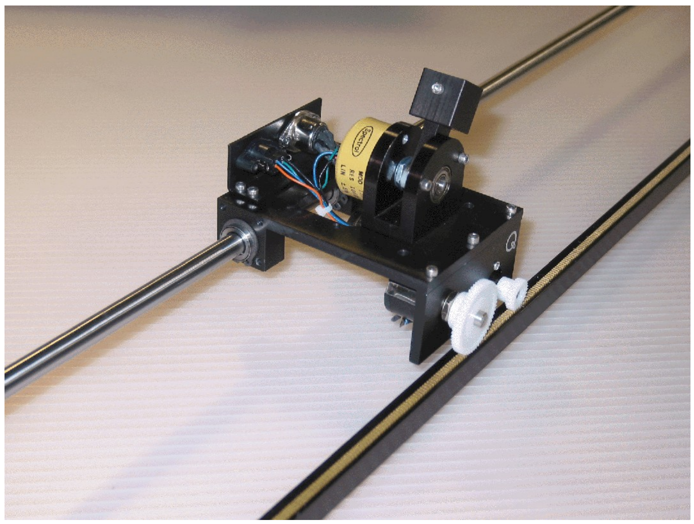
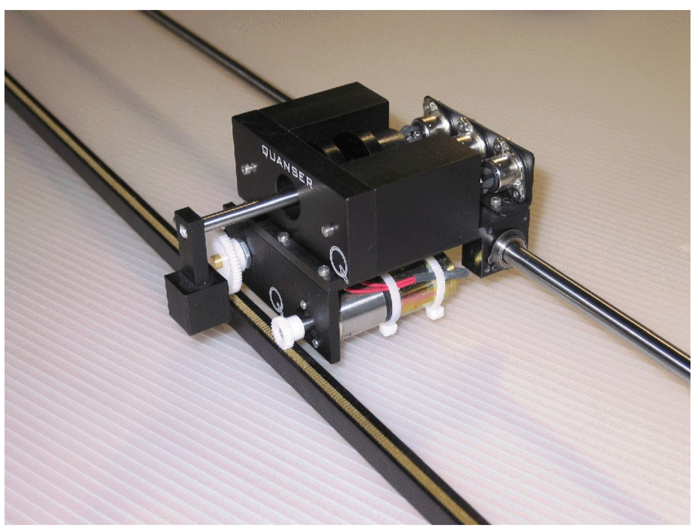
Linear Motion Servo Plants: IP01 or IP02

IP01 and IP02





User Manual

Table of Contents

1. IP01 and IP02 Presentation

1.1. General Description

The IP01 and IP02 are fundamental modules for the linear motion experiments.
They consist of a precisely machined solid aluminum cart driven by a high quality DC motor equipped with a planetary gearbox. The cart slides along a stainless steel shaft using linear bearings. The cart is driven via a rack and pinion mechanism as opposed to belts or wheels, in order to eliminate slippage, belt stretching and other undesirable effects. This, therefore, ensures consistent and continuous traction.

The following sections provide more insight into the differences between the IP01 and IP02 and their applications.

1.2. IP01 (Inverted Pendulum) Particularities

A typical IP01 is depicted in Figure 1, below. In the case of the IP01, the cart position is sensed via a ten-turn potentiometer. The IP01 cart is also equipped with a rotary joint with ball bearings to which a free turning erected rod can be attached. This rod functions as an "inverted pendulum" in subsequent experiments. The angle of the rod is sensed using a conductive plastic potentiometer.

However, the IP01 pendulum cannot suspend in front of the cart. Should you wish to deploy the pendulum to conduct a full 360-degree rotation the IP02 should be utilized instead.

1.3. IP02 (Self-Erecting Inverted Pendulum) Particularities

A typical IP02 is depicted in Figure 2, below. The IP02 pendulum can suspend in front of the cart to perform self-erecting and gantry experiments. Consistently, the IP02 system has encoders, as opposed to potentiometers as in the IP01, to allow for multiple turns.

The IP02 cart position is sensed via an quadrature incremental encoder whose shaft meshes with the track via an additional pinion. The IP02 is also equipped with a rotary joint to which a free-swinging rod can be attached and suspends in front of the cart. This rod functions, in subsequent experiments, as an "inverted pendulum", but more precisely as a self-erecting inverted pendulum as well as a regular inverted pendulum. The angle of the rod inclination about the vertical axis is also measured using a quadrature incremental encoder and is therefore unlimited and continuous over the entire range of motion. The pendulum in itself is a module and can be mounted on or remove from the cart.

Furthermore, in order to run the self-erecting experiment, the supplied extra mass needs to be attached to the cart, so that the swinging inertia of the pendulum does not lift the cart off the track.

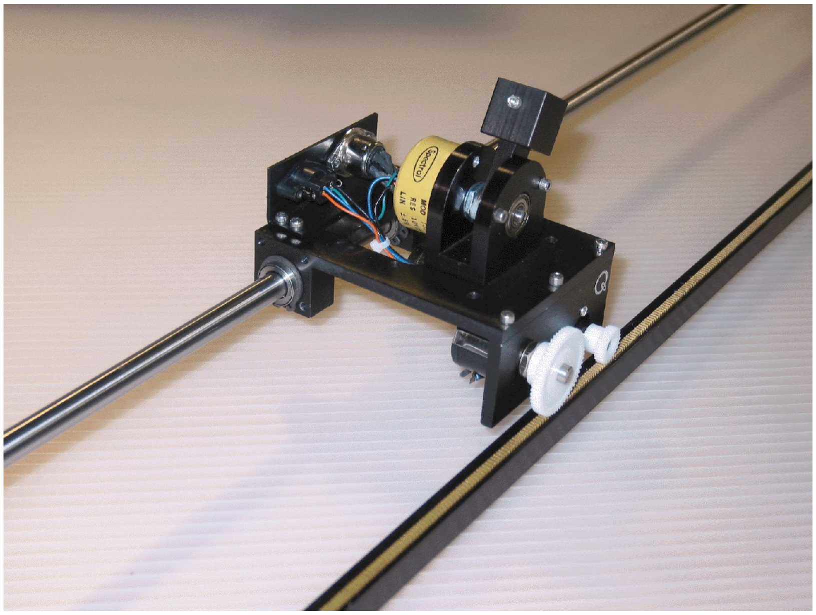


Figure 1 IP01 System

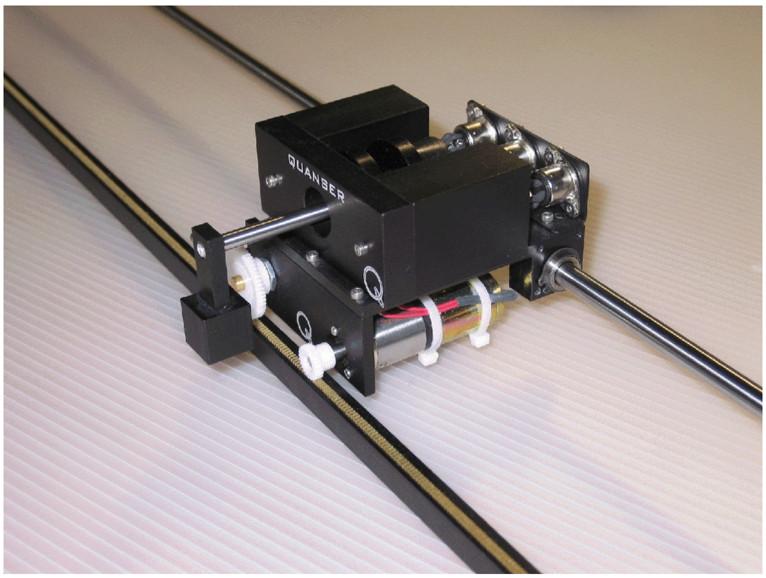


Figure 2 IP02 System

2. Module Options: List of Experiments Based on the IP02 Servo Plant

Quanser values itself for the modularity of its experiments. This modular philosophy facilitates the change from one experimental setup to another with relative ease of work.

2.1. Linear Family Package

The IP02 linear plant module serves as the base component for the linear family of experiments, also known as the Linear Family Package. The "Linear Family" is a package that has all the modules required to configure 7 completely different challenges based on the IP02 (thus maximizing the return on your investment).

Table 1, below, provides a list of the modules members of the Linear Family Package. Each one of them (individually or in combination) expands the range of possible experiments based on the IP02 linear motion servo plant.

