BALANCING ROBOT USING CONTROL SYSTEM

By

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FINAL YEAR PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
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CERTIFICATION OF APPROVAL

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Approved by,

(Mr. Mohd Haris Md Khir)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
Nov 2004

CERTIFICATE OF ORIGINALITY

This certificate is to certify that I am responsible for the work submitted in this project that the original work in on my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

FAIZAL BIN HAJI AHMAD

ACKNOWLEDGEMENT

In the Name of Allah, the Beneficient, the Merciful

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ABSTRACT

This project presents a Single Wheel Balancing Robot. Basically, the main idea of the project is to balance a structure on a wheel using motor. The wheel will balance the structure forward and backward, trying to make the structure not to fall. This project will involve with a precise weight distributed fabricated structure and a very fast control systems controlling the motor thus the robot itself.

The objective of the project is to balance the robot structure using control system methods, which is simulated using the MATLAB software and interface with the robot using Quanser systems. The objective also consists of solving the control problems using control systems theory such as Root Locus and Proportional-Integral-Differential, proving the effectiveness of the theory in fast response control systems.

The student's main mission of the project is to fabricate a good robot structure with a very stable center of gravity, study the basic and various type of controller techniques, study the robot components (motor, encoder and etc), study and experiment the Quanser interface module, interface the fabricated robot structure with MATLAB using Quanser systems, and proceed with balancing the structure. The second mission is to test the complete system with studied control systems and control troubleshooting. Lastly a technical paper will be produced regarding the results of the real simulation.

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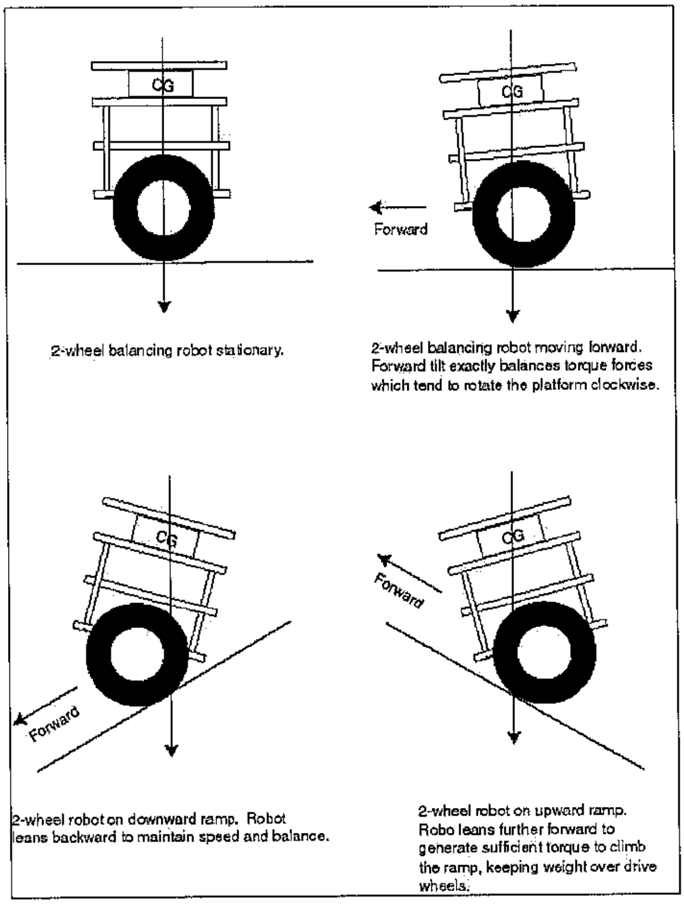
CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

1.1.1 THEORY STUDY

The study in developing the project consists of learning types of robotics mechanism, study on types of common materials used, the robot drives, the feedback and sensors. Also a specific study on the research on balancing and stability theory, and learning the methods to interpret the theory using MATLAB software. FIGURE 1 shows the meaning of robot balancing using center of gravity concept.



2-wheel balancing robot stationary.

2-wheel balancing robot moving forward. Forward tilt exactly balances torque forces which tend to rotate the platform clockwise.

2-wheel robot on downward ramp. Robot leans backward to maintain speed and balance.

2-wheel robot on upward ramp. Robo leans further forward to generate sufficient torque to climb the ramp, keeping weight over drive wheels.

FIGURE 1 : THE CONCEPT MOVEMENT OF BALANCING ROBOT

The purpose of this project is to design and fabricate a two balancing robot. Referring to FIGURE 1, the idea is to move the wheel at the direction of the robot falling, countering the fall. If the wheel can be driven in such a way as to stay under the robot's centre of gravity, theoretically the robot will remain balanced.

In practice this requires two feedback sensors, which are a tilt or angle sensor to measure the tilt of the robot with respect to gravity, and wheel encoders to measure the position of the base of the robot.
Four terms are sufficient to define the motion and position of the robot, and thereby balancing it. There are

- The tilt angle
- Angular velocity
- Platform position
- Platform velocity

These four measurements are summed and fed back to the controller as input, and the controller will give output to the motor as a motor voltage, which is proportional to the torque, thus balancing and driving the robot.

1.1.2 APPLICATION STUDY

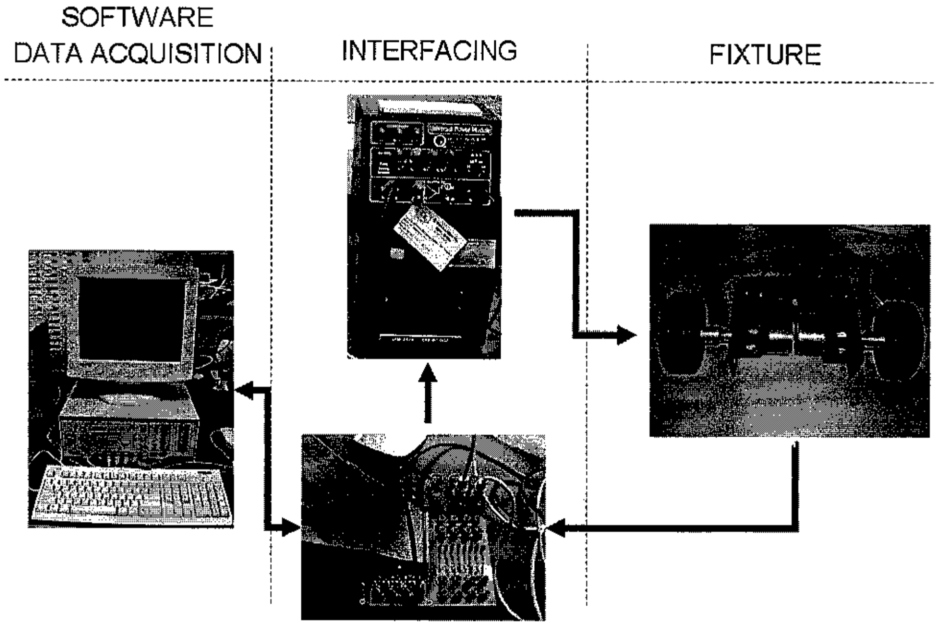


FIGURE 2 : COMPLETE SYSTEM INTERFACE

FIGURE 2 shows the overall idea of the construction of the project. The Fixture indicates the robot structure with motors. The second part is the Interfacing part, consists of power supply and the control board. The last part is the controller and monitoring part.

For the fixture study, it can be divided into 3 parts. The first part consists of the drives study. In this part, the function and specification of the motor (the main drive) must be understood.

The second part is the robot material study. The study consists of identifying and selecting on the possible material, the advantages and the disadvantages of the material. Using the knowledge, student will choose the best selection of all.

The third part is the design study. This study is the most important in the structure study, for it is basically on structure planning. All the study and results above must be included in this study as well, and come up with the best design possible.

For the interfacing study, it is divided into 2 parts, which is closely related to each other. The first part is the encoder interfacing and the second part is the motor interfacing.

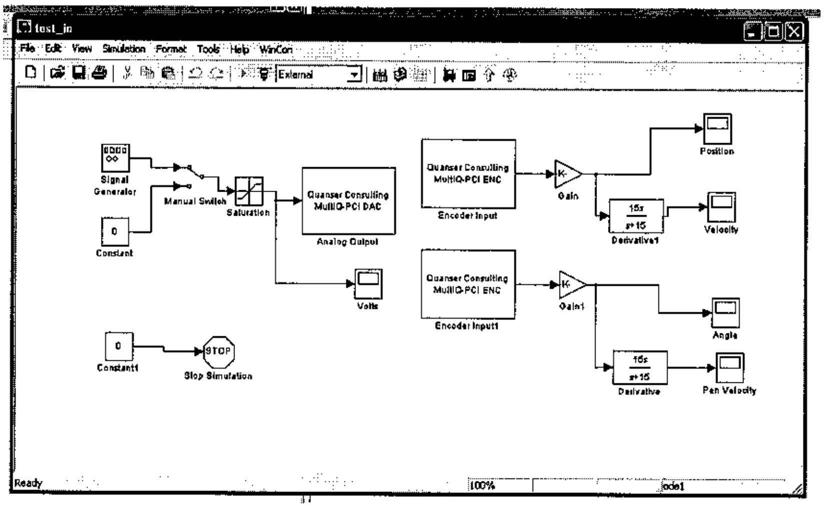


FIGURE 3 : SAMPLE OF MATLAB SIMULINK

For the encoder interfacing, the study consists of the minimum and maximum range input acceptable, the connection and encoder input reading using MATLAB software.

