Linear Motion Servo Plant: AMD-1

Active Mass Damper - One Floor (AMD-1)

User Manual

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1. Active Mass Damper – One Floor (AMD-1) Presentation

1.1. AMD-1: System Description

The typical Active Mass Damper - One Floor (AMD-1) plant is depicted in Figure 1. The AMD-1 plant is a bench-scale model to emulate a building controlled by an Active Mass Damper (AMD). The plant consists of a single-story building-like structure on top of which a linear cart (i.e. active mass) is driven by a rack and pinion mechanism. The top floor is instrumented with an accelerometer to measure the acceleration of the "roof" relative to ground. The structure frame is made of steel and is flexible along its facade. Such a scaled structure has been designed to study critical aspects of structural control implementations.

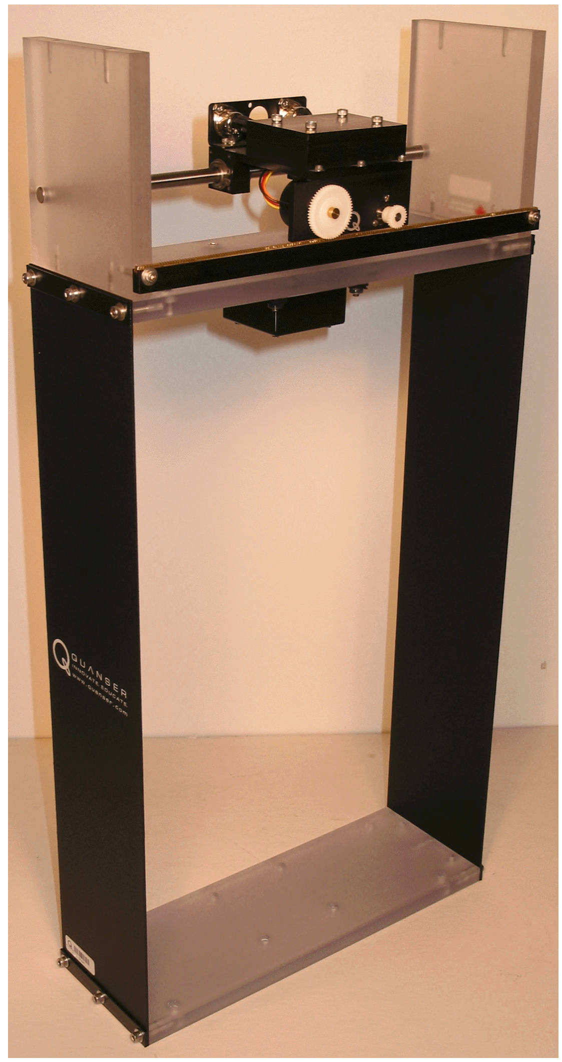


Figure 1 AMD-1 System

The top of the structure accommodates a rack and a shaft designed to work with an IP01- or IP02- type of linear cart, which thus constitutes the controllable mass at the top of the structure. The cart is free to move along in the same direction as the structure. Specifically, it is a precisely machined solid aluminum cart which is driven by a high quality DC motor equipped with a planetary gearbox. The cart slides along a stainless steel shaft using linear bearings. When the motor turns, the torque created at the output shaft is translated, through the rack and pinion mechanism, to a linear force (i.e. control force) which results in the cart's motion.

The cart position is directly measured using either a potentiometer (for the IP01-based cart) or an encoder (for the IP02-based cart) whose shaft meshes with the track via an additional pinion. Moreover, two masses are available for attachment to the cart, so that it has more inertia to absorb the structure's vibrations. These two weights can be used or removed for assessing the robustness of the controller and the effects of variations in parameters. For more details regarding the IP01 and IP02 linear servo plants and their applications, please review Reference [1].

Different building/linear cart configurations can be constructed by connecting several Quanser's AMD buildings and/or carts. For example, the Active Mass Damper – 2 Floors (AMD-2) experiment consists of a two-floor structure with a single active mass damper located at the top of the structure, as detailed in Reference [2]. Additionally, the system can also be excited using the Quanser Shake Table II, as described in Reference [3]. Of course, other combinations of the previously mentioned modules are also possible, in order to configure Multi-Input-Multi-Ouput (MIMO) experiments.

