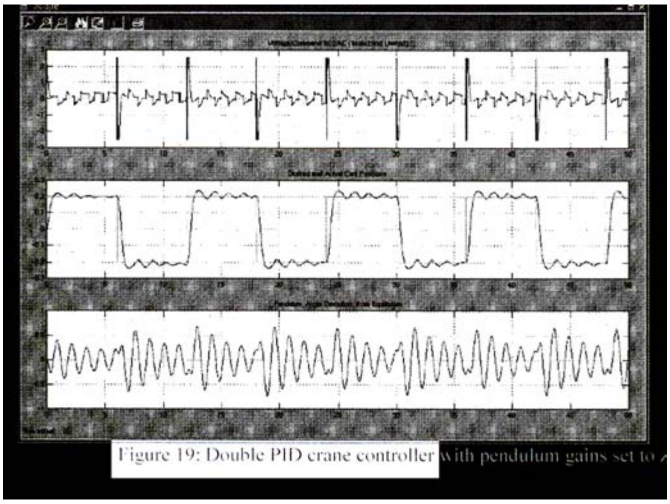

Figure 24

It can be seen that the cart is following the desired trajectory but that the pendulum continuously oscillates about the equilibrium point.

Notes

4 Experiment 2 - Inverted Pendulum - Swing Up and Stabilise

Theory and Model description

This experiment demonstrates the stabilization of the inverted pendulum. The sequence of operations for building the model, starting and stopping the program and changing parameters are the same as those described in Experiment 1.

Loading the RTWT Block Diagram

To load and execute the block diagram for the inverted pendulum control, follow the procedure outlined below:

Start MATLAB

Type the following commands into the MATLAB command window

```
cd C:\Feedback\Pendulum

Invertedpd
```

The Simulink block diagram for the Inverted Pendulum, appears and is shown in Figure 25.

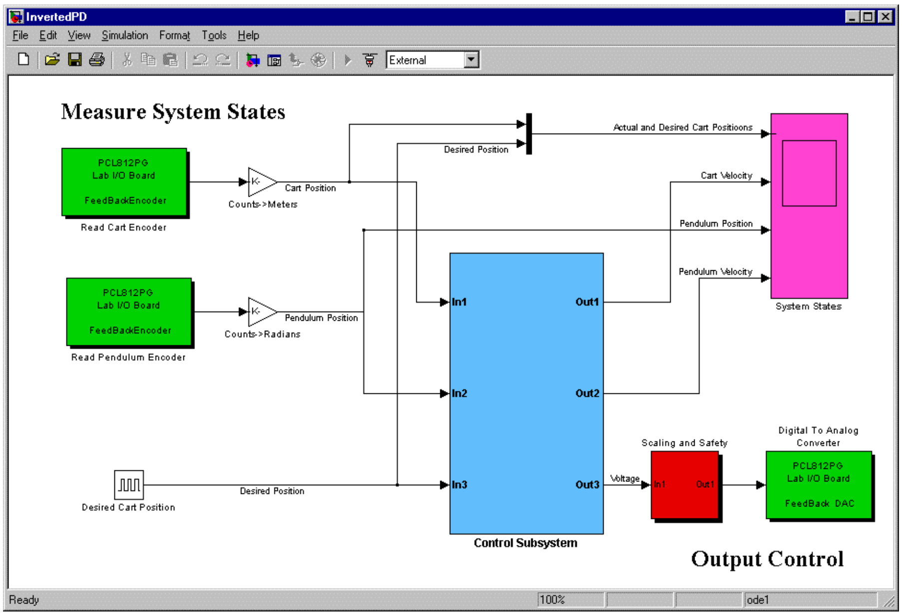

Figure 25: Simulink Block Diagram for Inverted Pendulum

The goal of this controller is to first move the pendulum near enough to a vertical region, see Figure 26, that a PD control can be switched in to stabilize the pendulum in the inverted position.