For the motor interfacing, the study consists of the range of analog I/O that the board able to interpret, the power supply amplification, and the connection between the supply and the load, which is the motor. Also, by using MATLAB software, student must be able to control the output voltage by using only the software.

For the control and data acquisition software study, the study is focused more on the software study. By using the calculated value of Proportional, Differential and Integral, student will use the MATLAB to interpret the data thus controlling the Quanser system.

Basically, this is all the study that is needed to complete the project. Future study will be about robot troubleshooting and further expansion of the robot if possible due to time.

1.2 PROBLEM STATEMENT

To balance a mechanism on a double wheel is not an easy task. Student must come up with a flexible design of the robot that is able to alter the centre of gravity of the robot. Also student must come up with a good structure that is stable to move.

By doing this project, student is able to understand the problems regarding stability and balancing of a moving robotic mechanism. If this project is successful, this means that student is able to apply the concept and theory to other sector which has stability problem like plant, automotive and even aeronautical. Also the project can be applied to Control System 2 subject as laboratory experiment.

1.3 OBJECTIVE AND SCOPE OF STUDY

The objectives scope of study is to understand more on stability theory and implement it to the project as balancing robot. The study is more towards current technology on balancing robot. The scope is to design and implement a computer controlled single wheel robot capable of balancing itself automatically using method such as PID control. The PID controller is being developed using the MATLAB software, the software that is used to interface the PC and the robot.

CHAPTER 2

LITERATURE REVIEW

2.1 WEB REVIEW

Until now, the perfect example of the project is the N-Bot Balancing robot, designed and fabricated by David P. Anderson, under NASA supervision.

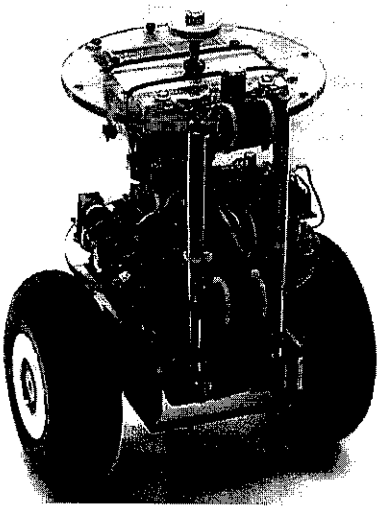


FIGURE 4 (LEFT) : BALANCING ROBOT BY DAVID P. ANDERSON
FIGURE 5 (RIGHT) : GYROSCOPE INCLINOMETER

Basically this project is more complex, for the robot is capable to operate in outdoor terrain. It is also has automatic navigating systems and radio control functions. The design use one motor for each wheel enables it to make turns while balancing.

For balancing, it uses an inclinometer, a gyroscope. The gyroscope provides accurate tilt reading, and this reading can be manipulated into tilt rate, which is the tilt velocity and acceleration. This reading is very important to design a perfect controller.

2.2 THEORY REVIEW

2.2.1 CONCEPT AND EXAMPLE

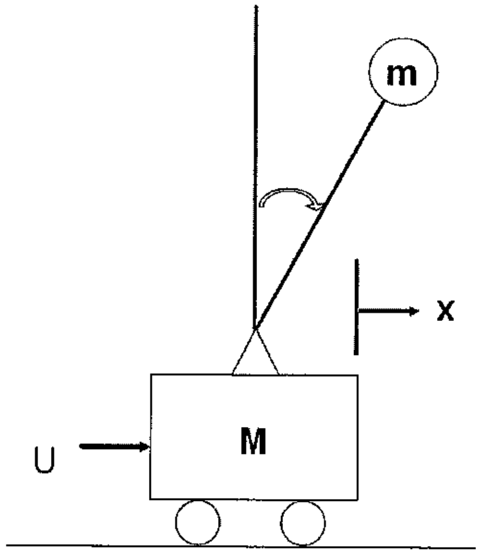


FIGURE 6 : CONTROL SYSTEM LAB INVERTED PENDULUM EXPERIMENT

This project is an application of the state-space control. The main idea is to understand the problem dynamically complex and non-linear. Analogy of the system is how to stabilize a walking robot, and how to maintain a rocket immediately after take-off. Thus this project will make use of a very fast feedback and in a very precise control system design.

For an example, referring to the figure above, considering the cart with an inverted pendulum is a rocket. The objective of the rocket control problem is to maintain the rocket in a vertical attitude while accelerating. The objective in the control of this model is to move the cart to a specified position (x) while maintaining the pendulum vertical (y).

2.2.2 CONTROLER DESIGN

Root locus is a graphical presentation of the closed-loop poles as a system parameter is varied, is a powerful method of analysis and design for stability and transient response. Feedback control systems are difficult to comprehend from a qualitative point of view and hence they rely heavily upon mathematics. The root locus technique able to use graph like figures to gives the qualitative description of a control system's performance that being evaluated.

The root locus can be used to describe qualitatively the performance of a system as various parameters are changed. The effect of varying gain upon percent overshoot, settling time and peak time can be vividly displayed. The qualitative description can then be verified with the quantitative analysis.

The root locus can give a graphical representation of a system's stability. From the graph, it can clearly display the ranges of stability, ranges of instability, and the conditions that causes a system to break into oscillation.

FIGURE 7 shows an example using the root locus. Basically, to achieve a stable response, the selected point must be at the left side of the graph, where the value of Y (in this case is σ) is negative. FIGURE 8 and FIGURE 9 shows the step response of two different points taken in the root locus graph. The FIGURE 8 shows the point taken at the left side, showing a fast response but slow in stability and FIGURE 9 shows the point taken at the right side, showing a slow response and has no stability (the error getting larger due time). To design a perfect controller, student must calculate and experiment the controller repeatedly, for there are many uncertainties in the systems.

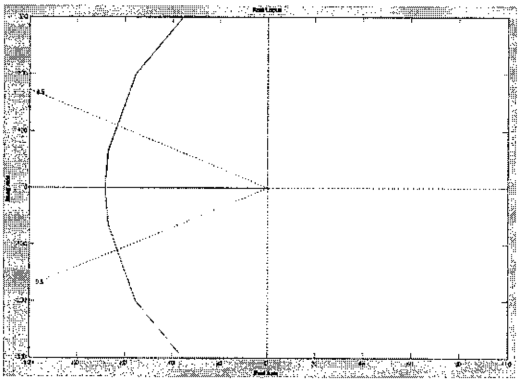
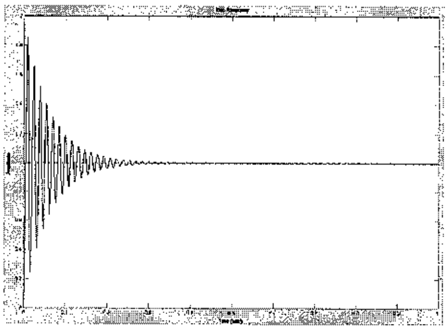


FIGURE 7 : ROOT LOCUS GRAPH



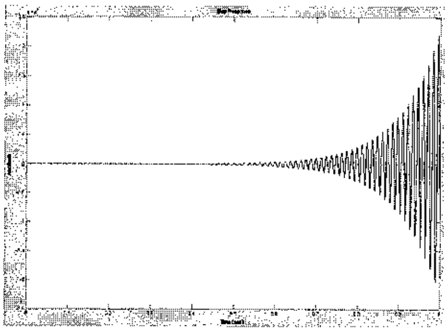


FIGURE 8 (LEFT) : CONTROL POINT SELECTED IN THE LEFT REGION
FIGURE 9 (RIGHT) : CONTROL POINT SELECTED IN THE RIGHT REGION

The root locus able to display the proper loop gain to meet the transient response specification. As the gain is varied, the point moves through different regions of response. Setting the gain at a particular value yields the transient response dictated by the poles at that pint on the root locus. This means that by manipulating the poles and zeros in the transfer function can largely affect the response and the behaviour, in order to search the best response.

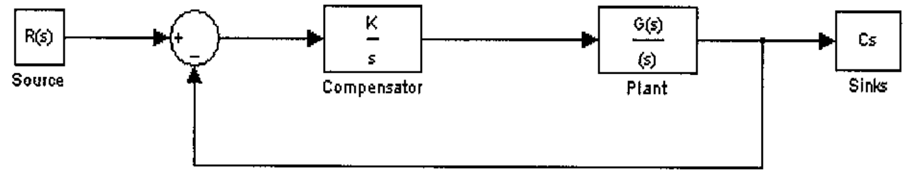


FIGURE 10 : CONTROL SYSTEM WITH INTEGRAL COMPENSATOR

The purpose of designing via root locus is to improve the transient response and the steady-state error. There are many kinds of improvement techniques that can be used. For a closed-loop system, compensators and PID controller is two commonly technique used in controls.

Compensators are basically a PID representation in a complex form. Usage of pure integration compensators able to improve the steady-state error and pure differentiation is for improving the transient response. These are defined as ideal compensators.

