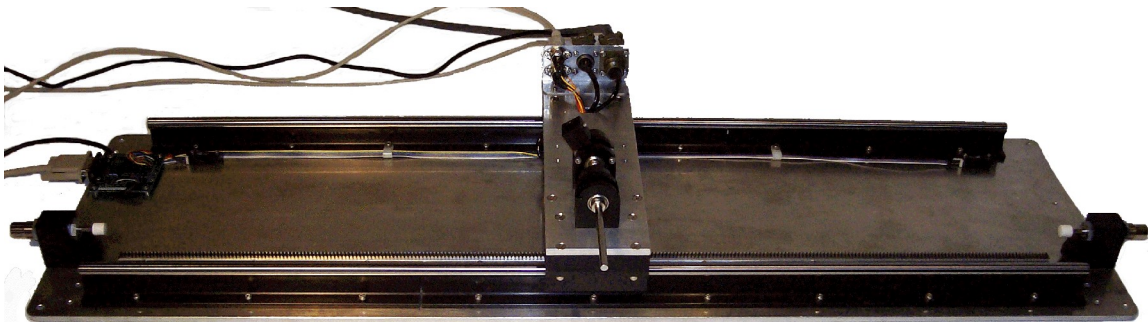


*Linear Motion Servo Plant: HFLC*

## *High Fidelity Linear Cart (HFLC)*



**User Manual**

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## 1. High Fidelity Linear Cart (HFLC) Presentation

The High Fidelity Linear Cart (HFLC) system, shown below in Figure 1, consists of a precisely machined solid aluminum cart driven by a high-power 400 Watt 3-phase brushless DC motor. The cart slides along two high precision, ground hardened steel guide rails with self-aligning linear bearings for true linear motion. The motor shaft has a pinion gear that rides on a track permitting the cart to move in a linear fashion. Both rack and pinion are made of hardened steel and mesh with a tight tolerance. Such a rack-and-pinion mechanism, when compared to belts or wheels, eliminates slippage, belt stretching and other undesirable effects. This ensures consistent and continuous traction. The complete assembly rests on a solid one-meter long aluminum base for straightness and increased rigidity and support. The resulting linear positioning system can obtain high speed, high acceleration, and excellent repeatability characteristics.

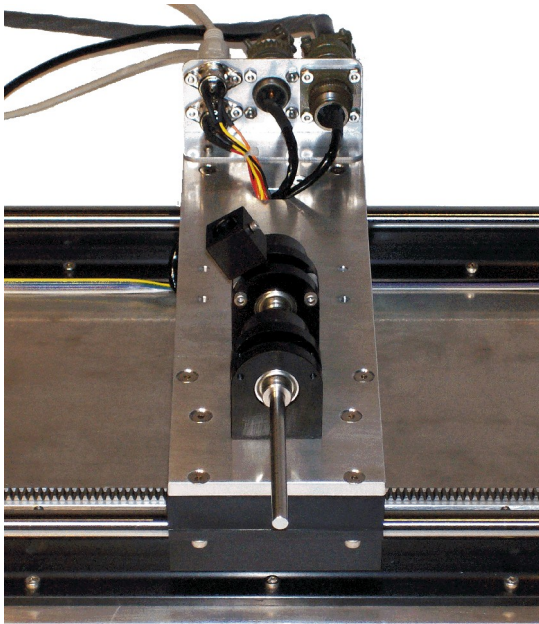


Figure 1 High-Fidelity Linear Cart (HFLC) system.

Furthermore, the cart is equipped with two un-powered rotary joints with ball bearings to which free turning rods, functioning as pendula, can be attached. Both rotating pendula can be configured individually or in combination to perform a variety of experiments of incremental complexity. One pendulum can be mounted directly on top of the cart. This rotation of this joint is mechanically limited to  $\pm 30.9$  degrees around its "inverted" vertical posture. The other pendulum can be suspended in front of the cart through an extended

pivot shaft and can be used to perform self-erecting and gantry experiments.

The motor shaft is coupled to a high-resolution optical encoder in order to measure the cart position accurately. Both pendulum angles are sensed using optical encoders as well and allow for multiple turns and continuous measurement over the entire range of motion.

## 2. HFLC Experiments Overview

The High Fidelity Linear Cart linear servo plant is the base component for a variety of experiments. The system package includes five different pendula: a short 6-inch single pendulum, medium 12-inch pendulum, long 24-inch single pendulum, double pendulum, and a triple pendulum. These pendula can be used individually or in combination to configure many experiments. Table 1 provides a list of some of the possible HFLC experiments and are arranged in a curriculum format.

<i>Laboratory Name</i>	<i>Experiment Description</i>
Experiment #1: Position Control	Design of a control system to regulate the position of the HFL Cart to a desired setpoint.
Experiment #2: Single Pendulum Gantry (SPG) Control	Design of a state-feedback control system to track a desired cart linear position while minimizing the swing of a suspended single pendulum.
Experiment #3: Single Inverted Pendulum (SIP) Control	Design of a state-feedback control system that keeps the inverted pendulum balanced and tracks the cart to a commanded position.
Experiment #4: Self-Erecting Single Pendulum (SESIP) Control	Design of a switching mode control system to swing up a single pendulum and balance it once in the upright position.
Experiment #5: Dual Inverted Pendulum (DLIP) Control	Design of a state-feedback control system that keeps two independent single inverted pendula balanced and tracks the cart to a commanded position.
Experiment #6: Double Pendulum Gantry (DBPG) Control	Design of a state-feedback control system to track a desired cart linear position while minimizing the swing of a suspended double pendulum.
Experiment #7: Double Inverted Pendulum (DBIP) Control	Design of a state-feedback control system that keeps a double inverted pendulum balanced and tracks the cart to a commanded position.

<i>Laboratory Name</i>	<i>Experiment Description</i>
Experiment #8: Triple Pendulum Gantry (TPG) Control	Design of a state-feedback control system to track a desired cart linear position while minimizing the swing of a suspended triple pendulum.
Experiment #9: Triple Inverted Pendulum (TIP) Control	Design of a state-feedback control system that keeps a triple inverted pendulum balanced and tracks the cart to a commanded position.
Experiment #10: Single Linear Flexible Joint (SLFJ) Control	Design of a state-feedback control system that regulates the position of the HFL cart and the LFJ cart to a desired setpoint while dampening the spring.

Table 1 Supplied HFLC experiments.

Switching from one configuration to another can be done with ease and the system parameters for each configuration is fully documented. Nonlinear and linear mathematical models as well as sample linear controllers are supplied for each of the experiments listed in Table 1, above. New types of systems can also be configured. For example, connecting a pendulum one one joint and a gantry on the other. The goal is now to balance the inverted pendulum and dampen the swinging motions of the gantry simultaneously.

### 3. HFLC Component Description

#### 3.1. Component Nomenclature

As a quick nomenclature, Table 2, below, provides a list of all the principal elements composing the HFLC system. Every element is located and identified, through a unique identification (ID) number, on the HFLC system represented in Figures 3, 4, and 20, below.

<i>ID #</i>	<i>Description</i>	<i>ID #</i>	<i>Description</i>
<b>1</b>	Cart	<b>12</b>	Home Position Sensor
<b>2</b>	Solid Aluminum Base Plate or Rack	<b>13</b>	Right Limit Sensor
<b>3</b>	Brushless DC Motor	<b>14</b>	Rear Pendulum Encoder
<b>4</b>	Motor Encoder	<b>15</b>	Rear Pendulum T-Fitting
<b>5</b>	Motor Pinion	<b>16</b>	Front Pendulum Encoder
<b>6</b>	Track	<b>17</b>	Front Swinging Pendulum Shaft

<i>ID #</i>	<i>Description</i>	<i>ID #</i>	<i>Description</i>
7	Hardened Steel Guide Rail	18	Motor Leads Connector
8	Linear bearing	19	Motor Encoder & Hall Sensors Connector
9	Hydraulic Shock Absorber	20	Front Pendulum Encoder Connector
10	Sensor Circuit Board	21	Rear Pendulum Encoder Connector
11	Left Limit Sensor		

Table 2 HFLC Component Nomenclature

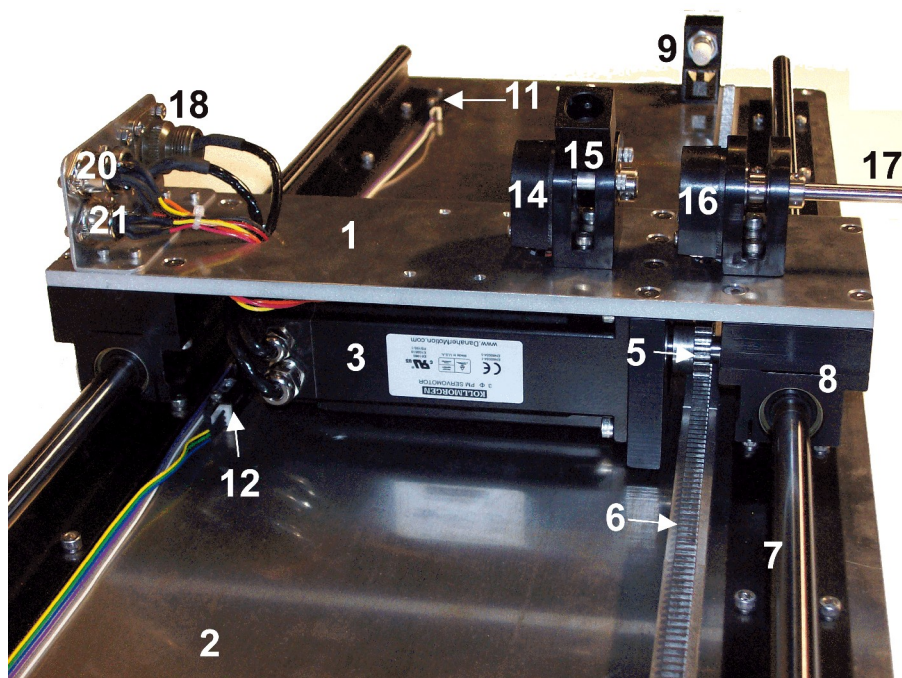


Figure 2 Side view of cart.