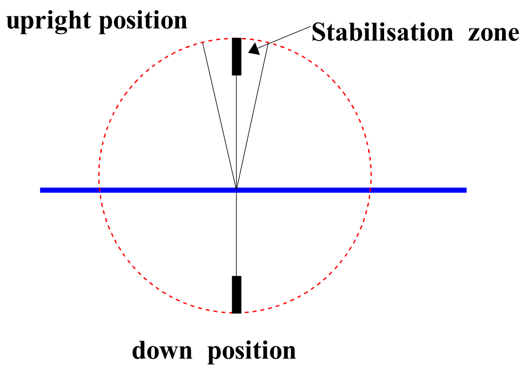

Figure 26: Upper Stabilisation Zone

Double Click on the Blue Control System Block in Figure 25 to reveal the detail shown in Figure 27

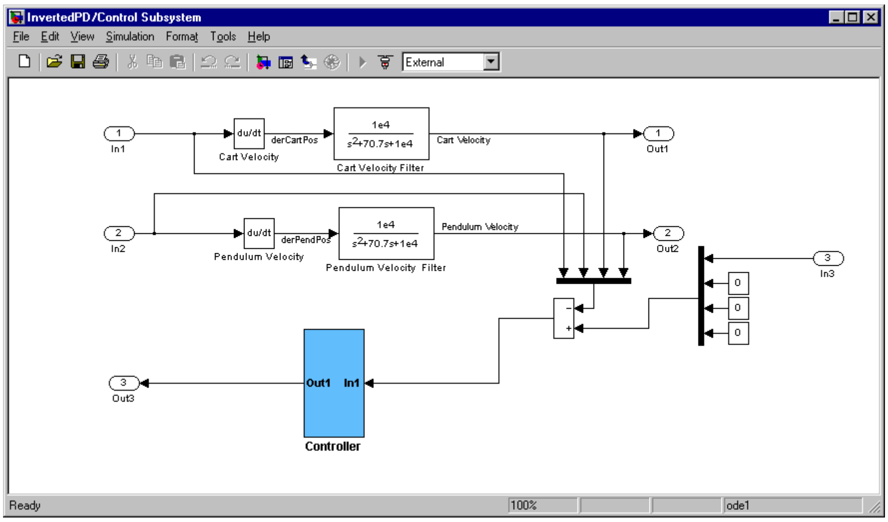

Figure 27

Out 1 and Out 2 are outputs to the Simulink scope for cart and pendulum velocity. Out 3 is the control output to the motor.

Double click on the blue Controller block in Figure 27 to reveal the details of the controllers, shown in Figure 28.

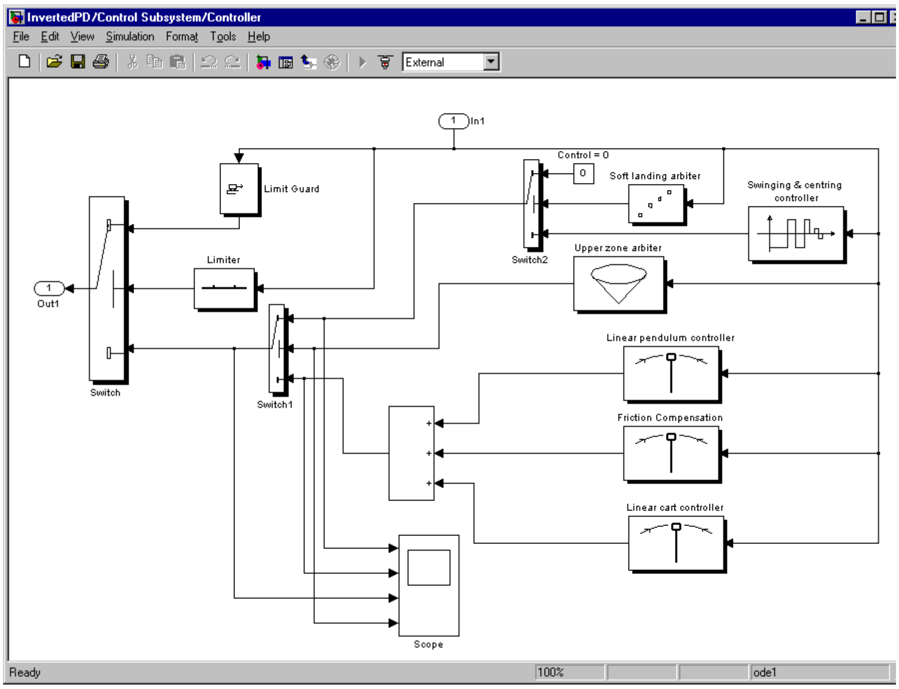

Figure 28: Inverted Pendulum Controllers

The block “Upper Zone Arbiter” determines the point at which the stabilizing control is activated.

