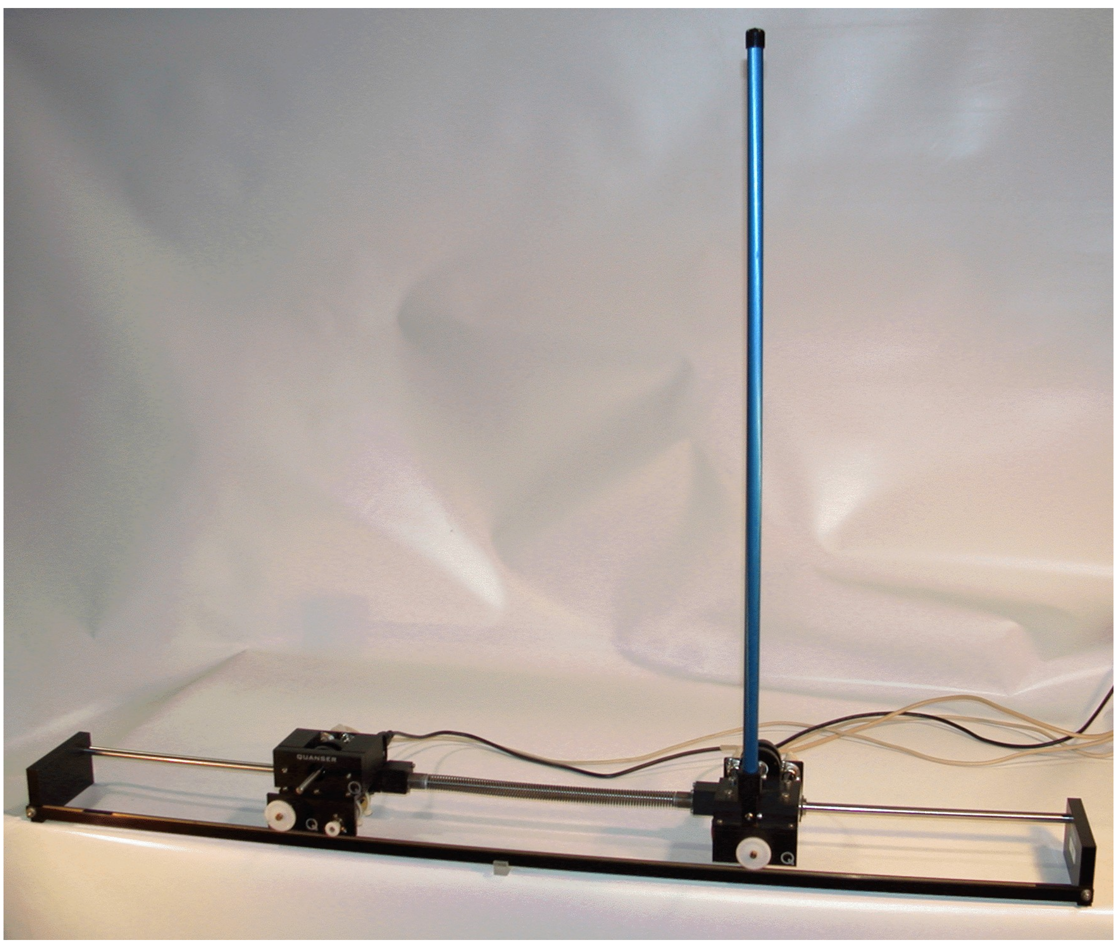
Linear Motion Servo Plants: IP01 and IP02

Linear Flexible Joint Cart Plus Single Inverted Pendulum (LFJC+SIP)



User Manual

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1. Linear Flexible Joint Cart Plus Single Inverted Pendulum System (LFJC+SIP)

1.1. Linear Flexible Joint Cart Plus Single Inverted Pendulum System Description

The Linear Flexible Joint Cart (LFJC) Plus Single Inverted Pendulum (SIP) experiment consists of a system of two carts sliding on an IP01 or IP02 track with a pendulum mounted on the output cart (i.e., LFJC). This is illustrated in Figure 1.

As shown in Figure 1, the cart on the left is an IP02 cart with the extra weight mounted atop of it in order to reduce slippage. An IP01 could also be used. Both IP01 and IP02 are solid aluminum carts. They are driven by a rack and pinion mechanism using a 6-Volt DC motor, ensuring consistent and continuous traction. Such cart slides along a ground stainless steel shaft using linear bearings. The cart position is measured using a sensor coupled to the rack via an additional pinion. Please review Reference [1] for a complete description of both IP01 and IP02 systems.