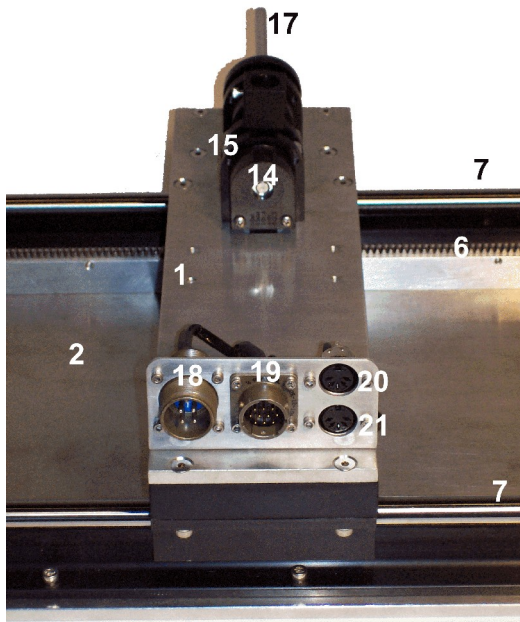


Figure 3 Back view of cart.

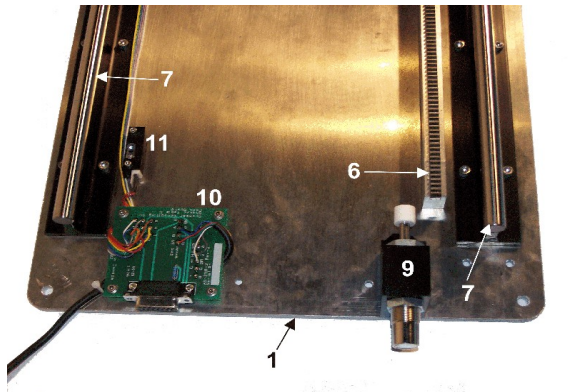


Figure 4 Left side of HFLC track.

## 3.2. Component Description

### 3.2.1. Rack (Component #2)

Table 3, below, lists and characterizes the overall dimensions of the rack used in the HFLC system:

<i>Description</i>	<i>Value</i>	<i>Unit</i>
Overall Rack Length	1.1	m
Overall Rack Height	0.18	m
Overall Rack Depth	0.31	m

Table 3 Overall dimensions of HFLC rack

### 3.2.2. Hydraulic Shock Absorbers (Components #9)

The system is equipped with two hydraulic dampers, one at each end of travel of the cart in



order to absorb the impact forces should the cart become unstable.

### 3.2.3. Brushless DC Motor (Component #3)

The HFLC incorporates a Kollmorgen AKM24 brushless 3-phase DC Motor, as shown in Figure 2 (component #3). The motor has a power of 400 Watts. It is mounted inside the aluminum cart and drives a pinion that is meshed on the toothed rack. The brushless commutation is ensured through three hall sensors with a phasing of 120 degrees. Some of the motor specifications are included in Table 4, below. More detailed motor specifications can be found in Reference [4].



**CAUTION: Input:  $\pm 180\text{V}$ , 15.6A peak, 3.89A continuous.**

### 3.2.4. Proximity Sensors (Components #11, #12, and #13)

Three reflective photomicrosensors are mounted on the HFLC base to detect the cart position at the two track limits, *Left* and *Right*, and at the center of the track, *Home*. The *Left* limit sensor is component #11 in Figure 4 and the Home and Right proximity sensors are components #12 and #13 in Figure 2.

The sensors output a low signal until the cart moves above them in which case the associated LED on the supplied blue Universal Power Amplifier, the UPM-180-25B, will illuminate. If the *Left* or *Right* sensor is triggered, that is if the cart reaches one of the track limits, the PIC inside the UPM disables the power amplifier and the motor stops being driven. This is one of the safety measures implemented in the HFLC system. In order to re-enable the UPM, the cart must be manually moved back to the *Home* position. See Reference [3] for more information about the UPM-180-25B and Reference [5] for the proximity sensor specifications sheet.

### 3.2.5. Encoders (Components #4, #14, and #16)

#### 3.2.5.1. Description

The encoder used to measure the linear position of the cart is embedded in the DC motor. It cannot be identified externally. The cart encoder has a resolution of 2048 lines per revolution. In quadrature mode this gives 8192 counts per full rotation motor shaft rotation. The effective resolution of the cart displacement is  $8.52\text{ }\mu\text{m}$ .

Two pendula can be mounted on the cart to perform a variety of experiments. As shown in Figure 2 by component #14, the *rear* pendulum encoder is mounted directly on top of the



cart. It senses the rotation of the pendulum rod and the T-Fitting, component #15 in Figure 2, is mechanically limited to  $\pm 30.9$  degrees. The *front* pendulum encoder, component #16 in Figure 2, is coupled to the cart's extended shaft, component #17 in Figure 2. It is used to perform self-erecting and gantry experiments as well as to calibrate the vertical angle as precisely as possible with the pendulum being suspended. This shaft is free to rotate 360 degrees.

Both the front and rear pendulum positions are measured using the US Digital S1 single-ended high-resolution optical shaft encoder. The encoder outputs 1024 lines per revolution and when used in quadrature mode the resolution increases up to 4096 counts per revolution. See Appendix A for the complete specification sheet of the S1 optical shaft encoder.

### 3.2.5.2. Wiring

The position signal generated by the encoder should be directly connected to a Quanser terminal board (a.k.a. I/O card) using a standard 5-pin DIN cable.

The internal wiring diagram of the HFLC encoder is depicted in Figure 5. The standard 5-pin DIN connector, shown in Figure 5, is also pictured as components #19 and #20 in Figure 4.

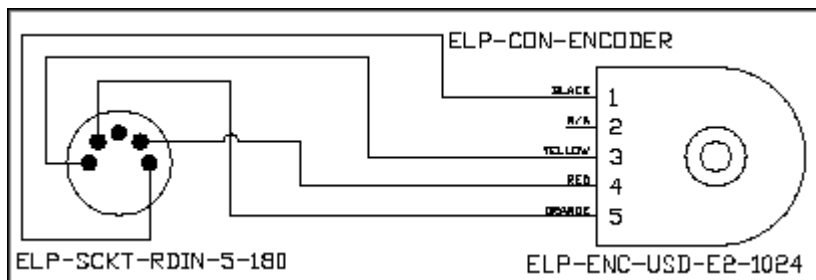


Figure 5 HFLC Encoder Wiring

## 4. HFLC System Parameters

Section 4.1 lists various parameters associated with the high-fidelity linear cart device and Section 4.2 discusses the physical characteristics of the pendula, or links, supplied with the HFLC system.

## 4.1. Cart Parameters

Table 4, below, lists the main mechanical and electrical specifications associated with the HFLC system. The shaded specifications are modeling parameters and encoder sensitivity gains that are actually used in the lab design files supplied.

<i>Symbol</i>	<i>Description</i>	<i>Value</i>	<i>Unit</i>
$K_t$	Motor Current-Torque Constant	0.36	N.m/A
$\eta_m$	Motor Efficiency	100	%
$R_m$	Line-To-Line (Armature) Resistance	2.94	$\Omega$
$L_m$	Line-To-Line (Armature) Inductance	6.16	mH
$K_m$	Back-ElectroMotive-Force (EMF) constant	23.4	V/k <sub>rpm</sub>
$V_{m_r}$	Rated voltage	320	Vdc
$T_{m\_dc}$	Continuous stall torque ( $\Delta T$ winding = 100 °C)	0.247	N.m
$I_{m\_dc}$	Continuous stall current	3.9	A
$T_{m\_p}$	Motor peak torque	4.82	N.m
$I_{m\_p}$	Motor peak current	15.6	A
$\omega_{m\_max}$	Motor maximum mechanical speed	838.0	rad/s
$M_m$	Motor mass	1.66	kg
$M_c$	Cart system mass	3.22	kg
$J_m$	Rotor moment of inertia	2.70E-005	kg.m <sup>2</sup>
$B_m$	Motor viscous damping coefficient	7.40E-003	N.m/k <sub>rpm</sub>
$B_{eq}$	Equivalent viscous damping coefficient	0	N.s/m
$r_{mp}$	Motor pinion radius	1.11E-003	m
$K_{EC}$	Cart encoder linear position sensitivity	-8.523E-006	m/count
$K_{EC,RES}$	Cart encoder resolution (in quadrature mode)	8192	counts/rev
$K_{EP}$	Pendulum encoder sensitivity	0.0015	rad/count
$K_{EP,RES}$	Pendulum encoder resolution (in quadrature mode)	4096	counts/rev
$\alpha_{range}$	Rear Pendulum Mechanical Range	$\pm 30.9$	degrees

Table 4 HFLC system parameters

## 4.2. Pendulum Parameters

There is a total of five pendula supplied with the HFLC system and they are all shown in Figure 6. All of the HFLC experiments given in Table 1 except *Position Control* involve the use of a pendulum.



Figure 6 Supplied pendula with the HFLC system.

