

The Quanser Method
Demonstration System
The Quanser Micropositioning System

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The Quanser Method?

The Quanser Method is a systematic approach used for developing and deploying advanced mechatronic systems. The Method is regularly and successfully used throughout our own R&D department when developing educational systems as well as advanced systems such as unmanned vehicles, haptic devices, robotic systems and virtual environments. The Quanser Method is crucial for successfully and quickly developing and deploying advanced and sophisticated systems. The Quanser Method systematically integrates concepts of mathematical modeling, advanced control design, simulation, hardware in the loop simulation, virtual plants, animation, data collection, system identification, parameter estimation, optimization, code generation, realtime systems, implementation and deployment.

We did not invent the Quanser Method. It defines Quanser.

QuaRC Demo Micro-positioning System

You have received a QuaRC Demo Micro-positioning System that was designed to demonstrate the advanced features of the Quanser Method in a very effective manner. We have taken an ordinary \$4 relay and made it do extraordinary things. Although the relay is a two state device, we have equipped it with the required electronics that will enable QuaRC to control the angle of a lever mounted mirror to within 0.05 degrees. This system truly demonstrates the **power of control !** Using this simply constructed plant, sophisticated concepts will be readily demonstrated, implemented and evaluated.

High realtime performance can be achieved using PCI bus based devices. The demo uses Quanser's USB based technology to demonstrate all the salient features associated with the Quanser Method. With this system you will experience a variety of advanced features that are sure to expedite the results in your field of application whether academic, advanced research or industrial. Please note that this inexpensive plant is only a vehicle intended to demonstrate the principles behind the Method. While this system adheres to our principle of producing the highest grade product it is constructed bearing in mind that we will be giving it away for free. Our products, whether educational or industrial cover a wide range of performance and cost that can be tailored to your application.

The Quanser Method for Education

Quanser's roots are in designing and manufacturing educational systems for higher learning. Our dedication to control education is unsurpassed and our goal

is to disseminate advanced concepts without compromising fundamental learning. As the abstraction layers in education accumulate, students are less likely to understand the fundamentals. Our mission is to advance the state of the art in education by using and creating the most advanced tools while maintaining a transparency that will allow the naturally curious students to explore the fundamentals. The systems are designed to intrigue, captivate and motivate with the underlying purpose of educating.

Today the Quanser Method is used worldwide to teach students all elements of control design. Our educational material is rigorous and all the elements that are described in the following chapters are expounded in detail with every experimental apparatus and curriculum we deliver. This detail is what students will need to become the successful engineers of the future.

The Quanser Method for Research

As your research leads you to explore more complex systems, the time taken to transition from concept to reality gets longer. The Quanser Method is an integrated and expandable solution that will allow you to explore your ideas quickly and help your graduate students attain their goals much faster.

The Quanser Method for Industry

Time to market is taking too long? Code generation, realtime performance, seamless integration, simulation, hardware in the loop testing – these are the tools that will help you achieve your goals on time. If you are still writing code, you are being left behind and your development cycles are getting longer and longer. Get the edge and use our tools. We use them ourselves.

Document purpose

This document is intended to demonstrate the Quanser Method in a quick and effective way. Please install the required software components as outlined in Appendix A. Following the installation, we want to ensure that you have a fully functional system. Please follow the instructions in Appendix B to ensure that your system is operating as expected.

Once you have completed the procedures in Appendix A and Appendix B, we propose that you execute the modules in the following sections sequentially. These sections are designed to effectively expose you to only a few features at a time. As time goes by we shall be creating more modules that you can download from our site.

Please take your time with each section. The whole process should not take longer than a couple of afternoons. We want you to enjoy this experience but we also want you to assess the Method effectively. We are sure that you will learn something new as you go along. We certainly did!

The Quanser Micro-Positioning Demo System

A photograph of the micro positioning system you have received is shown in Figure 1. It consists of the following components:

- Electromagnet
- Spring loaded lever
- Extended lever arm
- Mirror
- Position sensor
- Amplifier
- USB computer interface
- Relay contacts

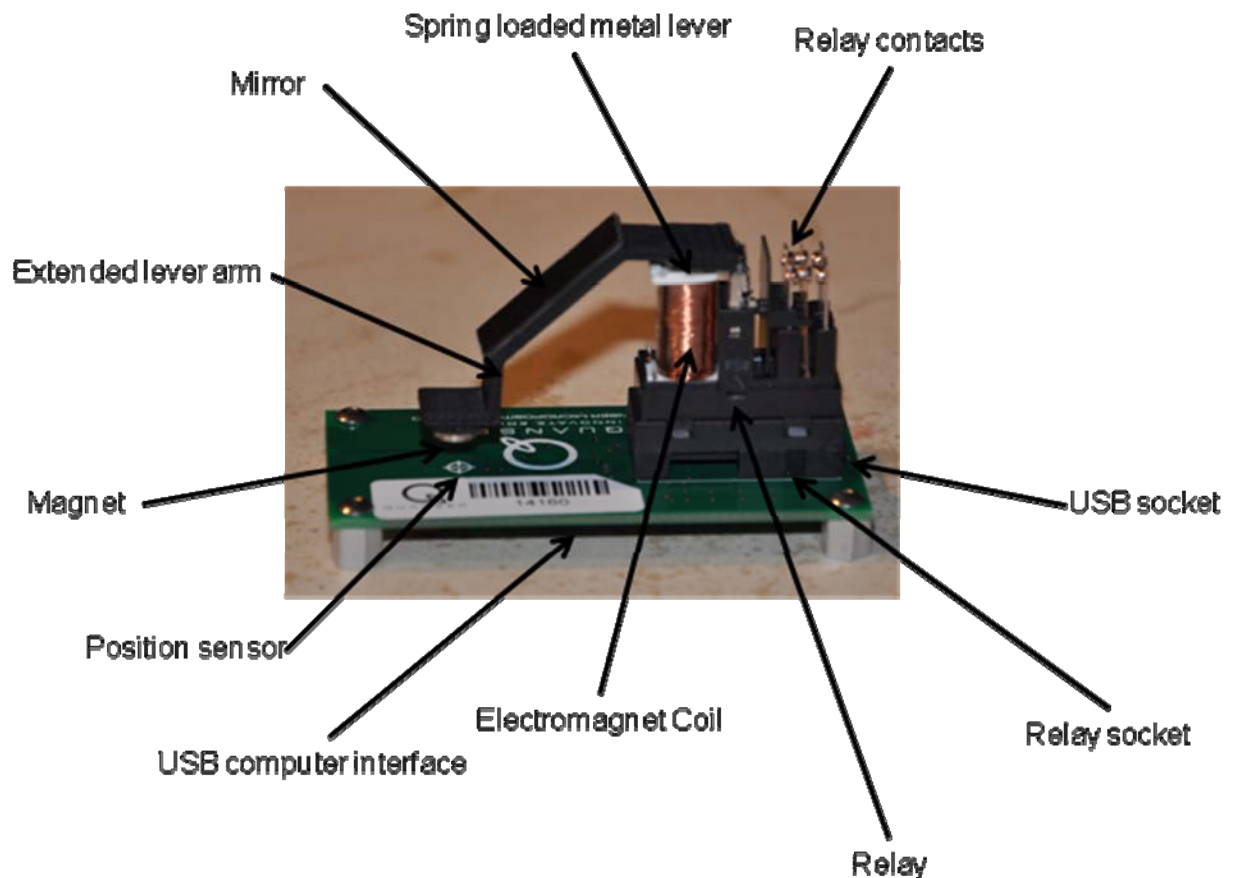


Figure 1 Quanser Micro-Positioning Demo System components

A block diagram of the system is shown in Figure 2.

The principle of operation is as follows: The D/A in the USB system can output a voltage in the range of 0 to 1.67 Volts. The voltage is amplified by a gain of 3 (Gamp) and then applied to the coil. The voltage causes a current in the coil which in turn creates a magnetic field that applies a force to the spring loaded lever. As the current increases, the magnetic force overcomes the spring torque and at a certain point the force is enough to make the lever move. As the lever moves it gets closer to the electromagnet which results in a stronger attractive force until the lever is pulled all the way down to $\theta = 0$. The system is open loop unstable; you cannot apply a fixed voltage and keep the lever at a desired angle. The system is equipped to measure the deflection of the lever arm using a permanent magnet and a hall effect sensor. A small magnet is mounted at the tip of the extended lever arm. A Hall Effect sensor is mounted right under the magnet on the board. As the lever arm moves down, the Hall Effect sensor measures the magnetic field strength and outputs a voltage proportional to the distance of the magnet from the sensor. The voltage from the Hall Effect sensor is measured by one of the A/D channels on the board. We will use this measurement to measure and control the angle θ . We can also measure the current in the coil: the voltage across a resistor wired in series with the coil can be measured by the other A/D on the board. This measurement can be calibrated to measure the current in the coil.