To run the LFJC+SIP experiment, the cart on the right must be the LFJC-PEN-E Quanser module. The LFJC-PEN-E module is equipped with a rotary joint atop of it, whose axis of rotation is perpendicular to the direction of motion of the cart. A free-swinging rod can be attached to it and suspends in front of the cart. This rod can function as an "inverted pendulum" as well as a regular pendulum. The LFJC-PEN-E is instrumented with two quadrature optical encoders. One encoder measures the position of the cart via a pinion which meshes with the track. The other encoder measures the angle of the rod mounted on the cart and is thus unlimited in range and continuous over the entire circle. It uses linear bearings to slide along a ground stainless steel shaft. Moreover, two masses are available for attachment to the cart. These two weights can be used to reduce slippage and/or assess the robustness of the controller and the effects of variations in parameters. While one of the two carts is motorized and drives the system (e.g. IP01 or IP02), the second cart is passive and coupled to the first one through a linear spring. The shafts of these elements are coupled to a rack and pinion mechanism in order to input the driving force to the system and to measure the two cart positions. When the motor turns, the torque created at the output shaft is translated to a linear force which results in the cart's motion. When the carts move, the potentiometer and/or encoder shafts turn and the resulting signals are calibrated to obtain the actuated cart's position.

The Single Inverted Pendulum (SIP) module consists of a single rod mounted on the LFJC whose axis of rotation is perpendicular to the direction of motion of the cart. The SIP is free to fall along the LFJC's axis of motion. Single pendulums come in two different lengths: namely there is a 12-inch "medium" pendulum and a 24-inch "long" pendulum.

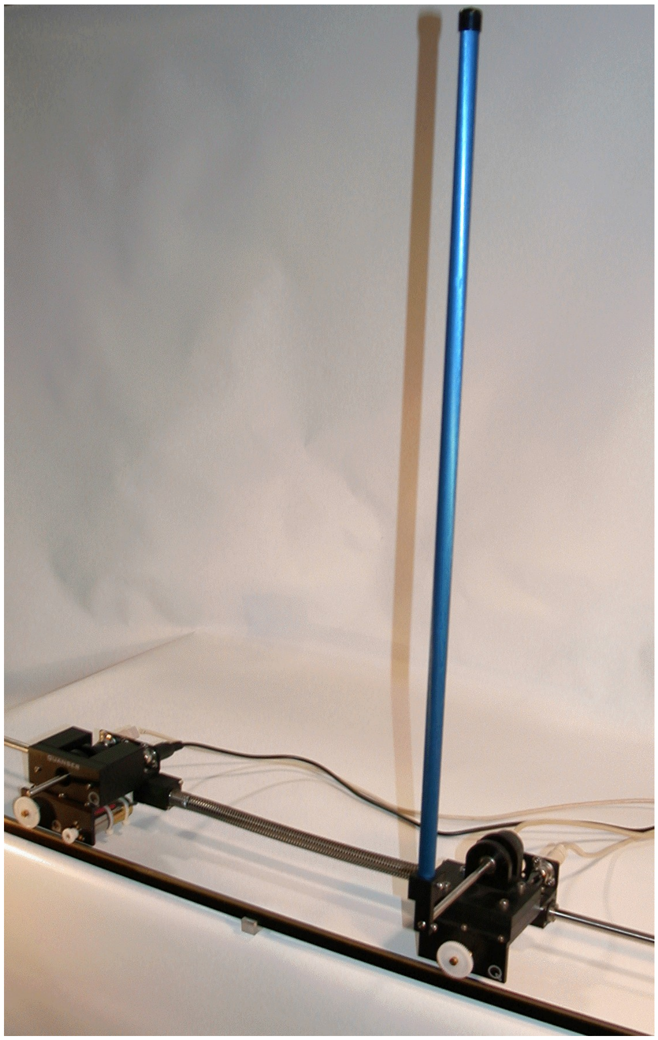


Figure 1 LFJC-PEN-E-Plus-SIP Coupled to an IP02

1.2. LFJC-Plus-SIP Experiment: Control Challenge

As illustrated in Figure 1, the objective of the Linear Flexible Joint Cart Plus Single Inverted Pendulum (LFJC+SIP) experiment is to design a controller that would balance the rod in the upright posture and regulate the spring-driven cart position while minimizing joint deflection (i.e., oscillation).

The ability to vary parameters and the hardware configuration is also available should you wish to modify the dynamics of the challenge, like for example changing the cart mass and/or spring stiffness and/or pendulum length. The system is supplied with a state-feedback controller but, of course, you may design any other controller you wish. The complete mathematical modelling and system parameters are provided to streamline the implementation of the control theory of your choice.

2. LFJC-PEN-E-Plus-SIP System Description

2.1. Component Nomenclature

Figures 2 and 3, below, depict the LFJC-PEN-E and SIP modules, respectively.