1.2. AMD-1: Control Challenge

The AMD-1 plant forms an autonomous servo system. The challenge in designing a control system that dampens out the vibrations in the building-like structure is that the top floor deflection (or horizontal displacement) is NOT measured. Instead, the structure's feedback sensor is an accelerometer mounted on the AMD-1's top floor. The only other sensor that is available is to measure the linear cart position. The input to the AMD-1 system is the cart motor voltage.

In order to dampen out the vibrations in the AMD-1 flexible structure, the system is supplied with a state-feedback controller based on a full-order observer. The closed-loop control scheme drives the active mass (i.e. linear cart) by taking into account the actual cart position and floor acceleration feedback signals. 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. References

[1] *IP01 and IP02 User Manual*.
[2] *Active Mass Damper – Two Floor (AMD-2) Experiment Manual.*
[3] *Shake Table II Experiment Manual.*

3. AMD-1 System Description

3.1. Component Nomenclature

As a quick nomenclature, Table 1, below, provides a list of all the principal elements composing the Active Mass Damper – One Floor (AMD-1) system. Every element is located and identified, through a unique identification (ID) number, on the AMD-1 plant represented in Figures 2, 3, 4, and 5, below.

ID #	Description	ID #	Description
1	AMD Cart	2	Stainless Steel Shaft
3	Track	4	Linear Bearing
5	Rack End Plate	6	Rack Set Screw: (7/64)"
7	Cart Load Weight	8	Cart Load Weight Set Screw: (3/32)"
9	Cart DC Motor	10	Cart Encoder
11	Cart Motor Pinion	12	Cart Position Pinion
13	Cart Motor Pinion Shaft	14	Cart Position Pinion Shaft
15	Cart Motor Connector	16	Cart Encoder Connector
17	Cart Planetary Gearbox	18	Single Floor Flexible Steel Structure
19	Flexible Structure Ground	20	Flexible Structure Floor
21	Accelerometer	22	Accelerometer Connector
23	Accelerometer Offset Potentiometer	24	Accelerometer Gain Potentiometer