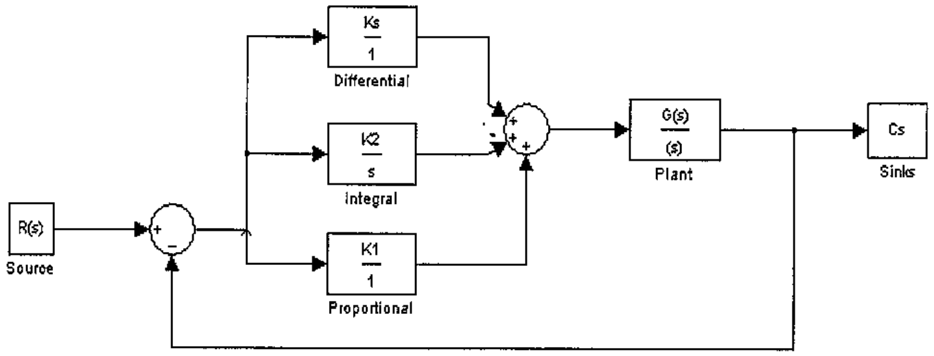


FIGURE 11 : CONTROL SYSTEM WITH BASIC PID CONFIGURATIONS

2.3 SYSTEM REVIEW

2.3.1 QUANSER SYSTEM

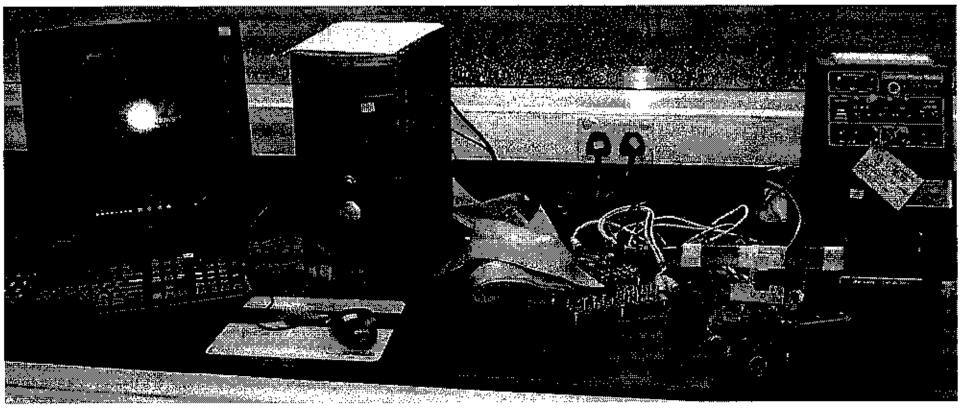


FIGURE 12 : COMPLETE SYSTEM IN THE CONTROL LABORATORY

The system consists of a Computer equipped with a Quanser Analog I/O PCI Card, a Quanser Terminal board and a Universal Power Module (UPM).

The board covers a broad range of input and output signals, that is able to interface a variety of devices via analog and digital signals. The current board used by student is the PCI MultiQ, slotted in the PCI slot in the PC. The PCI board has following features:

- 16 differential analog inputs, 14 bits, range: +/-5, +/-10 Volts
- 4 analog outputs, 12 bits, +/- 10 Volts
- 6 optical encoder inputs
- 48 programmable DIO

The terminal board is used for connection, and it is connected externally. It is also provides protection from external sources to the main devices, which is the PCI card. The features of the terminal board is:

- 48 digital I/O lines
- 6 single-ended or differential encoder inputs
- 8 A/D single-ended or differential analog inputs with optional RC-filtering
- 8 A/D differential analog inputs
- 8 of the analog inputs is low-passed filtered
- 4 analog outputs

The UPM used to drive the external load. The UPM amplify the current given from the Terminal Board while maintaining the voltage. The UPM model is UPM-24-05, means the module able to supply up to 24V at 5 amps. Student currently used the UPM capacity up to -5V to 5V at full load, directly connected to two Pitmman motor. A full data sheet on UPM is provided in **APPENDIX C**.

2.3.2 MOTOR

The motor that is currently being used is the Pittman 9232S001. This a DC motor with encoder integrated (the encoder will not be used in the project). FIGURE 13 shows the Pittman motor.

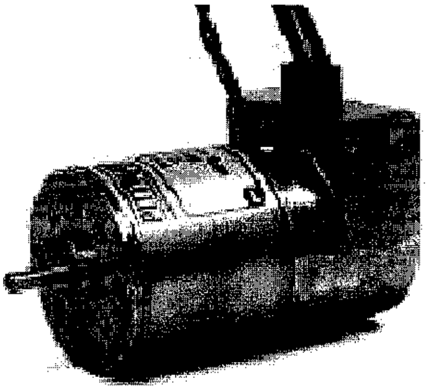


FIGURE 13 : 9232S001 PITTMAN MOTOR

The motor basic features are:

- 2-Pole Stator Ceramic Magnets
- 7-Slot Armature
- Copper-Graphite Brushes
- Motor Ball Bearings

The basic technical data of the Pittman motors is listed below. A full data sheet on Pittman motor is provided in **APPENDIX B.**

ASSEMBLY DATA	**SYMBOL**	**VALUE**
Reference Voltage	E	12V
No-Load Speed	S_{NL}	735 rad/s
Continuous Torque (max)	T_C	1.7E-02 N-m
Peak Torque (stall)	T_{PK}	9.7E-02 N-m
Weight	W_M	283g

MOTOR DATA	**SYMBOL**	**VALUE**
Torque Constant	K_T	1.55E-02 N-m
Resistance	R_T	1.93ohm
Inductance	L	1.16mH
Peak Current (stall)	I_P	6.22A
Friction Torque	T_F	3.5E-03 N-m
Damping Constant	K_D	1.3E-04 N-m-s

The robot uses two Pitmann motors, and both of the motors are run simultaneously. The simulated maximum current for one motor is not more than 3 Amps, which makes 6 Amps in total. For 3 Amps load, the motor fall into the circle region, shown in the FIGURE 14, which indicate that the loaded torque is varied from 6-8.

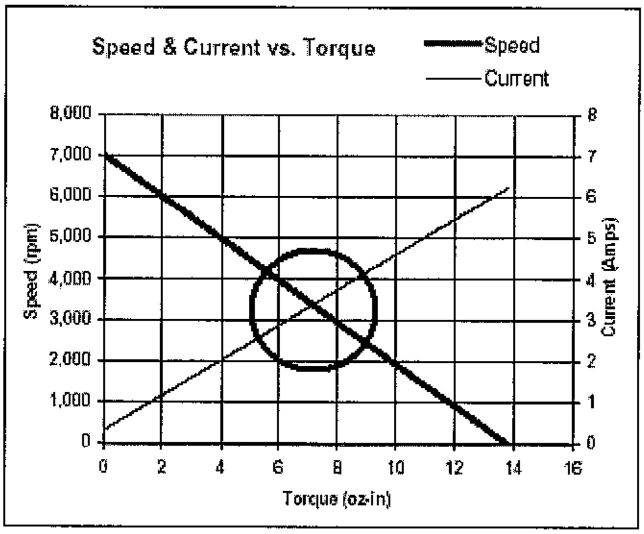


FIGURE 14 : 9232S001 SPEED & CURRENT VS. TORQUE

2.3.3 ENCODER

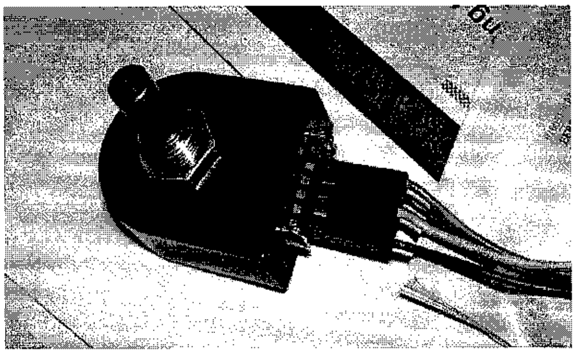


FIGURE 15 : US DIGITAL S1 SINGLE-ENDED OPTICAL SHAFT ENCODER

FIGURE 15 shows the US Digital S1 single-ended optical shaft encoder used in the robot sensing the robot angular position. It offers a high resolution of 4096 counts per revolution. The basic features of the encoder are:

- 2-channel quadrature, TTL square wave outputs
- 3rd channel index option
- Tracks from 0 to 100,000 cycles/sec
- Ball bearing tracks to 10,000 RPM
- -40°C to +100°C operating temperature
- Single +5VDC supply

A full data sheet of encoder is provided in **APPENDIX D.**

CHAPTER 3

METHODOLOGY

3.1 OVERVIEW

The methodology and procedure to complete the project can be divided into two parts, the first semester and the second semester. The methodology is planned by the student's supervisor himself, and cannot be changed by student. The plan is to gain as much basic knowledge on the project in the first semester and design a workable robot structure without the controller. The plan for the second semester is to interface the robot with an interface system, which able it to communicate with a computer. Also to design a controller that suit the robot need.

3.2 FIRST SEMESTER

- Overview study on current technology regarding balancing robot, the theory, concept, practicability and possible future problems predictions.
- Design the robot structure according to the criteria given.
- Obtain the robot components, which are the Pittman motor, base metal and the wheel.
- Fabricate the structure according to the design designed earlier.
- Test the stability of the robot in terms of structure rigidity, center of gravity and the smoothness of the movement.