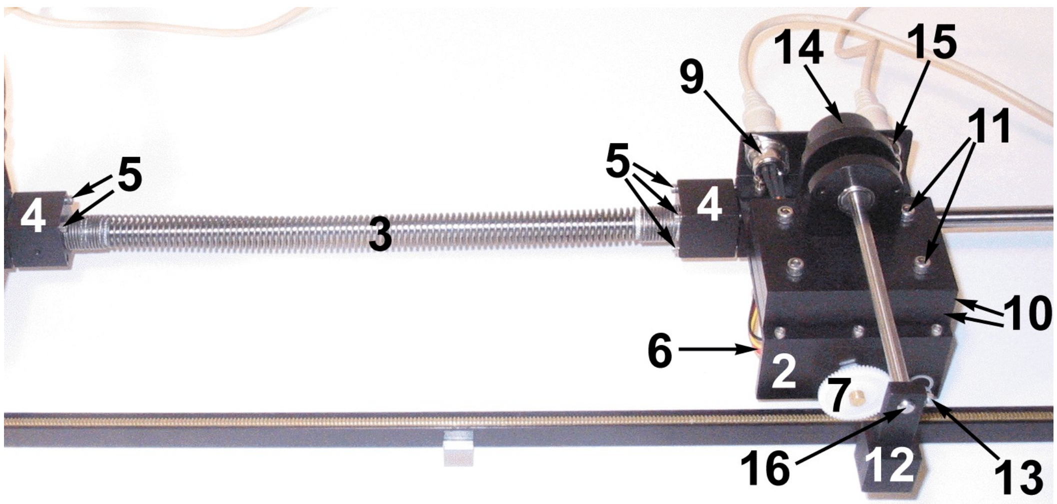


Figure 2 LFJC-PEN-E Nomenclature

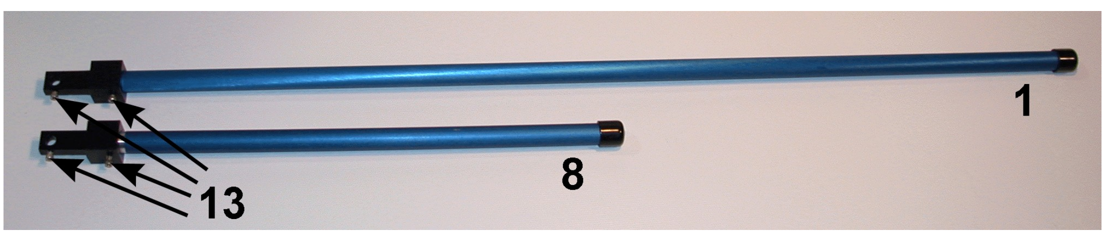


Figure 3 SIP Nomenclature

As a component nomenclature, Table 1, below, provides a list of all the principal elements composing the LFJC-PEN-E and SIP sub-systems. Each of these elements is located and identified, through a unique identification (ID) number, on both LFJC-PEN-E and SIP systems, as represented in Figures 2 and 3.

ID #	Description	ID #	Description
1	Long (24-inch) Pendulum	**2**	LFJC-PEN-E
3	Compression Spring	**4**	Spring Fitting
5	Spring Fitting Set Screw: (7/64)"	**6**	LFJC Cart Encoder
7	LFJC Cart Position Pinion	**8**	Medium (12-inch) Pendulum
9	LFJC Cart Encoder Connector	**10**	LFJC Load Weight
11	Load Weight Set Screw: (9/64)"	**12**	Pendulum T-Fitting (a.k.a. Socket)
13	Pendulum T-Fitting Set Screw: (3/32)"	**14**	LFJC Pendulum Encoder
15	LFJC Pendulum Encoder Connector	**16**	LFJC Pendulum Axis

Table 1 LFJC-PEN-E-Plus-SIP Component Nomenclature

The two masses (i.e. component #10) supplied for the load cart can be used, for instance, for assessing the robustness of the controller and the effects of variations in parameters.

The resulting IP01/IP02-Plus-LFJC-PEN-E-Plus-SIP assembly is shown in Figure 4.