The "Soft Landing Arbiter" calculates the kinetic energy KE of the pendulum at the lowest vertical point of travel, and the potential energy PE at the highest vertical point of travel. If KE is greater than PE then the pendulum will rotate *through* the vertical point. The function of this block is to limit the swing so that the kinetic energy of the pendulum when entering the stabilisation zone is almost zero.

The “Limiter” block switches the control to a safe mode that moves the cart in the direction away from a travel limit if the cart position approaches either end of travel.

Between these zones the “Swinging Controller” will move the cart in a manner such that the pendulum rotates near the equilibrium position.

The input, output, and friction compensation procedures are identical to the first experiment. The control gains are shown in Figure 30 to Figure 32.

The experiment is very sensitive to the values in Figure 30; that is, if alpha and beta are too small the cart will run into the overtravel as it attempts to swing up and if they are too large the pendulum will not rotate to within the stabilization zone. The difference between “too large” and “too small” is very little and you may need to make slight adjustments for a given electromechanical system.

The result of this control is shown in Figure 29 where it can be seen from the third plot that the pendulum is rotated until it can be stabilized near the zero position (vertical). A cart disturbance is added after the pendulum has balanced as shown in the first plot of Figure 29.

Note that the input-output setup, implementation, and execution are the same for both Control Experiments 1 and 2; hence, these topics are not discussed again in this section.

