Linear Motion Servo Plants: IP01 and IP02

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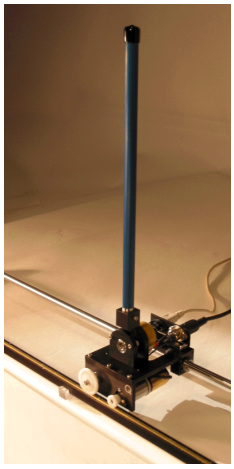
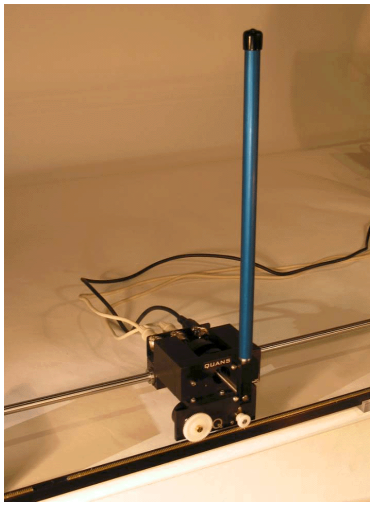
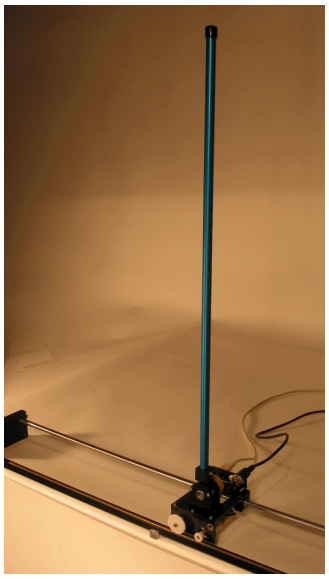
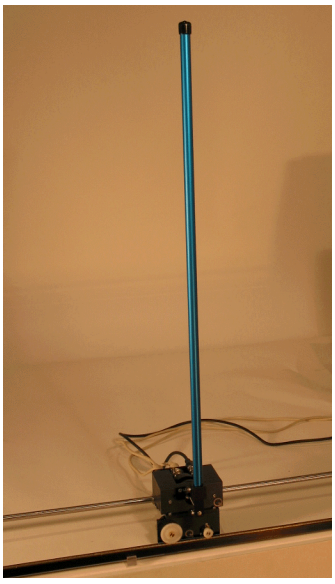
Single Inverted Pendulum (SIP)









User Manual

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1. Single Inverted Pendulum (SIP) Mounted on a Linear Cart (IP01 or IP02)

1.1. Single Inverted Pendulum: System Description

The Single Inverted Pendulum (SIP) system consists of a single rod mounted on a linear cart whose axis of rotation is perpendicular to the direction of motion of the cart. As illustrated in Figures 1, 2, 3, and 4, below, single pendulums come in two different lengths and can fit on Quanser's IP01 or IP02 linear cart. Namely, there is a 12-inch-long "medium" pendulum and a 24-inch-long "long" pendulum.

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 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.

However, it is reminded that, in the case of the IP01, a potentiometer is mounted on the axis of rotation, thus allowing the measurement of the rod angle with the vertical axis. By opposition, the same rod angle is measured, on the IP02, by use of a quadrature incremental encoder.

Furthermore on the IP01, the "inverted" rod angle from the upright position is mechanically constrained to ±32º. By contrast, on the IP02, the pendulum can be suspended in front of the cart as free to rotate ±360º many times over, along the cart's axis of motion. This particularity allows the IP02 to perform self-erecting and gantry experiments as well.

1.2. Inverted Pendulum Experiment: Control Challenge

This is the classic inverted pendulum example! As illustrated in Figures 1, 2, 3, and 4, below, the objective of the single inverted pendulum experiments is to design a controller that would balance the rod in the upright posture and track the cart to a desired position.

The ability to vary parameters and the hardware configuration is also available should you wish to change the dynamics of the challenge. 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.