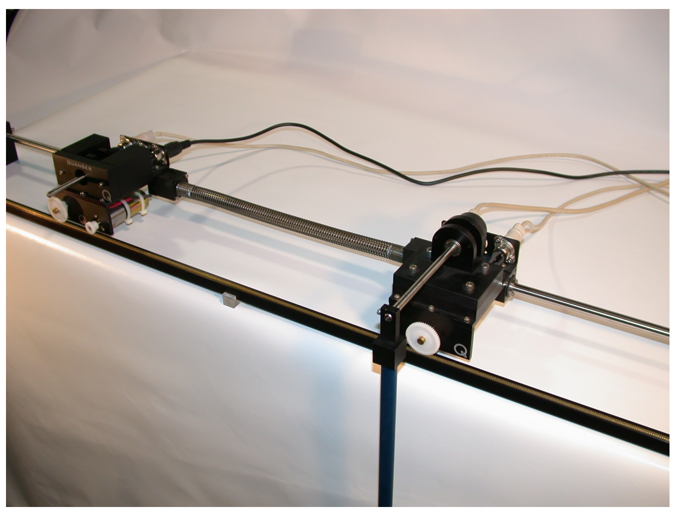


Figure 4 LFJC-PEN-E-Plus-SIP Assembly

2.2. Component Description

2.2.1. Linear Spring (Component #3)

The linear spring used in the LFJC-PEN-E is a compression spring coiled left hand from **Ashfield Springs Limited (UK)**. It has the following dimensions: an outside diameter of

15.90mm (i.e. 0.625"), a wire diameter of 1.40 mm (i.e. 0.056"), with approximately 3.54 coils/cm (i.e. 9 coils/inch), for a length of around 304 mm (i.e. 12"). The part stock number is: **S.618**. Furthermore, both ends of the linear spring are equipped with a square fitting in order to mate with either the IP01 or IP02 cart on one side and the LFJ cart on the other; thus obtaining a linear spring-mass system.

2.2.2. LFJC-PEN-E Encoders (Components #6 and #14)

The LFJC-PEN-E has one optical encoder to measure the cart position, as represented in Figure 2, by component #6. The encoder measuring the LFJ cart linear position does so through a rack-pinion system. The LFJC-PEN-E also offers a rotary joint atop of it, where a free-swinging rod can be attached to and suspend in front of the cart. It results that the LFJC-PEN-E module is instrumented with a second quadrature optical encoder, as represented in Figure 2 by component #14. This encoder measures the angle of the rod optionally mounted on the cart. Both encoders of the LFJC-PEN-E are typically identical. They are **US Digital S1 single-ended optical shaft encoders**. They offer a high resolution of 4096 counts per revolution (i.e., 1024 lines per revolution with two channels in quadrature). The complete specification sheet of the S1 optical shaft encoder is included in Appendix A.

The internal wiring diagram of the LFJC-PEN-E encoders is depicted in Figure 5. The standard 5-pin DIN connector shown in Figure 5 is also pictured as components #9 and #15 in Figure 2.

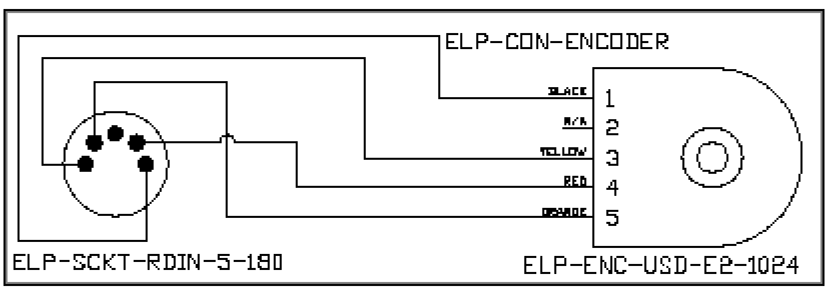


Figure 5 Wiring Diagram of the LFJC-PEN-E Encoders

If the LFJC-PEN-E encoder does not measure correctly, you should:

- check that the Q8/Q4/MultiQ is functional. The red LED on the board should be lit. If it is not, the fuse may be burnt and need replacement. Refer to your Hardware-In-the-Loop (HIL) data acquisition board reference manual as necessary. Also ensure that you are using the right driver corresponding to your type of HIL board. Check that you have an encoder chip and that it is properly installed. With the computer OFF, ensure that the Q8/Q4 (or equivalent) is properly installed in the PC.
- check that both signals from the encoder channels A and B are properly generated and

fed to the HIL board (ensure all cables are properly connected). Using an oscilloscope, you should observe, when manually rotating the encoder shaft, two square waves, representing channels A and B, with a phase shift of 90ºe (between the rising edge of the two channels). If you believe that your encoder is damaged and need to be replaced, refer to Section Error: Reference source not found, Error: Reference source not found, for information on contacting Quanser for technical support.

3. LFJC-PEN-E-Plus-SIP System Model Parameters

Table 2, below, lists and characterizes the main parameters associated with Quanser's LFJC-PEN-E-Plus-SIP assembly. These parameters are particularly useful for the mathematical modelling and simulation of the system. In Table 2, the SIP model parameters whose subscript finishes with an *"l"* correspond to the "long" pendulum (of 24 inches), and those whose subscript finishes with a *"m"* apply to the "medium" pendulum (of 12 inches).