Table 1 AMD-1 Component Nomenclature

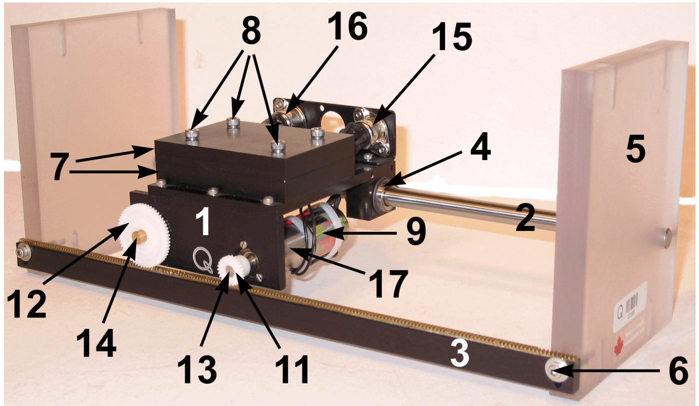


Figure 2 AMD-1 Cart: Front View

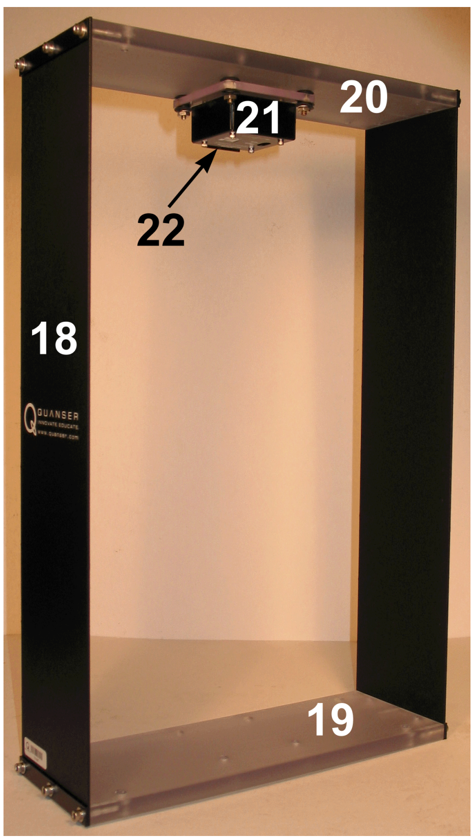


Figure 3 AMD-1 Flexible Structure: Front View

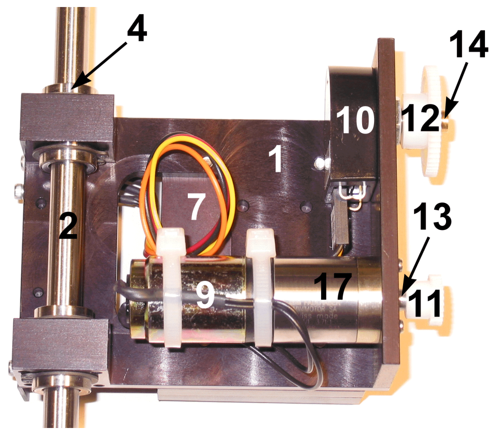


Figure 4 AMD-1 Cart: Bottom View

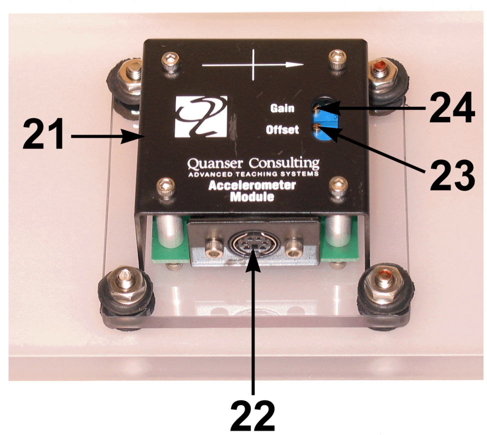


Figure 5 AMD-1 Accelerometer: Bottom View

3.2. Component Description

3.2.1. Flexible Structure (Component #18)

The Active Mass Damper – One Floor (AMD-1) flexible structure consists of two vertical steel beams. Each steel column has a section of 1.75 by 108.1 mm and a mass of 0.240 kg. The frame external dimensions are shown in Table 2, below.

Description	*Value*	*Unit*
Flexible Structure Length	0.32	m
Flexible Structure Height	0.5	m
Flexible Structure Depth	0.11	m

Table 2 AMD-1 Flexible Structure Dimensions

3.2.2. Cart Rack (Components #2, #3, and #5)

Table 3, below, characterizes the overall dimensions of the cart rack used in the Active Mass Damper – One Floor (AMD-1) system.

Description	*Value*	*Unit*
Overall Cart Rack Length	0.31	m
Overall Cart Rack Height	0.13	m
Overall Cart Rack Depth	0.11	m

Table 3 AMD-1 Cart Rack Overall Dimensions

3.2.3. Accelerometer (Component # 21)

The building-like structure's floor is equipped with a capacitive DC accelerometer with full-scale range of ±5 g. It consists of a single-chip accelerometer with signal conditioning. The AMD-1 accelerometer is calibrated in-house to generate 1 Volt per 9.81 m/s^2 (i.e. 1 V/g), as characterized by the accelerometer sensitivity shown in Table 4, on page 9.

The accelerometer has the capability to measure both AC/dynamic accelerations (e.g. vibrations) or DC/static accelerations (e.g. gravity). The arrow represented on the accelerometer, and depicted in Figure 5, shows the positive direction of the AC acceleration sensor measurement on its axis of sensitivity. To best measure the AMD-1 floor vibration, the accelerometer is mounted such that its sensitive axis is longitudinal to the structure. Quickly pushing the AMD-1 floor towards the right, when facing the structure, should result in an initial positive measured acceleration voltage.

Although the AMD-1 accelerometer has already been calibrated at the factory, the signal conditioning circuit properties may vary depending on the external conditions (e.g. humidity, temperature). Therefore, you may want to adjust the Offset potentiometer (shown as component #23 in Figure 5) such that it reads approximately zero Volts with zero acceleration (i.e. sensor resting flat/horizontally). Likewise, the Gain potentiometer (shown as component #24 in Figure 5) can be adjusted to read minus one Volts when the sensor is resting vertically on its right side (i.e. with the arrow pointing downwards).

3.2.4. Cart DC Motor (Component #9)

The AMD-1 cart incorporates a **Faulhaber Coreless DC Motor (2338S006)**, as represented in Figures 2 and 4 by component #9. 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.**

3.2.5. Cart Planetary Gearbox (Component #17)

The AMD-1 cart DC motor is coupled to a Faulhaber Planetary Gearhead Series 23/1, as represented in Figures 2 and 4 by component #17. Its reduction ratio is 3.71:1. The complete specification sheet of the planetary gearbox is included in Appendix B.