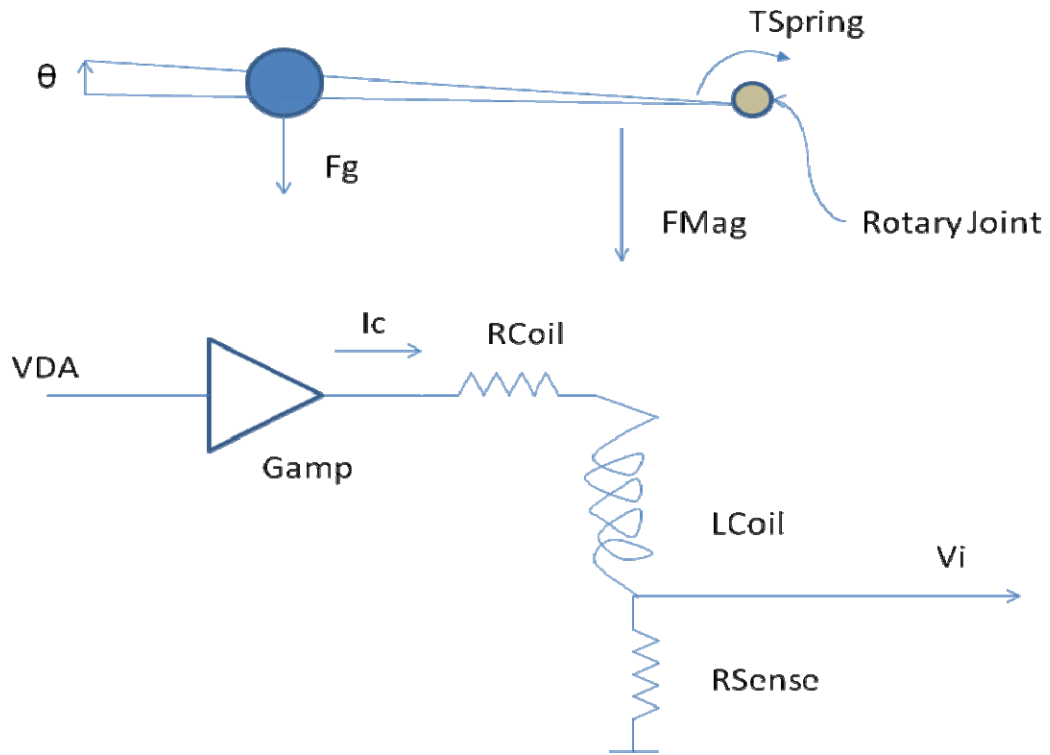


Figure 2 Electrical schematic and free body diagram

We will be moving the mirror in a very small range which is not readily visible to the human eye. The extended lever motion can be seen, but only slightly. You will be able to see the sensor data on realtime plots.

You may want to use a laser pointer to observe the motion of the mirror by deflecting the laser beam from the mirror onto a distant wall. Using this approach you will be able to move the beam vertically on the wall by several cm.

For safety reasons, we do not supply the laser pointer. Please note that laser beams, even weak ones, can be dangerous. Do not point them onto anything but an inanimate object.



System parameters

The mechanical dimensions and system parameters are shown in the table below.

LSensor	3.69E-02	m	Distance from hinge to hall effect sensor
Lcg	2.24E-02	m	Distance from hinge to lever cg
LMag	7.15E-03	m	Distance from hinge to center of electromagnet
theta max	4	degrees	Max angle
theta min	0	degrees	Min angle
M	3E-03	Kg	Lever mass
J	2.35E-06	Kg-m ²	Lever inertia about hinge point
RCoil	47	Ohm	Coil resistance
LCoil	0.4	Henry	Coil inductance
RSense	5	Ohm	Sense resistor resistance
Gamp	3	V/V	Amplifier gain following D/A
Vmax	5	V	Max output voltage of amplifier
VmaxDA	1.67	V	Maximum output voltage of D/A

Control Objective

The purpose of the experiment is to design a control system that will make the mirror track a commanded angle. The performance requirements are as follows:

Cmd amplitude	0.5	degrees
Cmd mid point	3	degrees
Cmd frequency	0.1	Hz
Mean tracking error	0.1	degrees or better
Max speed	0.2	deg/sec

Mathematical Modelling

Consider the simplified schematics shown in Figure 2 and Figure 3

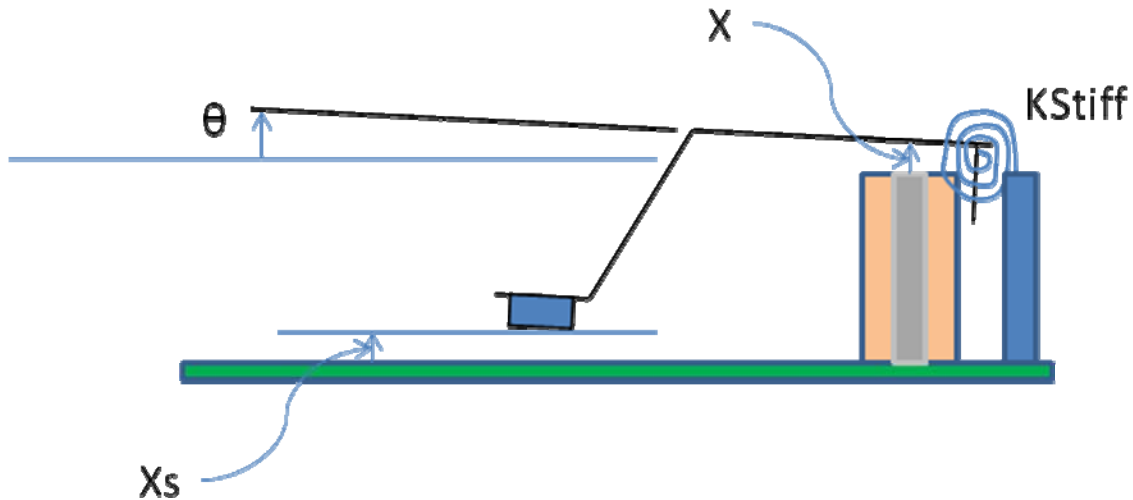


Figure 3 Simplified mechanical representation. The return spring is shown as a torsional spring with torsional stiffness K_{Stiff} . The extended lever arm deflects by the angle θ which is directly related to the distance x of the metal lever from the top of the electromagnet. At $x = 0$, the metal lever is in contact with the core of the electromagnet.

The electromagnet creates a force F that is related to the current as follows:

$$F = \frac{K_{Mag} I_c^2}{x^2}$$

Where

F is the force in Newton

x is the distance of the lever arm from the electromagnet core

I_c is the current in the coil

With

$$x = L_{Mag} \theta$$

Where

θ is the angle (radians) of the lever from the horizontal position – up is positive.

The force F creates a Torque given by

$$T = F L_{Mag}$$

$$T = \frac{KMag I_c^2}{LMag \theta^2}$$

The spring in the system also creates a torque given by

$$T_{spring} = KStiff (\theta - \theta_{home})$$

Where **theta_home** is a virtual zero return position of the spring. The lever cannot reach that position due to the mechanical construction of the relay.

Gravity creates a torque given by:

$$T_g = M g Lcg \cos(\theta)$$

These three torques add up to make the lever move as follows:

$$J \left(\frac{d^2}{dt^2} \theta(t) \right) = - \frac{KMag V_c^2}{LMag (R_{coil} + R_{Sense})^2 \theta^2} - M g Lcg \cos(\theta) - KStiff (\theta - \theta_{home})$$

Assuming the inductance of the coil LCoil is negligible, the current in the coil is related to the applied voltage Vc:

$$I_c := \frac{V_c}{R_{coil} + R_{Sense}}$$

Resulting in:

$$T := - \frac{KMag V_c^2}{LMag (R_{coil} + R_{Sense})^2 \theta^2} - M g Lcg \cos(\theta) - KStiff (\theta - \theta_{home})$$

The torque equation can be linearized about an operating point:

$$\theta = \theta_q$$

$$V_c = V_q$$

to obtain a linear model:

$$J \left(\frac{d^2}{dt^2} \theta(t) \right) = a \theta + b Vc$$

with

$$b = - \frac{2 KMag Vc}{LMag (Rcoil + RSense)^2 \theta^2}$$

$$a = \frac{2 KMag Vc^2}{LMag (Rcoil + RSense)^2 \theta^3} + M g Lcg \sin(\theta) - KStiff$$

Where a and b evaluated at the operating point.