3.3 SECOND SEMESTER

- Study on the interface system, which is the Quanser system.
- Test run the system by reading inputs (sensor) and giving outputs (motors).
- Study the control theory and control system needed to balance the robot.
- By using MATLAB simulink, the control system stability and the block diagrams is designed
- After the robot is fully designed and working properly, experiment is done on the robot to test a number of controller types and compare the results.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 OVERVIEW

This section will discuss about student's work towards achieving the goal. The progress can be divided into 3, the structure, the interface hardware and the controller design. The first progress is the experiment on Pittman encoder, the second progress is the experiment on the output analog and the motor voltage, and the last progress is the controller design using PI.

4.2 STRUCTURE (PROTOTYPE)

The development of the structure is started by designing and drawing the desired structure. FIGURE 16 shows the basic design of overall robot structure.

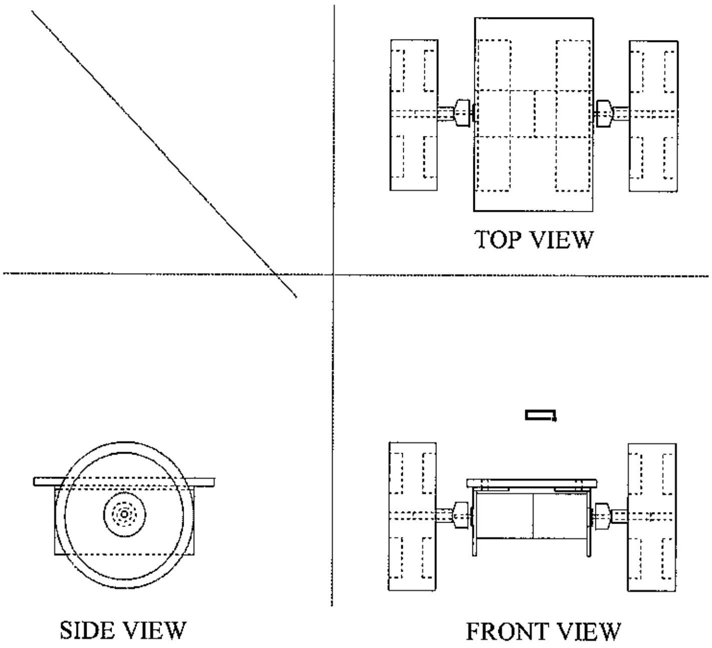


FIGURE 16 : INITIAL ROBOT STRUCTURE DRAWING

After several discussions with the supervisor, the design criteria given to student are:

- Use 2 wheels
- Use Pittman motors
- Weight less than 2 kg
- No fixed joint
- Wheel is direct mounted to the motor
- Use Quanser Interface system

The design must have no fixed joint, which make full use of bolts and nuts. This is crucial because student need to alter the structure center of gravity accordingly, which can never be achieved using fixed joint structure.

Initially, the design is more towards using aluminium plate as the basic material, for it has decent strength, lightweight and easy to fabricate. Since aluminium is very hard to obtain and costly, the main material is changed to a simple L-shape construction metal, where it is more affordable and easy to obtain. The price at that time is RM13.00 for 3 meters. The metal piece is complete with holes, which makes it easier to mount components (motor, encoder and etc.) using bolts and nuts. FIGURE 17 shows the main material which is the L-shape metal used in the project.

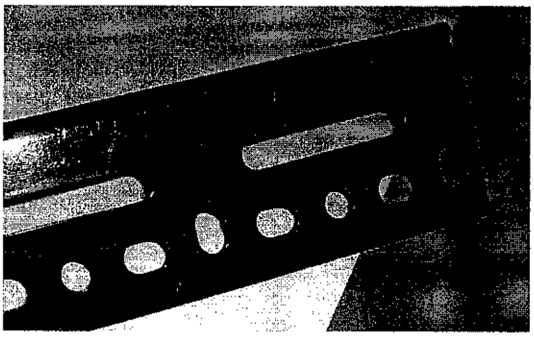


FIGURE 17 : L-SHAPE CONSTRUCTION METAL

The wheel will be directly mounted to the motor. In order to do this, the coupling is needed to connect the motor shaft to the wheel. The coupling is designed and fabricated using aluminium. FIGURE 18 shows the selected wheel for the robot. The wheel diameter is 9 cm, and weight around 200gm. FIGURE 19 shows the coupling fabricated by student with the help from UTP Mechanical technicians. The coupling will be used as shown in FIGURE 20, tighten using a screw.

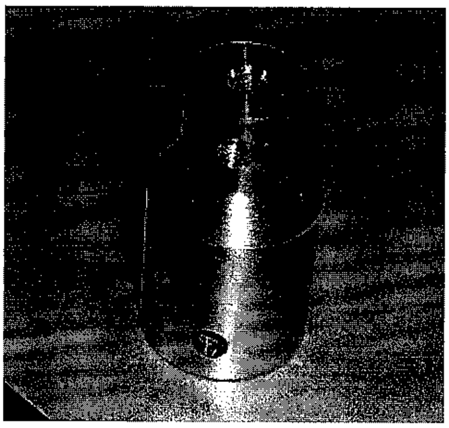


FIGURE 18 (LEFT) : ROBOT WHEEL
FIGURE 19 (RIGHT) : MOTOR-WHEEL COUPLING

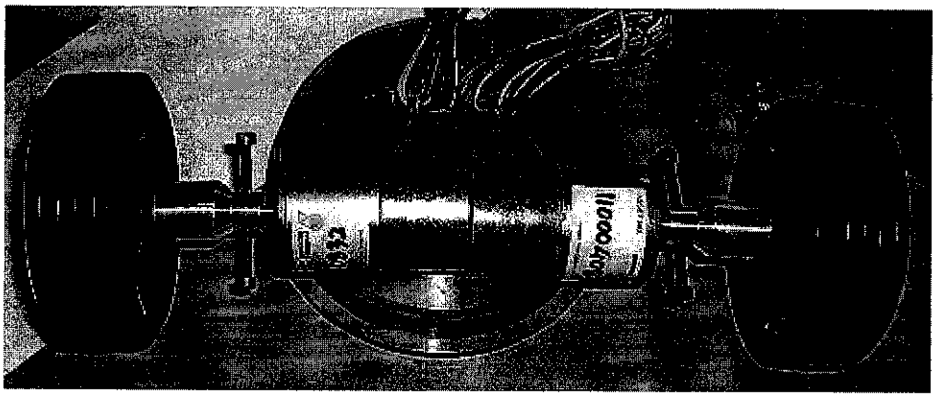


FIGURE 20 : CONNECTION MOTOR-WHEEL USING COUPLING

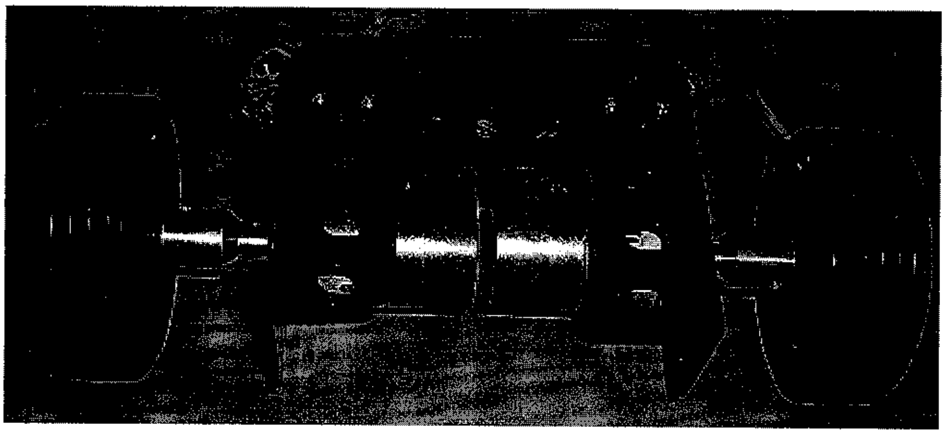


FIGURE 21 : COMPLETE ROBOT PROTOTYPE

FIGURE 21 above shows the prototype of the robot structure, finished fabricated around middle of April 2004. Several problems occur in this design during trial run.

The first problem is on the robot alignment, which not able to move straight. This is a minor problem, but in order to achieve the best structure, this matter will be put into consideration.

The second problem is on the coupling. The coupling is quite large and long, which effects the wheel alignment. Also the coupling was not able to stick on the motor shaft when running at high speed, tend to slip out from the motor shaft. This is one of the major problems and need to solve effectively.

The third problem is on the robot weight. Even though it was still less than 2kg, but it has an undesirable effect on the robot. The robot weight cannot synchronize with the fast response from controller. Also this weight problem has contributed to large load, which results of larger current drawn from supply to the motor. The wheel is quite large and heavy, which affect the motor fast response and electrical load.

4.3 STRUCTURE (TROUBLESHOOT AND REDESIGN)

The first problems solved are the coupling and wheel problems. Students solve the coupling problems by finding wheel from toy shop, supplies and spare parts. After minor alterations, the diameter of the wheel is around $5^{1}/_{2}$ cm and weight around 100gm, which is better than the prototype wheels. The coupling has no alignment problems, is precisely manufactured, as expected from remote controlled car spare parts. With this wheel, the whole robot weight is slightly reduced. FIGURE 22 below shows the rim used as the solution alternatives. FIGURE 23 and FIGURE 24 shows the complete wheel attached to the rim thus to the motor shaft.