Symbol	*Description*	*Value*	*Unit*
M_{c2_pc}	LFJC-PEN-E Mass (Cart Alone)	0.240	kg
M_{w2}	LFJC-PEN-E Weight Mass	0.120	kg
M_{pf2}	LFJC-PEN-E Pendulum Fixture Mass	0.135	kg
B_{eq2}	LFJC-PEN-E Equivalent Viscous Damping Coefficient as seen at the Cart Position Pinion	1.1	N.s/m
K_s	LFJC-PEN-E Spring Stiffness Constant	160	N/m
M_s	LFJC-PEN-E Spring Assembly Mass	0.145	kg
L_s	LFJC-PEN-E Spring Length	0.29	m
N_{pp2}	LFJC-PEN-E Position Pinion Number of Teeth	56	
r_{pp2}	LFJC-PEN-E Position Pinion Radius	1.48E-2	m
P_{pp2}	LFJC-PEN-E Position Pinion Pitch	1.664E-3	m/tooth
M_{pl}	Long Pendulum Mass (with T-fitting)	0.230	kg
M_{pm}	Medium Pendulum Mass (with T-fitting)	0.127	kg
L_{pl}	Long Pendulum Full Length (from Pivot to Tip)	0.6413	m
L_{pm}	Medium Pendulum Full Length (from Pivot to Tip)	0.3365	m
l_{pl}	Long Pendulum Length from Pivot to Center Of Gravity	0.3302	m
l_{pm}	Medium Pendulum Length from Pivot to Center Of Gravity	0.1778	m
I_{pl}	Long Pendulum Moment of Inertia, about its Center Of Gravity	7.88E-3	kg.m^2
I_{pm}	Medium Pendulum Moment of Inertia, about its Center Of Gravity	1.20E-3	kg.m^2

Symbol	***Description***	***Value***	***Unit***
B_p	Viscous Damping Coefficient, as seen at the Pendulum Axis	0.0024	N.m.s/rad
g	Gravitational Constant on Earth	9.81	m/s^2
K_{EC_LFJC}	LFJC-PEN-E Position Encoder Resolution	2.275E-5	m/count
K_{EP_LFJC}	LFJC-PEN-E Pendulum Encoder Resolution	0.0015	rad/count

Table 2 LFJC-PEN-E-Plus-SIP System Parameters

4. LFJC-Plus-SIP Configuration and Setup

4.1. LFJC-Plus-SIP: Default Configuration

Figure 6 illustrates the mounting and assembly, in the default configuration, of the LFJC-PEN-E-Plus-SIP modules with an IP02 cart-and-track system.

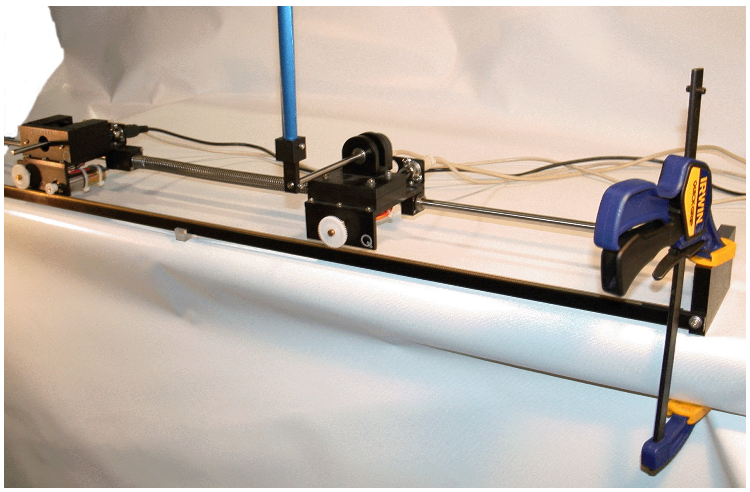


Figure 6 Default Configuration of the LFJC-PEN-E-Plus-SIP-Plus-IP02 Plant

The default configuration for the LFJC-PEN-E-Plus-SIP-Plus-IP01-or-IP02 system is the one used in the Quanser laboratory described in References [4] and [5].

The default configuration is depicted in Figure 6 and can be described as follows:

Concerning both IP01 and IP02 cart-and-track systems, the default configuration consists of the cart with its additional weight mounted atop of it (the extra mass for the motorized cart reduces slippage). Besides, the two load weights provided for the LFJC-PEN-E should also be mounted on the output cart and the long (i.e., 24-inch) pendulum, pointing downwards, attached to it. Additionally, the system should be rigidly clamped down to a table or workbench.