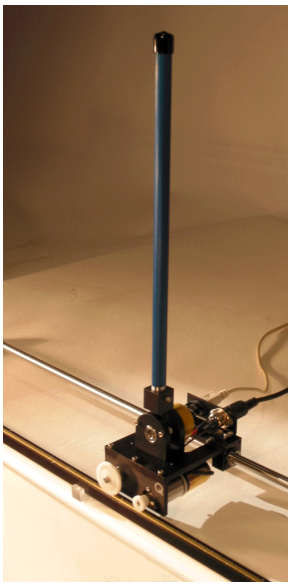

Figure 1 Medium SIP on the IP01

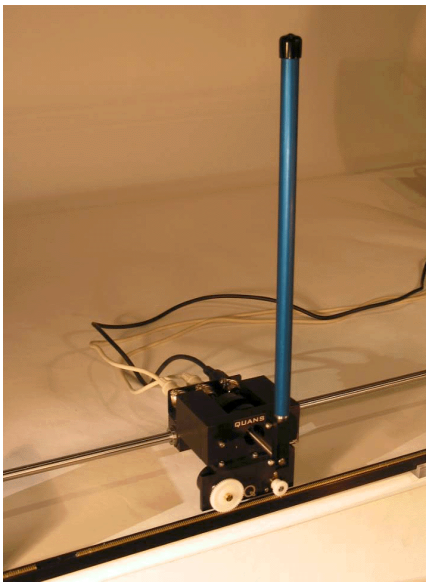

Figure 2 Medium SIP on the IP02

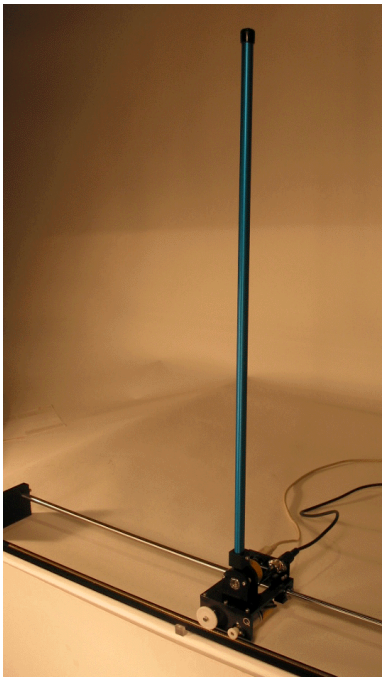

Figure 3 Long SIP on the IP01

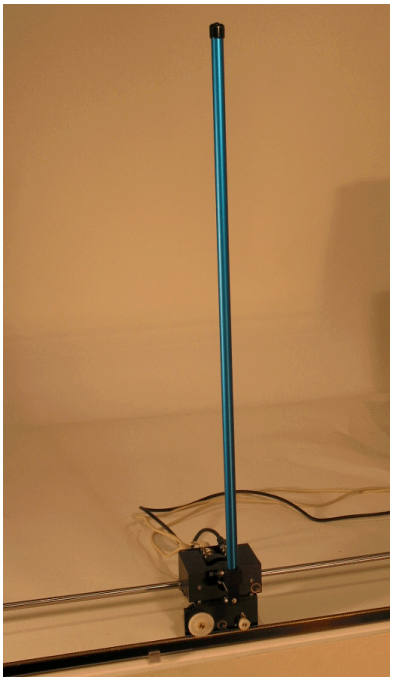

Figure 4 Long SIP on the IP02

2. Single Pendulum Module: Applications

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.

Table 1, below, provides a list of the Quanser linear motion experiments using the single pendulum module. Quanser's basic linear motion servo plants are the IP01 and the IP02. The single pendulum can be used individually or in combination with other Quanser modules, as shown in Table 1.

Experiment Name	*Experiment Description*	*Linear Motion Servo Plant*
Single Inverted Pendulum (SIP)	Design of a control system that keeps the classical inverted pendulum balanced and tracks the linear cart to a commanded position.	IP01 IP02
Single Pendulum Gantry (SPG)	Design of a control system to track a desired linear cart position while minimizing the swing of the suspended pendulum.	IP02
Self-Erecting Single Inverted Pendulum (SESIP)	Design of a control system to swing up the single pendulum, keep it upright, and maintain/track the linear cart position.	IP02
Single Inverted Pendulum on a Seesaw	Design of a control system to balance an inverted pendulum on top of a seesaw (MIMO system).	IP01 IP02
Linear Flexible Joint Cart with Single Inverted Pendulum (LFJC with SIP)	Design of a control system to balance a single inverted pendulum on a spring driven linear cart.	IP01 IP02

Table 1 IP01- and IP02-Based Experiments Involving a Single Pendulum

3. Single Pendulum Description

3.1. Component Description and Nomenclature

As shown in Figures 5 and 6, below, there are two kinds of single pendulums, depending on their length. The "medium" pendulum is 12-inch long, in contrast with the "long" pendulum, which has a length of 24 inches.