Nominal Control Design

Demonstrated features	Nominal controller design
Filename	mpd_nominal_lqr.m

Run the MATLAB m file above – it will calculate the gains for a nominal design using the linear quadratic regulator method.

The nominal design uses the following values:

$$Q = \text{diag}([1000 \ 0 \ 100])$$

$$R = 0.08$$

Resulting in the following gains

Kp	-1.06	V/deg
Kd	-0.0077	V sec/deg
Ki	-0.62	V/(Deg sec)

The file prints out the following in the Matlab window

```
***** MPD Nominal Design *****
***** Feedback Gains -1.06 -0.0077 -0.62
***** Operating point 3.000 Degrees
***** Operating current 50.000 MilliAmperes
***** Operating voltage 2.600 Volts
***** Linear model: J d2/dt2 = -45583.32 theta -627.54 Vc

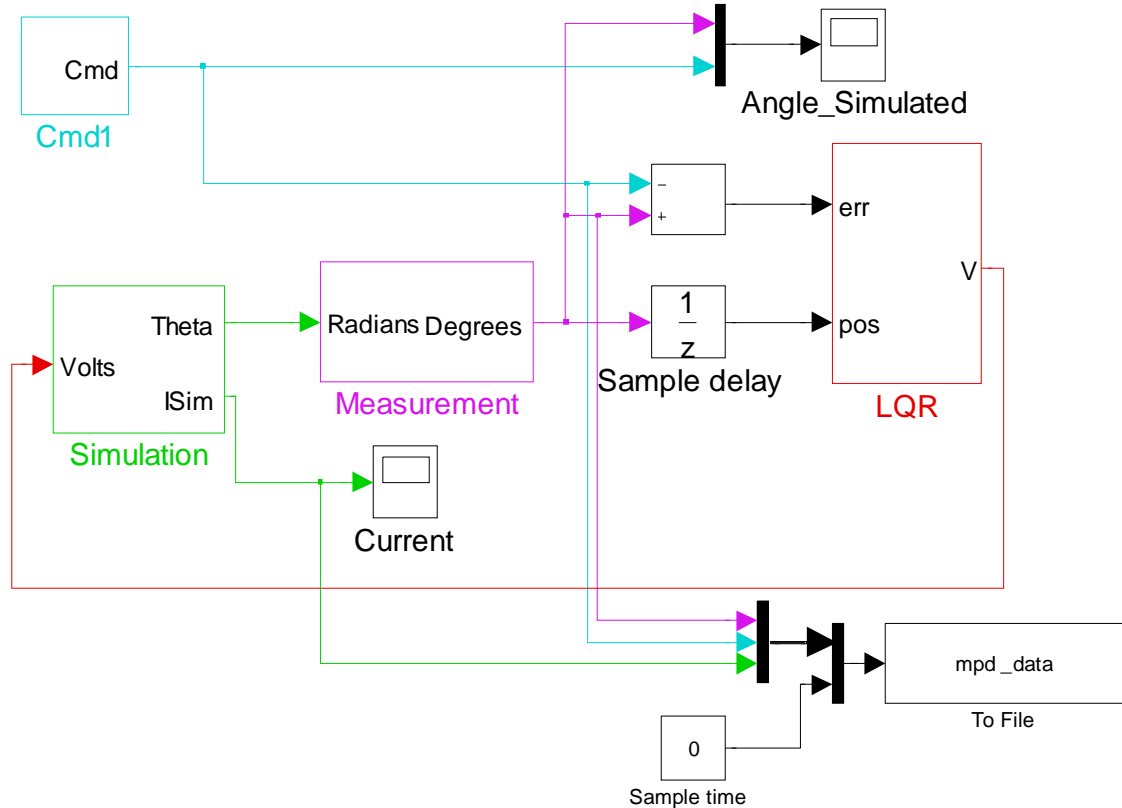
***** Closed loop poles *****
-138.00 + 254.22 i
-138.00 + -254.22 i
-0.27 + 0.00 i
```

This shows that there are a couple of fast poles and one slow one. The sample rate must be chosen well to accommodate for the fast poles. The dominant response of the system is the slow pole largely due to the integration.

Non linear Simulation of Nominal Controller

Demonstrated features	Simulating the system using Simulink
Filename	mpd_nonlinear_simulation.mdl

Open the Simulink model specified above – you will see the diagram shown here:



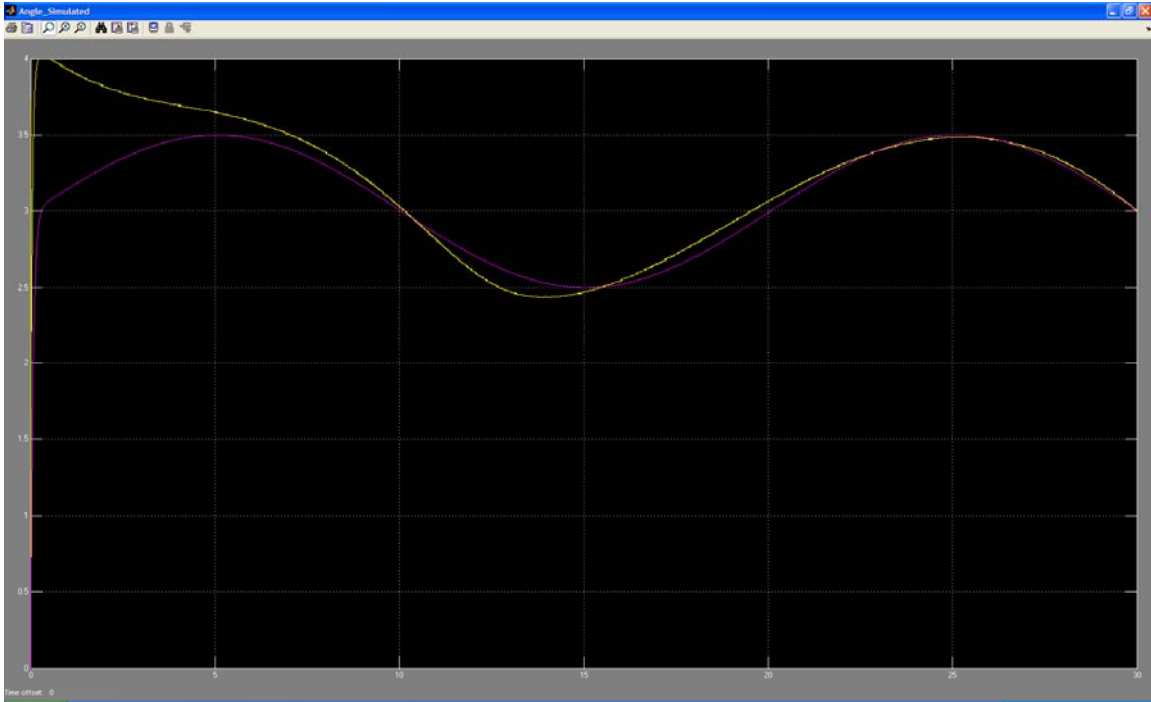
- ❖ Open the scope labeled Angle_Simulated
- ❖ Run the controller design file **mpd_nominal.lqr.m**
This will calculate the feedback gains based on the nominal design – it will print the following in the Matlab window:

```

***** MPD Nominal Design *****
***** Feedback Gains -1.06 -0.0077 -0.62
***** Operating point 3.000 Degrees
***** Operating current 50.000 MilliAmperes
***** Operating voltage 2.600 Volts

```

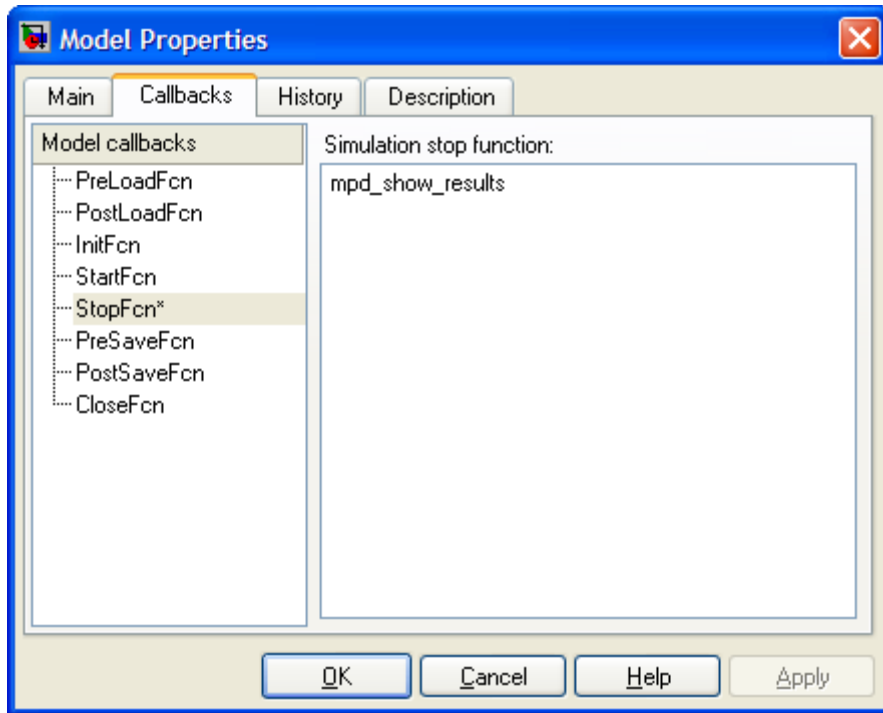
- ❖ Run the simulation - it will simulate 30 seconds then stop. The scope will show the commanded sine wave centered at 3 degrees and the response in yellow.