Module Name	***Experiment Description***
N/A	Design of a control system to manipulate the position of the IP01 or IP02 cart.
N/A	Design of two different control systems to manipulate the speed of the IP01 or IP02 cart.
Single Inverted Pendulum (SIP)	Design of a control system that keeps the classical inverted pendulum balanced and tracks the cart to a commanded position.
Single Pendulum Gantry (SPG)	Design of a control system to track a desired cart linear position while minimizing the swing of the suspended pendulum.
Self-Erecting Single Inverted Pendulum (SESIP)	Design of a control system to swing up the pendulum, keep it upright and maintain the cart position.
Single Linear Flexible Joint (SLFJ)	Design of a control system to manipulate the position of a spring driven cart.
Seesaw	Design of a control system to balance a seesaw using a sliding powered mass.

Module Name	Experiment Description
Seesaw with SLFJ	Design of a control system to balance a seesaw using a flexible structure mounted atop of it.

Table 1 Modules of the Linear Family Package

2.2. Module Options for either IP01 or IP02

Table 2, below, provides a list of all the modules compatible with the IP01 and IP02 linear motion servo plants. These modules can be used individually or in combination. Some of them are part of the Linear Family Package.

Module Name	Experiment Description
Single Inverted Pendulum (SIP)	Design of a control system that keeps the classical inverted pendulum balanced and tracks the cart to a commanded position.
Flexible Inverted Pendulum (FLEXPEN)	Design of a control system to balance a flexible inverted pendulum.
Linear Flexible Joint Cart (LFJC)	Design of a control system to manipulate the position of a spring driven cart.
Single Linear Flexible Joint with Inverted Pendulum (SLFJ with IP)	Design of a control system to balance a pendulum on a spring driven cart.
Seesaw	Design of a control system to balance a seesaw using a sliding powered mass.
SLFJ on Seesaw	Design of a control system to balance a seesaw using a flexible structure mounted atop of it.
Active Mass Damper – 1 Floor (AMD)	Design of a control system to dampen the vibrations in a building-like structure.

Table 2 IP01- and IP02-Based List of Modules

2.3. Module Options Specific to the IP02

Table 3, below, provides a list of the modules only compatible with the IP02 linear motion servo plants. Some of them are part of the Linear Family Package.

Module Name	*Experiment Description*
Single Pendulum Gantry (SPG)	Design of a control system to track a desired cart position while minimizing the swing of the linear suspended pendulum.
Self-Erecting Single Inverted Pendulum (SESIP)	Design of a control system to swing up the pendulum, keep it upright and maintain the cart position.
Double Inverted Pendulum (DBIP)	Design of a control system to balance a double inverted pendulum on a linear motion cart.

Table 3 IP02-Based Modules

2.4. Two-Cart (i.e. MIMO) Systems with either IP01 or IP02

Table 4, below, lists some of the possible combinations of the previous modules to configure Multi-Input-Multi-Ouput (MIMO) experiments, based on either the IP01 or IP02.

Module Name	*Experiment Description*
Seesaw / Inverted Pendulum	Design of a control system to balance an inverted pendulum on top of a seesaw.
Active Mass Damper – 2 Floors (AMD-2)	Design of a control system to dampen the vibrations in a building-like structure using a MIMO approach.

Table 4 IP01- or IP02-Based MIMO Experiments

3. IP01 and IP02 Component Description

3.1. Component Nomenclature

As a quick nomenclature, Table 5, below, provides a list of all the principal elements composing the IP01 and IP02 systems. Every element is located and identified, through a unique identification (ID) number, on the IP01 and/or IP02 systems represented in Figures 3, 4, 5, and 6, below, as well as Figures 7 and 8.

ID #	*Description*	*ID #*	*Description*
1	IP02 Cart	**2**	Stainless Steel Shaft
3	Rack	**4**	Cart Position Pinion
5	Cart Motor Pinion	**6**	Cart Motor Pinion Shaft
7	Pendulum Axis	**8**	IP02 Cart Encoder
9	IP02 Pendulum Encoder	**10**	IP02 Cart Encoder Connector
11	IP02 Pendulum Encoder Connector	**12**	Motor Connector
13	DC Motor	**14**	Planetary Gearbox
15	Linear Bearing	**16**	Pendulum Socket
17	IP02 Weight	**18**	IP01 Cart Potentiometer
19	IP01 Pendulum Potentiometer	**20**	IP01 Cart
21	S1 & S2 Connector	**22**	Rack End Plate
23	Rack Set Screw: (7/64)"	**24**	Track Discontinuity

Table 5 IP01 and IP02 Component Nomenclature

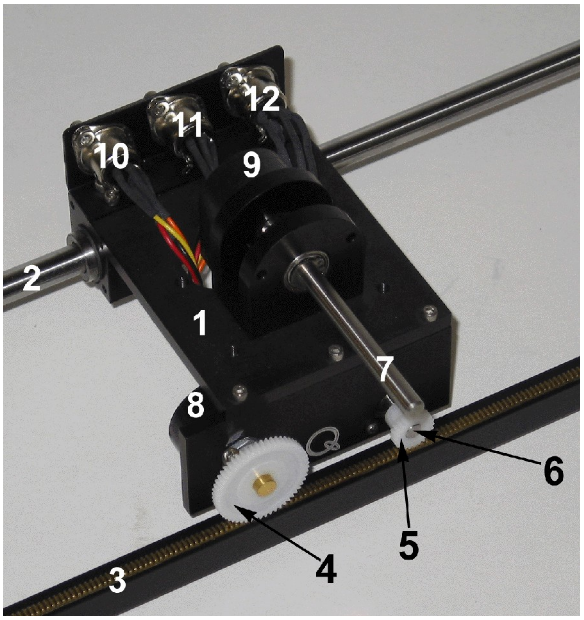


Figure 3 IP02: Front View

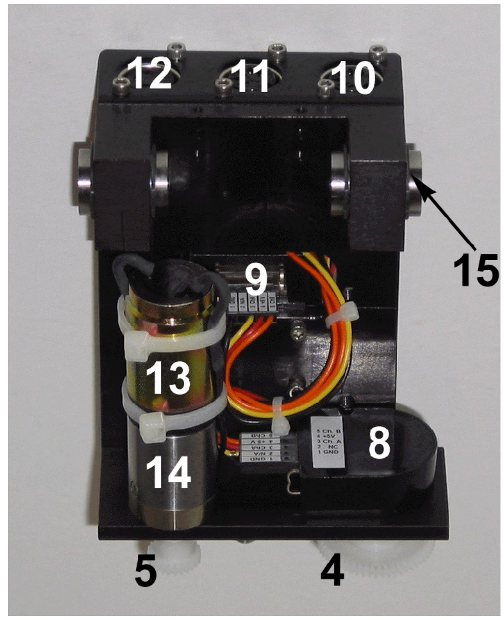


Figure 4 IP02: Bottom View

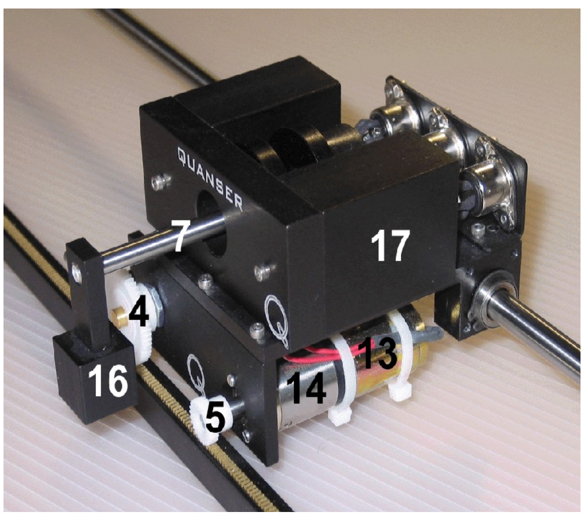


Figure 5 IP02 with Weight: Front View

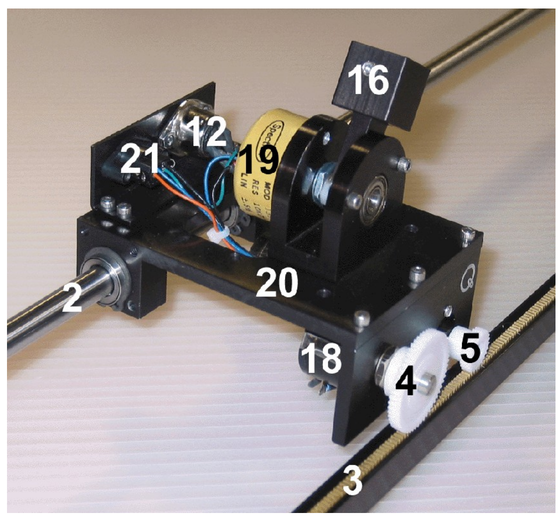


Figure 6 IP01: Front View

3.2. Component Description

3.2.1. Rack (Component # 3)

Table 6, below, lists and characterizes the overall dimensions of the rack used in the IP01 and IP02 systems:

Description	*Value*	*Unit*
Overall Rack Length	1.02	m
Overall Rack Height	6.10E-002	m
Overall Rack Depth	0.15	m

Table 6 IP01 and IP02 Rack Overall Dimensions

Moreover as illustrated in Figures 7 and 8 below, parts of the track are missing (feature or "component" #24) at both ends of the IP01 or IP02 rack. This feature plays the role of a hardware safety watchdog in preventing the IP01 or IP02 cart from running into one of the track's ends, which could potentially be damaging.

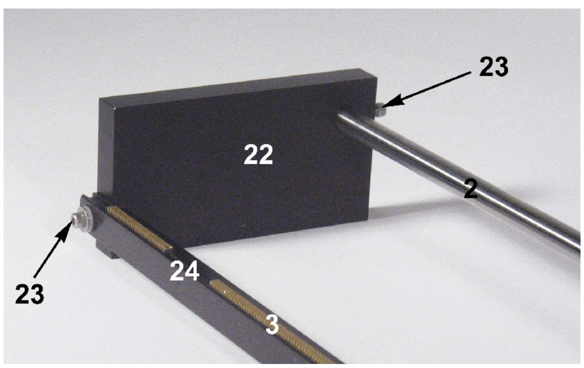


Figure 7 Rack Left End

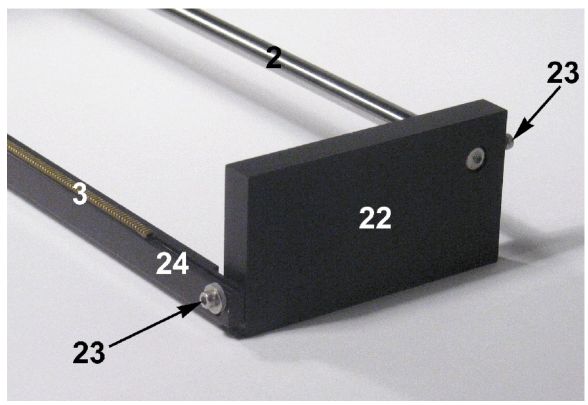


Figure 8 Rack Right End

3.2.2. DC Motor (Component # 13)

3.2.2.1. Description

The IP01 and IP02 incorporate a **Faulhaber Coreless DC Motor (2338S006)**, as shown in Figures 4 and 5 (component # 13), on page 7. This model is a high efficiency low inductance motor resulting in a much faster response than a conventional DC motor. The complete specification sheet of the motor is included in Appendix A.

CAUTION: High Frequency signals applied to a motor will eventually damage the gearbox and/or the motor brushes. The most likely source for high frequency noise is derivative feedback. If the derivative gain is too high, a noisy voltage will be fed into the motor. To protect your motor, you should always band limit your signal (especially derivative feedback) to a value of **50Hz.**

CAUTION: Input: ±15V, 3A peak, 1A continuous.

CAUTION: Exposed moving parts.

3.2.2.2. Wiring

The supplied motor cable is designed to connect from a Quanser Universal Power Module to a 4-pin DIN connector, shown as component # 12 in Figures 3, 4, and 6, on page 7.

3.2.3. Planetary Gearbox (Component # 14)

In the IP01 and IP02, the DC motor is coupled to a **Faulhaber Planetary Gearhead Series 23/1**, as shown in Figures 4 and 5 (component # 14), on page 7. Its reduction ratio is 3.71:1. The complete specification sheet of the planetary gearbox is included in Appendix B.

3.2.4. IP01 Potentiometers (Components # 18 and 19)

3.2.4.1. Description

The main difference between the IP01 and the IP02 is that the IP01 makes use of two potentiometers to sense both cart and pendulum positions, as opposed to the IP02 which uses two encoders instead.

As depicted in Figure 6 by component # 18, on page 7, the IP01 cart position is sensed by a 10-turn black potentiometer, namely the **Vishay Spectrol model 534-1-1-103**. As illustrated by its wiring diagram in Figure 9, the IP01 cart potentiometer is connected to a ±12 Volt DC power supply through two bias resistors of 7.15 kÙ each. According to the wiring diagram Figure 9 and under normal operations, potentiometer terminal 1 should measure +5VDC while terminal 3 should measure -5VDC. The actual position voltage is available at terminal 2. The total output range of the cart position potentiometer results to be ±5V over its 10 complete turns (i.e. 3600 degrees). The main specifications of the IP01 cart potentiometer are included in Appendix C, on page 27. Regarding the inverted pendulum potentiometer, it is a **Vishay Spectrol model 138-0-0-103**. It is represented in Figure 6 by component # 19. Its wiring diagram is also depicted in Figure 9. No bias resistor is used. On the IP01, the inverted pendulum is mechanically constrained to the upright position and limited to a ±32º-deviation from the vertical, during which the pendulum potentiometer output is within approximately a 5-volt range. The main specifications of the IP01 pendulum potentiometer are included in Appendix D, on page 28. Refer to Table 7, on page 13, for the resulting potentiometer sensitivities.

3.2.4.2. Wiring

Both IP01 potentiometers are wired to one 6-pin mini DIN socket, as seen in the wiring schematic in Figure 9. A picture of the same 6-pin mini DIN socket, represented as component # 21, is also available in Figure 6. Once the 6-pin mini DIN socket is connected to a Quanser UPM or Q3, the potentiometer signals are typically available on *S1* and *S2*, where S1 and S2 are, respectively, the voltages proportional to the IP01 cart position and pendulum angle.

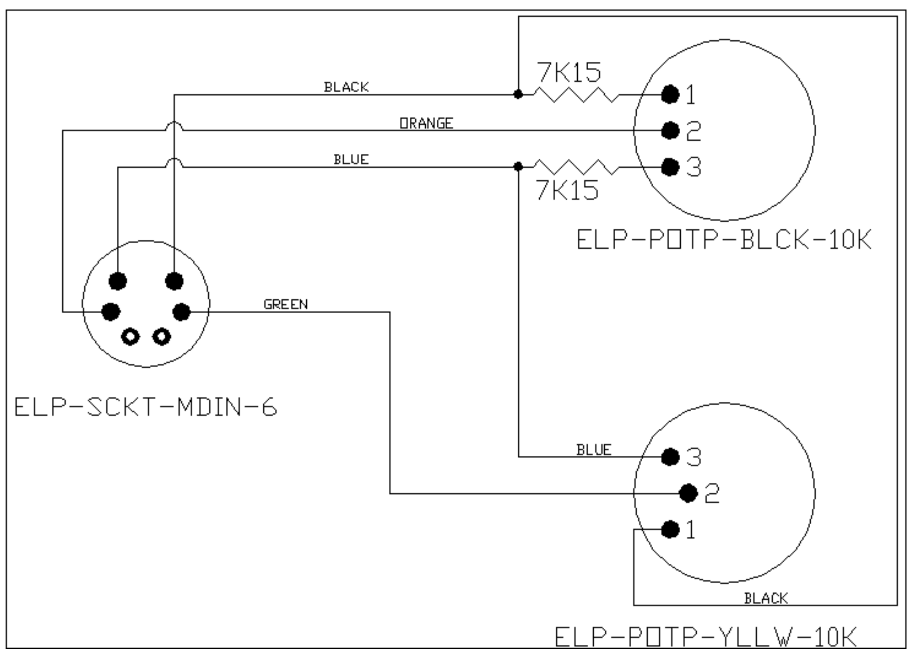


Figure 9 IP01 Wiring of the Two Potentiometers

As a remark, it should be noted that a potentiometer measures an **absolute** position signal. However, the zero position can be modified by manually adjusting the potentiometer "neutral" mounting position.