3.2.6. IP01-Based Cart Potentiometer

If the AMD-1 cart is based on the IP01 cart, described in Reference [1], its linear position is sensed by a 10-turn black potentiometer, namely the Vishay Spectrol model 534-1-1-103. The cart potentiometer is connected to a ±12 Volt DC power supply through two bias resistors of 7.15 kΩ each. 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-

based AMD-1 cart potentiometer are included in Appendix C.

Refer to Table 4, on page 9, for the resulting potentiometer sensitivity. Pushing manually the AMD-1 cart towards the right side of the track, when facing it, should result in a positive change in the cart position potentiometer voltage. Likewise, pushing the cart towards the left side of the track, when facing it, should result in a decreasing cart position potentiometer voltage.

3.2.7. IP02-Based Cart Encoder (Component #10)

If the AMD-1 cart is based on the IP02 cart, described in Reference [1], its linear position is measured with one optical encoder, which is represented in Figure 4 by component #10. The encoder model used in the AMD-1 cart 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 D. The internal wiring diagram of the cart encoder is depicted in Figure 6. The standard 5-pin DIN connector, shown in Figure 6, is also pictured as component #16 in Figure 2.

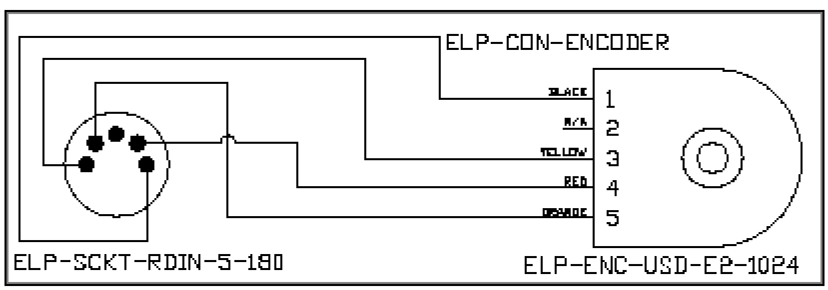


Figure 6 Cart Encoder Wiring

Refer to Table 4, on page 9, for the resulting encoder resolution. Pushing manually the AMD-1 cart towards the right side of the track, when facing it, should result in a positive change in the cart position. Likewise, pushing the cart towards the left side of the track, when facing it, should result in a decreasing cart position.

4. AMD-1 Model Parameters

Table 4, below, lists and characterizes the main parameters (e.g. mechanical and electrical specifications, convertion factors) associated with the Active Mass Damper – One Floor (AMD-1) plant. Some of these parameters can be used for mathematical modelling of the AMD-1 system as well as to obtain the structure-plus-cart's Equations Of Motion (EOM).

Symbol	*Description*	*Value*	*Unit*
H_f	Structure Floor Height	0.53	m
M_s	Flexible Structure Total Mass	1.60	kg
M_{tf}	Structure Top Floor Mass	0.68	kg
M_r	Rack Mass	0.70	kg
f_n	Top Floor (a.k.a. Roof) Natural Frequency	2.5	Hz
K_f	Top Floor (a.k.a. Roof) Linear Stiffness Constant	500	N/m
M_c	Cart Mass	0.39	kg
M_w	Cart Weight Mass	0.13	kg
T_c	Cart Travel (i.e. Stroke)	0.19	m
P_r	Rack Pitch	1.664E-003	m/tooth
V_{nom}	Cart Motor Nominal Input Voltage	6.0	V
fv_{max}	Cart Motor Input Voltage Maximum Frequency	50	Hz
R_m	Cart Motor Armature Resistance	2.6	Ω
L_m	Cart Motor Armature Inductance	0.18	mH
K_t	Cart Motor Torque Constant	0.00767	N.m/A
η_m	Cart Motor Efficiency	100	%
K_m	Cart Back-ElectroMotive-Force (EMF) Constant	0.00767	V.s/rad
J_m	Cart Rotor Moment of Inertia	3.90E-007	kg.m^2
B_{eq}	Equivalent Viscous Damping Coefficient, as seen at the Motor Pinion	3.0	N.s/m
K_g	Cart Planetary Gearbox Gear Ratio	3.71	
η_g	Cart Planetary Gearbox Efficiency	100	%