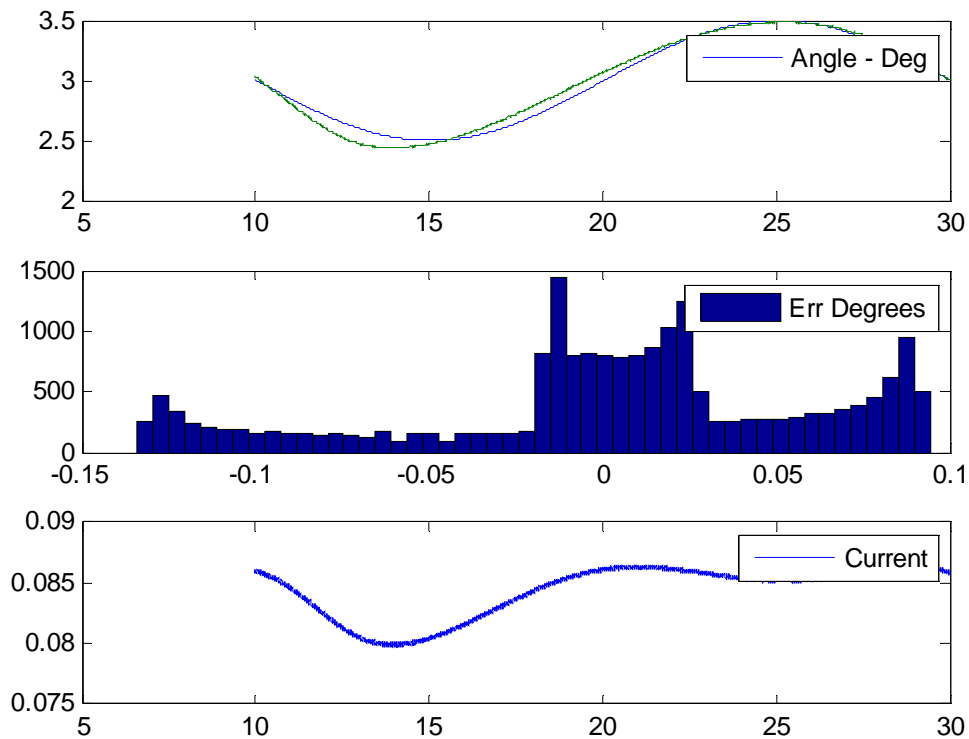
- ❖ The diagram saves the data from the run in a file called **mpd_data.mat**

Note the **nonlinearity** in the system causes distortion in the response. We will keep these gains to start with. The variability in the mechanical relays is considerable and we need to keep the gains low in order to get a stable controller as a starting point.

- ❖ Once the simulation stops, a Matlab script is run automatically to show the results of the run. The script is called '**show_results.m**' and is defined in a callback function as part of the simulink model as shown below:



The script `mpd_show_results.m` displays the following plot:



The top chart shows the commanded (green) and actual angle (blue). The second chart is a distribution of the error over the last 10 seconds of data. The third chart is the current drawn by the electromagnet in amperes.

The script also calculates the mean error and prints out the following in the Matlab window:

```
***** Results *****  
***** Mean of error 0.045 Degrees  
***** Mean Current 84.3 MilliAmperes  
***** Mean Voltage 4.38 Volts
```

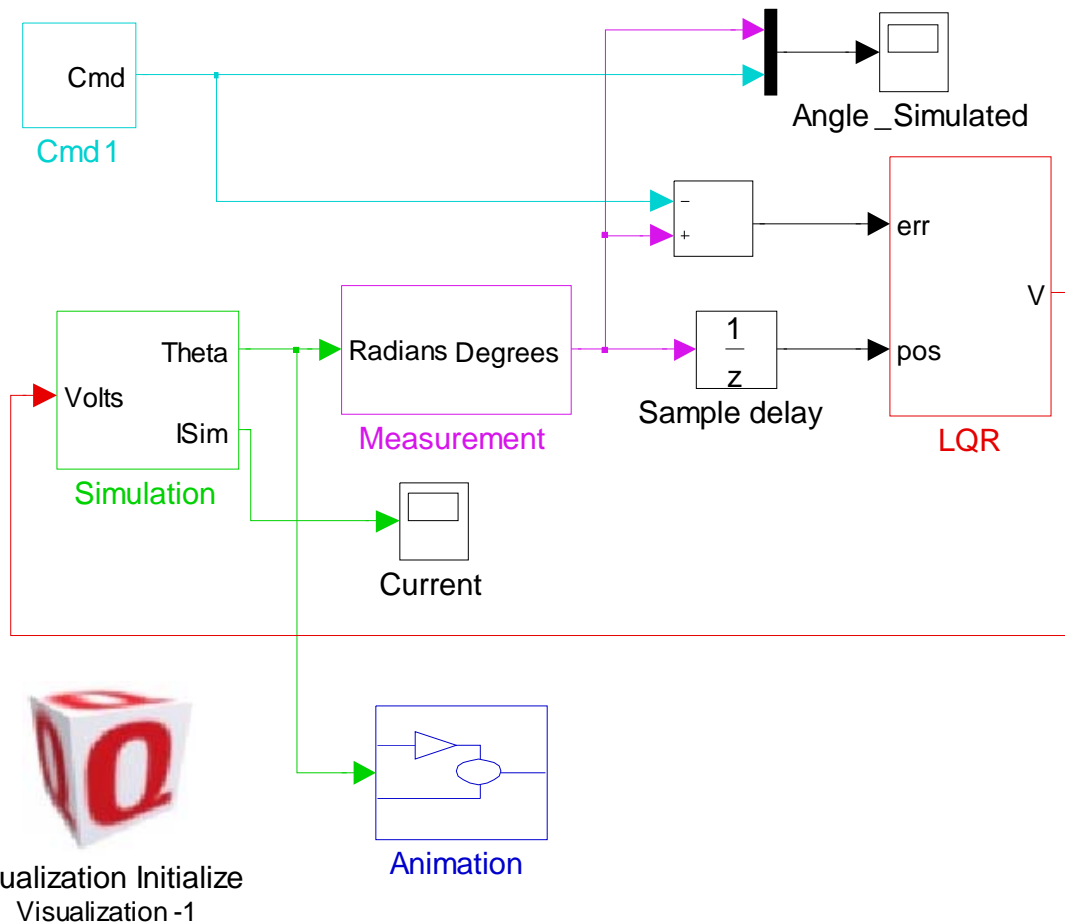
This is a good starting point for further tuning. The variability in the mechanical relays is considerable and we need to keep the gains low in order to get a stable controller to start.

Simulation with Animation

Demonstrated features	Simulating the system using Simulink and viewing an animation of the plant
Filename	mpd_nonlinear_simulation_3D.mdl

In order to run the controllers following this section you must first have QuaRC installed. Please follow the QuaRC installation guide.