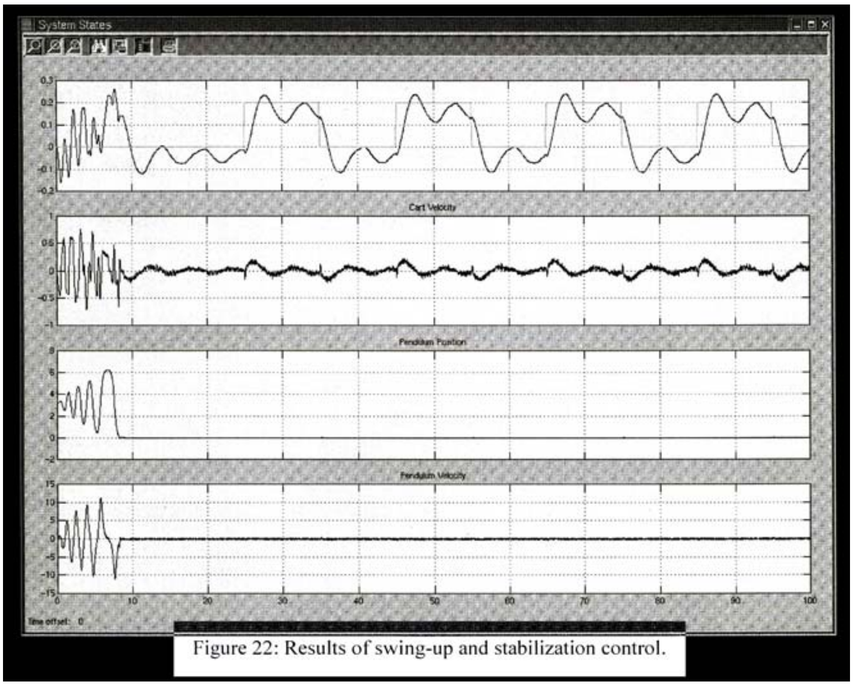

Figure 29: Results of Swing up and stabilisation control

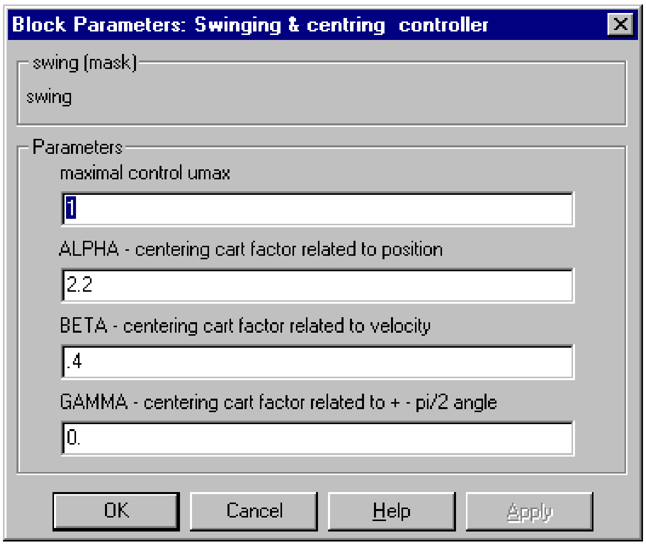

Figure 30: Parameters to control swing behaviour

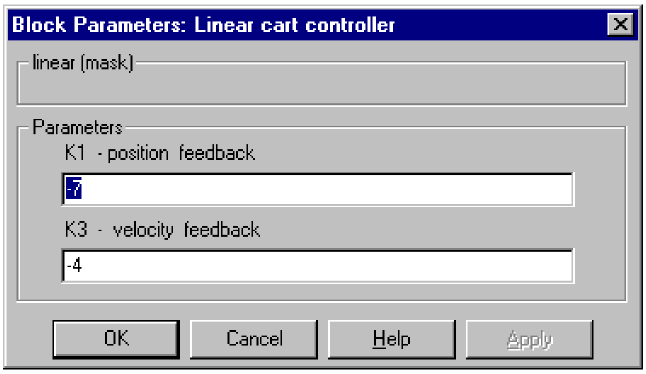

Figure 31: Cart PD gains

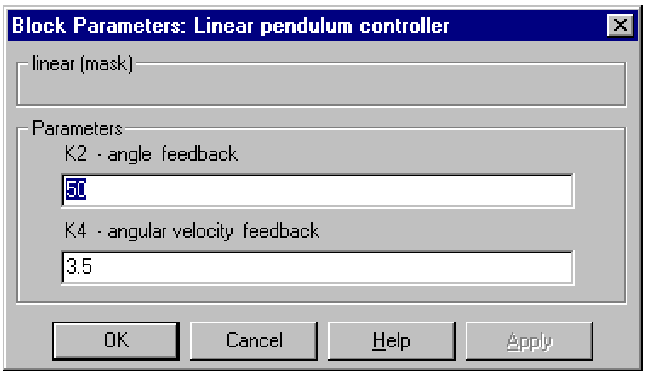

Figure 32

Notes

5 Experiment 3 - UpDownDemo

This experiment combines both the CranePID and the InvertedPd control experiments, by switching between them on a periodic basis.

Start MATLAB

Type the following commands into the MATLAB command window

```
cd C:\Feedback\Pendulum

UpDownDemo
```

The Simulink block diagram for the UpDownDemo, appears and is shown in Figure 33.