Symbol	Description	Value	Unit
r_{mp}	Cart Motor Pinion Radius	6.35E-003	m
N_{mp}	Cart Motor Pinion Number of Teeth	24	
r_{pp}	Cart Position Pinion Radius	1.48E-002	m
N_{pp}	Cart Position Pinion Number of Teeth	56	
K_{EC}	Cart Encoder Resolution (if IP02-Based)	2.275E-005	m/count
K_{PC}	Cart Potentiometer Sensitivity (if IP01-Based)	0.0931	m/V
K_{ACC}	Floor Accelerometer Sensitivity	9.81	$m/s^2/V$

Table 4 AMD-1 System Paremeters

5. Wiring Procedure For The AMD-1 System

This section describes the standard wiring procedure for the Active Mass Damper – One Floor (AMD-1) plant.

The following hardware, accompanying the AMD-1, is assumed:

- Power Amplifier: Quanser UPM 1503 / UPM 2405 or equivalent.
- Data Acquisition Card: Quanser Q8 / MultiQ-PCI / MultiQ-3, or one of the National Instruments E-Series cards, or equivalent.

5.1. Cable Nomenclature

Table 5, below, provides a description of the standard cables used in the wiring of the AMD-1.

Cable	***Designation***	***Description***
 Figure 7 "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 8 "To Load" Cable Of Gain 1	4-pin-DIN to 6-pin-DIN	This cable connects the output of the power module, after amplification, to the desired actuator (e.g. cart motor). One end of this cable contains a resistor that sets the amplification gain (e.g. 1, 3, 5).

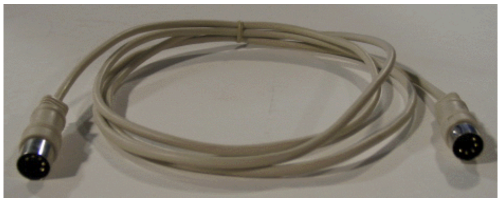
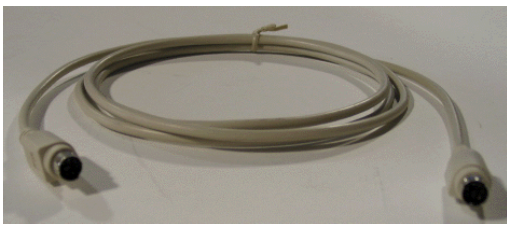
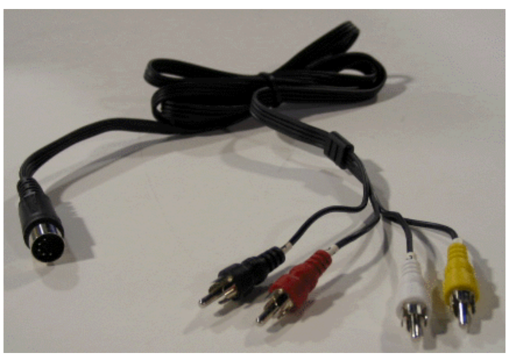
Cable	*Designation*	*Description*
 Figure 9 "Encoder" Cable	5-pin-stereo-DIN to 5-pin-stereo-DIN	This cable carries the encoder signals between the encoder connector and the data acquisition board (to the encoder counter). Namely, these signals are: +5VDC power supply, ground, channel A, and channel B.
 Figure 10 "From Analog Sensors" Cable	6-pin-mini-DIN to 6-pin-mini-DIN	This cable carries analog signals from one or two plant sensors (e.g. accelerometer, cart potentiometer) to the UPM, where the signals can be either monitored and/or used by an analog controller. The cable also carries a ±12VDC line from the UPM in order to power a sensor and/or signal conditioning circuitry.
 Figure 11 "To Analog-To-Digital" Cable	5-pin-DIN to 4xRCA	This cable carries the analog signals, previously taken from the plant sensors (e.g. accelerometer, cart potentiometer), unchanged, from the UPM to the Digital-To-Analog input channels on the data acquisition terminal board.

Table 5 Cable Nomenclature

The connectors are also fully compatible with our quick-connect system enabling you to switch from one experiment to another quickly and efficiently.

5.2. Hardware Requirements

Figures 12, 13, and 14, below, show, respectively, the Q8 Terminal Board, the back of the AMD-1 plant, and the Universal Power Module (e.g. UPM-1503), all connected with the necessary cabling to interface to and use the Active Mass Damper – One Floor (AMD-1) plant.