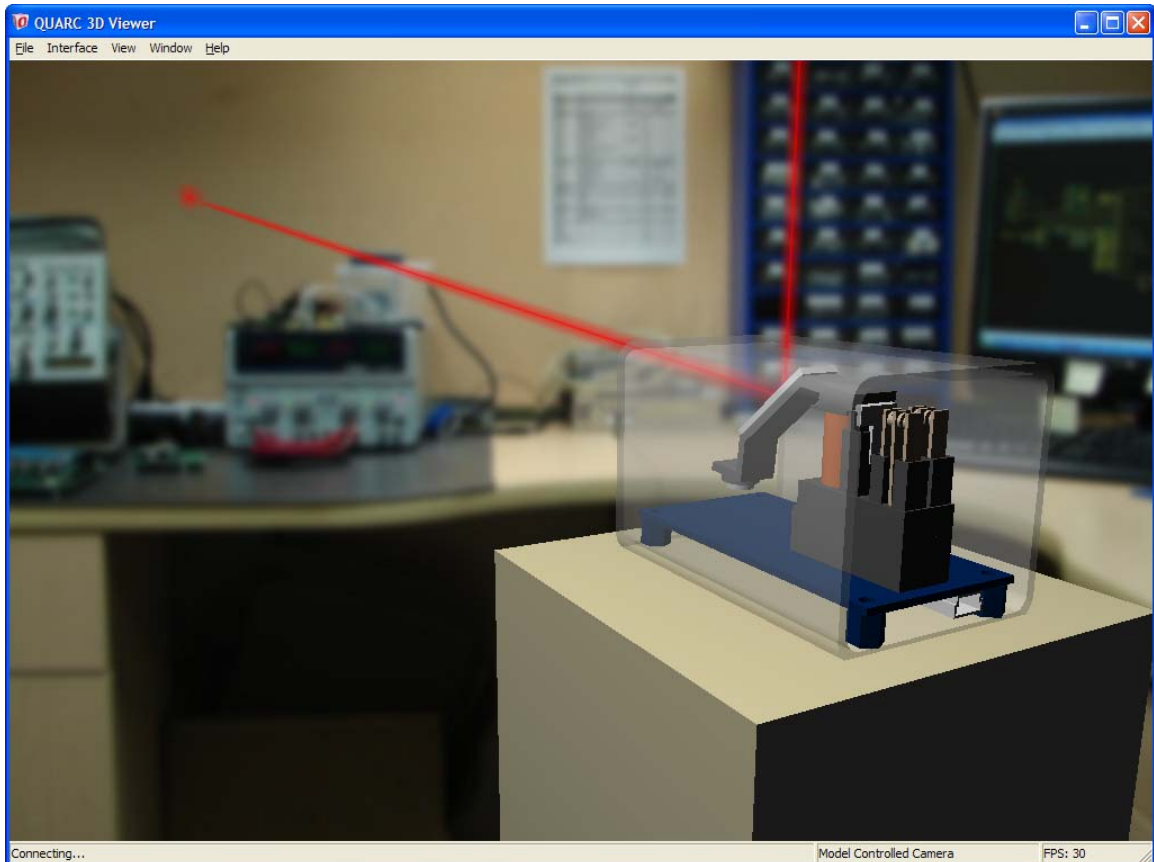
Open the Simulink model specified above – you will see the diagram shown here:



This model is the same as the previous simulation except that:

- ❖ It runs indefinitely until you click stop

- ❖ It does not save the data to file since it runs indefinitely and the file will become very large
- ❖ It displays a 3D animation of the plant with a virtual laser beam using the QuaRC Visualization Tools.
- ❖ Run the model as in the previous section you will see the following window open up :



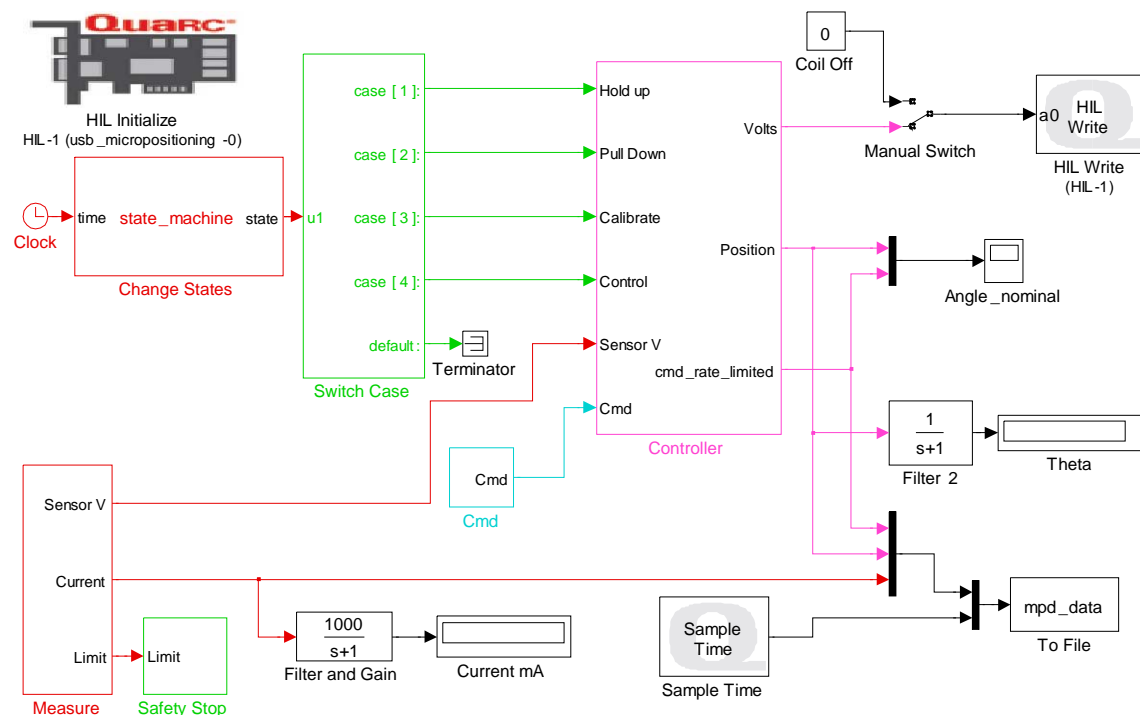
The virtual plat will move with the data that is streamed to it from the simulation. Note that the simulation is not in realtime. The lever angle is commanded at a frequency of 0.1 Hz. The animation will move faster.

The next step is to try the controller on the real plant!

Nominal Controller

Demonstrated features	Realtime control using USB
Filename	mpd_lqr_nominal.mdl

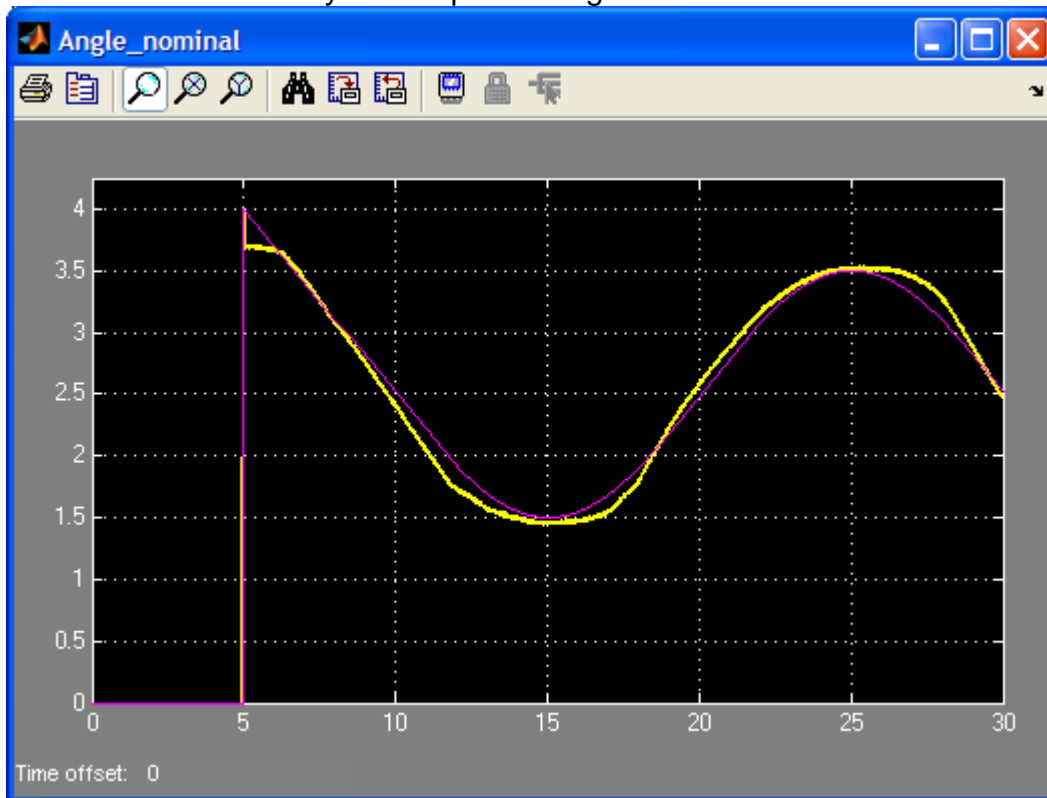
- ❖ Open the Simulink model named above – you will see the following diagram



