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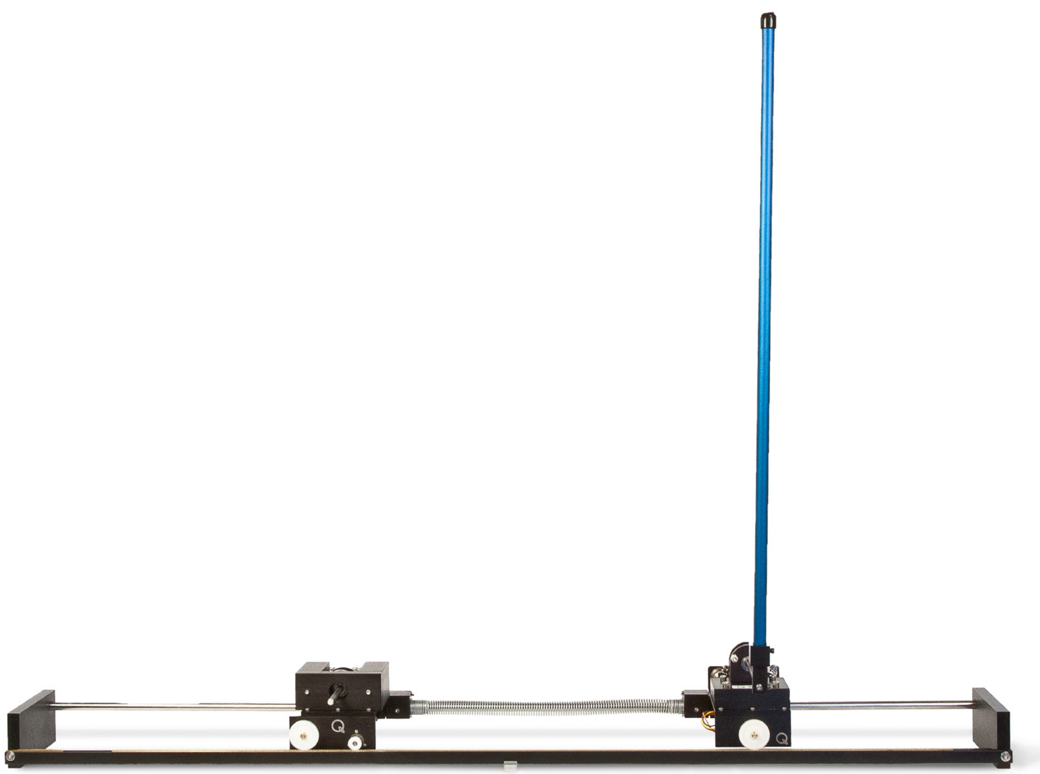
USER MANUAL

Linear Flexible Joint with Inverted Pendulum Experiment

Set Up and Configuration



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1 PRESENTATION

1.1 Description

The Linear Flexible Joint Cart (LFJC) experiment consists of a system of two carts sliding on an IP02 track with a pendulum mounted on the output cart (i.e., LFJC). This is illustrated in Figure 1.1.

As shown in Figure 1.1, the cart on the left is an IP02 cart with the extra weight mounted atop of it in order to reduce slippage. The 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 [3] for a complete description of the IP02 system.

To run the LFJC 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. 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.

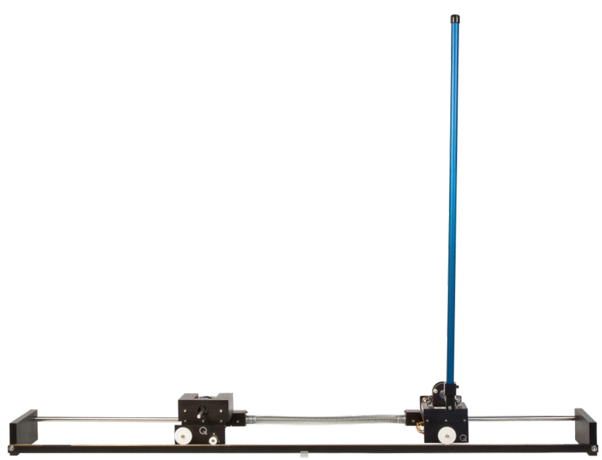


Figure 1.1: LFJC-PEN-E Coupled to an IP02

■ **Caution: This equipment is designed to be used for educational and research purposes and is not intended for use by the general public.** The user is responsible to ensure that the equipment will be used by technically qualified personnel only.