4.2. Setup Procedure for the Default Configuration

The setup procedure for the default configuration, as previously described, is as follows:

Step 1. Do not mount the pendulum rod on your IP01 or IP02 cart. Remove it if necessary.
Step 2. Mount your LFJC-PEN-E module on your IP01 or IP02 track. To do so, first remove one of your IP01 or IP02 rack end plates by unfastening the two corresponding set screws. Consult Reference [1] if necessary. You can then slip both linear spring and the LFJC-PEN-E cart on the IP01 or IP02 stainless steel shaft. Finally once the LFJC-PEN-E system can slide smoothly on the guide rail, you can then mount the rack end plate back and tighten the two set screws.
Step 3. Attach the linear spring square fitting (component #4 in Figure 2) to your IP01 or IP02 cart. To do so, fasten the set screws numbered 5 in Figure 2.
Step 4. Place the additional weight on your IP01 or IP02 cart, if not already done.
Step 5. Mount the two additional weights (components #10 in Figure 2) on top of your LFJC-PEN-E system, if not already done. To that effect, fasten the set screws numbered 11 in Figure 2.
Step 6. Insert the long pendulum rod (i.e., 24-inch) inside its corresponding T-fitting (i.e. component #12 in Figure 2). Ensure that it sits properly. Tighten set screw #13, as required.
Step 7. On the LFJC-PEN-E module, attach the single pendulum, pointing downwards, at the tip of the LFJC's pendulum axis by tightening set screw #13 as necessary. As a remark, it is reminded that in this configuration, the pendulum is free to rotate over a 360-degree range in front of the cart.
Step 8. You should also clamp the IP01 or IP02 track down to the table using its end plates, as pictured in Figure 6.
Step 9. Wire both your IP01 or IP02 cart and LFJC-PEN-E module as described in the following Section, Typical Connections.

4.3. Typical Connections

This section describes the standard wiring procedure and typical cabling connections that are used by default in the Quanser LFJC-Plus-SIP laboratory described in References [4] and [5]. These cabling connections use standard cables, whose description and nomenclature can be found in Reference [1]. Figure 7, below, shows the LFJC-Plus-SIP system, the DAQ board, and the amplifier (e.g., VoltPAQ), all connected with the necessary cabling to interface to and use the LFJC-Plus-SIP system.

4.3.1. IP01 or IP02 Connections

Wire up your IP01 or IP02 cart as per dictated in Reference [1], where the Quanser's standard wiring conventions for the IP01 and IP02 systems are fully described.

4.3.2. LFJC-PEN-E Connections

To run the Quanser LFJC-Plus-SIP laboratory described in References [4] and [5], both LFJC cart and pendulum encoders must be connected.

Proceed according to the two following steps described below:

1. **Connect the LFJC-PEN-E Position "Encoder" Cable – Cable #4:**
   The "Encoder" cable is the 5-pin-stereo-DIN-to-5-pin-stereo-DIN cable described in Reference [1]. First connect one end of the cable to the **LFJC-PEN-E Encoder Connector**, which is shown as component #9 in Figure 2. Then connect the other cable end to the **Encoder Input 2** on your DAQ device terminal board. This is illustrated by cable #4 in Figure 7.
2. **Connect the LFJC-PEN-E Pendulum Angle "Encoder" Cable – Cable #5:**
   First connect one end of the cable to the **LFJC-PEN-E Pendulum Encoder Connector**, which is shown as component #15 in Figure 2. Then connect the other cable end to the **Encoder Input 3** on your DAQ device terminal board. This is illustrated by cable #5 in Figure 7.

⚠ **CAUTION:**
Any encoder should be directly connected to the Quanser terminal board (or equivalent) using a standard 5-pin DIN cable. **DO NOT connect the encoder cable to the amplifier!**

Figure 7 and Table 3 sum up the electrical connections recommended to run the LFJC-Plus-SIP system.