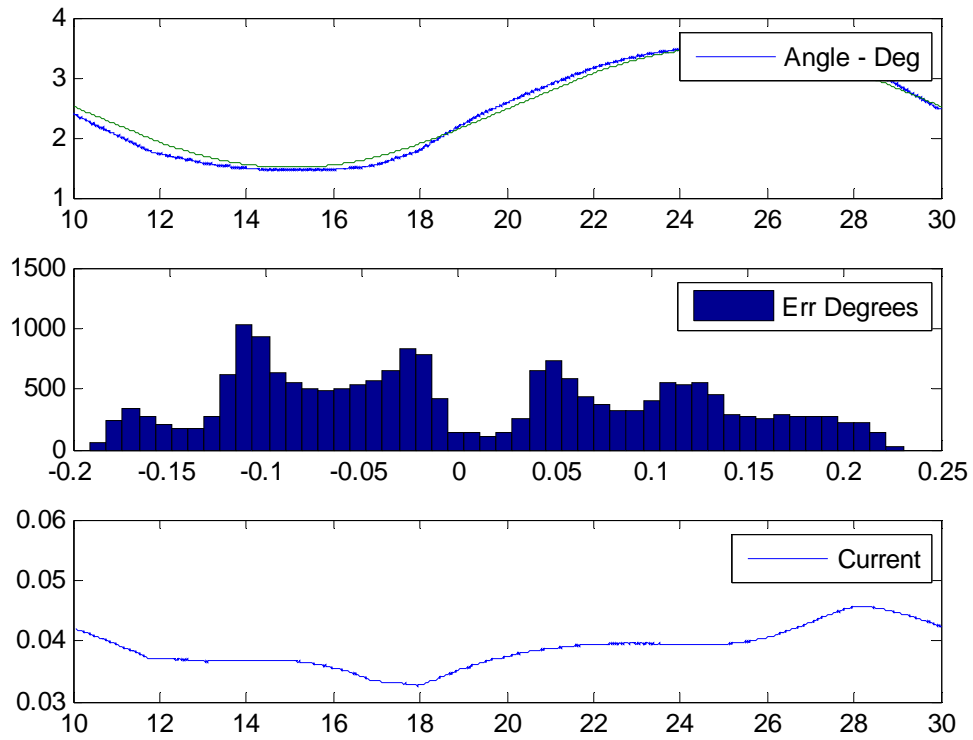
- ❖ Build the model as per the QuaRC manual
- ❖ Run the diagram
- ❖ The system will cycle through the following steps:
 - **Autocalibration**
 - It will measure the sensor voltage when the relay is inactive: the up position
 - It will activate the relay which will cause the lever to go all the way down
 - It will measure the voltage from the sensor at the down position
 - It will calculate the calibration constants for the sensor such that up is 4 degrees and down is 0 degrees.
 - **Trajectory tracking**

- It will then start the feedback control system such that the relay tracks the desired trajectory
- It will stop after 30 seconds
- When it stops it launches the **mpd_show results** which will display the last 10 seconds of data.

A typical realtime plot result is shown below. The first 5 seconds do not have any useful data since the system is performing the autocalibration.



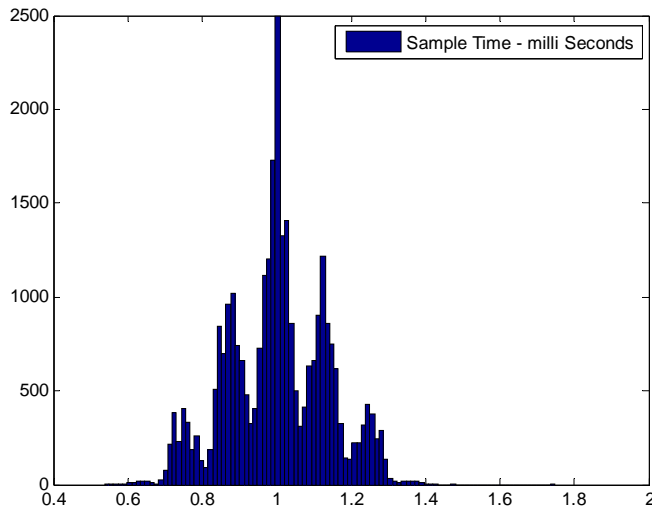
Typical results are shown below:



```
***** Results *****
***** Mean of error 0.092 Degrees
***** Mean Current 38.7 MilliAmperes
***** Mean Voltage 2.01 Volts
```

USB sample rates

Note that this diagram also collects an extra piece of data that it saves in the file **mpd_data.mat**. This is a special QuaRC block that collects the time between samples and is a measure of the realtime performance of the system. We have asked for a sampling period of 1 msec for this controller (Simulation parameters) using the USB data acquisition we have supplied. A chart of the sample time distribution can be obtained by running the file **mpd_show_sample_time.m**. A typical sample time distribution using the Quanser USB system is shown below.



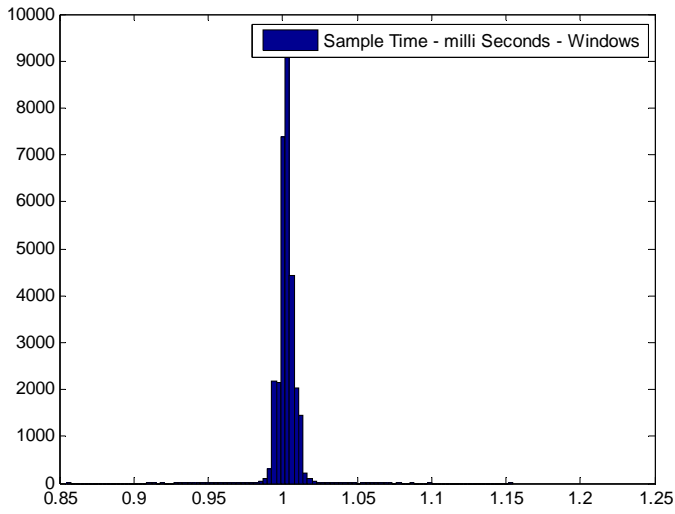
This is a typical distribution using the USB system. We have consistent sampling at 1 msec with variations occurring in multiples of 62.5 useconds due to the USB 125 usec microframe rate.

Note that the data is sampled on the USB system at precisely 1kHz. It is the time taken to arrive to the PC that is variable.

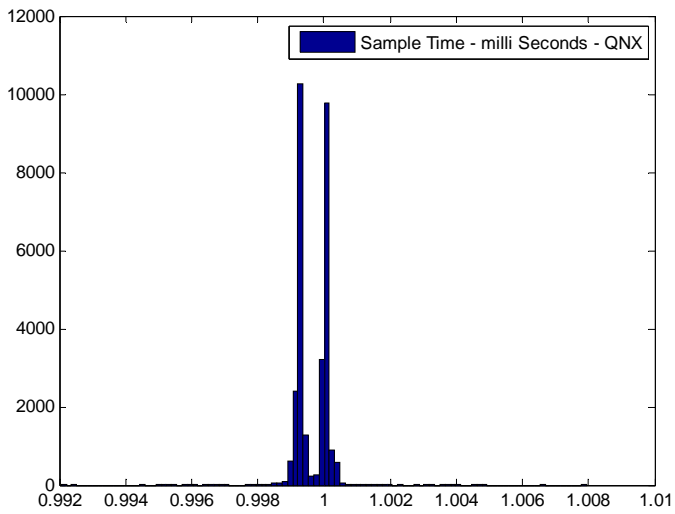
Better sample rates – PCI bus

Using a PCI base data acquisition system such as the Quanser Q8 results in more consistent data acquisition rates which might be required for time critical systems. The Quanser USB based systems however are sufficient for most applications.

The chart below shows the typical sample times obtained using our PCI based systems on a Windows PC. The jitter in this case is bound under 0.25 milliseconds.