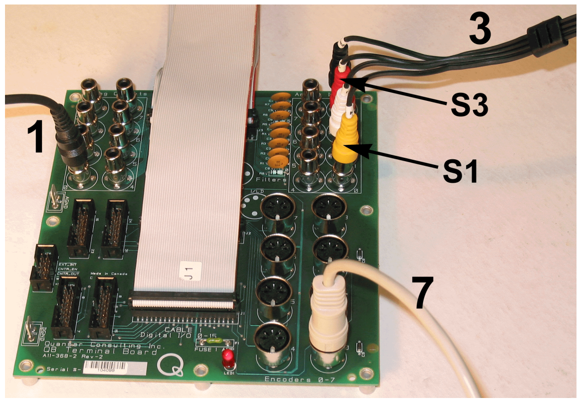


Figure 12 Q8 Terminal Board Connections

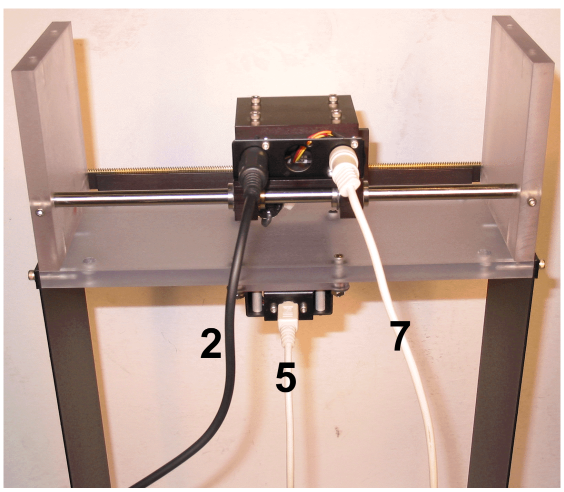


Figure 13 AMD-1 Connections

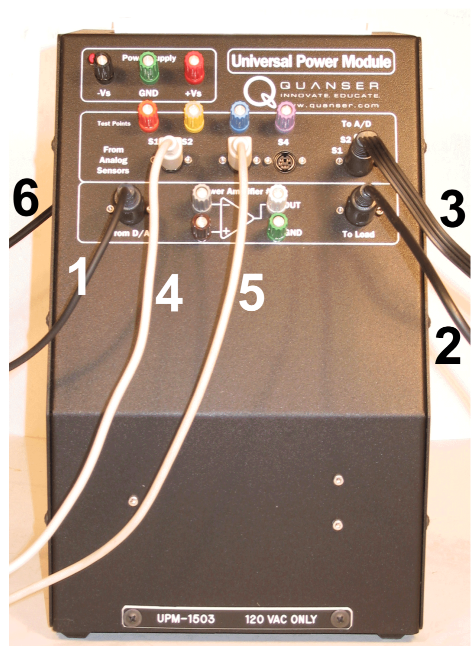


Figure 14 Universal Power Module: UPM1503

Together with the power supply for the amplifier, all Quanser power modules are equipped with a 1-ampere ±12-volt regulated DC power supply for signal conditioning of external analog sensors.

5.3. Typical Connections For The AMD-1 System

5.3.1. Wiring Of The Cart DC Motor Power Line

The "power" line wiring of the AMD-1 cart DC motor consists of two connections, as described below:

1. **Connect the "From Digital-To-Analog" Cable – Cable #1:**
   The "From Digital-To-Analog" cable is the 5-pin-DIN-to-RCA cable described in Table 5 and shown in Figure 7. Connect the RCA end of this cable to the **Analog Output 0** (i.e. DAC # 0) of your data acquisition card terminal board and its 5-pin-DIN connector to the socket labelled **"From D/A"** on the Quanser Universal Power Module (UPM). These two connections are illustrated by cable #1 in Figures 12 and 14, above.

2. **Connect the "To Load" Cable Of Gain 1 – Cable #2:**
   The "To Load" cable of gain 1 is the 4-pin-DIN-to-6-pin-DIN cable described in Table 5 and shown in Figure 8. First, connect the cable 4-pin-DIN connector to the AMD-1 cart motor **Connector**, which is shown as component #15 in Figure 2. Then connect the cable 6-pin-DIN connector to the UPM socket labelled **"To Load"**. These two connections are illustrated by cable #2 in Figures 13 and 14, above.