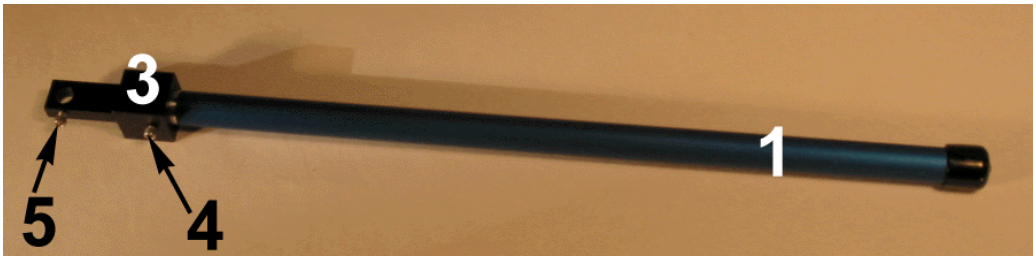

Figure 5 Medium Single Pendulum

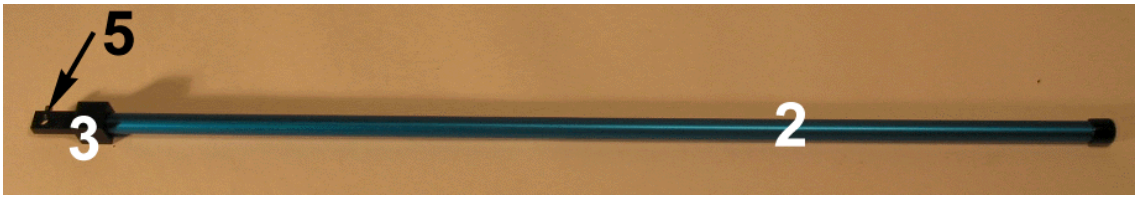

Figure 6 Long Single Pendulum

As a component nomenclature, Table 2, below, provides a list of all the principal elements composing both single pendulum systems. Each of these elements is located and identified, through a unique identification (ID) number, on both medium and long single pendulum systems as represented in Figures 5 and 6, above.

ID #	*Description*	*ID #*	*Description*
1	Medium-Length Rod	**4**	Rod Set Screw: (3/32)"
2	Long-Length Rod	**5**	Axis Set Screw: (3/32)"
3	Rod Socket (a.k.a. T-Fitting)		

Table 2 Single Pendulum Component Nomenclature

3.2. Space Requirements

In the single inverted pendulum configuration (i.e. when the pendulum rod is vertical, pointing upwards), both IP01 and IP02 systems require an overall space of 40-inch long by 28-inch high by 6-inch deep, as characterized in Table 3, below.

Description	*Value*	*Unit*
Overall SIP System Length	1.02	m
Overall SIP System Height	0.71	m
Overall SIP System Depth	0.15	m

Table 3 Overall Dimensions of the SIP-plus-IP01-or-IP02 System Space Requirements

However in the case of the IP02, the single pendulum can be mounted in front of that cart in such a way that it can operate freely over a 360-degree range. Therefore, you should ensure that the pendulum does not collide with any objects while it swings/rotates. Note that the pendulum will swing even while the cart is at one of the extremities of the track!

In such a configuration (i.e. when the pendulum rod goes from the inverted to the gantry position and vice-versa), the IP02 requires an overall space of 86-inch long by 50-inch high (22 inches below table and 28 inches above) by 12-inch deep. That clearance needed to avoid collisions is characteirized in Table 4, below.

Description	*Value*	*Unit*
Overall IP02-plus-SP System Length	2.19	m
Overall IP02-plus-SP System Height	1.27	m
Overall IP02-plus-SP System Depth	0.30	m

Table 4 Overall Dimensions of the Single-Pendulum-plus-IP02 System Space Requirements

4. Single Inverted Pendulum: Configuration and Setup

The mounting of the single pendulum on both IP01 and IP02 is illustrated in Figures 7, and 8, respectively. The nomenclature of both system assemblies can be found in Table 2, previously reviewed, and Table 5, below, which complements the listing.

ID #	*Description*	*ID #*	*Description*
6	IP01 Cart System	**7**	IP02 Cart System