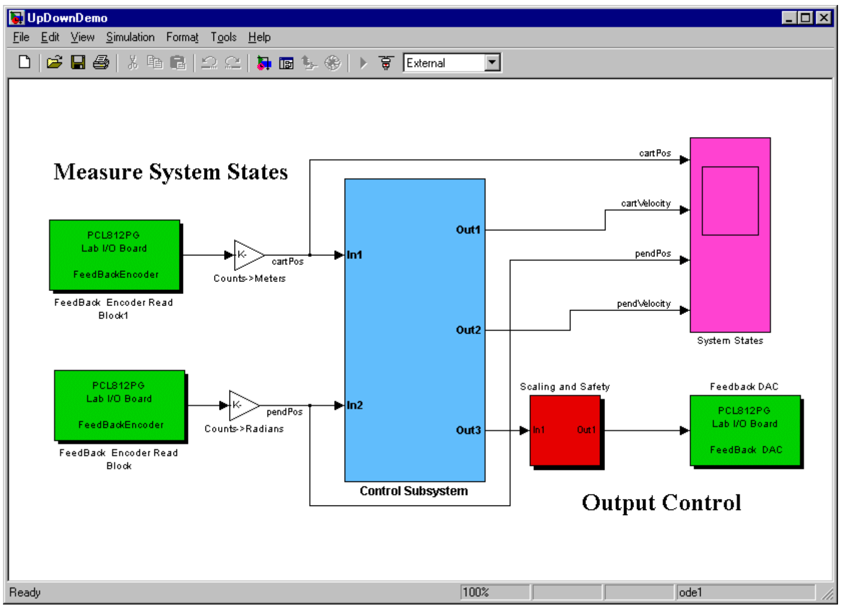

Figure 33: UpDownDemo

Double click the blue Control subsystem block to reveal its structure with the two controllers for each timed interval.

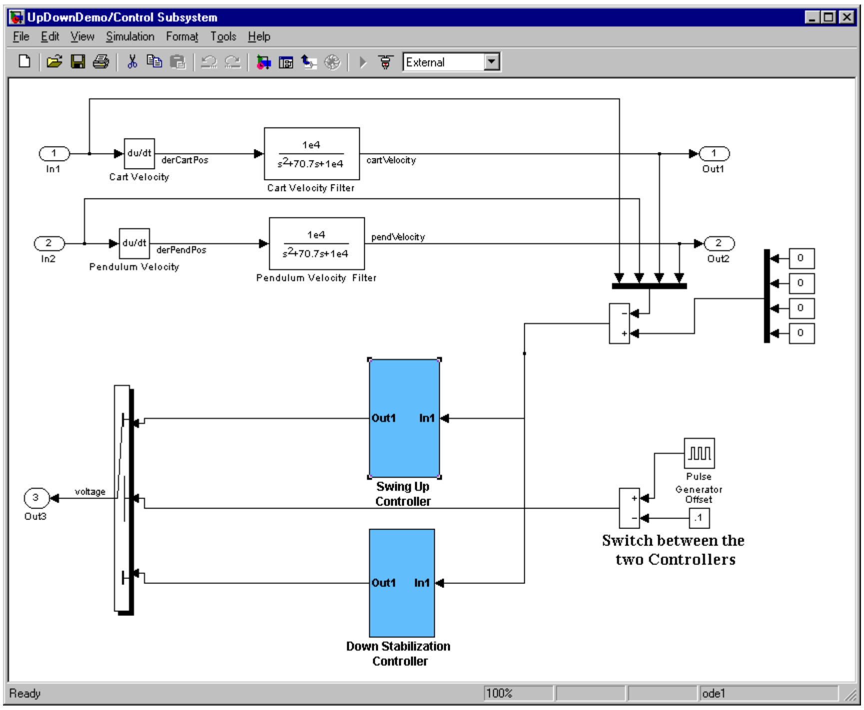

Figure 34: UpDownDemo

6 Customised Control

RTWT combines the powerful functionality of MATLAB, Simulink and Real-Time Workshop and allows users to implement any kind of control algorithm.

If you wish to implement a different kind of controller you may copy one of the supplied block diagrams, and simply replace the existing control blocks with customised control blocks (or subsystems).

However, before you start designing and implementing customised control algorithms, it is strongly recommended that you refer to the RTWT User's Manual and the Simulink User's Guide.

Notes

7 Some Common Problems

CranePID

1 If the Friction Compensation Parameter is set to high you may notice high frequency oscillations of the cart about its desired position. To remove these you should gradually reduce the friction compensation parameter value shown in Figure 12 until the oscillation stops.

Inverted PD

2 If the pendulum never reaches a vertically upright position, the parameter umax, the maximum power applied to the motor, may be too low (Figure 30). Try increasing this in small increments, until the pendulum swings with sufficient speed to reach this position.

3 If you wish to change other parameters (such as alpha or beta), then choose the parameter to vary and make small positive and negative increments to the initial value. Find the optimum value of *this* parameter which gives the "best" quality of control. Then, using this value and the same procedure find the optimum value of another parameter. After changing relevant parameters, you can repeat the sequence starting with the first parameter if necessary.

Notes