3.2.5. IP02 Encoders (Components # 8 and 9)

3.2.5.1. Description

On the IP02, both cart and pendulum positions are measured with two optical encoders, represented in Figure 3 by components # 8 and 9, respectively. Having an encoder (as opposed to a potentiometer) sensing the pendulum angular position no longer constrains the range of motion of the pendulum to the inverted position. Therefore, self-erecting inverted pendulum experiments become possible. The encoder measuring the IP02 cart linear position does so through a rack-pinion system. Both encoders are typically identical. The encoder model used in the IP02 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 Appendix E. An incremental encoder gives a **relative** position signal.

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. **DO NOT connect the encoder signal to the UPM**. The internal wiring diagram of the IP02 encoder is depicted in Figure 10. The standard 5-pin DIN connector, shown in Figure 10, is also pictured as component # 10 or 11 in Figure 3.

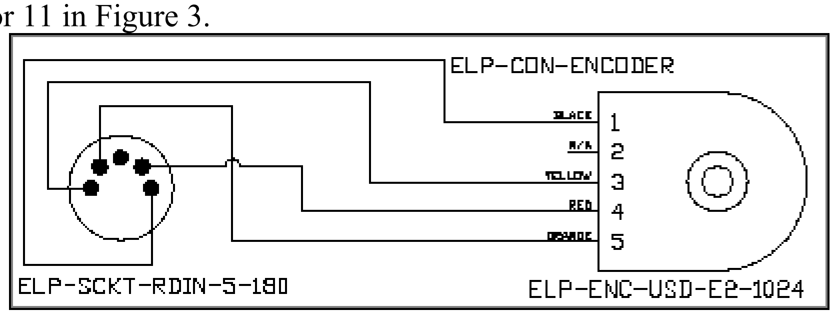


Figure 10 IP02 Encoder Wiring

4. IP01 and IP02 Model Parameters

Table 7, below, lists and characterizes the main parameters (e.g. mechanical and electrical specifications, convertion factors) associated with the IP01 and IP02. Some of these parameters can be used for mathematical modelling of the IP01 and IP02 systems.

Symbol	*Description*	*Value*	*Unit*
V_{nom}	Motor Nominal Input Voltage	6.0	V
f_{max}	Motor Input Voltage Maximum Frequency	50	Hz
I_{max}	Maximum input current	1.0	A
ω_{max}	Maximum motor speed.	628.3	rad/s
R_m	Motor Armature Resistance	2.6	Ω
L_m	Motor Armature Inductance	0.18	mH
K_t	Motor Torque Constant	0.00767	N.m/A
η_m	Motor Efficiency	100	%
K_m	Back-ElectroMotive-Force (EMF) Constant	0.00767	V.s/rad
J_m	Rotor Moment of Inertia	3.90E-007	$kg.m^2$
K_g	Planetary Gearbox Gear Ratio	3.71	
η_g	Planetary Gearbox Efficiency	100	%
M_{c1}	IP01 Cart Mass	0.52	kg
M_{c2}	IP02 Cart Mass	0.57	kg
M_w	IP02 Cart Weight Mass	0.37	kg
L_t	Track Length	0.990	m
T_c	Cart Travel	0.814	m
P_r	Rack Pitch	1.664E-003	m/tooth
r_{mp}	Motor Pinion Radius	6.35E-003	m
N_{mp}	Motor Pinion Number of Teeth	24	
r_{pp}	Position Pinion Radius	0.01482975	m
N_{pp}	Position Pinion Number of Teeth	56	
K_{EC}	IP02 Cart Encoder Resolution	2.275E-005	m/count

Symbol	Description	Value	Unit
K_{EP}	IP02 Pendulum Encoder Resolution	0.0015	rad/count
α_{range}	IP01 Inverted Pendulum Mechanical Range	±32°	°
K_{PC}	IP01 Cart Potentiometer Sensitivity	0.000	m/V
K_{PP}	IP01 Pendulum Potentiometer Sensitivity	-0.2482	rad/V

Table 7 IP01 and IP02 System Paremeters

5. Wiring Procedure For The IP01 And IP02

This section describes the standard wiring procedure for both IP01 and IP02.

The following hardware, accompanying the IP01 or IP02, is assumed:

- **Data Acquisition Board**: Quanser Q4, Q8, Q3 ControlPAQ-FW, or equivalent.
- **Power Amplifier**: Quanser UPM 1503 / UPM 2405, Q3 ControlPAQ-FW, or equivalent.

5.1. Cable Nomenclature

Table 8, below, provides a description of the standard cables used in the wiring of the IP01 and IP02.

Cable	***Designation***	***Description***
 Figure 11 "From Digital-To-Analog" Cable	5-pin-DIN to RCA	This cable connects an analog output of the data acquisition terminal board to the power module for proper power amplification.
 Figure 12 "To Load" Cable	4-pin-DIN to 6-pin-DIN	This cable connects the output of the power module, after amplification, to the desired actuator (i.e. IP01 or IP02 motor). One end of this cable contains a resistor that sets the amplification gain. The cable gains currently available are: 1, 3, or 5. Every cable carries a label, at both ends, with its particular gain on it.

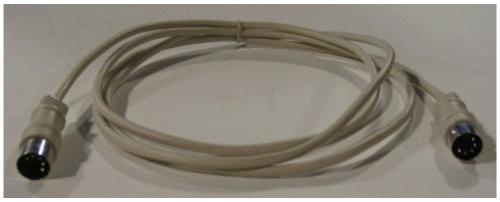
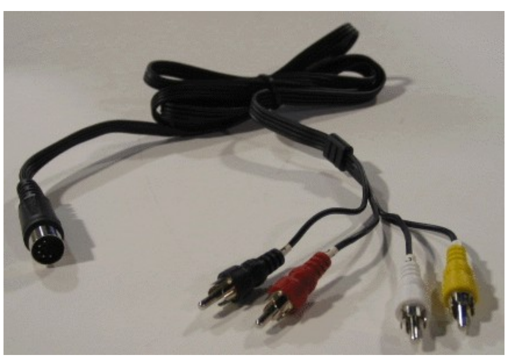
Cable	*Designation*	*Description*
 Figure 13 "Encoder" Cable	5-pin-stereo-DIN to 5-pin-stereo-DIN	This cable is specific to the IP02 system. It carries the encoder signals between an encoder connector and the data acquisition board (to the encoder counter). Namely, these signals are: +5VDC power supply, ground, channel A, and channel B.
 Figure 14 "From Analog Sensors" Cable	6-pin-mini-DIN to 6-pin-mini-DIN	This cable is specific to the IP01 system. It carries analog signals between one or two plant sensors and the UPM or Q3, where the signals can be either monitored and/or used by an analog controller. For example, connected to the IP01, the cable provides a ±12VDC bias to the two potentiometers and carries the two wiper voltages to S1 and S2 on the UPM.
 Figure 15 "To Analog-To-Digital" Cable	5-pin-DIN to 4xRCA	This cable is needed by the IP01 system. It carries the analog signals, previously taken from the plant sensors, unchanged, from the UPM to the Digital-To-Analog input channels on the data acquisition terminal board.

Table 8 Cable Nomenclature

5.2. Typical Connections for the IP01/IP02 when using the UPM

Figure 16 and Figure 17, below, show the Q8 Terminal Board and the Universal Power Module (UPM) with a cabling necesary to interface to an IP01 or IP02. The procedure is discussed below and summarized in Table 9.