Table 5 Additional Nomenclature for the Single Inverted Pendulum Assembly

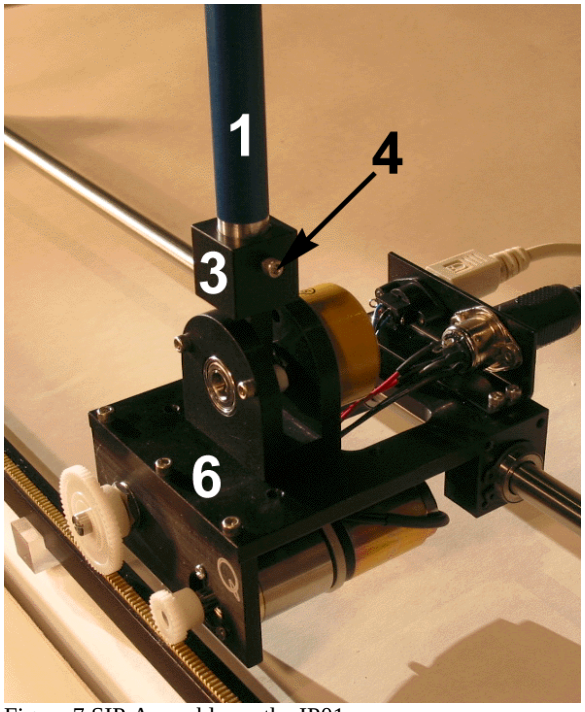

Figure 7 SIP Assembly on the IP01

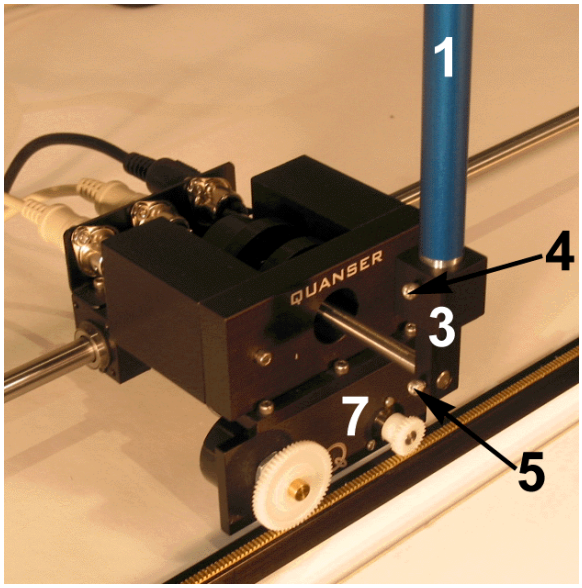

Figure 8 SIP Assembly on the IP02

4.1. Default SIP Configuration

The default SIP configuration is the one used in the single inverted pendulum laboratory, as decribed in References [2] and [3]. It can be described as follows:

- **When using an IP01, the default SIP configuration consists of the IP01 cart on top of which the long pendulum (of 24 inches) is mounted, pointing upwards.**
- **When using an IP02, the default SIP configuration consists of the IP02 cart without its additional weight on top and in front of which the long pendulum (of**

24 inches) is attached, pointing downwards.

4.2. Setup Procedure for the Default SIP Configuration

The setup procedure for the default configuration is as follows:

Step 1. Insert the long pendulum rod inside its T-fitting (i.e. component #3). Ensure that it sits properly. Tighten set screw #4, as required.

Step 2. On the IP02, attach the single pendulum, pointing downwards, at the tip of the IP02 cart's pendulum axis by tightening set screw #5 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 3. Optionally, you can clamp the track down to the table using its end plates.

Step 4. Wire up the IP01 or IP02 cart as per dictated in Reference [1], where the Quanser's standard wiring conventions are fully described. No further electrical cabling is required in setting up the pendulum, as all the connections are done at the IP01 or IP02 level.

4.3. Other SIP Configurations Possible

However, for the IP01 or IP02, six other configurations are also possible. They can be described as follows:

i. An IP01 cart on top of which the medium pendulum (of 12 inches) is mounted, pointing upwards. This configuration is illustrated in Figure 7.

ii. An IP02 cart without its additional weight and in front of which the medium pendulum is attached, pointing downwards. This configuration is illustrated in Figure 8.

iii. An IP02 cart with its additional weight and in front of which the long pendulum is attached, pointing downwards.

iv. An IP02 cart with its additional weight and in front of which the medium pendulum is attached, pointing downwards.

v. An IP02 cart without its additional weight and on top of which the long pendulum is mounted, pointing upwards. In order to install the pendulum in this configuration, slide the T-fitting (i.e. component #3) all the way back on the IP02 cart pendulum axis, so that the pendulum sits on top of the cart in the "inverted" position. In this configuration, the angular range of motion of the inverted pendulum is mechanically constrained by two plastic washers to ±32º from the upright position. This setup is very similar to that of with the IP01.

vi. An IP02 cart without its additional weight and on top of which the medium pendulum is mounted, pointing upwards.

5. Single Pendulum Model Parameters

Table 6, below, lists and characterizes the main parameters associated with Quanser's two types of single pendulums: "medium" and "long". These parameters are particularly useful for the mathematical modelling and simulation of the single inverted pendulum system(s). In Table 6, the model parameters, whose subscript finishes with an *"l"* correspond to the "long" pendulum (of 24 inches). Likewise, the model parameters, whose subscript finishes with a *"m"* apply to the "medium" pendulum (of 12 inches).

Symbol	*Description*	*Value*	*Unit*
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-003	$kg.m^2$
I_{pm}	Medium Pendulum Moment of Inertia, about its Center Of Gravity	1.20E-003	$kg.m^2$
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

Table 6 Single Pendulum System Parameters

6. References

[1] *IP01 and IP02 User Manual*.
[2] *IP01 and IP02 - Single Inverted Pendulum (SIP) – Linear Experiment #5: LQR Control - Student Handout*.
[3] *IP01 and IP02 - Single Inverted Pendulum (SIP) – Linear Experiment #5: LQR Control – Instructor Manual*.