The "short" pendulum is 7 inches long and is pictured in Figure 6 with ID #1. See Table 5 for the physical characteristics of the pendulum such as mass, moment of inertia, and center of mass.

<i>Symbol</i>	<i>Description</i>	<i>Value</i>	<i>Unit</i>
$L_p$	Short Pendulum Full Length (from Pivot to Tip)	0.2096	m
$M_p$	Short Pendulum Mass	0.072	kg
$J_p$	Short Pendulum Moment of Inertia	$2.63 \times 10^{-4}$	$\text{kg} \cdot \text{m}^2$
$B_p$	Equivalent Pendulum Viscous Damping (as seen at pendulum axis)	$2.40 \times 10^{-3}$	$\text{N} \cdot \text{m} \cdot \text{s} / \text{rad}$
$l_p$	Short Pendulum Length from Pivot to Center Of Gravity	0.1143	m

Table 5 "Short" 7-inch pendulum specifications.

The "medium" link is shown in Figure 6 and labeled with ID #2. It is 12-inches long and its properties are given below in Table 6.

<i><b>Symbol</b></i>	<i><b>Description</b></i>	<i><b>Value</b></i>	<i><b>Unit</b></i>
$L_p$	Medium Pendulum Full Length (from Pivot to Tip)	0.3365	m
$M_p$	Medium Pendulum Mass	0.127	kg
$J_p$	Medium Pendulum Moment of Inertia	$1.20 \times 10^{-3}$	$\text{kg} \cdot \text{m}^2$
$B_p$	Equivalent Pendulum Viscous Damping (as seen at pendulum axis)	$2.40 \times 10^{-3}$	$\text{N} \cdot \text{m} \cdot \text{s} / \text{rad}$
$l_p$	Medium Pendulum Length from Pivot to Center Of Gravity	0.1778	m

Table 6 "Medium" 12-inch pendulum specifications.

The "long" 24-inch pendulum is pictured in Figure 6 with ID #3 and its physical parameters are listed Table 7 below.

<i><b>Symbol</b></i>	<i><b>Description</b></i>	<i><b>Value</b></i>	<i><b>Unit</b></i>
$L_p$	Long Pendulum Full Length (from Pivot to Tip)	0.6413	m
$M_p$	Long Pendulum Mass	0.230	kg
$J_p$	Long Pendulum Moment of Inertia	$7.88 \times 10^{-3}$	$\text{kg} \cdot \text{m}^2$
$B_p$	Equivalent Pendulum Viscous Damping (as seen at pendulum axis)	$2.40 \times 10^{-3}$	$\text{N} \cdot \text{m} \cdot \text{s} / \text{rad}$
$l_p$	Long Pendulum Length from Pivot to Center Of Gravity	0.3302	m

Table 7 "Long" 24-inch pendulum specifications.

The "short" and "medium" pendula are used in combination with each other to make the double pendulum, pictured in Figure 6 above and labeled ID #4. The middle joint has an S1 series rotary optical encoder (see Appendix A for details) that is used to measure the angle of the "medium" link. The mass of the middle encoder and hinge assembly is 0.170 kg.

The triple-pendulum is shown in Figure 6 with ID #5. It is composed of a bottom "mini" link, a middle "short" pendulum, and a "medium" pendulum at the end. The "mini" pendulum is 2.5" long and its modeling parameters are listed in Table 8 (not supplied as a separate unit). There are two encoders on the triple pendulum: one measuring the angle of the "short" link and another measuring the angle of the "medium" link. The mass of the

encoder/hinge assemblies are 0.170 kg.

<i>Symbol</i>	<i>Description</i>	<i>Value</i>	<i>Unit</i>
$L_p$	Mini Pendulum Full Length (from Pivot to Tip)	0.0953	m
$M_p$	Mini Pendulum Mass	0.0257	kg
$J_p$	Mini Pendulum Moment of Inertia	$1.94 \times 10^{-5}$	$\text{kg} \cdot \text{m}^2$
$B_p$	Equivalent Pendulum Viscous Damping (as seen at pendulum axis)	$2.40 \times 10^{-3}$	$\text{N} \cdot \text{m} \cdot \text{s} / \text{rad}$
$l_p$	Mini Pendulum Length from Pivot to Center Of Gravity	0.0572	m

Table 8 "Mini" pendulum specifications.

These pendula modeling parameters are compiled in the Matlab script file *setup\_sp\_configuration.m*. The function returns the pendulum modeling parameters depending on the user-specified pendulum size: "MINI\_2\_5IN", "SHORT\_7IN", "MEDIUM\_12IN", or "LONG\_24IN". It also returns the gravitational constant,  $g$ , that is used for modeling purposes.

## 5. Hardware Setup Procedure

This section describes the standard procedure to safely setup the mechanical components of your HFLC system.



### **CAUTION: Exposed moving parts.**

Follow the steps described below:

1. **Mount the HFLC track on a very rigid and heavy table!** Screw down the track using four screws. Otherwise, the high acceleration of the cart can cause the HFLC track to displace. Further, it can cause compliant tables to flex and thus introduce undesirable effects into the dynamics of the system that you are trying to control. The desired stiffness can be achieved by bracing the legs with cables and turnbuckles if necessary.
2. **Clear all space around the system!** When the HFLC is setup with a pendulum, verify that if the cart is at either end of the track and the pendulum swings 360 degrees no objects will be in the way. In addition, always ensure that there is no personnel within the operating area when the HFLC is running.
3. The rear encoder is only used in the Dual-Inverted Pendulum experiment described in Table 1. For any experiment that does not require the use of the rear encoder it is

recommended that the rear encoder T-Fitting be fastened as shown in Figure 7 below. Otherwise the T-Fitting will be knocked back and forth as the cart changes position.

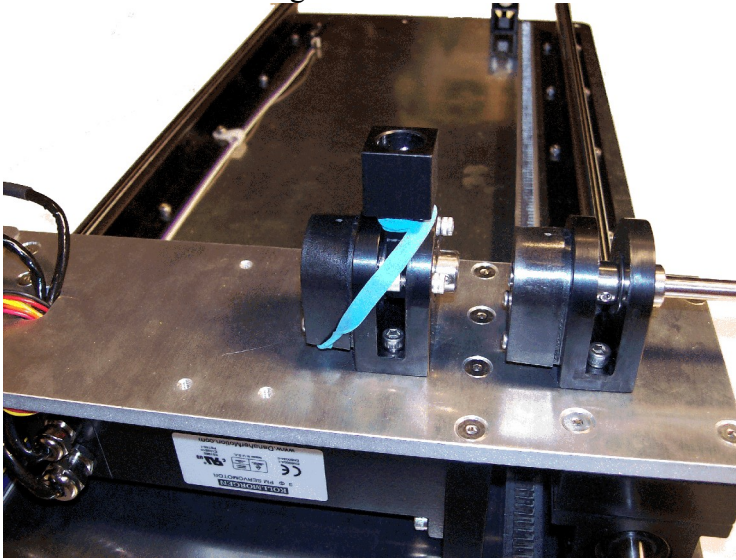


Figure 7 Fastening rear T-Fitting.

## 6. Wiring Procedure

This section describes the wiring procedure for the HFLC system. Section 6.1 goes through the cables that were supplied with the system and their functionality. The typical connection setup that can be used to run many of the HFLC experiments is described in Section 6.2.

The following hardware, accompanying the HFLC, is assumed:

- Data Acquisition Board: Quanser Q4 or Q8 Hardware-in-the-Loop board, or another equivalent data-acquisition device.
- Power Amplifier: Quanser UPM 180-25B, or equivalent.

### 6.1. Cable Nomenclature

Table 9, below, provides a description of the standard cables used in the wiring of the HFLC system.




<i>Cable</i>	<i>Description</i>
	The "Motor" cable corresponds to the 3-phase motor power leads. This cable is designed to connect from the Quanser's Universal Power Module model 180-25B (i.e. the output of the power module after signal amplification) to the desired brushless DC motor.
	The "To Device" cable corresponds to a DB15 cable. It connects the HFLC circuit board to the UPM. It carries to the UPM all three proximity sensors' signals, the motor encoder signals, as well as the brushless motor hall sensor signals used by the amplifier for proper commutation. It also supplies the DC power required by the different sensors.
	The "From MultiQ" cable connects the UPM to the data acquisition card terminal board. It is compatible with Quanser's quick-connect system. It carries the cart encoder signals, limit sensor signals (right, left, and home), calibrate signal, and the S1, S2, S3, and S4 analog signals from the UPM. The cable also carries the control signal (to be amplified and sent to the cart motor) as well as the calibrate and enable digital signals sent from the DAC.

Figure 8 "Motor" Cable

Figure 9 "To Device" Cable

Figure 10 "From MultiQ" Cable





<i>Cable</i>	<i>Description</i>
 <p data-bbox="264 676 607 703">Figure 11 "Emergency Stop" Cable</p>	<p data-bbox="743 325 1385 541">The "Emergency Stop" or E-Stop cable has a 6-pin-mini-DIN connector to be plugged into the side of the UPM. The UPM can be enabled if and only if E-Stop is connected to the UPM and the remote safety pushbutton switch is in the <i>depressed</i> position.</p>
 <p data-bbox="232 913 493 940">Figure 12 "Encoder" Cable</p>	<p data-bbox="743 718 1385 970">The "Encoder" cable is a 5-pin-stereo-DIN-to-5-pin-stereo-DIN cable. It can directly connect, as necessary, the HFLC front pendulum encoder and/or the HFLC rear pendulum encoder to the data acquisition card terminal board. This cable carries the encoder signals and encoder DC power supply.</p>

Table 9 Cable Nomenclature

## 6.2. Typical Connections for the HFLC System

This section describes the HFLC connections required to run experiments 1-5 listed in Table 1, namely position control, single-pendulum gantry, single-inverted pendulum, self-erecting single-inverted pendulum, and dual-inverted pendulum. For experiments 6-9, such as the double-inverted pendulum, see its corresponding laboratory manuals for extra wiring instructions needed to connect the additional sensors.