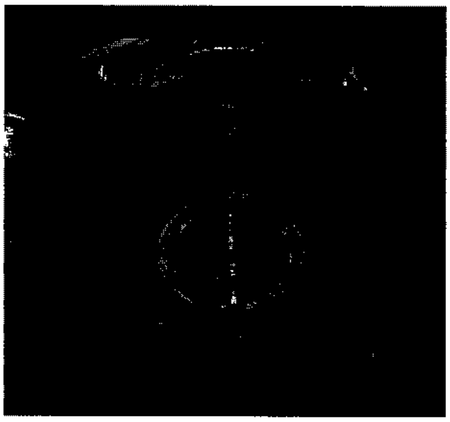


FIGURE 22 (LEFT) : THE WHEEL RIM
FIGURE 23 (RIGHT) : COMPLETE WHEEL

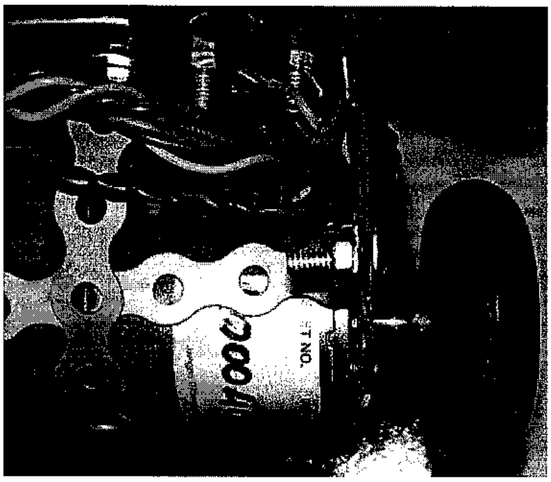


FIGURE 24 : MOTOR-WHEEL CONNECTION USING RIM COUPLING

4.4 STRUCTURE (ENCODER)

Student has to design a pole, acting as a tilt sensor, the most important part in the robot system. The initial design was to mount the pole directly to the encoder shaft.

The characteristic of the pole is it must have large inertia to prevent it from deviation. The pole is restricted from swinging and will only move based on the robot response and base falling. Thus the designed pole is heavy in nature as required to achieve less deviation caused from low inertia. FIGURE 25 and FIGURE 26 below shows the pole designed using aluminium, and the alterations done to the robot as preparation to install the pole.

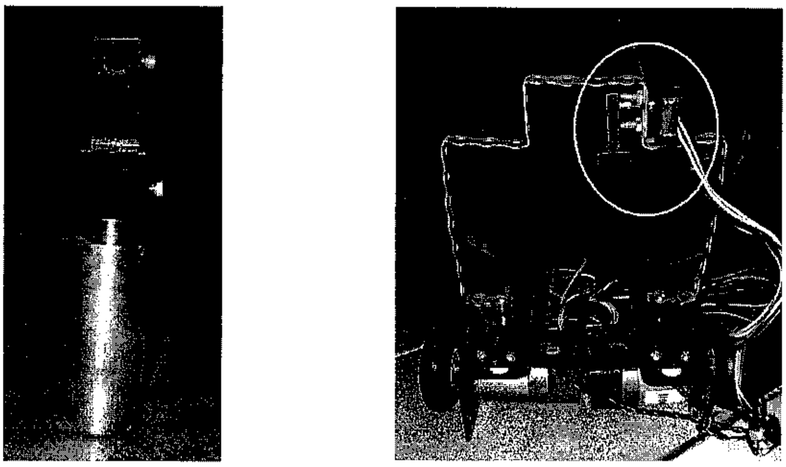
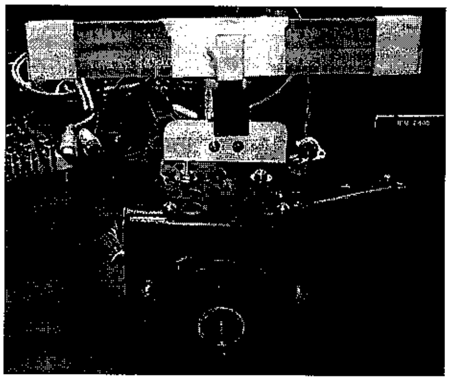


FIGURE 25 (LEFT) : THE ALUMINIUM POLE
FIGURE 26 (RIGHT) : ROBOT STRUCTURE AFTER POLE INSTALLED

As for the results, this pole design is a failure, for the error caused and accumulated by the pole is unacceptable. The vibration caused by the motor has a great effect to the pole, accumulating the error and thus making the pole swinging uncontrollable. A new design has been developed to overcome this problem.

The next alternative for the pole is horizontal pole. The pole is horizontally designed to achieve the best stability. Because the robot is moving in horizontal way, the inertia and force generated has less effect on the horizontal pole. Referring to FIGURE 27 and FIGURE 28 below, it can be seen that the pole tend to stay in horizontal position even the robot is tilting, and this behaviour is used as the controller reading.



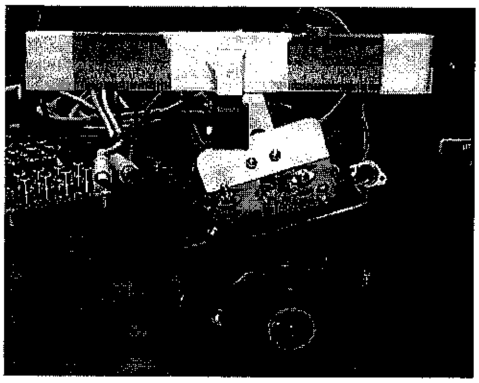


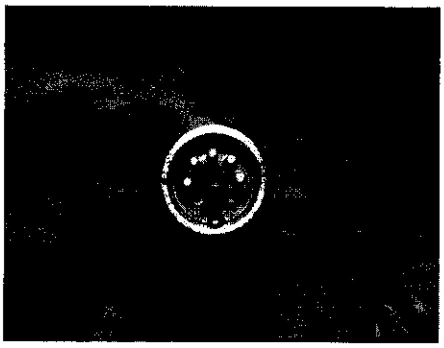
FIGURE 27 (LEFT) : POLE POSITION WHEN ROBOT IS STATIC
FIGURE 28 (RIGHT) : POLE POSITION WHEN ROBOT IS TILTING

After a number of redesigning and troubleshooting on the robot structure, the robot has been completed at early October 2004, and the project is ready to enter the controller experiment part, which later discussed in the next section.

4.5 QUANSER SYSTEM

The project is using Quanser interface systems as the main system used for interfacing, power supply and data collection. In order for student to familiarize with this system, several experiment is done, which includes the encoder experiment, which is inputs, and analog experiment, which are outputs.

The experiment is started by testing the encoder connection and thus its function. FIGURE 29 below shows the type of connector used for the encoder reading. The 5-pin male connector is connected to the Multi-Q Terminal Board while the other end of the cable is connected to the tilt sensor encoder.



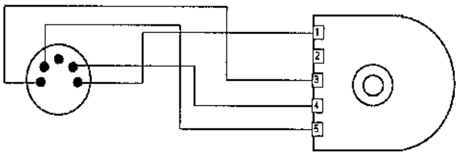


FIGURE 29 (LEFT) : 5-PIN ENCODER CONNECTOR
FIGURE 30 (RIGHT) : ENCODER CABLE CONFIGURATION

FIGURE 31 below shows the encoder reading using MATLAB Simulink. The Quanser Consulting MultiQ-PCI ENC block will accept encoder signals from the Terminal Board and use it according to the program, which in this case, is monitored using a display. The display 'Display' representing the encoder according to steps, while the display 'deg' representing the encoder in degrees.

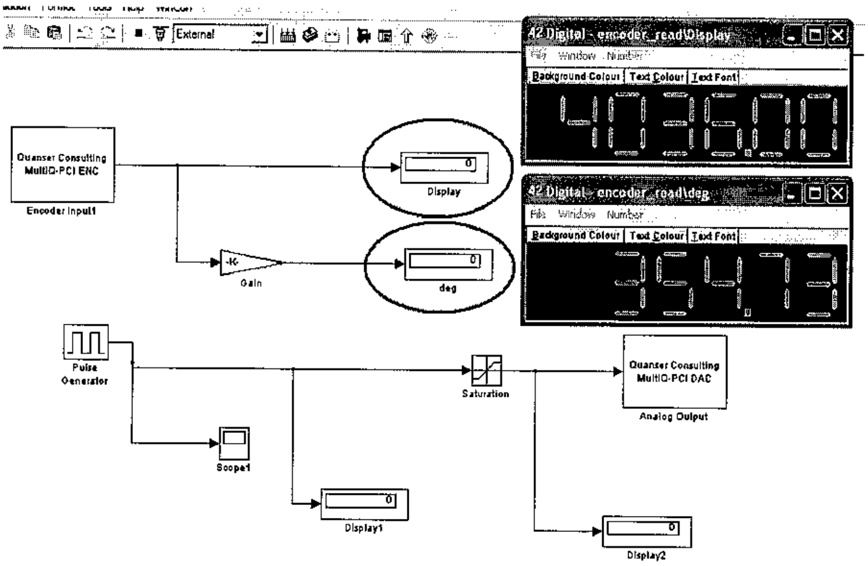
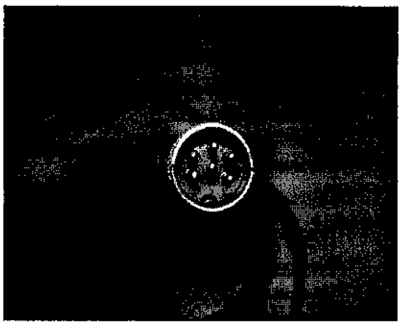


FIGURE 31 : MATLAB SIMULINK PROGRAM FOR ENCODER READING

The experiment is then continued by testing the analog outputs, which will be the supply to the motor. FIGURE 32 and FIGURE 33 below shows the type of connector used for motor supply. The type of cable connected between the power supply and the motor is a 6-point to 4-point cable. From the experiment, student has discovered that the power supply (UPM) is supplying voltage proportional to the analog input feed to the UPM. The UPM is maintaining the voltage while amplifying the current, up to 5amps.