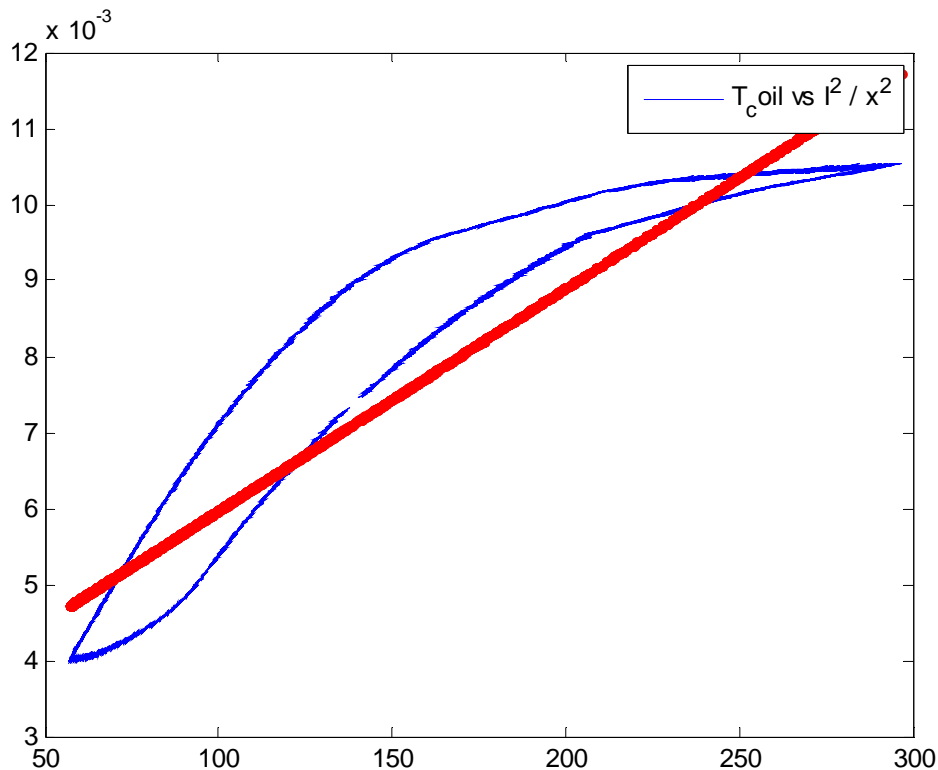
The chart below shows the typical sample times obtained using our PCI based systems on a QNX PC. Note the jitter is no more than 8 microseconds!



Parameter Estimation

Demonstrated features	Estimate Magnet gain KMag
Filename	mpd_id_params_and_design.m

The m file above uses the collected data from the first run to estimate a new value for KMag. The plot below shows the estimated Force versus I^2/x^2 for that particular run:



Note the hysteresis in the system – this is typical of magnetic circuits.

The blue trace is the collected data and the red trace is a least squares fit that uses the new estimate of KMag. The estimated value for KMag is used to redesign the controller. A typical result of the parameter estimation procedure is shown below:

```
***** Sys ID results and design *****
***** Estimated KMag: 2.99e-005
***** Feedback Gains -1.60 -0.0063 -1.75
***** Operating point 2.496 Degrees
***** Operating current 38.552 MilliAmperes
```

```

***** Operating voltage 2.005 Volts
***** Linear model: J d2/dt2(theta) = -12570.32 theta -
1394.64 Vc

```

```

***** Closed loop poles *****
-252.45 + 276.23 i
-252.45 + -276.23 i
-1.00 + 0.00 i

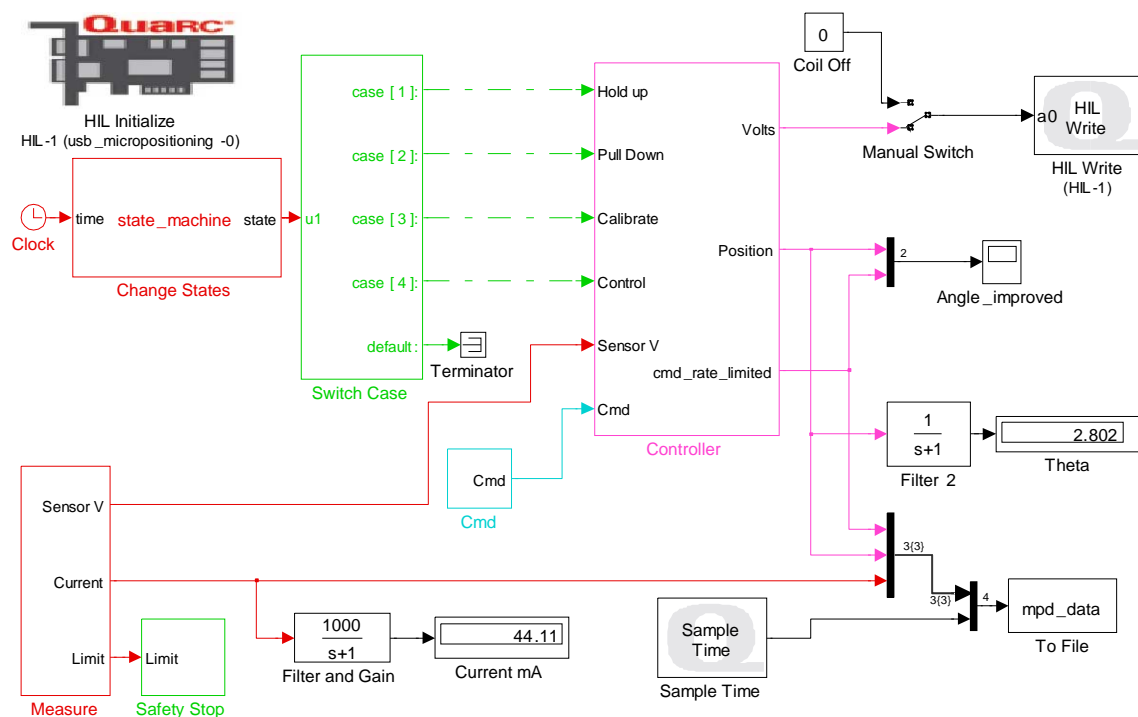
```

A new set of gains is computed using the new value for Kmag. This value will be specific to the unit you are using.

Controller With New Gains

Demonstrated features	Realtime control using USB
Filename	mpd_lqr_sys_id.mdl

❖ Open the Simulink model named above – shown below



- ❖ Build the model as per the QuaRC manual
- ❖ Run the diagram
- ❖ The diagram uses the function **mpd_id_params_and_design.m** to calculate new gains from the previous run. You can repeat this process continuously. If

there is no data file available from a previous run, then the nominal design is used.

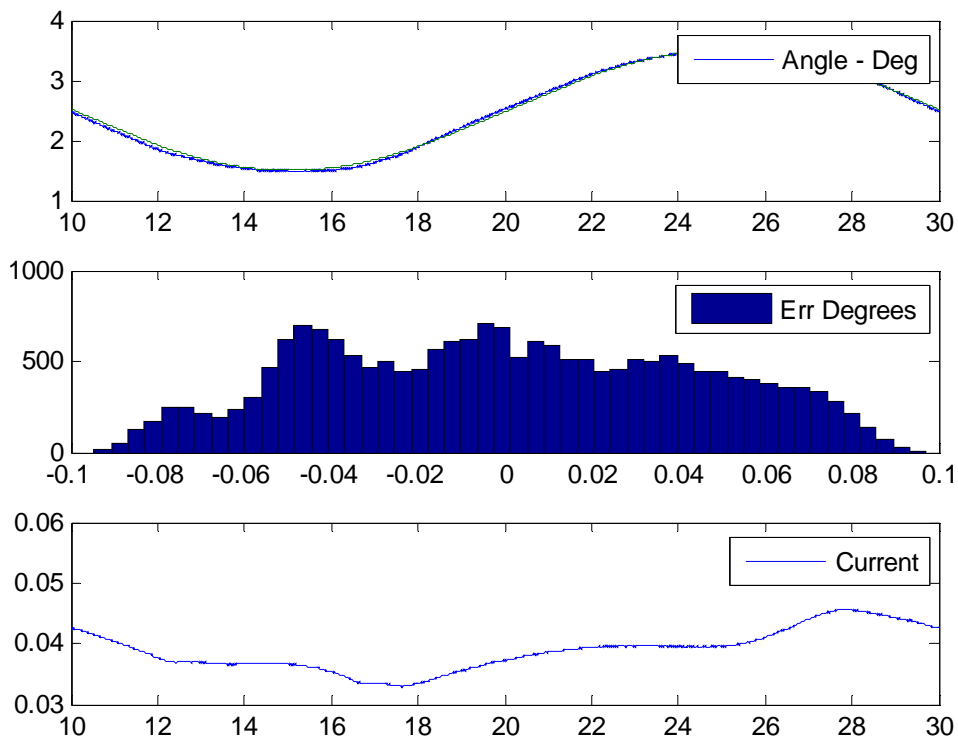
❖ The system will cycle through the following steps:

➤ **Autocalibration**

- It will measure the sensor voltage when the relay is inactive: the up position
- It will activate the relay which will cause the lever to go all the way down
- It will measure the voltage from the sensor at the down position
- It will calculate the calibration constants for the sensor such that up is 4 degrees and down is 0 degrees.