5.3.2. Wiring Of The Feedback Signals

The AMD-1 system provides two feedback signals. First, the linear cart position signal is produced using either a potentiometer, if the cart is based on the IP01, or an encoder, if the cart is based on the IP02. Second and last, the flexible structure top floor's acceleration signal is provided by using an accelerometer. To connect these feedback sensors, follow the steps described below:

1. **Connect the "From Analog Sensors" Position Cable – Cable #4:**
   In case of an IP01-based cart, the position potentiometer has to be connected. The "From Analog Sensors" cable is the 6-pin-mini-DIN-to-6-pin-mini-DIN cable described in Table 5 and shown in Figure 10. First connect one end of the cable to the IP01-based cart's **S1 & S2 Connector**, as shown in Reference [1]. Then connect the cable's other end to the UPM socket labelled **"S1 & S2"**, which is contained inside the UPM "From Analog Sensors" front panel. This connection to the UPM is illustrated by cable #4 in Figure 14, above.

2. **Connect the "Encoder" Position Cable – Cable #7:**
   In case of an IP02-based cart, the position encoder has to be connected. The "Encoder" cable is the 5-pin-stereo-DIN-to-5-pin-stereo-DIN cable described in Table 5 and shown in Figure 9. First connect one end of the cable to the IP02-based cart's **Encoder Connector**, which is shown as component #16 in Figure 2. Then connect the cable's other end to the **Encoder Input 0** on your data acquisition card terminal board. These two connections are illustrated by cable #7 in Figures 12 and 13, 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!**

3. **Connect the "From Analog Sensors" Acceleration Cable – Cable #5:**
   The "From Analog Sensors" cable is the 6-pin-mini-DIN-to-6-pin-mini-DIN cable described in Table 5 and shown in Figure 10. First connect one end of the cable to the **Accelerometer Connector**, located at the back of the AMD-1 structure and which is shown as component #22 in Figures 3 and 5, above. Then connect the cable's other end to the UPM socket labelled **"S3"**, which is contained inside the UPM "From Analog Sensors" front panel. These connections are illustrated by cable #5 in Figures 13 and 14, above.

4. **Connect the "To Analog-To-Digital" Cable – Cable #3:**
   The "To Analog-To-Digital" cable is the 5-pin-DIN-to-4xRCA cable described in Table 5 and shown in Figure 11. First, connect the cable 5-pin-DIN connector to the UPM socket labelled **"To A/D"**, as illustrated by cable #3 in Figure 14, 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 data acquisition card 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 12, above.

In other words, the AMD-1 cart position is either sensed using A/D #0 through the UPM analog channel S1 if the cart has a potentiometer (i.e. based on the IP01), or using Encoder Channel #0 if the cart has an encoder (i.e. based on the IP02). The flexible structure top floor's acceleration is measured using A/D #2 through the UPM analog channel S3.

5.3.3. AMD-1 Wiring Summary

Table 6, below, sums up the electrical connections necessary to run the AMD-1 system.

Cable #	***From***	***To***	***Signal***
1	DAC #0	UPM "From D/A"	Control signal to the UPM.
2	UPM "To Load"	AMD-1's "Motor Connector"	Power leads to the cart DC motor.
3	UPM "To A/D"	Terminal Board: S1 to ADC #0 S3 to ADC #2	IP01-based cart potentiometer, if present, and accelerometer signals to the data acquisition terminal board, through the UPM.
4	AMD-1 cart's "S1 & S2 Connector"	UPM "S1 & S2"	IP01-based cart position feedback signal, if necessary, to the UPM.
5	AMD-1 structure's "Accelerometer Connector"	UPM "S3"	Top floor accelerometer feedback signal to the UPM.
6	Power Supply Outlet	UPM Power Socket	UPM Power Supply.
7	AMD-1 cart's "Encoder Connector"	Terminal Board: Encoder Channel #0	IP02-based cart position feedback signal, if necessary, to the data acquisition card.

Table 6 AMD-1 Wiring Summary

6. Setting Up the AMD-1 Plant

For safety and proper operation, the AMD-1 base plate (a.k.a. "ground" floor) should be rigidly clamped or screwed down to a table or workbench.