Section 6.2.1 demonstrates how to connect a Quanser Q4 or Q8 HIL board to the Quanser Q8 Extended Terminal Board. Section 6.2.2 gives the procedure to connect the HFLC system to the UPM-180-25B and the Q8 Extended Board.

### 6.2.1. Connecting the Q8 Extended Terminal Board

Before wiring the HFLC system, the Q4 or Q8 data-acquisition card must first be installed and connected to Q8 Extended Terminal Board. This terminal board is made specifically to interface with the Quanser UPM-180-25B device and is different than the standard terminal

boards used.

See Reference [1] to install the Q4 or Q8 hardware-in-the-loop board in your PC. Ensure that the PC is powered off and that you are grounded. Then, follow these instructions to connect the Q4 or Q8 hardware-in-the-loop board to the Q8 Extended Terminal Board:

1. Connect the ribbon cable labeled **J3** into the **Cable 3** connector on the Extended Terminal Board. Cable 3 is the shortest cable. In a tower PC, it will be the topmost cable where it comes out of the PC.



**CAUTION: The red line on the ribbon cable should be closest to the "Table X" and "Table Y" parallel input connectors on the terminal board. The connectors have a tab such that they only go in one way.**

2. If using a Q8 control board, connect the **J2** ribbon cable from the Q8 into the **Cable 2** connector on the Q8 Extended Terminal Board. Cable 2 is the second shortest cable. In a tower unit, it is the middle cable where the ribbon cables exit the PC. If using a Q4 control board, there is no J2 cable and the Cable 2 connector on the terminal board is left unused.
3. Connect the **J1** ribbon cable to the **Cable 1** connector on the Q8 Extended Terminal Board. This is the longest ribbon cable.
4. With the terminal board sitting on top of the tower unit, the ribbon cables should not be twisted and should all lie neatly on top of one another. The cables are slightly offset from one another on the terminal board to match the offset of the connectors on the data acquisition card. The text on the terminal board should face the front of the computer.
5. Use the ribbon cable clamp provided to secure the ribbon cables together. The clamp comes with a peel-and-stick base so that you can mount the clamp to a clean surface, such as the top of your PC. Put the cables in the clamp before mounting it. If you do not wish to mount the clamp, then do not remove the peel-and-stick paper. Use of the clamp is unnecessary, but helps to keep your Q8 data acquisition system neat and tidy.

As mentioned in the procedure, in the Q4 DAQ board setup there is no **J2** ribbon cable. As a result, the **Cable 2** connector on Q8 Extended Terminal Board is not used. Table 10 summarizes the connections between the Q4 and Q8 HIL board and the Q8 Extended Terminal Board.

<i>Data Acquisition Card</i>	<i>Extended Terminal Board</i>	<i>Connections</i>
Q8	Q8	J1 -> CHANNEL 1 J2 -> CHANNEL 2 J3 -> CHANNEL 3
Q4	Q8	J1 -> CHANNEL 1 J3 -> CHANNEL 3

Table 10 Ribbon cable connections between Q4 and Q8 data-acquisition card and the Q8 Extended Terminal Board.

See Reference [1] for instruction on how to install the necessary drivers for the Q4 or Q8 board. Once the Q4/Q8 has been properly tested, you can proceed to Section 6.2.2 and wire the HFLC system.

### 6.2.2. HFLC Wiring Procedure

Wire your HFLC system as described, the following connections, presented in Table 11 below, are attained. Figures 13, 15, 7, and 16 show, respectively, that the HFLC system typical connections on the Q8 Extended Terminal Board, the Universal Power Module (UPM-180-25B), the linear cart, and the HFLC circuit board. The HFL cart wiring is discussed in

<i>Cable #</i>	<i>Cable Type</i>	<i>From</i>	<i>To</i>	<i>Signal</i>
1	"From MultiQ" Parallel Cable	"From MultiQ" on UPM	"Table X" on Terminal Board	Receives the cart encoder, calibrate, and limit detector signals from the UPM. Sends control signal to the UPM input, which in turn drives the cart motor, and the calibrate and enable signals to the PIC on the UPM. See Appendix B for more details.
2	"To Device" Parallel Cable	"To Device" on UPM	HFLC Circuit Board	Limit sensors, motor hall sensors, and encoder signals.
3	"Emergency Stop" Cable	Emergency Stop Switch	UPM E-Stop Connector	Emergency Stop signal.
4	"Motor" Cable	"Motor" on UPM	Motor connector on Cart	Three-phase motor power leads.

<i>Cable #</i>	<i>Cable Type</i>	<i>From</i>	<i>To</i>	<i>Signal</i>
5	"Circuit Board" Cable	Linear Cart	HFLC Circuit Board	Motor hall sensors and encoder signals.
6	Encoder Cable: 5-pin-stereo-DIN to 5-pin-stereo-DIN	HFL Cart Front Pendulum Encoder Connector	Encoder #1 on the Q8 Terminal Board	Measures the front pendulum angle, $\alpha$ .
7	Encoder Cable: 5-pin-stereo-DIN to 5-pin-stereo-DIN	HFL Cart Rear Pendulum Encoder Connector	Encoder #2 on the Q8 Terminal Board	Measures the rear pendulum angle, $\theta$ .

Table 11 HFLC System Wiring Summary

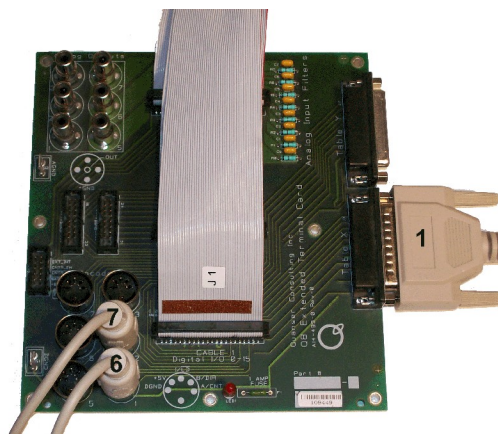


Figure 13 Connections on the Q8 Extended Terminal Board.

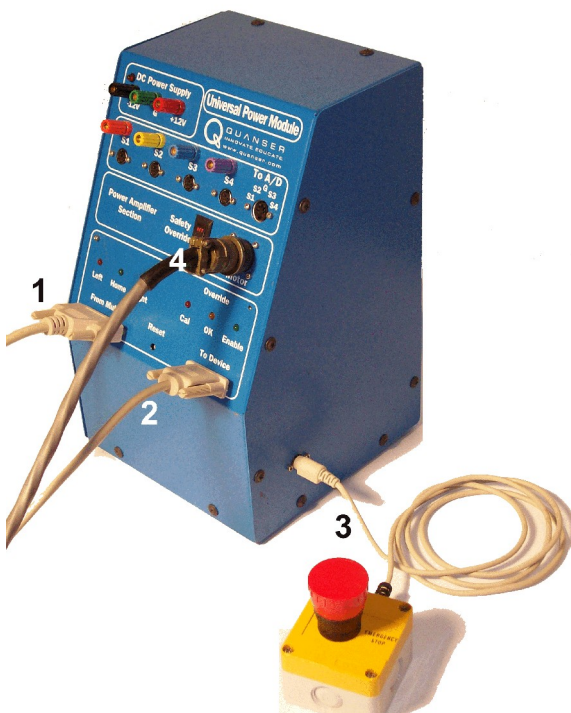


Figure 14 Connections on the UPM-180-25B.

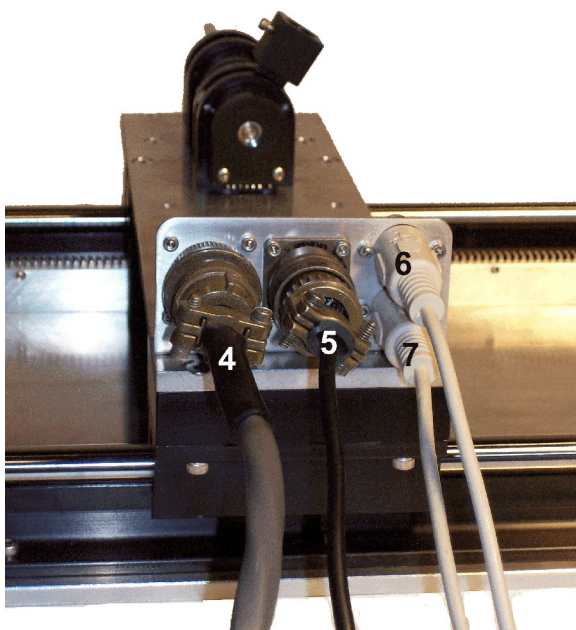


Figure 15 Connections on the linear cart.

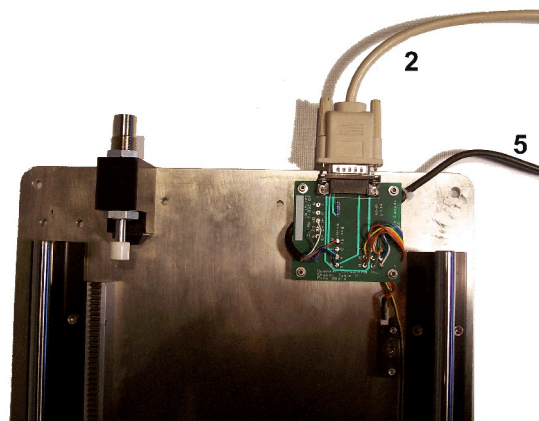


Figure 16 Connections on HFLC circuit board.