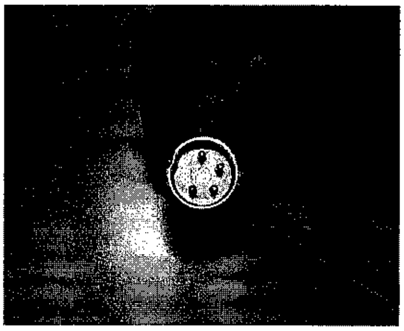


FIGURE 32 (LEFT) : 6-PIN UPM CONNECTOR
FIGURE 33 (RIGHT) : 4-PIN UPM CONNECTOR

FIGURE 34 shows the schematic diagram of cable connection from the analog output to the UPM, the amplifier inside the UPM, and the connection from the UPM to the load, which is the motor.

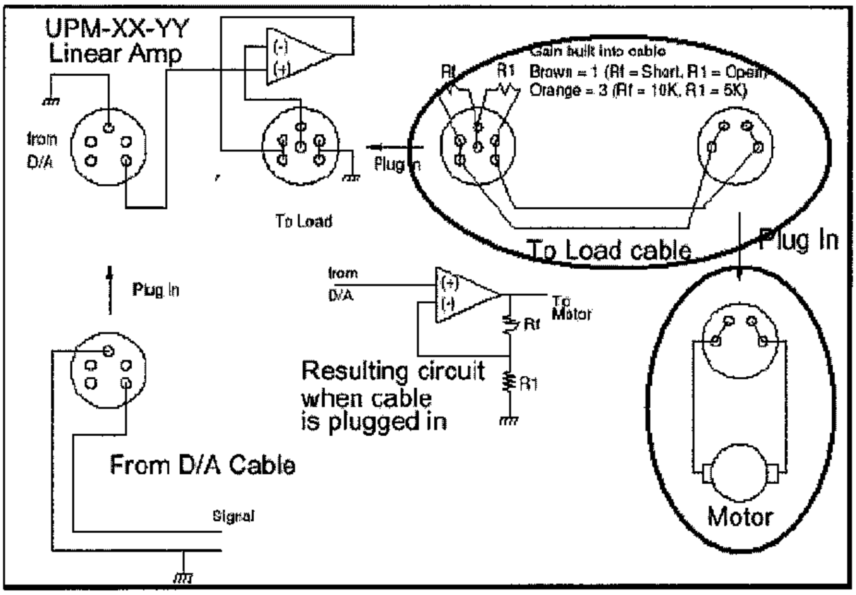
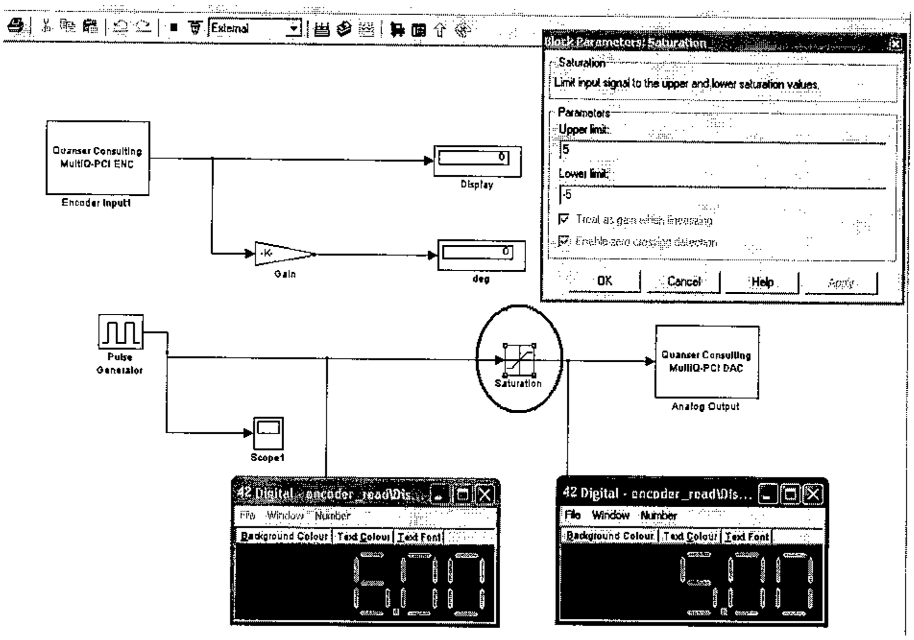


FIGURE 34 : SCHEMATICS OF UPM CONNECTIONS



Block Parameters: Saturation

Saturation

Limit input signal to the upper and lower saturation values.

Parameters

Upper limit: 5

Lower limit: -5

☑ Treat as gain when linearizing

☑ Enable zero crossing detection

FIGURE 35 : MATLAB SIMULINK PROGRAM FOR ANALOG OUTPUT

FIGURE 35 shows the analog output manipulation using MATLAB to the Terminal Board. In this experiment, student use a Pulse Generator to provide step signals. The Terminal Board, which is represented by Quanser Consulting MultiQ-PCI DAC, should provide the same output when checked with a multimeter. The maximum range for the Terminal Board is +/- 5V. For safety, a saturation block is used to limit the input to the Terminal Board within the stated range.

In this experiment, student able to manipulate the board to provide outputs which is the same as the signal observed from the Pulse Generator. The amplitude of the outputs can be controlled to supply within the safe range, using a saturation block, to protect the equipment from overvoltage.

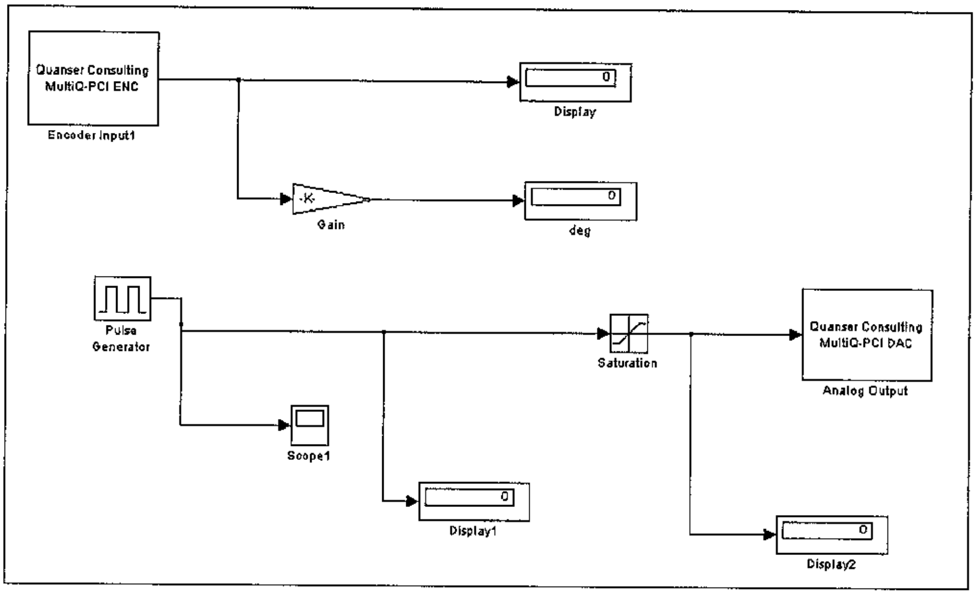


FIGURE 36 : MATLAB SIMULINK PROGRAM FOR FULL SYSTEM TEST

As a conclusion, student managed to finish the interfacing between the Quanser system and the robot. By using MultiQ-PCI ENC block, student able to read the encoder using MATLAB, and by using a sources, like a pulse generator, student able to control motor voltage and direction also using MATLAB.

4.6 Controller DESIGN (TRANSFER FUNCTION)

To design a controller, the plant transfer function must be determined first. As an introduction, a DC motor directly provides rotary motion and, coupled with wheels or drums and cables, can provide transitional motion. The electric circuit of the armature and the free body diagram of the rotor are shown in FIGURE 37.