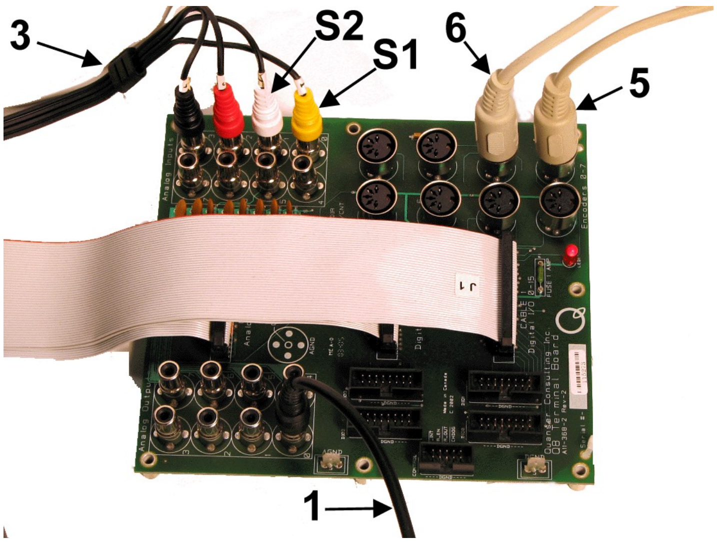


Figure 16 Q8 Terminal Board

Figure 17 Universal Power Module (UPM)

5.2.1. Connections Common to both IP01 and IP02

As both IP01 and IP02 share the same DC motor, the "power" connections for both IP01 and IP02 are identical. These connections are described below:

1. **Connect the "From Digital-To-Analog" Cable**
   The "From Digital-To-Analog" cable is the 5-pin-DIN-to-RCA cable described in Table 8 and shown in Figure 11. Connect the RCA end of this cable to the **Analog Output 0** (i.e. DAC # 0) of the Q8 terminal board and its 5-pin-DIN connector to the socket labelled **"From D/A"** on the UPM. This connection is illustrated by cable # 1 in Figures 16 and 17, above.

2. **Connect the "To Load" Cable**

The "To Load" cable is the 4-pin-DIN-to-6-pin-DIN cable described in Table 8 and shown in Figure 12. First, connect the cable 4-pin-DIN connector to the IP01 or IP02 **motor connector**, which is shown as component # 12 in Figure 6 for the IP01 or Figure 3 for the IP02. Then connect the cable 6-pin-DIN connector to the UPM socket labelled **"To Load"**. The connection to the UPM is illustrated by cable # 2 in Figure 17, above.

5.2.2. Connections Specific to the IP01

In the case of the IP01, the two potentiometers have to be connected. To do so, follow the two steps described below:

3. **Connect the "To Analog-To-Digital" Cable**
   The "To Analog-To-Digital" cable is the 5-pin-DIN-to-4xRCA cable described in Table 8 and shown in Figure 15. First, connect the cable 5-pin-DIN connector to the UPM socket labelled **"To A/D"**, as illustrated by cable # 3 in Figure 17, above. The other end of the cable is split into four RCA connectors, each one labelled with a single digit ranging from one to four. This numbering corresponds to the four possible analog sensor signals passing through the UPM, namely S1, S2, S3 and S4. In order for the analog signals to be used in software, you should then connect all four RCA connectors to the first four analog input channels of your Q8 Terminal Board. Specifically, connect **S1 to Analog Input 0, S2 to Analog Input 1**, S3 to Analog Input 2, and S4 to Analog Input 3, as illustrated by cable #3 in Figure 16, above.

4. **Connect the "From Analog Sensors" Cable**
   The "From Analog Sensors" cable is the 6-pin-mini-DIN-to-6-pin-mini-DIN cable described in Table 8 and shown in Figure 14. First connect one end of the cable to the IP01 **S1 & S2 Connector**, which is shown as component # 21 in Figure 6. Then connect its other end to the UPM socket labelled **"S1 & S2"**, which is contained inside the UPM "From Analog Sensors" front panel. The connection to the UPM is illustrated by cable # 4 in Figure 17, above.

5.2.3. Connections Specific to the IP02

In the case of the IP02, the two encoders have to be connected. To do so, follow the two steps described below:

5. **Connect the Cart Position "Encoder" Cable**
   The "Encoder" cable is the 5-pin-stereo-DIN-to-5-pin-stereo-DIN cable described in Table 8 and shown in Figure 13. First connect one end of the cable to the **IP02 Cart Encoder Connector**, which is shown as component # 10 in Figure 3. Then connect the other cable end to the **Encoder Input 0** on your Q8 Terminal Board, as

illustrated by cable # 5 in Figure 16, above.

6. **Connect the Pendulum Angle "Encoder" Cable**
The "Encoder" cable is the 5-pin-stereo-DIN-to-5-pin-stereo-DIN cable described in Table 8 and shown in Figure 13. First connect one end of the cable to the **IP02 Pendulum Encoder Connector**, which is shown as component # 11 in Figure 3. Then connect the other cable end to the **Encoder Input 1** on your Q8 Terminal Board, as shown by cable # 6 in Figure 16, above.

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 UPM!**

Cable #	*From*	*To*	*Signal*
1	Terminal Board: Analog Output #0	UPM "From D/A" connector	Control signal to the UPM
2	UPM "To Load" connector	IP01_2 "Motor" connector	Power leads to the IP01_2 DC motor.
3	UPM "To A/D" connector	Terminal Board: S1 to Analog Input #0 S2 to Analog Input #1 S3 to Analog Input #2 S4 to Analog Input #3	Carries the analog signals connected to the S1 & S2, S3, and S4 connectors on the UPM to the data-acquisition board.
4	UPM "S1 & S2" connector	IP01 “S1 & S2” connector	IP01 cart (S1/AI #0) and pendulum (S2/AI #1) potentiometer measurements.
5	Terminal Board: Encoder Input #0	“IP02 Cart” encoder connector	IP02 cart position measurement.
6	Terminal Board: Encoder Input #1	"IP02 Pendulum" encoder connector	IP02 pendulum shaft angle measurement.

Table 9: IP01_2 system wiring summary when using UPM.

5.3. Typical Connections for the IP01/IP02 when using the Q3

The connections needed on the Q3 ControlPAQ-FW device when using the IP01 are shown in Figure 18, below. In Figure 19, the connections required to run the IP02 with the Q3 are illustrated. The connection procedure is discussed below and summarized in Table 10.

Figure 18: Connections on Q3 when using IP01.

Figure 19: Connections on Q3 when using IP02.

5.3.1. Connections Common to both IP01 And IP02

As both IP01 and IP02 share the same DC motor, the "power" connections for both IP01 and IP02 are identical. These connections are described below:

1. **Connect the "To Load" Cable**
   The "To Load" cable is the 4-pin-DIN-to-6-pin-DIN cable described in Table 8 and shown in Figure 12. First, connect the cable 4-pin-DIN connector to the IP01 or IP02 **motor connector**, which is shown as component # 12 in Figure 6 for the IP01 or Figure 3 for the IP02. Then connect the cable 6-pin-DIN connector to the Q3 socket labelled **"MOTORS 0"**. The connection to the Q3 is illustrated by cable # 1 in Figure 18 and Figure 19, above.

5.3.2. Connections Specific to the IP01

In the case of the IP01, the two potentiometers have to be connected. To do so, follow the two steps described below:

2. **Connect the "From Analog Sensors" Cable**
   The "From Analog Sensors" cable is the 6-pin-mini-DIN-to-6-pin-mini-DIN cable described in Table 8 and shown in Figure 14. Connect of the cable from the IP01 **S1 & S2 Connector**, shown as component # 21 in Figure 6, to the **"ANALOG IN"** socket on the front panel of the Q3. The connection to the is illustrated by cable # 2 in Figure 18, above.

5.3.3. Connections Specific to the IP02

In the case of the IP02, the two encoders have to be connected. To do so, follow the two steps described below:

3. **Connect the Cart Position "Encoder" Cable**
   The "Encoder" cable is the 5-pin-stereo-DIN-to-5-pin-stereo-DIN cable described in Table 8 and shown in Figure 13. First connect one end of the cable to the **IP02 Cart Encoder Connector**, which is shown as component # 10 in Figure 3. Then connect the other cable end to the “**ENCODERS 0”** socket on your Q3, as illustrated by cable # 3 in Figure 19, above.

4. **Connect the Pendulum Angle "Encoder" Cable**
   The "Encoder" cable is the 5-pin-stereo-DIN-to-5-pin-stereo-DIN cable described in Table 8 and shown in Figure 13. First connect one end of the cable to the **IP02 Pendulum Encoder Connector**, which is shown as component # 11 in Figure 3. Then connect the other cable end to the **ENCODERS 1** on your Q3 device, as shown by cable # 4 in Figure 19, above.

Cable #	From	To	Signal
1	Q3 "Motors 0" connector	IP01_2 "Motor" connector	Power leads to the IP01_2 DC motor.
2	Q3 "Analog In" connector	IP01 “S1 & S2” connector	IP01 cart (S1/AI #0) and pendulum (S2/AI #1) potentiometer measurements.
3	Q3 “Encoders 0” connector	“IP02 Cart” encoder connector	IP02 cart position measurement.
4	Q3 “Encoders 1” connector	"IP02 Pendulum" encoder connector	IP02 pendulum shaft angle measurement.