The following two sections describe in detail how to connect the HFLC, UPM and Q8 Extended Terminal Board together:

1. **Connect cable #1** from the "Table X" connector on the Quanser Q8 Extended Terminal Board, shown in Figure 13, to the "From MultiQ" connector on the Quanser UPM-180-25B, as depicted Figure 14. This connection is done using the parallel cable shown in Figure 10. See Appendix B for a listing of all the signals that are passed through this cable.
2. **Connect cable #2** from the "To Device" connector located on the UPM front panel, as shown in Figure 14, to the HFLC circuit board illustrated in Figure 16. This cable used in this connection is the DB15 cable described in Table 9 and pictured in Figure 9. It carries all three proximity sensor signals, the motor encoder signals, and the brushless motor hall sensor signals to the UPM-180-25B unit. The motor encoder is used to calculate the linear position of the cart and is denoted by the variable  $x$ .
3. **Connect cable #3** into the side of the UPM, as presented in Figure 15. Cable #3 is the "Emergency Stop" cable described in Table 9 and illustrated in Figure 11. The UPM is active if and only if the remote E-Stop switch is *depressed*.
4. **Connect cable #4** from the "Motor" connector located on the UPM front panel, as depicted in Figure 14, to the "Motor" connector on the linear cart, as shown Figure 15. Cable #4 plugs into the motor leads connector represented in the nomenclature by component #18 and pictured in Figure 3. This connection is done using the "Motor" cable described in Table 9 and illustrated in Figure 8. It carries the required 3-phase power to the brushless motor.
5. **Connect cable #5** from the HFLC embedded circuit board, see Figure 16, to the linear cart as illustrated in Figure 15. Cable #5 plugs into the motor encoder and hall sensors connector represented in the nomenclature by component #19 and pictured in Figure 3. It carries the brushless DC motor encoder signals and power supply, as well as its hall sensor signals used by the amplifier for proper commutation.
6. **Connect cable #6** from the "Front Pendulum" connector on the linear cart, shown in Figure 15, to the "Encoder Input #1" connector on the Q8 Extended Terminal Board, as illustrated in Figure 13. This connection is done using the 5-pin-stereo-DIN to 5-pin-stereo-DIN encoder cable listed in Table 9 and shown Figure 12. It carries the necessary signals to measure the angular position of the linear cart's front shaft and the corresponding variable is  $\alpha$ .
7. **Connect cable #7** from the "Rear Pendulum" connector on the linear cart, shown in Figure 15, to the "Encoder Input #2" connector on the Q8 Extended Terminal Board, as depicted in Figure 13. This connection is done using the 5-pin-stereo-DIN to 5-pin-stereo-DIN encoder cable listed in Table 9 and shown Figure 12. It carries the signals required to measure the angle the rear T-fitting that sits on top of the linear cart and its associated variable is  $\theta$ .

## 7. Running Experiments with QuaRC

The HFLC system is supplied with various Simulink models and Matlab scripts that are used to run the list of experiments listed in Table 1. These Simulink models are used with QuaRC to generate code and control the HFLC plant in real-time. See the laboratory manual corresponding to the particular HFLC experiment (e.g. position control or single pendulum gantry) for a procedure on how to run the actual laboratory with QuaRC.

Section 7.1 describes the standard *HFLC* Simulink block that is used in all the supplied Simulink models that interface with the actual HFLC system (not used in the simulation-only Simulink models however). In Section 7.2, the general layout of a Matlab script that needs to be run before using any of the supplied Simulink models is discussed.

### 7.1. HFLC QuaRC Library

The *HFLC* subsystem in the HFLC Simulink library *hflc\_lib.mdl*, shown in Figure 17, contains Simulink and QuaRC blocks necessary to drive the cart motor as well as measure the cart position and pendulum angles using the on-board encoders.

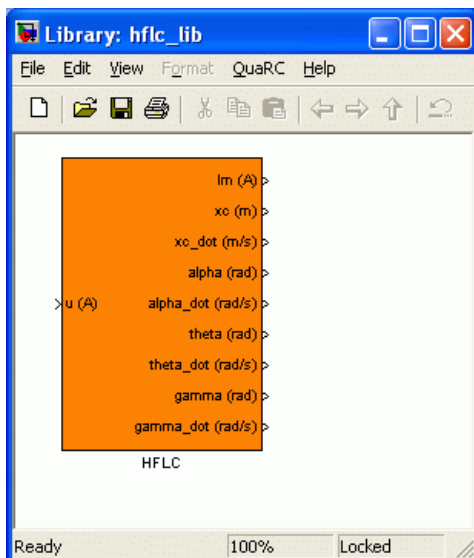


Figure 17 HFLC Library

The interior of the *HFLC* subsystem is given in Figure 18. This subsystem is standard and is used in all the experiments listed in Table 1. The details of driving the HFLC motor is described in Section 7.1.2. Section 7.1.3 summarizes the calibration gains used to calculate



the cart and pendulum positions from the encoders. The filters used to measure the velocity of the cart and the pendulums are discussed in Section 7.1.4. In Section 7.1.5 the safety features implemented in the HFLC block are discussed. This includes the cart position watchdog and the limit switches on the HFLC. Finally, the subsystem that enables the amplifier in order to drive the motor is explained in Section 7.1.6.

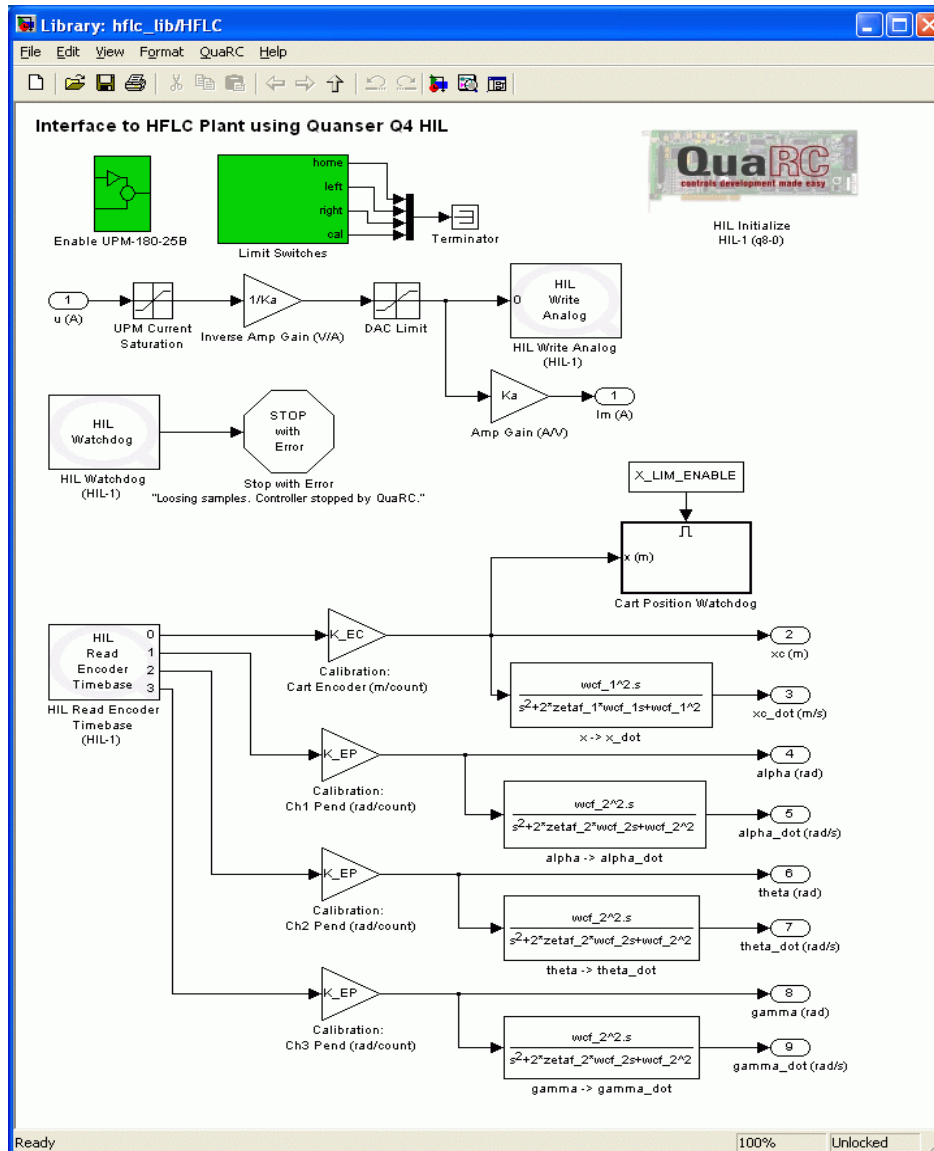


Figure 18 Interface subsystem to the actual HFLC plant.

### 7.1.1. Configuring HIL Board

The *HIL Initialize* block is used to select the type of DAQ board used with the HFLC and also to configure its inputs and outputs. For the HFLC, either the Q4 or Q8 hardware-in-the-loop boards are used. As shown in Figure 19, this can be selected under the *Main* tab via the *Board type* field.