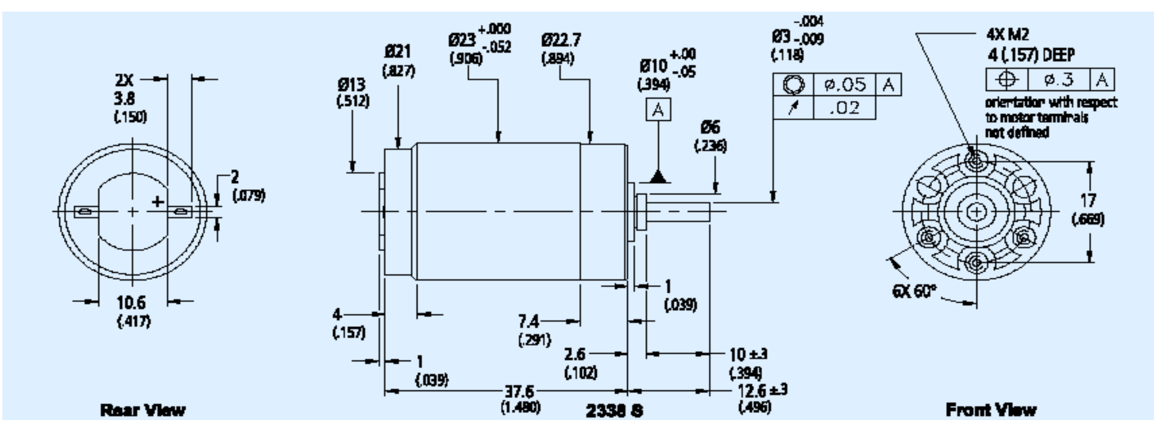
7. Obtaining Support

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. 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. Cart 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-in-sec²
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. Cart 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)

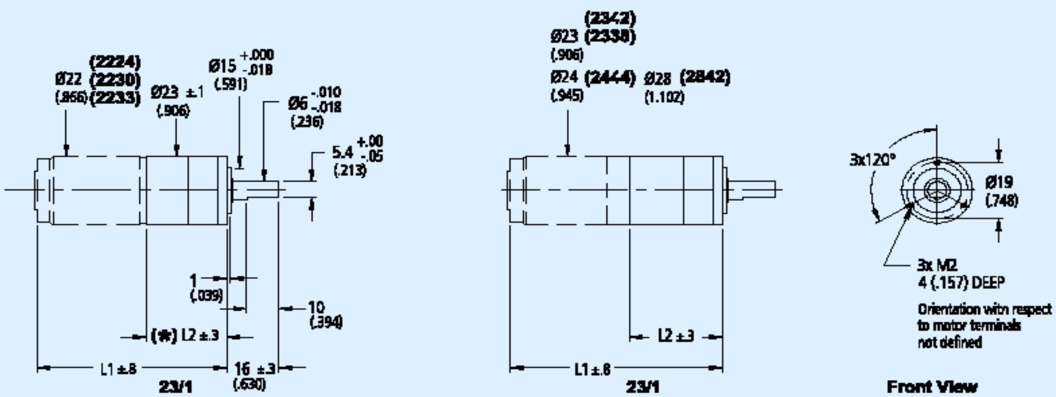
Specifications

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.



Appendix C. IP01-Based 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. IP02-Based Cart 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.

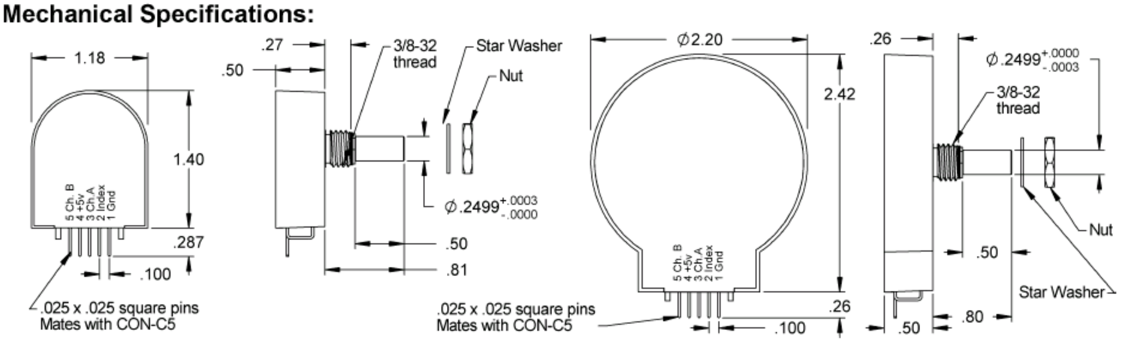
The **S1** and **S2** encoders are available with ball bearings for motion control applications or torque-loaded to feel like a potentiometer for front-panel manual interface.

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.