2 LFJC-PEN-E COMPONENTS

2.1 Component Nomenclature

Figure 2.1 and Figure 2.2, below, depict the LFJC-PEN-E modules, respectively.

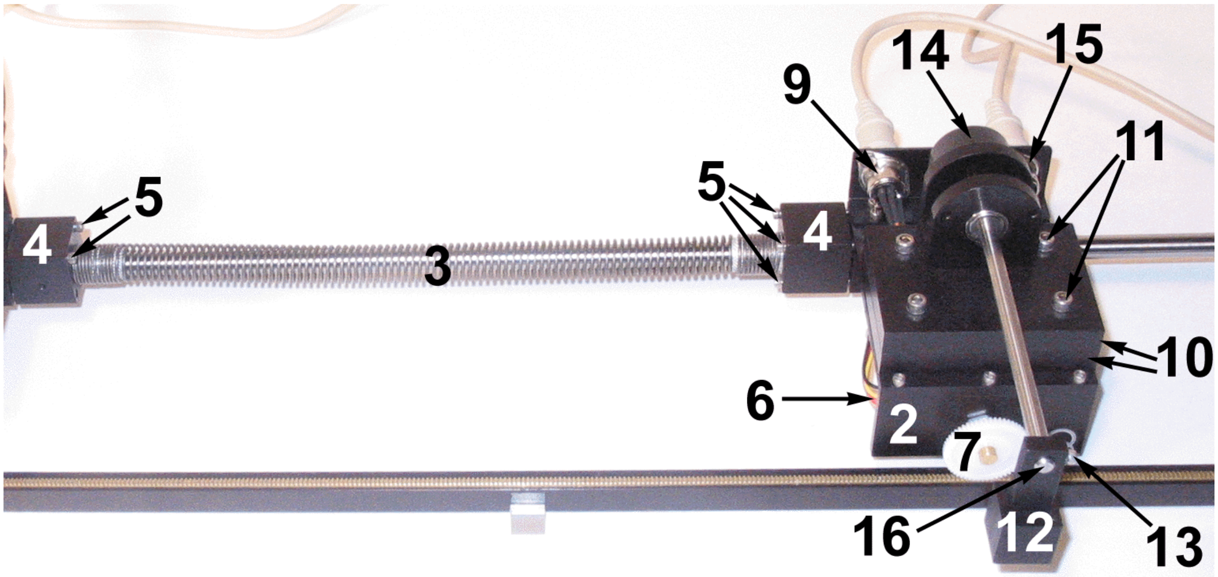


Figure 2.1: LFJC-PEN-E Nomenclature

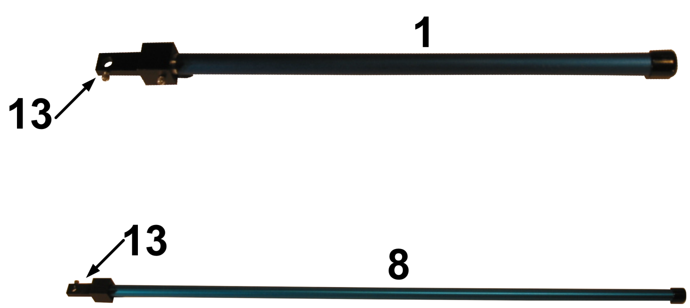


Figure 2.2: SIP Nomenclature

As a component nomenclature, Table 2.1, below, provides a list of all the principal elements composing the LFJC-PEN-E sub-systems. Each of these elements is located and identified, through a unique identification (ID) number, on both LFJC-PEN-E systems, as represented in Figure 2.1 and Figure 2.2.

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.

2.2 Component Description

2.2.1 Linear Spring

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

ID	Component	ID	Component
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 2.1: LFJC-PEN-E Component Nomenclature Components

stock number is: S.618. Furthermore, both ends of the linear spring are equipped with a square fitting in order to mate with the 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

The LFJC-PEN-E has an optical encoder which is used to measure the cart position, represented in Figure 2.1 by components # 5. The encoder measuring the LFJC-PEN-E cart linear position does so through a rack-pinion system. The encoder model used in the LFJC-PEN-E is a US Digital S1 single-ended optical shaft encoder. It offers 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 [1]. Remark that incremental encoders measure the relative angle of the shaft.