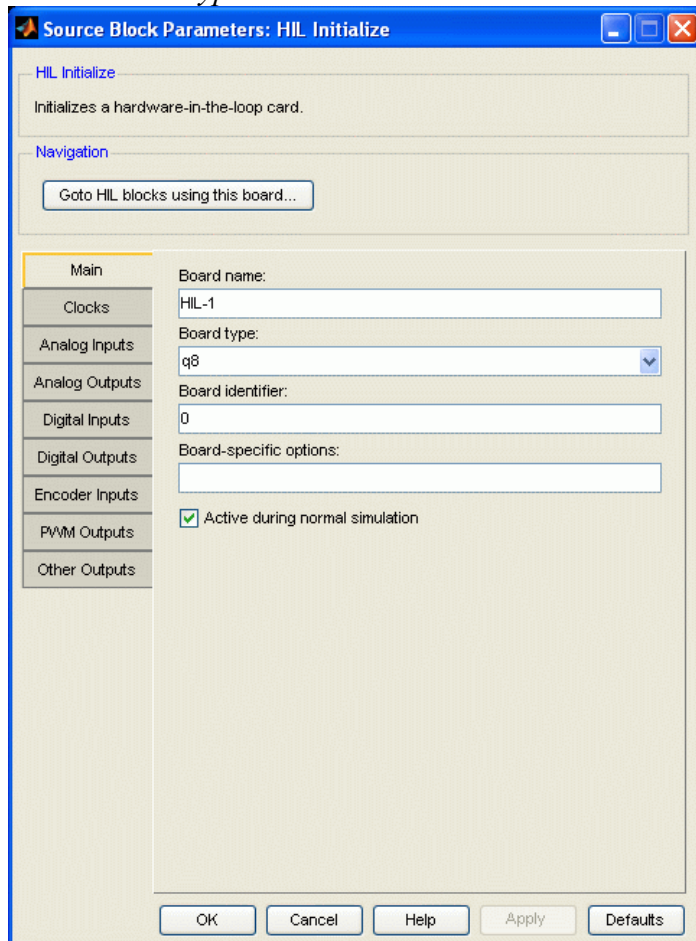


Figure 19: Configuring the HIL Initialize block.

See Reference [2] for more information regarding the HIL Initialize block.

### 7.1.2. Driving HFLC Motor

The values fed to the input terminal of the *HIL Write Analog QuaRC* block shown in Figure 18 are outputted by the Analog Output channel on the DAQ board which is then fed to the power amplifier to drive the motor. The Simulink source node labeled  $u(A)$  is the control input to the HFLC. When facing the front of the HFLC, as shown in Figure 1, the cart

moves towards the right along the track given positive control input,  $u > 0$ .

As depicted in Figure 20, the control input  $u$  is divided by amplifier gain  $K_a$  in the Simulink model so that the control input equals the current entering the cart motor. The attenuated control input gets amplified when passing through the actual amplifier, as illustrated in Figure 20. This way the amplifier gain can be neglected when mathematically modeling the HFLC system.

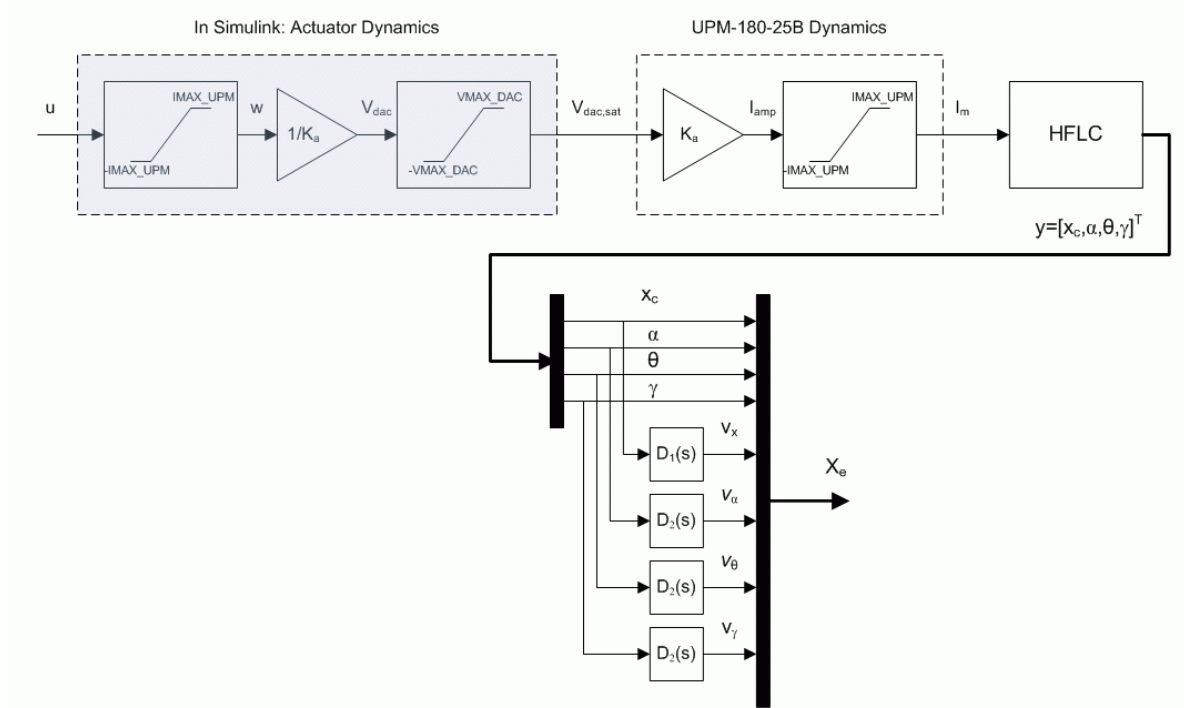


Figure 20 Overview HFLC system.

There are some nonlinear dynamics associated with the actuator that need to be considered and they are illustrated in Figure 20. The control input is limited by the maximum current of the HFLC motor as well as the maximum voltage deliverable by the D/A output channels of the data-acquisition board. Thus the motor input current is defined

$$I_m = \begin{cases} K_a V_{dac} & |V_{dac}| \leq VMAX\_DAC \\ K_a VMAX\_DAC & VMAX\_DAC < V_{dac} \\ -K_a VMAX\_DAC & V_{dac} < -VMAX\_DAC \end{cases} \quad [1]$$

with respect to data-acquisition output voltage  $V_{dac}$ . The maximum voltage of the analog output, i.e. D/A, channel is denoted by the variable  $VMAX\_DAC$  and is by default set to its maximum output of 10 V. Note that the Quanser Q4 and Q8 Analog Output block range can

be changed from 10 to 5 in which case the VMAX\_DAC should also be set to 5.

The next level of saturation is due to the power amplifier and motor limits. The voltage outputted by the data-acquisition board is defined

$$V_{dac} = \begin{cases} \frac{u}{K_a} & |u| \leq IMAX\_UPM \\ \frac{IMAX\_UPM}{K_a} & IMAX\_UPM < u \\ -\frac{IMAX\_UPM}{K_a} & u < -IMAX\_UPM \end{cases} \quad [2]$$

where  $K_a$  is the amplifier gain,  $u$  is the control input, and  $IMAX\_UPM$  is the maximum continuous current deliverable by the power amplifier or the maximum rated peak current of the HFLC motor, as defined in Table 4. By default  $IMAX\_UPM$  is set to 15.0 A which is just below the maximum peak current of the HFLC motor, 15.6 A. With this imposed limitation, the control input is saturated at  $\pm 15.0$  A (and not by the data-acquisition board). The  $Im$  (A) output node shown in Figure 18 is used to read the current running in the HFLC motor.

### 7.1.3. Measuring Cart and Pendulum Position

The *HIL Read Encoder Timebase* block in Figure 18 outputs the number of counts measured by the encoders connected to the Encoder Input channels 0-3 on the DAQ board. The positive cart direction is defined when the cart moves towards the right when facing the front of the HFLC cart, as shown in Figure 1. This is achieved by having a negative sign in the cart encoder sensitivity constant,  $K\_EC$ , defined in Table 4. In quadrature mode, the encoder mounted on the HFLC motor outputs 8192 counts per revolution. Therefore the sensor gain used to obtain the linear position of the cart is

$$K\_EC = -\frac{1}{4096} \pi r_{mp} \quad [3]$$

where  $r_{mp}$  is the motor pinion gear radius given in Table 4.

The positive direction of each pendulum is defined as being counter-clockwise when facing the cart. The pendulum encoders output 4096 counter per revolution when used in quadrature-mode. The sensitivity gain used to calculate the angular position of a pendulum link in radians is

$$K\_EP = \frac{\pi}{2048} \quad [4]$$

### 7.1.4. Measuring Cart and Pendulum Velocity

As illustrated in Figure 20, the velocities of the cart and pendula are calculated using high-gain observers. The velocity is computed by taking the derivative of the position and filtering the result using a second-order low-pass filter (or equivalently, taking the high-pass filter of the position). The cart velocity is calculated using

$$V_x(s) = D_1(s) X_c(s) \quad [5]$$

where

$$D_1(s) = \frac{\omega_{c,1}^2 s^2}{s^2 + 2\zeta_1 \omega_{c,1} s + \omega_{c,1}^2} \quad [6]$$

is a second-order high-pass filter,  $\omega_{c,1}$  is the cutoff frequency parameter that determines what frequencies in the input position signal the filter removes, and  $\zeta_1$  is the damping ratio that primarily determines the response time of the filter.