Table 10: IP01_2 system wiring summary when using Q3.

6. Testing and Troubleshooting

The present section, and following subsections, describe some basic functional tests to determine if your IP01 or IP02 is operating normally. It is assumed that the IP01 or IP02 have been entirely connected as described in Section Wiring Procedure For The IP01 And IP02, 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. See the manual entitled *IP01_2 Integration with QuaRC* to learn how to interface the IP01 or IP02 with Quarc. Alternatively, these tests can be performed with a signal generator and an oscilloscope.

6.1. The IP01 or IP02 DC Motor

6.1.1. Testing

Ensure the IP01_2 motor is operating correctly by going through this procedure:

1. Apply a small voltage (e.g. around 1V) to analog output channel 0 of the terminal board using, for example, the QuaRC software.
2. A positive voltage should result in a motion of the cart to the right, when facing the IP01 or IP02 (i.e. when facing the position and motor pinions in front of the cart, with the cables connected to the back of the cart). Likewise a negative voltage should result in a motion of the cart to the left part of the track, when facing the IP01 or IP02.

6.1.2. Troubleshooting

If the motor is not responding to any signals applied, you should:

- Verify that the power amplifier is functional. For example when using the Quanser UPM device, is the red LED in the top-left corner lit?
- Check that the data-acquisition board is functional, e.g. the red LED on the Quanser Q4/Q8 terminal board should be bright red. The DAC board fuse may be burnt and need replacement.
- Make sure the voltage is actually reaching the motor terminals (use a voltmeter or oscilloscope).
- If the motor terminals are receiving the signal and the motor is still not turning, your motor might be damaged and will need to be repaired. Please refer to Section Obtaining Support on page 24 for information on contacting Quanser for technical support.

6.2. The IP01 Potentiometers

6.2.1. Testing

Assuming that all the connections in relation to the IP01 have been made as described in Section Wiring Procedure For The IP01 And IP02, on page 14, you should be able to measure and monitor the two IP01 potentiometer signals (i.e. S1 and S2). Using a program such as QuaRC, the two potentiometer voltages can be traced on scopes and/or displayed on digital meters. On the DAQ board, the cart position potentiometer voltage (i.e. S1) is available on the analog input channel 0 and the pendulum angle potentiometer voltage (i.e. S2) on the analog input channel 1.

Test the IP01_2 potentiometers with the following procedure

1. Measure analog input channel #0. Pushing manually the IP01 cart to the right side of the track, when facing it, should result in a positive change in the cart position potentiometer voltage, which should gradually increase up to +5V. Likewise, pushing the IP01 cart towards the left side of the track, when facing it, should result in a negative change in the cart position potentiometer voltage, which should gradually decrease down to -5V. Combining this with the observations made in Section The IP01 or IP02 DC Motor, on page 21, it is seen that a positive motor voltage results in an increasing cart position potentiometer voltage, and vice-versa.
2. Measure analog input channel #1. Manually rotating the inverted pendulum (or pendulum socket) clockwise (CW), when facing the cart, should result in a positive change in the pendulum potentiometer voltage, gradually increasing to +2.5V. Likewise, rotating the inverted pendulum counter-clockwise (CCW), when facing

the cart, should result in a negative change in the pendulum potentiometer voltage, gradually decreasing to -2.5V.

6.2.2. Troubleshooting

If one of the potentiometers does not measure correctly, you should:

- Verify that the power amplifier is functional. For example when using the Quanser UPM device, is the red LED in the top-left corner lit? Recall that the analog sensor signal goes through the UPM before going to the data-acquisition device. Therefore the UPM needs to be turned on to read the potentiometer.
- Check that the data-acquisition board is functional, e.g. the red LED on the Quanser Q4/Q8 terminal board should be bright red. If not then the DAC board fuse may be burnt and need replacement.
- The power to the UPM needs to be switched on in order for it to supply both potentiometers with ±12VDC. Ensure that the potentiometer is powered with ±12VDC at the 6-pin-mini-DIN connector, as shown in Figure 9. You should observe ±5VDC at the cart position potentiometer terminals, and ±12VDC at the pendulum potentiometer terminals. Moreover, if the voltage from the wiper does not change when you rotate the potentiometer shaft (measuring with, for example, a voltmeter or an oscilloscope), your potentiometer may need to be replaced. To obtain technical assistance, please refer to Section Obtaining Support on page 24 for information on contacting Quanser.

6.3. The IP02 Encoders

6.3.1. Testing

Assuming that all the connections in relation to the IP02 have been made as described in Section Wiring Procedure For The IP01 And IP02, on page 14, you should be able to measure and monitor the two IP02 encoder signals. For example with QuaRC, the two encoder counters can be read by the Encoder Input block and displayed in scopes and/or digital meters. The cart encoder signal is available on the encoder input channel 0 and the pendulum encoder signal on the encoder input channel 1.

1. Moving the IP02 cart, when facing it, to the right side of the track should result in a positive change (i.e. increase) in the cart position encoder counts, which should increase at a rate of +4096 counts per revolution of the position pinion. Likewise, moving the IP02 cart, when facing it, towards the left side of the track should result in a negative change in the cart position (i.e. decrease) in the cart position encoder counts, which should decrease at a rate of -4096 counts per revolution of the

position pinion. Combining this with the observations made in Section The IP01 or IP02 DC Motor, on page 21, it is seen that a positive motor voltage results in increasing cart position encoder counts, and vice-versa.

2. Similarly, rotating the IP02 free-falling pendulum (or pendulum socket) counter-clockwise (CCW), when facing the cart, should result in a positive change in the pendulum encoder counts, which should increase at a rate of +4096 counts per pendulum revolution. Likewise, rotating the free-falling pendulum clockwise (CW), when facing the cart, should result in a negative change in the pendulum encoder counts, which should decrease at a rate of -4096 counts per pendulum revolution.

Notes: Some data acquisition systems do not measure in quadrature, in which case you will receive a quarter of the expected counts, resulting to a lesser resolution. Other data acquisition systems do measure in quadrature but increment the count by 0.25 (as opposed to having integer number of counts). Therefore, you should know how the system you are using operates. All Quanser counters measure a total of four times the number of encoder lines per rotation. Therefore a 1024-line encoder results in 4096 integer number of counts for every full revolution.

6.3.2. Troubleshooting

If one of the encoders does not measure correctly, you should:

- Check that the data-acquisition board is functional, e.g. the red LED on the Quanser Q4/Q8 terminal board should be bright red. If not, then the terminal board or DAC board fuses may be burnt and need replacement.
- 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. If you believe that your encoder is damaged and need to be replaced, refer to Section Obtaining Support, below, for information on contacting Quanser for technical support.

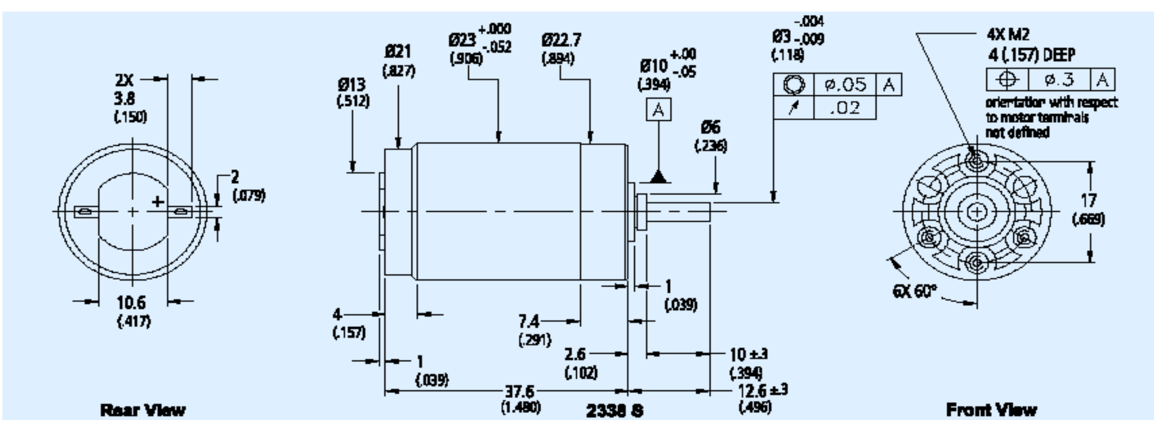
7. Obtaining Support

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.