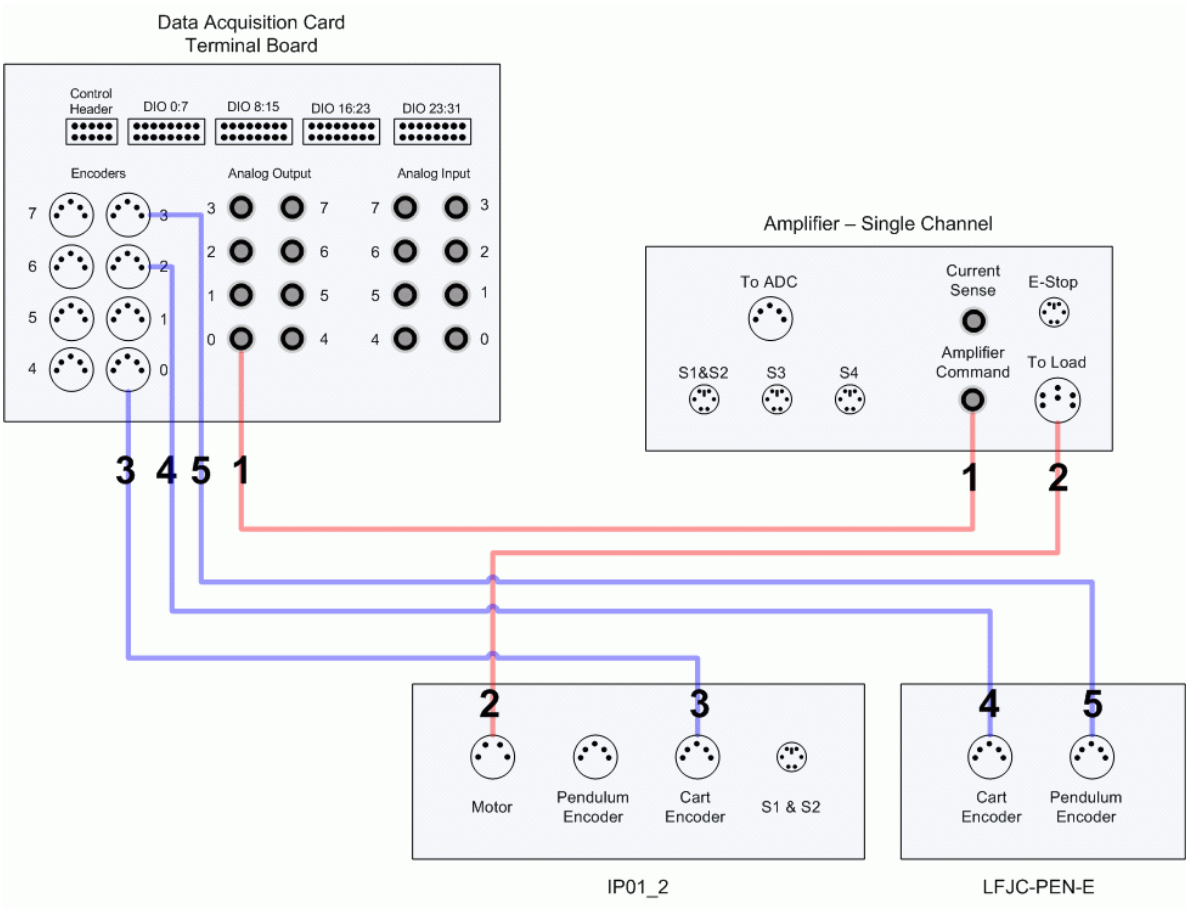


Figure 7: Connecting the LFJC-Plus-SIP system to an amplifier and DAQ board.

Cable #	***From***	***To***	***Signal***
1	Terminal Board: DAC #0	Amplifier "Amplifier Command"	Control signal to the amplifier.
2	Amplifier "To Load"	IP02 (or IP01) "Motor Connector"	Power leads to the IP02 (or IP01) DC motor.
3	IP02 Cart "Encoder Connector"	Terminal Board: Encoder Channel #0	IP02 cart linear position.
4	LFJC-PEN-E Cart "Encoder Connector"	Terminal Board: Encoder Channel #2	LFJ cart linear position.

Cable #	From	To	Signal
5	LFJC-PEN-E Pendulum "Encoder Connector"	Terminal Board: Encoder Channel #3	SIP pivot shaft angular position.

Table 3 IP02-Plus-LFJC-Plus-SIP System Wiring Summary

4.3.3. Connecting to the Quanser ControlPAQ-FW

When connecting the IP02-Plus-LFJC-Plus-SIP system to the Quanser Q3 ControlPAQ-FW device, follow the connections summarized in Table 4 and illustrated in Figure 8.

Cable #	From	To	Signal
1	Q3 "Motors 0" connector	IP02 "Motor" connector	Power leads to the IP01_2 DC motor.
2	Q3 “Encoders 0” connector	IP02 Cart “Encoder” connector	IP02 cart position measurement.
3	Q3 “Encoders 1” connector	LFJC-PEN-E “Cart" encoder connector	LFJ cart linear position
4	Q3 “Encoders 2” connector	LFJC-PEN-E “Pendulum" encoder connector	SIP pivot shaft angular position

Table 4: IP02-Plus-LFJC-Plus-SIP system wiring summary when using Q3.