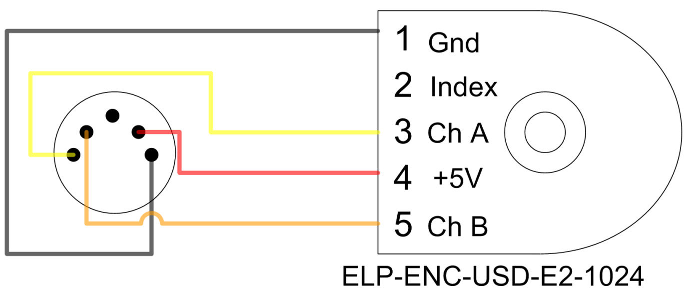


Figure 2.3: Wiring Diagram of the LFJC-PEN-E Encoders

The position signal generated by the encoder can be directly connected to the data-acquisition device using a standard 5-pin DIN cable. The internal wiring of the encoder and the 5-pin DIN connector on the LFJC-PEN-E is illustrated in Figure 2.3.

■ **Caution:** Make sure you connect the encoder directly to your data-acquistion device and not to the power amplifier.

3 LFJC-PEN-E SPECIFICATIONS

Table 3.1 lists and characterizes the main parameters associated with Quanser's LFJC-PEN-E assembly. These parameters are particularly useful for the mathematical modelling and simulation of the system. In Table 3.1, 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
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 Resolutiont	0.0015	rad/count

Table 3.1: LFJC-PEN-E System Parameters

4 LFJC-PEN-E CONFIGURATION AND SETUP

■ **Caution: If the equipment is used in a manner not specified by the manufacturer, the protection provided by the equipment may be impaired.**

4.1 LFJC-PEN-E: Default Configuration

Figure 4.1 illustrates the mounting and assembly, in the default configuration, of the LFJC- PEN-E modules with an IP02 cart-and-track system.

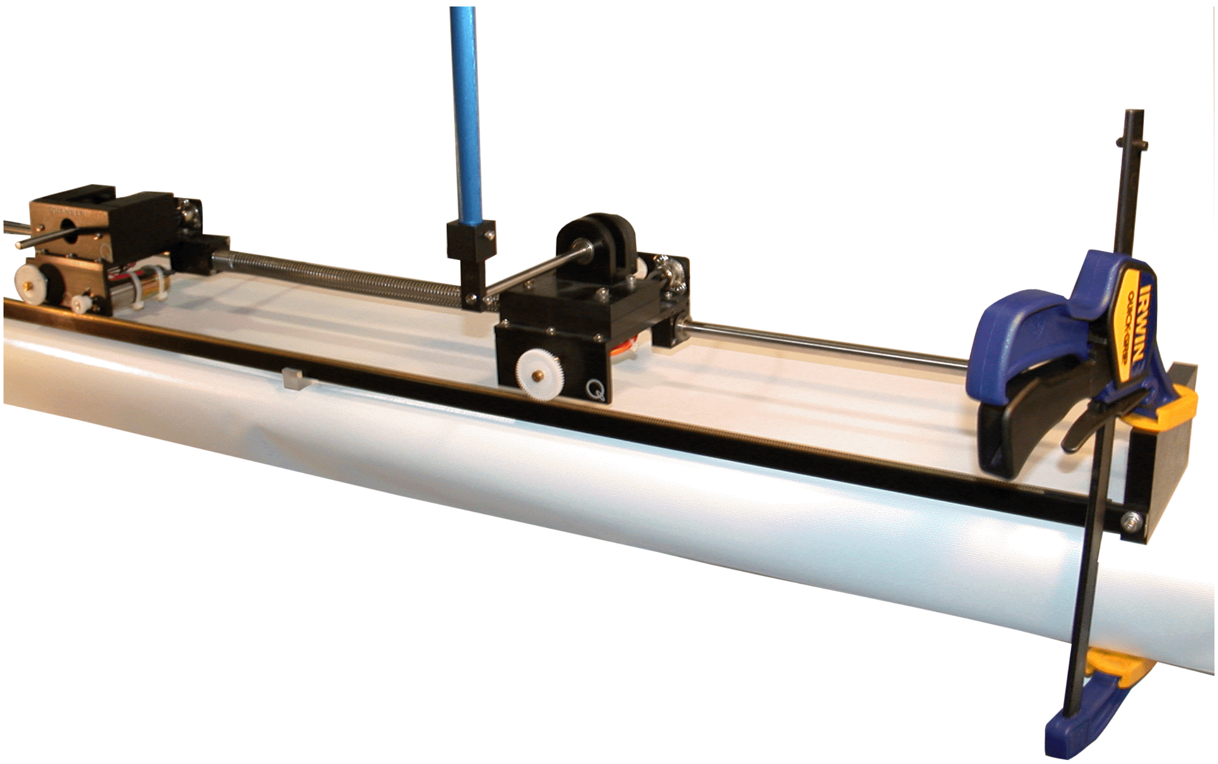


Figure 4.1: Default Configuration of the LFJC-PEN-E Plant

As shown in Figure 4.1, the **the default configuration consists of a 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:

1. Do not mount the pendulum rod on your IP02 cart. Remove it if necessary.
2. Mount your LFJC-PEN-E module on your IP02 track. To do so, first remove one of your IP02 rack end plates by unfastening the two corresponding set screws. Consult the LFJC-E User Manual [4] for full details. You

can then slip both linear spring and the LFJC-PEN-E cart on the 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.

3. Attach the linear spring square fitting (component #4 in Figure 2.1) to your IP02 cart. To do so, fasten the set screws labeled ID #5 in Figure 2.1.
4. Place the additional weight on your IP02 cart, if not already done.
5. Mount the two additional weights (components #10 in Figure 2.1) on top of your LFJC-PEN-E system, if not already done. To that effect, fasten the set screws numbered 11 in Figure 2.1.
6. Insert the long pendulum rod (i.e., 24-inch) inside its corresponding T-fitting (i.e. component #12 in Figure 2.1). Ensure that it sits properly. Tighten set screw #13, as required.
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.
8. You should also clamp the IP02 track down to the table using its end plates, as pictured in Figure 4.1.
9. Wire both your IP02 cart and LFJC-PEN-E module as described in the following Section.

5 WIRING PROCEDURE

This section describes the standard wiring procedure and typical cabling connections that are used by default in the Quanser LFJC-PEN-E laboratory described in [2]. These cabling connections use standard cables, whose description and nomenclature can be found in [3]. Figure 5.1, below, shows the LFJC system, the DAQ board, and the amplifier (e.g., VoltPAQ), all connected with the necessary cabling to interface to and use the LFJC-PEN-E system.

5.1 Cable Nomenclature

The cables used to connect the Quanser LFJC-PEN-E system with a power amplifier and data-acquisition device is shown in Table 5.1. Depending on your configuration, not all these cables are necessary.

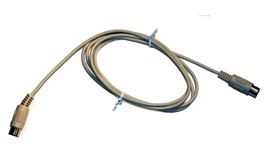
Cable	Type	Description
 (a) RCA Cable	2xRCA to 2xRCA	This cable connects an analog output of the data acquisition terminal board to the power module for proper power amplification.
 (b) Motor Cable	4-pin-DIN to 6-pin-DIN	This cable connects the output of the power module, after amplification, to the DC motor.
 (c) Encoder Cable	5-pin-stereo-DIN to 5-pin-stereo-DIN	This cable carries the encoder signals between an encoder connector and the data acquisition board (to the encoder counter). Namely, these signals are: +5 VDC power supply, ground, channel A, and channel B

Table 5.1: Cables used to connect IP02 to amplifier and DAQ device

5.2 IP02 Connections

Wire up your IP02 cart as per dictated in [3], where the Quanser's standard wiring conventions for the IP02 systems are fully described.

5.3 LFJC-PEN-E Connections

To run the Quanser LFJC-Plus-SIP laboratory described in [2], both LFJC-PEN-E 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 #5**: The "Encoder" cable is the 5-pin-stereo-DIN-to-5-pin-stereo-DIN cable described in [3]. First connect one end of the cable to the **LFJC-PEN-E Encoder Connector**, which is shown as component #9 in Figure 2.1. 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 5.1.
2. **Connect the LFJC-PEN-E Pendulum Angle "Encoder" Cable-Cable #6**: First connect one end of the cable to the **LFJC-PEN-E Pendulum Encoder Connector**, which is shown as component #15 in Figure 2.1. 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 5.1.

■ **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 5.1 and Table 5.2 sum up the electrical connections recommended to run the LFJC-PEN-E system.