Appendix A. DC Motor Specification Sheet

Series 2338 ... S

	2338 S		4.5 S	006 S	009 S	012 S	018 S	024 S	
1	Nominal voltage	U_N	4.5	6	9	12	18	24	Volt
2	Terminal resistance	R ± 12%	1.4	2.6	5.7	10.0	23.5	38.0	Ω
3	Output power	$P_{2\ max.}$	3.39	3.23	3.29	3.31	3.18	3.50	W
4	Efficiency	$\eta_{max.}$	70	69	67	66	67	67	%
5	No-load speed	n_o ± 12%	7,200	7,200	7,400	7,800	7,400	7,600	rpm
6	No-load current (with shaft ø 0.12 in)	I_o ± 50%	0.100	0.080	0.060	0.050	0.030	0.025	A
7	Stall torque	M_H	2.55	2.42	2.41	2.29	2.32	2.49	oz-in
8	Friction torque	M_R	0.082	0.086	0.095	0.099	0.095	0.102	oz-in
9	Speed constant	k_n	1,650	1,240	855	678	428	330	rpm/V
10	Back-EMF constant	k_E	0.606	0.804	1.170	1.470	2.340	3.030	mV/rpm
11	Torque constant	k_M	0.818	1.088	1.586	1.997	3.158	4.107	oz-in/A
12	Current constant	k_I	1.222	0.919	0.630	0.501	0.317	0.244	A/oz-in
13	Slope of n-M curve	$\Delta n/\Delta M$	2,824	2,975	3,071	3,406	3,190	3,052	rpm/oz-in
14	Rotor inductance	L	100	180	380	630	1,400	2,600	µH
15	Mechanical time constant	τ_m	20	17	17	17	17	17	ms
16	Rotor inertia	J	$6.797 \cdot 10^{-5}$	$5.523 \cdot 10^{-5}$	$5.240 \cdot 10^{-5}$	$4.815 \cdot 10^{-5}$	$5.098 \cdot 10^{-5}$	$5.381 \cdot 10^{-5}$	$oz\text{-}in\text{-}sec^2$
17	Angular acceleration	$\alpha_{max.}$	38	44	46	48	46	47	$\cdot 10^3 rad/s^2$
18	Thermal resistance	R_{th1} / R_{th2}	3 / 24						°C/W
19	Thermal time constant	τ_{w1} / τ_{w2}	5.7 / 645						s
20	Operating temperature range:								
	– motor		– 30 to +85 (– 22 to +185)						°C (°F)
	– rotor, max. permissible		+125 (+257)						°C (°F)
	Note: Special operating temperature models for		–55°C to +125°C (– 67°F to +257°F) available on request.						
21	Shaft bearings		sintered bronze sleeves		ball bearings		ball bearings, preloaded		
22	Shaft load max.:		(standard)		(optional)		(optional)		
	– with shaft diameter		0.1181		0.1181		0.1181		in
	– radial at 3,000 rpm (0.12 in from bearing)		9		72		72		oz
	– axial at 3,000 rpm		1.08		7.2		7.2		oz
	– axial at standstill		72		72		72		oz
23	Shaft play:								
	– radial	≤	0.0012		0.0006		0.0006		in
	– axial	≤	0.0079		0.0079		0		in
24	Housing material		steel, zinc galvanized and passivated						
25	Weight		2.47						oz
26	Direction of rotation		clockwise, viewed from the front face						
	Recommended values								
27	Speed up to	$n_{e\ max.}$	6,000	6,000	6,000	6,000	6,000	6,000	rpm
28	Torque up to	$M_{e\ max.}$	0.566	0.566	0.566	0.566	0.566	0.566	oz-in
29	Current up to (thermal limits)	$I_{e\ max.}$	1.380	1.000	0.680	0.510	0.330	0.260	A



Appendix B. Planetary Gearhead Specification Sheet

Series 23/1

	23/1
Housing material	metal
Geartrain material	all steel
Recommended max. input speed for:	
– continuous operation	4,000 rpm
Backlash, at no-load	≤ 1°
Bearings on output shaft	preloaded ball bearings
Shaft load, max.:	
– radial (10 mm (0.394 in) from mounting face)	≤ 612 oz
– axial	≤ 540 oz
Shaft press fit force, max.	≤ 540 oz
Shaft play (on bearing output):	
– radial	≤ 0.0006 in
– axial	= 0.0039 in
Operating temperature range	–30 to +100 °C (– 22 to +212 °F)

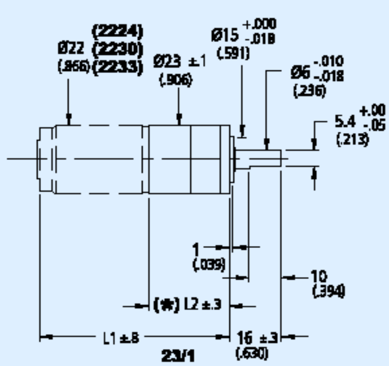
Specifications

reduction ratio (nominal)	weight without motor	length without motor L2		length with motor 2224 U L1		2230 U L1		2233 U L1 (1)		2444 S L1		2342 S 2842 S L1		output torque continuous operation M max.	intermittent operation M max.	direction of rotation (reversible)	efficiency
	oz	mm	(in)	mm	(in)	mm	(in)	mm	(in)	mm	(in)	mm	(in)	oz-in	oz-in		%
3.71 : 1	2.12	23.8	(0.937)	44.1	(1.74)	53.8	(2.12)	56.6	(2.23)	-	-	-	-	28.32	56.65	=	88
3.71 : 1	2.12	27.8	(1.09)	-	-	-	-	-	-	71.8	(2.83)	69.8	(2.75)	28.32	56.65	=	88
14 : 1	2.47	34.1	(1.34)	54.4	(2.14)	60.2	(2.37)	63.0	(2.48)	78.1	(3.07)	76.1	(3.00)	42.48	84.97	=	80
43 : 1	3.17	40.3	(1.59)	60.6	(2.39)	66.4	(2.61)	69.2	(2.72)	84.3	(3.32)	82.3	(3.24)	99.13	141.6	=	70
66 : 1	3.17	40.3	(1.59)	60.6	(2.39)	66.4	(2.61)	69.2	(2.72)	84.3	(3.32)	82.3	(3.24)	99.13	141.6	=	70
134 : 1	3.53	46.4	(1.83)	66.7	(2.63)	72.5	(2.85)	75.3	(2.96)	90.4	(3.56)	88.4	(3.48)	99.13	141.6	=	60
159 : 1	3.53	46.4	(1.83)	66.7	(2.63)	72.5	(2.85)	75.3	(2.96)	90.4	(3.56)	88.4	(3.48)	99.13	141.6	=	60
246 : 1	3.53	46.4	(1.83)	66.7	(2.63)	72.5	(2.85)	75.3	(2.96)	90.4	(3.56)	88.4	(3.48)	99.13	141.6	=	60
415 : 1	3.88	52.6	(2.07)	72.9	(2.87)	78.7	(3.10)	81.5	(3.21)	96.6	(3.80)	94.6	(3.72)	99.13	141.6	=	55
592 : 1	3.88	52.6	(2.07)	72.9	(2.87)	78.7	(3.10)	81.5	(3.21)	96.6	(3.80)	94.6	(3.72)	99.13	141.6	=	55
989 : 1	3.88	52.6	(2.07)	72.9	(2.87)	78.7	(3.10)	81.5	(3.21)	96.6	(3.80)	94.6	(3.72)	99.13	141.6	=	55
1,526 : 1	3.88	52.6	(2.07)	72.9	(2.87)	78.7	(3.10)	81.5	(3.21)	96.6	(3.80)	94.6	(3.72)	99.13	141.6	=	55

(1) For gearhead length with motor 2338 add 8.7 mm (0.343 in) to 2233 motor length column.

Note: Reduction ratios have been rounded off.
Exact values are available upon request.

(*) Subtract 3.9 mm (0.154 in) from L2 column to account for smaller mounting flange.