The transfer function must include following values for the motor physical parameters. These values can be obtained from the motor datasheet, produced from the manufacturer. The parameters are

- moment of inertia of the rotor (J)
- damping ratio of the mechanical system (b)
- electromotive force constant (K=Ke=Kt)
- electric resistance (R)
- electric inductance (L)
- input (V) - Source Voltage
- output (theta) - position of shaft

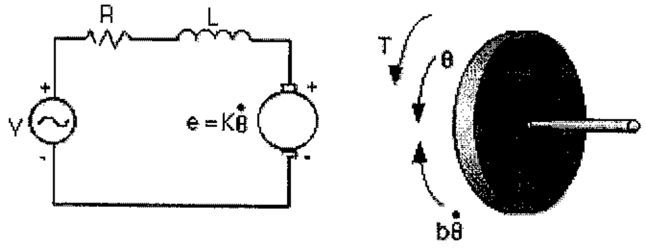


FIGURE 37 : ELECTRIC CIRCUIT OF ARMATURE AND THE FREE BODY DIAGRAM OF ROTOR

The motor torque, **T**, is related to the armature current, **i**, by a constant factor **Kt**. The back emf, **e**, is related to the rotational velocity by the following equations:

$$T = K_t i \qquad (1)$$

$$e = K_e \dot{\theta} \qquad (2)$$

Kt (armature constant) is equal to **Ke** (motor constant).

Combining equation (1) and (2) based on Newton's law and Kirchhoff's law will obtain:

$$J\ddot{\theta} + b\dot{\theta} = Ki \qquad (3)$$

$$L\frac{di}{dt} + Ri = V - K\dot{\theta} \qquad (4)$$

Using Laplace Transforms, the modelling equations of (3) and (4) can be expressed in terms of s.

$$s(Js + b)\theta(s) = KI(s) \qquad (5)$$

$$(Ls + R)I(s) = V - Ks\theta(s) \qquad (6)$$

By eliminating I(s) at the equation (5) and (6), the following open-loop transfer function is produced, stating the rotational speed is the output and the voltage is the input.

$$\frac{\theta}{V} = \frac{K_T}{s((Js + b)(Ls + R) + K^2)} \qquad (7\text{-}1)$$

$$\frac{\theta}{V} = \frac{K_T}{s((J_M s + K_D)(Ls + R) + {K_T}^2)} \qquad (7\text{-}2)$$

Using the motor data from **APPENDIX B**, the transfer function for the motor is

$$\frac{\theta}{V}=\frac{15.5m}{s((1.9\mu s+130\mu)(1.16ms+1.93)+240.25\mu)} \tag{8}$$

Rounding the gain and factoring will obtain

$$\frac{\theta}{V}=\frac{1.55}{220.4ns(s+1592)(s+140.2)} \tag{9}$$

Simplifying equation (9),

$$\frac{\theta}{V}=\frac{1.55(4537205.082)}{s(s+1592)(s+140.2)} \tag{10}$$

Which is a third order transfer function.

4.7 CONTROL DESIGN (ROOT LOCUS)

$$\frac{\theta}{V}=\frac{1.55(4537205.082)}{s(s+1592)(s+140.2)}$$

Root locus method is used to reduce the transfer function order, and to locate the most suitable value for P, I and D. A 3rd order transfer function is complex and must be reduced to a lower order for easy manipulation.

According to the transfer function obtained, the poles are at 0, -140.2 and -1592. Then using the transfer function, a root locus plot is generated using MATLAB.

A design criteria must be set first, in this case, the design criteria are

- Settling time less than 0.04sec
- Overshoot is less than 16%
- Assume there is no steady state error
- Assume there is no steady state error due to disturbance

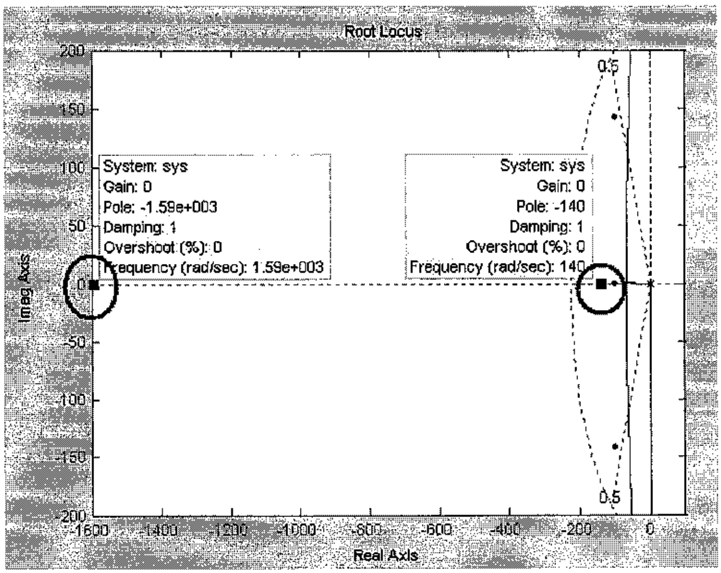


FIGURE 38 • ROOT LOCUS PLOT USING THE MOTOR TRANSFER FUNCTION

FIGURE 38 above shows the basic root locus plot, without any enhancement. The two circles indicate the poles at -140.2 and -1592.

The -1592 pole can be neglected since the root locus line intersects only between 0 and -140.2 poles. By ignoring the third pole, the transfer function is automatically became a second order function, which is easier to manipulate. Figure 39 below shows the root locus graph on 2^{nd} order transfer function.

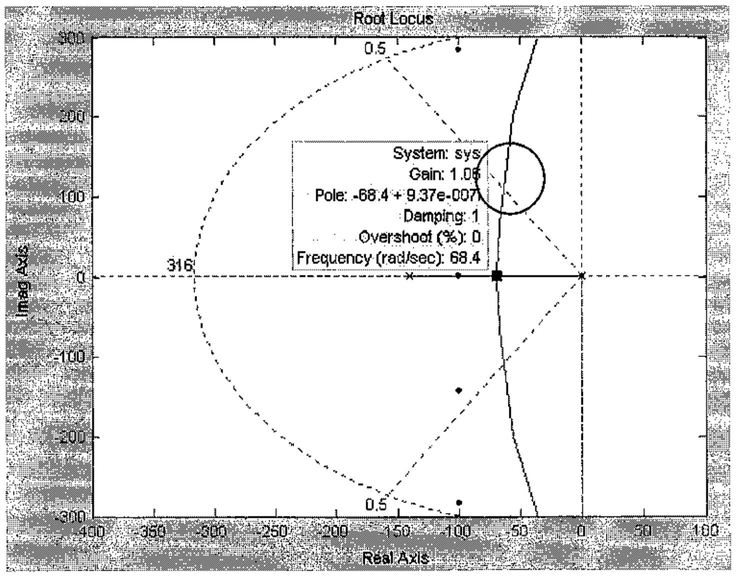


FIGURE 39 • ROOT LOCUS PLOT USING 2^{ND} ORDER TRANSFER FUNCTION

The K value is 3.7850 if the study point is selected in the circle region, using the OS=16% line.

4.8 CONTROL DESIGN (EXPERIMENT)

After the basic root locus obtained, student can proceed with the experiment on actual simulation using the circuit shown in the FIGURE 40 below. The value for K is 3.7850 obtained earlier, is multiplied by 10 considering the structure weight effect. Until now, student has completed experiment using PI controller, where a study to see the effect of Integral while maintaining the Proportional gain.

The concept of the controller design is shown below in FIGURE 40. The source input is 0, which means that 0 voltage. The encoder block (feedback) is changed into values ranged from -1 to 1, subtracted by the source, and processed by the compensator. The sign of the subtracted value, negative or positive, will determined the direction of the motor moving. The magnitude of the processed value, ranged from -5 to 5V, determine the motor torque and speed in overcoming the imbalance on the structure.

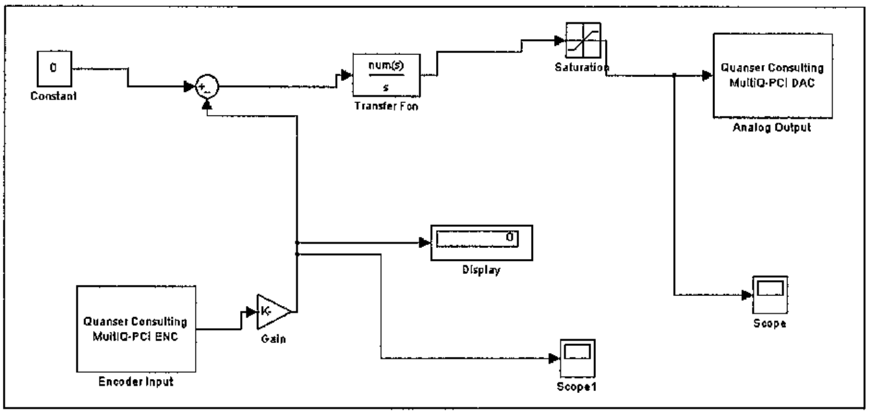


FIGURE 40 : MATLAB SIMULINK PROGRAM FOR ACTUAL SIMULATION

The experiment is done by using a compensator, Integral type. The transfer function of the compensator is

$$\frac{K(s+z)}{s}$$

where z is the additional zero added to improve the response. A range of z will be used in the experiment and evaluate it using the actual simulation. The experiment is stated by using an additional zero at 20, followed by 10, 1 and 0.1.

FIGURE 41 and FIGURE 42 below shows the simulation results on MATLAB for z = 20, or has additional zero at -20.