To calculate the angular rates of the pendula in radians per second, the high-pass filter

$$D_2(s) = \frac{\omega_{c,2}^2 s^2}{s^2 + 2\zeta_2 \omega_{c,2} s + \omega_{c,2}^2} \quad [7]$$

is used. This high-pass filter has a different cutoff frequency,  $\omega_{c,2}$  and damping ratio,  $\zeta_2$ , then the cart observer. The filter parameters vary depending on the experiment and are set in the corresponding Matlab design file of the laboratory.



**CAUTION: Ensure the velocity signal is properly filtered in order to eliminate high-frequency components.** The velocity signal is used in the control loop and fed to the DC motor of the HFLC plant. Therefore, it is important to place a low-pass filter after taking the derivative of an encoder signal.

### 7.1.5. Safety Features

In addition to the safety measures provided by the UPM-180-25B and the limit sensors of the HFLC system, as described in Reference [3], QuaRC offers some safety precautions.

The *Cart Position Watchdog* block shown in Figure 18 stops the real-time controller when the measured cart position goes beyond the variables X\_MIN and X\_MAX from its starting position. As shown in Figure 21, this is implemented in the *Cart Position Watchdog* block using *Relational Operators* and *Stop With Error* blocks. The X\_MIN and X\_MAX variables are specified in the corresponding laboratory Matlab setup file. Further, the safety limit can be enabled/disabled using the X\_LIM\_ENABLE variable.

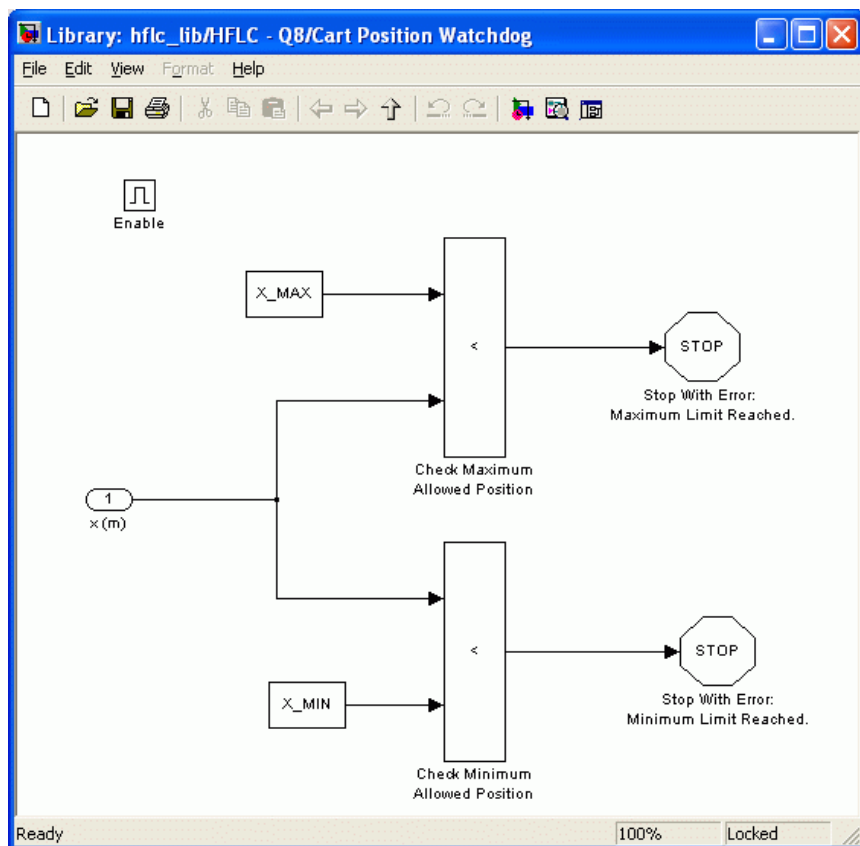


Figure 21 Cart position watchdog.

The *Limit Switches* subsystem, illustrated in Figure 22 below, is included in the *HFLC* block. It automatically stops running the QuaRC controller when either the *Left* or *Right* proximity sensors are triggered. Note that the UPM-180-25B has its own safety mechanism that disables the power amplifier when the limit switches are triggered, as discussed in Reference [3], but this does not stop running the real-time controller.

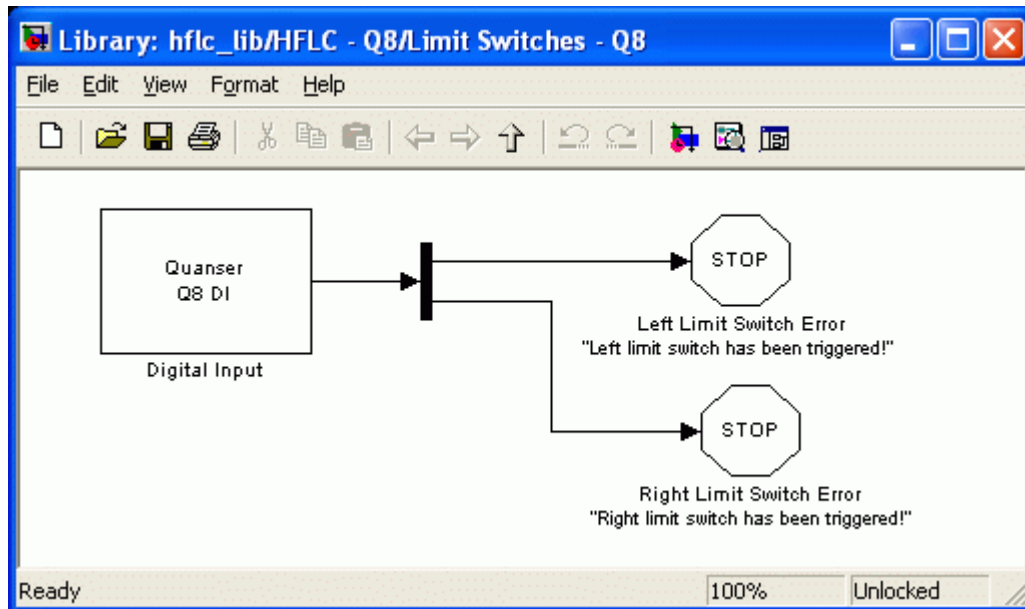


Figure 22 Subsystem checking the status of both limit switches

**Note:** If at any time one of the limits is attained, the associated LED will illuminate on the UPM and QuaRC will stop. The cart must then be manually moved back to the *Home* position in order to reset the system. QuaRC will not start if the *Left* or *Right* LEDs are on.

### 7.1.6. Enabling Amplifier

The *Enable UPM-180-25B* subsystem is also contained in the *HFLC* block, as shown in Figure 18. This block is required to enable the power amplifier in order to drive the HFLC motor and therefore perform experiments. The amplifier is therefore not enabled unless QuaRC is running a controller that was built from a Simulink model that included this block. See Reference [3] for details on enabling the UPM-180-25B device.

## 7.2. Matlab Experiment Setup Files

Each experiment has a corresponding Matlab script file entitled *setup\_lab\_hflc\_yy.m* that sets all the necessary modeling, control, and configuration parameters for the Simulink files of the corresponding experiment. The *yy* suffix denotes the laboratory in Table 1, such as *pos* for Position Control or *sip* for Single-Inverted Pendulum. The first section of a laboratory setup file is similar to the script shown in Text 1 below.



```

% ##### USER-DEFINED HFLC CONFIGURATION #####
% Type of motorized cart: set to 'HFLC'
CART_TYPE = 'HFLC';
% Type of single pendulum: set to 'MEDIUM_12IN' or 'LONG_24IN'
PEND_TYPE = 'LONG_24IN';
%PEND_TYPE = 'MEDIUM_12IN';
% Turn on or off the safety watchdog on the cart position: set it to 1 , or 0
X_LIM_ENABLE = 1;          % safety watchdog turned ON
%X_LIM_ENABLE = 0;         % safety watchdog turned OFF
% Safety Limits on the cart displacement (m)
X_MAX = 0.3;               % cart displacement maximum safety position
X_MIN = - X_MAX;           % cart displacement minimum safety position
% Turn on or off the safety watchdog on the pendulum angle: set it to 1 , or 0
ALPHA_LIM_ENABLE = 1;      % safety watchdog turned ON
%ALPHA_LIM_ENABLE = 0;     % safety watchdog turned OFF
% Safety Limits on the pendulum angle (deg)
global ALPHA_MAX ALPHA_MIN
ALPHA_MAX = 20;            % pendulum angle maximum safety position (deg)
ALPHA_MIN = - ALPHA_MAX;   % pendulum angle minimum safety position (deg)
% Universal Power Module (UPM) Type: 'UPM_180-25B'
UPM_TYPE = 'UPM_180-25B';

% Digital-to-Analog Maximum Voltage (V); for Q4/Q8 cards set to 10
VMAX_DAC = 10;
% ##### END OF USER-DEFINED HFLC CONFIGURATION #####

```

Text 1 Typical first section in a HFLC Matlab script setup file.

By default the CART\_TYPE is set to HFLC. The user may elect to have different configurations depending on the CART\_TYPE. For example, HFLC\_BEQ could return an estimated value of the viscous damping of the cart instead of returning 0.

The script shown in Text 1 is actually the setup file used for the Single-Inverted Pendulum experiment. As a result, there are some associated pendulum parameters. The PEND\_TYPE has to be set to LONG\_24IN for the long 24-inch pendulum or MEDIUM\_12IN if the medium sized 12-inch link is going to be used. The X\_LIM\_ENABLE variable activates and deactivates the safety watchdog that monitors the position of the cart. The watchdog is activated when set to 1 and deactivated when set to 0. The X\_MAX and X\_MIN specify the range in meters that the cart is allowed to move from its starting position. Similarly there are watchdogs implemented for the three pendulum angles  $\alpha$ ,  $\theta$ , and  $\gamma$ . For example, the ALPHA\_LIM\_ENABLE in the script shown in Text 1 above activates the safety watchdog on the  $\alpha$  angle when set to 1 and deactivates it when set to 0. Safety watchdogs on angles are placed outside the HFLC subsystem.