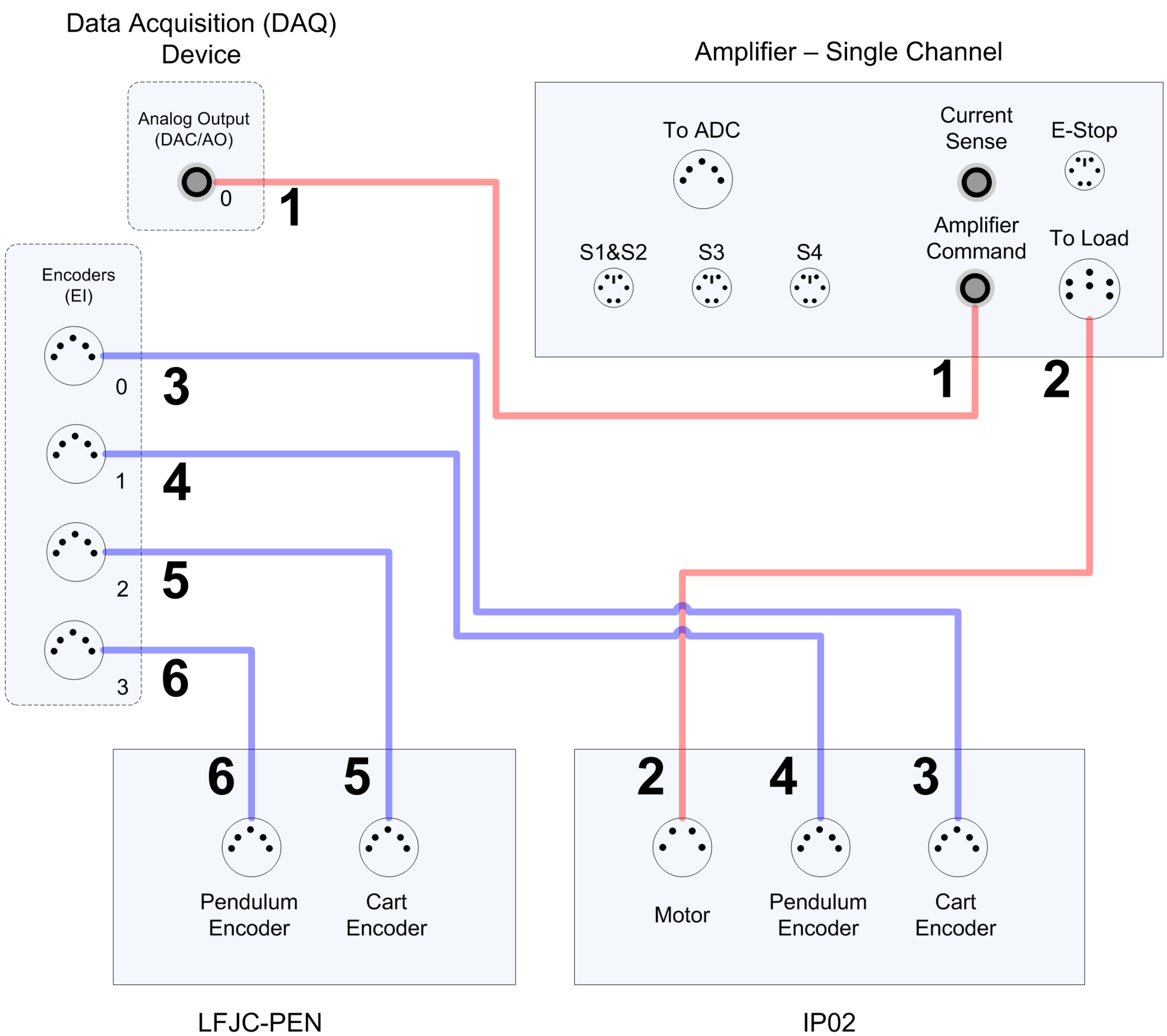


Figure 5.1: Connecting the LFJC-PEN-E system to an amplifier and DAQ board.

Cable#	From	To	Signal
1	Terminal Board: DAC #0	Amplifier "Amplifier Command"	Control signal to the amplifier.
2	Amplifier "To Load"	IP02 "Motor Connector"	Power leads to the IP02 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	LFJC cart linear position.
5	LFJC-PEN-E Pendulum "Encoder Connector"	Terminal Board: Encoder Channel #3	SIP pivot shaft angular position.