➤ **Trajectory tracking**

- It will then start the feedback control system such that the relay tracks the desired trajectory
- It will stop after 30 seconds
- When it stops it launches the **mpd_show results** which will display the last 10 seconds of data.



```
***** Results *****
***** Mean of error 0.036 Degrees
***** Mean Current 38.7 MilliAmperes
***** Mean Voltage 2.01 Volts
```

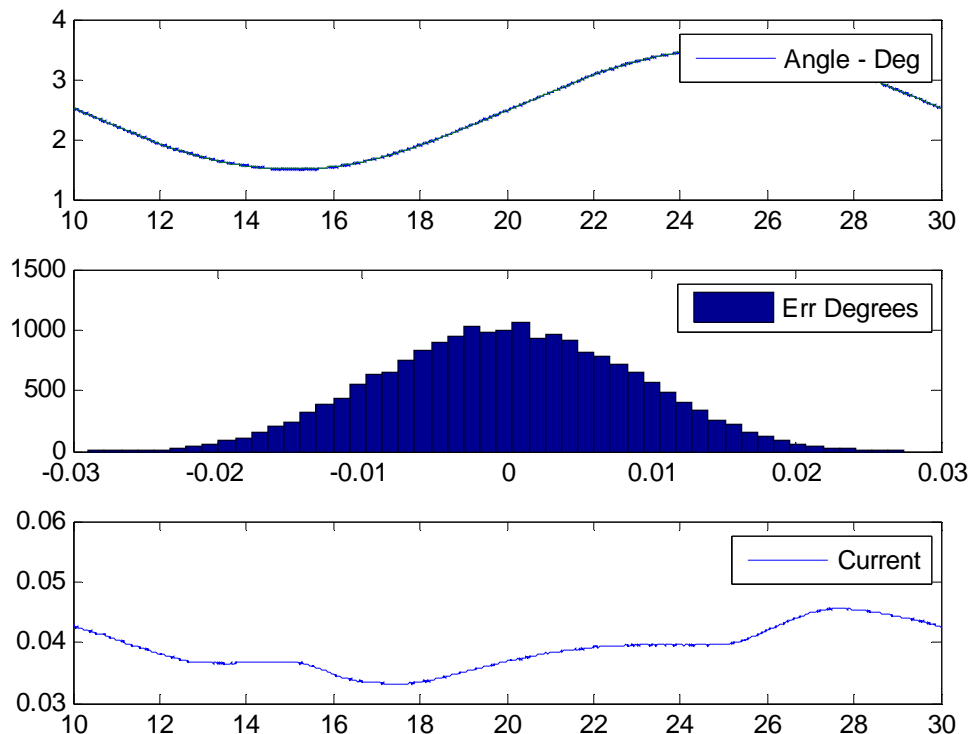
Clearly the new controller improves the tracking performance of the system. In this particular case, the mean magnitude of the error has been reduced from 0.092 degrees to 0.036 degrees.

You play around !

Feel free to experiment with the supplied models and controllers. **NOTE: The relay we are using was never intended for this type of application! It is a very delicate mechanical system. Running it unstable for long periods will deteriorate its performance.** Although there is a safety block that shuts down the controller if the system goes unstable, try to minimize the number of times you run unstable controllers.

- ❖ You can easily change the Q and R matrices in the design files. Try different values and run the simulations – what are the ranges of values that will result in a stable system?
- ❖ Do all stable values in simulation work in reality?
- ❖ Try different sample rates in the controller – how does this affect performance?
- ❖ Try to improve the tracking error to below 0.02 degrees.

The chart below shows how the system that was used throughout this document was further improved **to attain a mean error of 0.007 degrees!**



```
***** Results *****
***** Mean of error 0.007 Degrees
***** Mean Current 38.9 MilliAmperes
```

***** Mean Voltage 2.02 Volts

Troubleshooting

❖ Demo system does not do anything

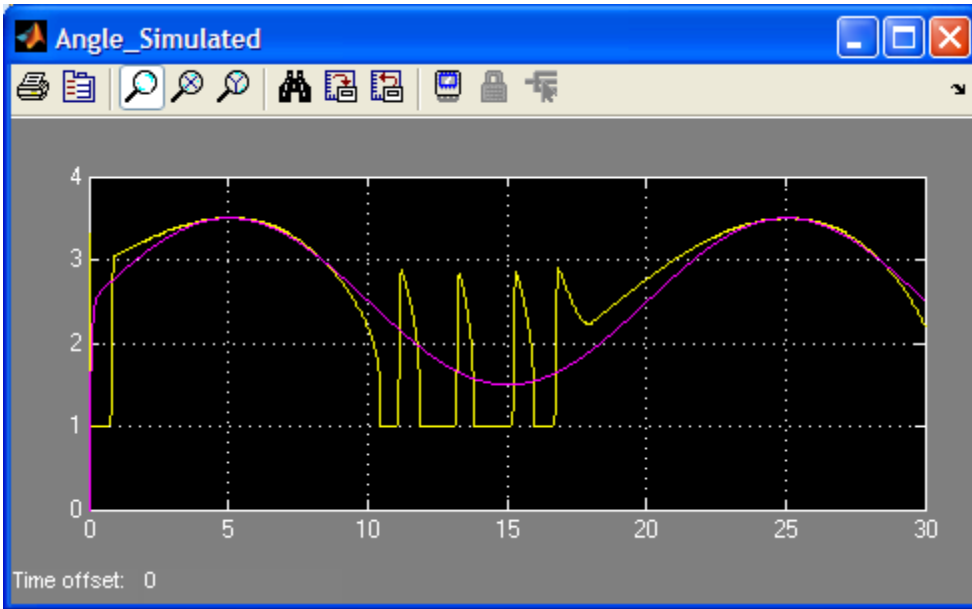
- If the system does not work at all – try running **mpd_test_measurements.mdl**.
- You can apply a voltage to the coil and see it move. You can also examine the voltages coming from the position sensor and the current sensor.
- Apply 0 volts to the relay coil. Observe the measurement from the position sensor – it should be close to 0 volts (at most 0.3 Volts)
- Apply 5 volts to the coil. The lever arm should move to the end position (down) – the voltage from the sensor should be around 2 to 3 volts.
- Examine the current measurement – it should read about 0 milliamperes when 0 volts is applied to the coil and around 90 milliamperes when 5 volts are applied to the coil.

❖ System is never stable

- Did it pass all the tests above?
- If it did, it may be that the system you have is not very close to the nominal system in performance – possibly due to shipping and shaking.
 - Try to adjust the way the relay is seated in the socket. Manually adjust the relay such that the permanent magnet is centered about the crosshairs on the board. Then run the measurements tests again. **DO NOT push against the lever arm, always adjust the relay position by holding on the body of the relay.**

❖ Low frequency instability

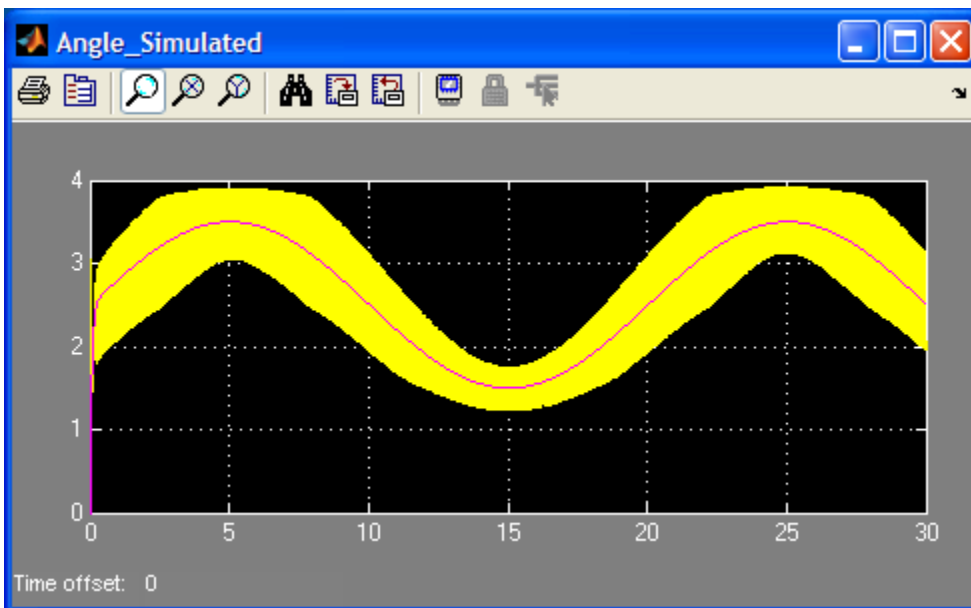
This happens when the integrator starts charging up and the lever starts moving but suddenly moves to one end and then the integrator discharges and the arm goes back and the cycle repeats – at a relatively low frequency – such a response is shown in the figure below:



In this case $Q(1)$ and $Q(3)$ are low and in particular $Q(1)$ is small relative to $Q(3)$ – try increasing them slowly.

❖ **High frequency instability**

This exhibits as a high frequency vibration that will definitely damage the mechanism. The gain is too high – in particular $Q(1)$ - reduce $Q(1)$.



Appendix A Installation