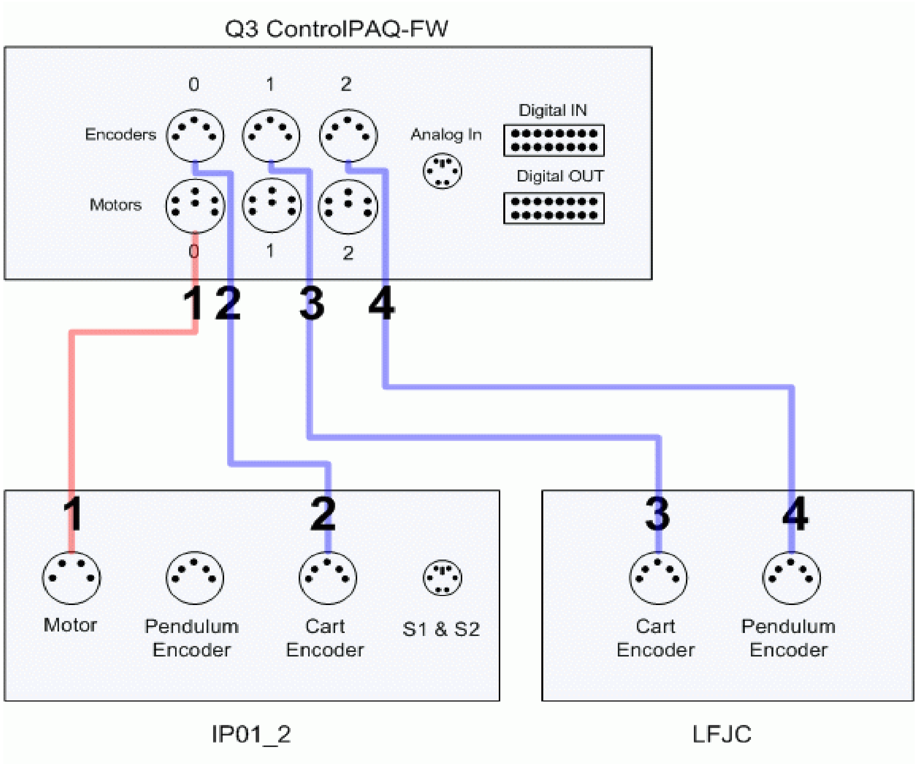


Figure 8: Connecting the LFJC-Plus-IP02 system to the Quanser Q3-ControlPAQ-FW.

5. 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. Submit the form. Be sure to include your email address and a telephone number where you can be reached. A qualified technical support person will contact you.

6. References

[1] IP01 and IP02 User Manual
[2] Power Amplifier User Manual
[3] QUARC User Manual
[4] IP01 and IP02 - Linear Flexible Joint Cart Plus Single Inverted Pendulum (LFJC+SIP) – Linear Experiment #11: LQR Control - Student Handout.
[5] IP01 and IP02 - Linear Flexible Joint Cart Plus Single Inverted Pendulum (LFJC+SIP) – Linear Experiment #11: LQR Control – Instructor Manual.

Appendix A. LFJC-PEN-E 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.

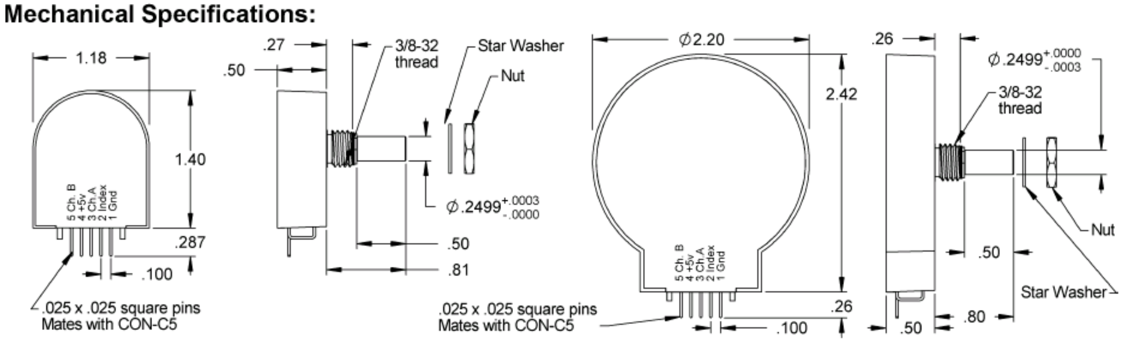
The **S1** and **S2** encoders are available with ball bearings for motion control applications or torque-loaded to feel like a potentiometer for front-panel manual interface.

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/sec²
Vibration	20 g. 5 to 2KHz
Shaft Speed	10,000 RPM max. continuous
Acceleration	50K rad/sec² 10K rad/sec² (**S2** series)
Shaft Torque	0.05 in. oz. max.
Shaft Loading	1 lb. max.
Bearing Life	$(40/P)^3$ = 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/sec²
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.