Table 5.2: LFJC-PEN-E System Wiring Summary

6 TESTING AND TROUBLESHOOTING

This section describes some functional tests to determine if your IP02 is operating normally. It is assumed that the IP02 is connected as described in the Section 5, above. To carry out these tests, it is preferable if the user can use a software such as QUARC®or LabVIEW™ to read sensor measurements and feed voltages to the motor. Alternatively, these tests can be performed with a signal generator and an oscilloscope.

6.1 Motor

See [3] for more information on testing and troubleshooting the IP02 separately.

6.2 Encoder

6.2.1 Testing

Follow this procedure to test the LFJC-E encoders:

1. Measure Encoder Input Channel #0, #1 and #2.
2. Move the IP02 cart towards the right side of the track. This movement should result in a positive change in the cart position encoder counts at a rate of +4096 counts per revolution.
3. Similarly, moving the LFJC-E cart towards the right side of the track should result in a positive change in the cart encoder counts at a rate of +4096 counts per rotation.

   Note: Some data acquisition systems do not measure in quadrature and, in this case, one-quarter of the expected counts are received. In addition, some data acquisition systems measure in quadrature but increment the count by 0.25 (as opposed to having an integer number of counts). Make sure the details of the data-acquisition system being used is known. The counters on the Quanser DAQ boards measure in quadrature and therefore a total of four times the number of encoder lines per rotation, e.g. a 1024-line encoder results in 4096 integer counts for every full rotation.

6.2.2 Troubleshooting

If the encoder is not measuring properly, go through this procedure:

- Check that the data-acquisition board is functional, e.g. ensure it is properly connected, that the fuse is not burnt.
- Check that both the A and B channels from the encoder are properly generated and fed to the data-acquisition device. Using an oscilloscope, there should be two square waves, signals A and B, with a phase shift of 90 degrees. If this is not observed then the encoder may be damaged and need to be replaced. Please see Section 7 for information on contacting Quanser for technical support.

7 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 the requested software and hardware information as well as a description of the problem encountered. Also, make sure your e-mail address and telephone number are included. Submit the form and a technical support person will contact you.

REFERENCES

[1] US Digital. *E2 Optical Kit Encoder*, 2007.

[2] Quanser Inc. *LFJC-PEN-E Laboratory Manual*.

[3] Quanser Inc. *Linear Servo Users Manual*.

[4] Quanser Inc. *LFJC-E Users Manual*, 2008.

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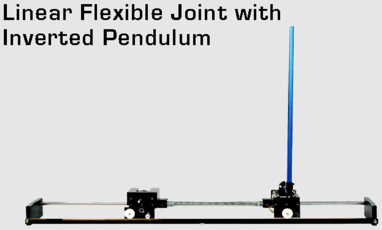
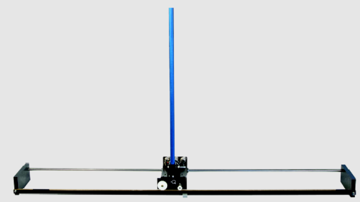
IP02 Base Unit

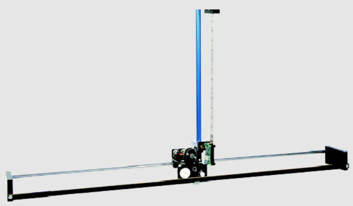
Linear Flexible Joint with Inverted Pendulum



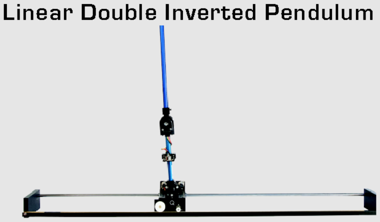
Linear Pendulum



Linear Flexible Inverted Pendulum

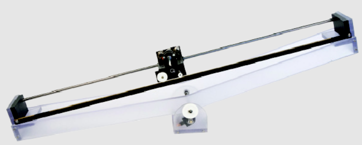


Linear Double Inverted Pendulum

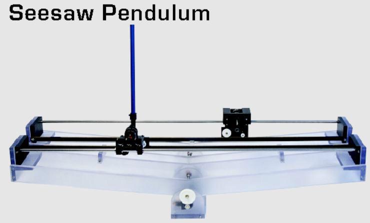


Linear Flexible Joint

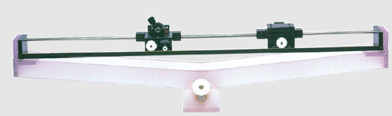
Seesaw



Seesaw Pendulum



Linear Flexible Joint on Seesaw



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