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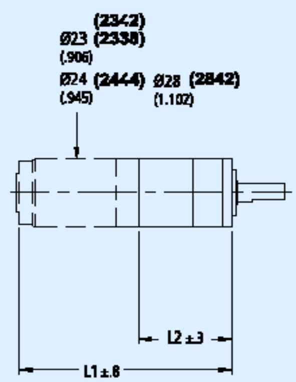

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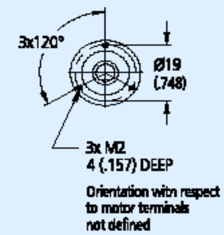


Front View

Appendix C. IP01 Cart Potentiometer Specification Sheet

7/8" (22mm) Precision Wirewound Potentiometer

FEATURES

- Special Resistance Tolerances to 1%
- Rear Shaft Extensions and Support Bearing
- Non Turn Lug
- Insulating Plastic Shaft
- Special Independent Linearity to ± 0.75%
- Dual Gang Configuration and Concentric Shafts
- High Torque and Center Tap
- Special Markings and Front Shaft Extensions
- Servo Unit available and Slipping Clutch

ELECTRICAL SPECIFICATIONS

PARAMETER	MODEL 533	MODEL 534	MODEL 535
Resistance Range Standard Values	50Ω to 20KΩ	100Ω to 100KΩ	50Ω to 50KΩ
Capability Range	5Ω to 60KΩ	10Ω to 200KΩ	5Ω to 100KΩ
Standard Tol	± 5%	± 5%	± 5%
Linearity (Independent)	± 0.25%	± 0.25%	± 0.25%
Noise	100Ω ENR	100Ω ENR	100Ω ENR
Rotation (Electrical & Mechanical)	0° + 10°	0° + 10°	0° + 10°
Power Rating (@ 70°C)	1.0 watts	2.0 watts	1.5 watts
Additional Sections	75% of section 1		
Insulation Resistance	1000MΩ minimum 500VDC		
Dielectric Strength	$1000V_{RMS}$ minimum 60Hz		
Absolute Minimum Resistance	Not to exceed linearity x total resistance or 1Ω, whichever is greater		
Tempco	20ppm/°C (standard values, wire only)		
End Voltage	0.25% of total applied voltage, maximum		
Phasing	CCW end points - section 2 phased to section 1 within ± 2°		
Taps	Center tap only		

MARKING

Unit Identification	Manufacturer's name and model number, resistance value and tolerance, linearity specification date code and terminal identification

RESISTANCE VALUES

Ohms	
533:	50R, 100R, 200R, 500R, 1K, 2K, 5K, 10K, 20K
534:	100R, 200R, 500R, 1K, 2K, 5K, 10K, 20K, 50K, 100K
535:	50R, 100R, 200R, 500R, 1K, 2K, 5K, 10K, 20K, 50K

ORDERING INFORMATION

The Models 533 (3 turn), 534 (10 turn) and 535 (5 turn) can be ordered by stating

534	**1**	**2**	**XXX**
MODEL	MOUNTING	NUMBER OF SECTIONS	RESISTANCE EIA CODE SECTION #N
	1. Bushing **2**. Servo		(consult factory)

Appendix D. IP01 Pendulum Potentiometer Specification Sheet

1-5/16” (33.3mm) Low Cost Industrial Single Turn Wirewound, Conductive Plastic, Cermet

FEATURES

- Choice of Three Elements for Broad Resistance Range
- Center Tap Available
- Continuous Rotation & Mechanical Stops Both Standard
- High Power Rating (139)

ELECTRICAL SPECIFICATIONS

PARAMETER	MIL-PRF-12934/MIL-PRF-39023 TEST PROCEDURES APPLY		
	STANDARD	**SPECIAL**	
Total Resistance: Model 132 Wirewound	5Ω to 20KΩ	to 35KΩ	
Tolerance: 50Ω and above	± 3%	± 1%	
Below 50Ω	± 5%	± 3%	
Model 138 Conductive Plastic	1KΩ to 50KΩ	–	
Tolerance:	± 10%	± 5%	
Model 139 Cermet	500Ω to 2MΩ	–	
Tolerance:	± 20%	± 5%	
Linearity (Independent)	**STANDARD**	**BEST PRACTICAL**	
Total Resistance (132)			
5Ω to 20Ω	± 1.0%	± 0.75%	
20Ω to 200Ω	± 1.0%	± 0.50%	
200Ω and above	± 0.5%	± 0.25%	
138/139	± 0.5%	± 0.25%	
Noise (132)	100Ω ENR		
Output Smoothness (138 & 139)	0.1% maximum		
Power Rating	40°C Ambient		
Model 132	2.75 watts		
Model 138	2 watts		
Model 139	5 watts		
	All Models derated to zero at 125°C		
Electrical Rotation	**MODEL 132**	**MODEL 138**	**MODEL 139**
Continuous	352° ± 2°	345° ± 4°	345° ± 4°
Stops	336° ± 2°	336° ± 4°	336° ± 4°
Insulation Resistance	1000MΩ minimum at 500VDC		
Dielectric Strength	1000V_{RMS}, 60Hz		
Absolute Minimum Resistance	1.0% of total resistance or 0.5Ω whichever is greater (132 only)		
Minimum Voltage	0.5% maximum		
Temperature Coefficient of Resistance			
132	Refer to standard resistance element data		
138	± 500ppm/°C maximum		
139	± 100ppm/°C maximum		

MATERIAL SPECIFICATIONS

Housing	Molded glass filled thermoplastic
Rear Lid	Glass filled thermoset plastic
Shaft	Stainless steel, non-magnetic
Terminals	Brass, plated for solderability, Non-passivated
Mount Hardware	
Lockwasher Internal Tooth:	Steel, nickel plated
Panel nut:	Brass, nickel plated

ENVIRONMENTAL SPECIFICATIONS

Vibration	15Gs thru 2000 Hz
Shock	50g
Salt Spray	48 Hours
Rotational Life	
Shaft Revolutions	
Model 132	500,000
Model 138	2 million
Model 139	2 million
Operating Temperature Range	- 55°C to + 125°C
Moisture Resistance	–

ORDERING INFORMATION

The Models 132, 138 and 139 can be ordered from this specification sheet by stating. Example: **139 - 0 - 0 - 203**

139	**0**	**0**	**203**
MODEL	MECHANICAL OPTIONS	OTHER OPTIONAL FEATURES	RESISTANCE CODE
132, 138 or 139	**0**. Continuous **2**. Stops	**0**. Standard (End Taps) **1**. Center Tap (Within 5° of Electrical Center)	**2**: 1st Significant digit **0**: 2nd significant digit **3**: Number of Zero's

Other characteristics will be standard as described on this specification sheet. If special characteristics are required such as special linearity tolerance, special resistance tolerance, non-linear functions, etc., please state these on your order

Appendix E. IP02 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.

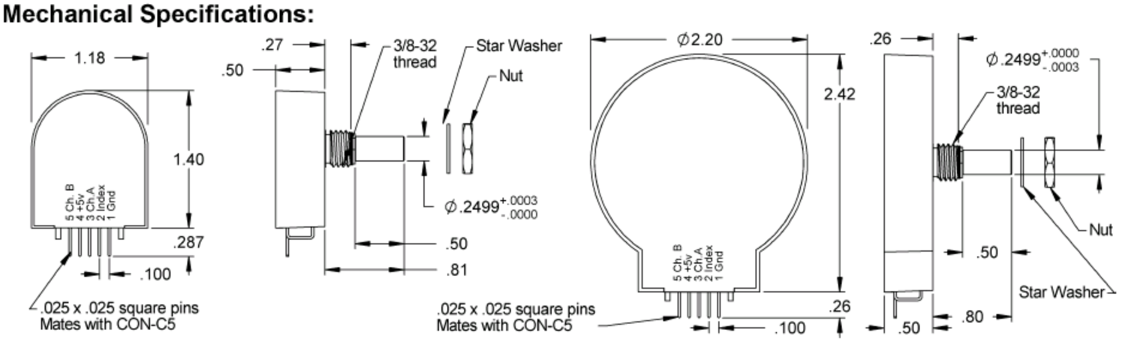
The **S1** and **S2** encoders are available with ball bearings for motion control applications or torque-loaded to feel like a potentiometer for front-panel manual interface.

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^2
Vibration	20 g. 5 to 2KHz
Shaft Speed	10,000 RPM max. continuous
Acceleration	50K rad/sec^2 10K rad/sec^2 (**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/sec^2
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.