The Universal Power Module type variable, UPM\_TYPE, is set to UPM\_180-25B. The VMAX\_DAC variable is the maximum voltage that can be outputted by the data-acquisition board through its analog output terminal. As previously noted, this is usually set to 10V when using the Quanser Q4 or Q8 data-acquisition systems but can be changed, for

instance, to 5V if desired.

Text 2 shows the general layout of the next section in an experiment setup file.

```
% ##### USER-DEFINED CONTROLLER DESIGN #####
% Type of Controller: set it to 'AUTO', 'MANUAL'
CONTROLLER_TYPE = 'AUTO'; % controller design: automatic mode
%CONTROLLER_TYPE = 'MANUAL'; % controller design: manual mode
% PV Controller Design Specifications #1: max percentage overshoot (%)
PO = 12.5;
% PV Controller Design Specifications #2: peak time (s)
tp = 0.05;
% Maximum position command step input to calculate min peak time (m)
x_max = 30e-3;
% Specifications for second-order high-pass filters
if strcmp( CART_TYPE, 'HFLC' )
    % Cart Encoder Resolution
    global K_EC K_EP
    % Specifications of a second-order low-pass filter
    wcf_1 = 2 * pi * 50; % filter cutting frequency for cart velocity
    (encoder channel #0)
    zetaf_1 = 0.9; % filter damping ratio for cart velocity
    wcf_2 = 2 * pi * 10; % filter cutting frequency for velocity of encoder
    channels #1,2,3
    zetaf_2 = 0.9; % filter damping ratio - encoder channels #1,2,3
else
    error( 'Error: Set the type of motorized cart.' )
end
% ##### END OF USER-DEFINED CONTROLLER DESIGN #####
```

Text 2 Controller design section in HFLC setup Matlab script.

If the `CONTROLLER_TYPE` is set to `AUTO` then the control gain is calculated automatically later in the setup script or in a corresponding laboratory controller design file, called *d\_hflc\_yy.m*. The gain is calculated based on time-domain requirements or on given control parameters. For example in the Position Control experiment setup file shown in Text 2 above the controller is designed such that the closed-loop system has an overshoot that is less than 12.5% and has a peak time of 0.05 seconds. If set to `'MANUAL'` then the gain must be stored in the Matlab workspace manually.

The `wcf_1` and `zetaf_1` parameters are the cutoff frequency (in radians per second) and the damping ratio of the high-gain observer used to compute the velocity of the cart. Next the `wcf_2` and `zetaf_2` parameters are the cutoff frequency and damping ratio used in the velocity filtering for all three pendulum angles. The cart and pendulum cutoff frequency varies depending on the experiment listed in Table 1 and can be a crucial parameter that determines whether a system goes unstable or unstable.

## 8. Obtaining Support

**Note that a support contract may be required to obtain technical support.** To obtain support from Quanser, go to <http://www.quanser.com> and click on the *Tech Support* link. Fill in the form with all requested software version and hardware information and a description of the problem encountered. Be sure to include your email address and a telephone number where you can be reached. A qualified technical support person will contact you.

## 9. References

- [1] Quanser Inc. *Q4 or Q8 User Manual*.
- [2] Quanser Inc. QuaRC Help files (type `doc quarc` in Matlab).
- [3] Quanser Inc. *UPM User Manual*.
- [4] Danaher Motion. *AKM Series Motors*. Page 19 in the AKM24F column of *AKM\_Motor\_Selection\_Guide.pdf*.
- [5] Omron. *EE-SPY415 Specifications*. See *EE-SPY415.pdf*.

## Appendix A. HFLC Pendulum Encoder Specification Sheet

### S1 & S2

### Optical Shaft Encoders

#### Description:

The **S1** and **S2** series optical shaft encoders are non-contacting rotary to digital converters. Useful for position feedback or manual interface, the encoders convert real-time shaft angle, speed, and direction into TTL-compatible quadrature outputs with or without index. The encoders utilize an unbreakable mylar disk, metal shaft and bushing, LED light source, and monolithic electronics. They may operate from a single +5VDC supply.

The **S1** and **S2** encoders are available with ball bearings for motion control applications or torque-loaded to feel like a potentiometer for front-panel manual interface.

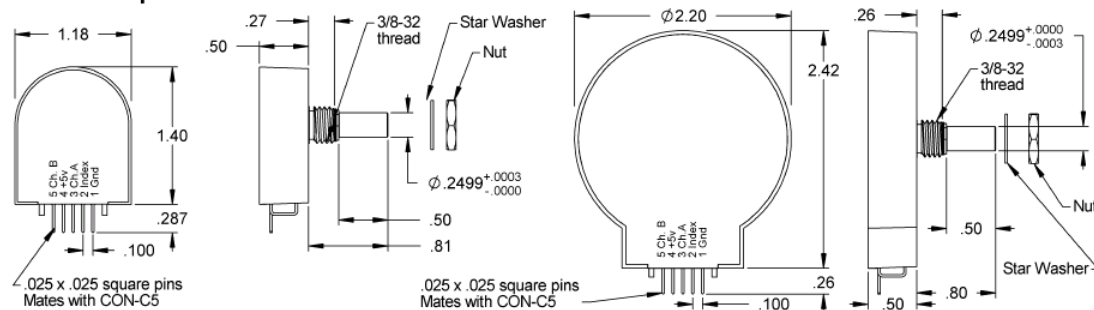
#### Electrical Specifications:

B leads A for clockwise shaft rotation, A leads B for counter clockwise shaft rotation viewed from the shaft/bushing side of the encoder. For complete details see our **HEDS** data sheet.

#### Features:

- Small size
- Low cost
- 2-channel quadrature, TTL square wave outputs
- 3rd channel index option
- Tracks from 0 to 100,000 cycles/sec
- Ball bearing option tracks to 10,000 RPM
- -40 to +100°C operating temperature
- Single +5V supply
- US Digital warrants its products against defects and workmanship for two years. See complete warranty for details.

#### Mechanical Specifications:



#### Mechanical Notes: (ball bearing)

Acceleration	10,000 rad/sec <sup>2</sup>
Vibration	20 g, 5 to 2KHz
Shaft Speed	10,000 RPM max. continuous
Acceleration	50K rad/sec <sup>2</sup>
	10K rad/sec <sup>2</sup> ( <b>S2</b> series)
Shaft Torque	0.05 in. oz. max.
Shaft Loading	1 lb. max.
Bearing Life	(40/P) <sup>3</sup> = Life in millions of revs. P = radial load in pounds.
Weight	0.7 oz.
Shaft Runout	0.0015 T.I.R. max.

#### Mechanical Notes: (sleeve bushing)

Acceleration	10,000 rad/sec <sup>2</sup>
Vibration	20 g, 5 to 2KHz
Shaft Speed	100 RPM max. continuous
Shaft Rotation	Continuous & reversible
Shaft Torque	0.5 ± 0.2 in. oz. 0.3 in. oz. max. (NT-option)
Shaft Loading	2 lbs. max. dynamic 20 lbs. max. static
Weight	0.7 oz.
Shaft Runout	0.0015 T.I.R. max.

#### Materials & Mounting:

Shaft	Brass or stainless
Bushing	Brass
Connector	Gold plated
Hole Diameter	0.375 in. +0.005 - 0
Panel Thickness	0.125 in. max.
Panel Nut Max Torque	20 in.-lbs.

## Appendix B. Q8 Extended Terminal Board Signals

The Q8 Extended Terminal Board does *not* have separate analog input channels and does not have the Encoder Input 0 and Encoder Input 4 connectors. The A/D channels 0-3 and Encoder Input Channel 0 are integrated in the *Table X* connection and, similarly, the A/D channels 4-7, and Encoder Input Channel 4 are integrated in the *Table Y* connection. The limit detector signals – *Left*, *Home*, and *Right* – and the *Calibrate* and *Enable* signals from the PIC in the UPM are also carried in the *Table X* connection. Table 12 specifies the various signals carried between the UPM and *Table X* connection on the Q8 Extended Terminal Board.

<i>Signal</i>	<i>QuaRC Interface</i>	<i>Description</i>
D/A #0	Analog Output: Channel 0	Drives the amplifier in the UPM.
A/D #0	Analog Input: Channel 0	Analog sensor (i.e. accelerometer) connected to <i>S1</i> on UPM.
A/D #1	Analog Input: Channel 1	Analog sensor connected to <i>S2</i> on UPM.
A/D #2	Analog Input: Channel 2	Analog sensor connected to <i>S3</i> on UPM.
A/D #3	Analog Input: Channel 3	Analog sensor connected to <i>S4</i> on UPM.
Encoder #0	Encoder Input: Channel 4	Measurement from HFLC motor encoder.
DI #0	Digital Input: Channel 0	<i>Left</i> limit detector signal.
DI #1	Digital Input: Channel 1	<i>Home</i> limit detector signal.
DI #2	Digital Input: Channel 2	<i>Right</i> limit detector signal.
DI #3	Digital Input: Channel 3	<i>Calibrate</i> signal.
DO #0	Digital Output: Channel 8	Sends <i>Calibrate</i> signal to PIC on UPM.
DO #1	Digital Output: Channel 9	Sends <i>Enable</i> signal to PIC on UPM.

Table 12 *Table X* Connection Signals