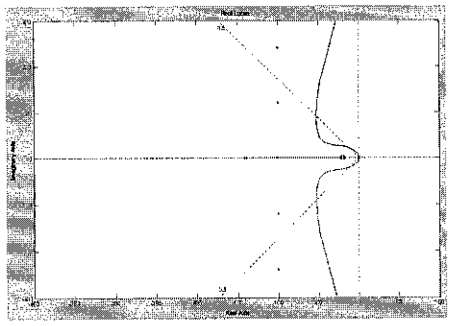


FIGURE 41 : ROOT LOCUS PLOT

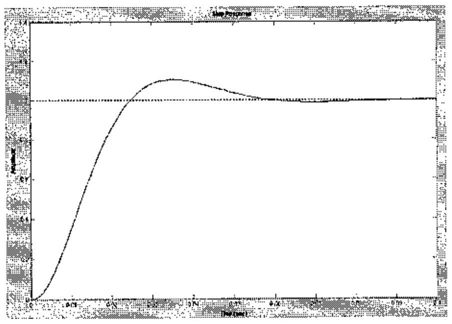


FIGURE 42 : STEP RESPONSE

FIGURE 43 and FIGURE 44 below shows the real simulation using the integral compensator on the robot. Take note that the encoder error is getting larger and larger, thus making the motor voltage larger, in this case it is up to -5 and 5V, which the results will be uncontrollable. Balancing is not achieved by using this compensator. Further experiment will test on smaller value of z.

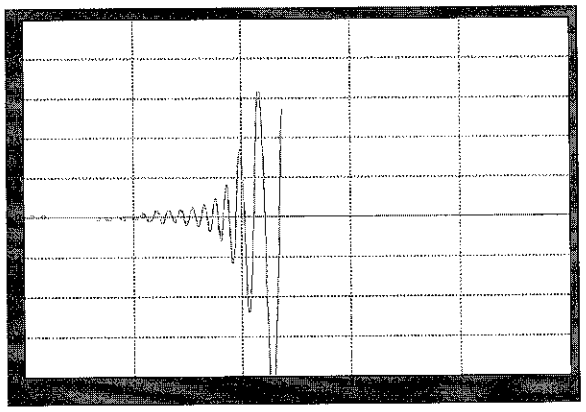


FIGURE 43 : ENCODER RESPONSE

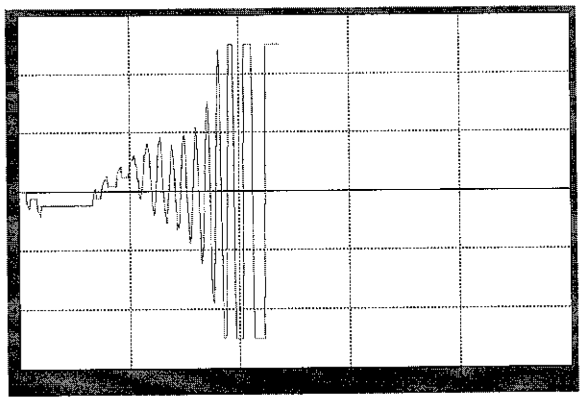


FIGURE 44 : MOTOR VOLTAGE RESPONSE

FIGURE 45 and FIGURE 46 below shows the simulation results on MATLAB for z = 10, or has additional zero at -10.

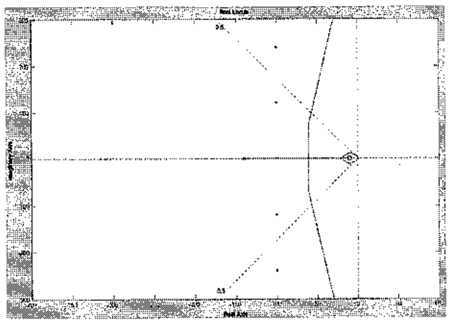


FIGURE 45 : ROOT LOCUS PLOT

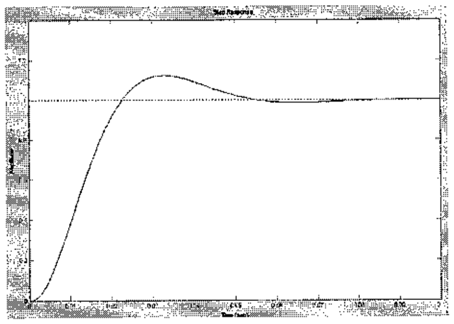


FIGURE 46 : STEP RESPONSE

FIGURE 47 and FIGURE 48 below shows the real simulation using smaller value of z. Take note that the encoder accumulated error is still exist, but the reading is slower than before. The motor voltage shows no improvement, but the balance is further to around 1.5 seconds, rather than 1.3 seconds before, before entering the uncontrollable region. Still balancing is not achieved by using this compensator and further experiment will test on smaller value of z.

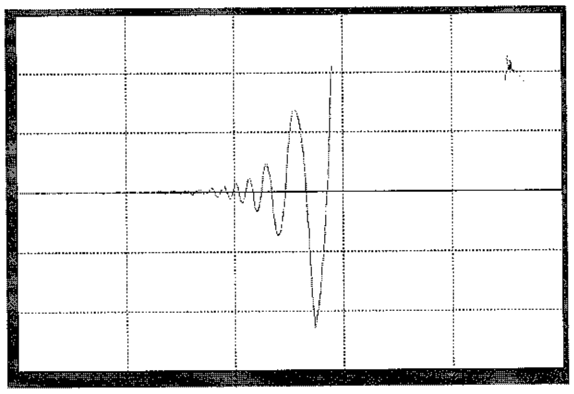


FIGURE 47 • ENCODER RESPONSE

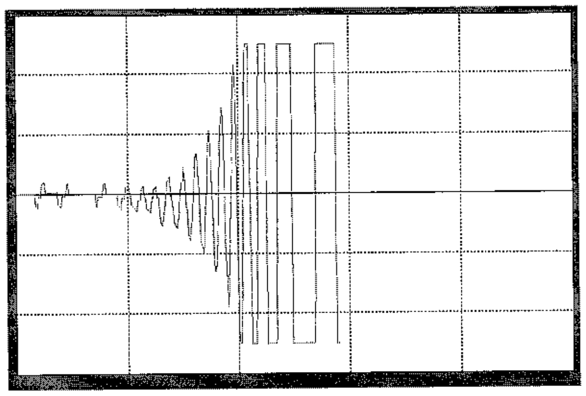


FIGURE 48 • MOTOR VOLTAGE RESPONSE

FIGURE 49 and FIGURE 50 below shows the simulation results on MATLAB for z = 1, or has additional zero at -1.

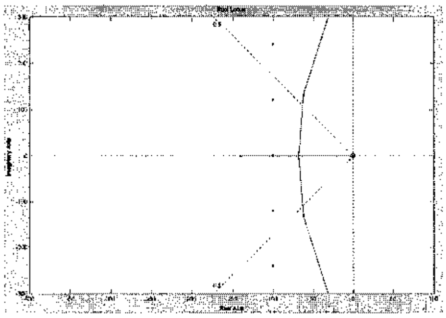


FIGURE 49 • ROOT LOCUS PLOT

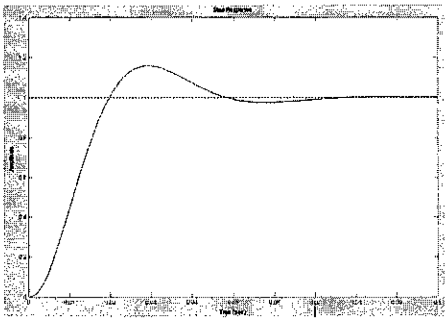


FIGURE 50 • STEP RESPONSE

FIGURE 51 and FIGURE 52 below shows the real simulation using smaller value of z. Take note that the encoder reading shows that the robot attempt to balance, and the robot able to balance for 7 seconds, before going uncontrolled. The motor voltage shows a very large improvement, synchronizing with the encoder, and maintaining a good control voltage at -/+ 3 volts. Next experiment is to see the effect of smaller value of z.

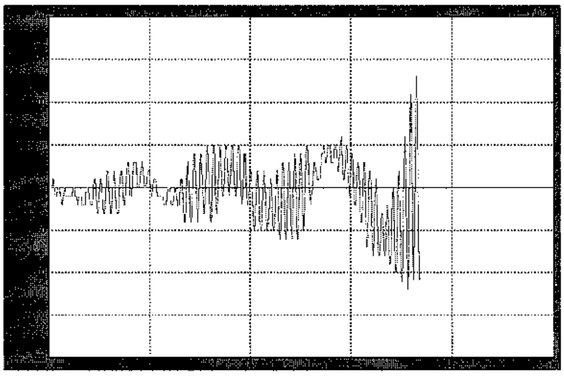


FIGURE 51 • ENCODER RESPONSE

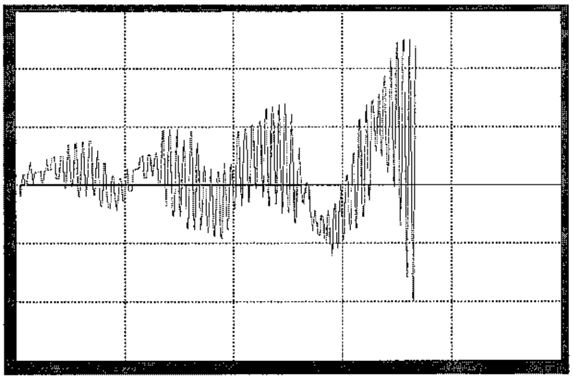


FIGURE 52 • MOTOR VOLTAGE RESPONSE

FIGURE 53 and FIGURE 54 below shows the simulation results on MATLAB for z = 0.1, or has additional zero at -0.1.

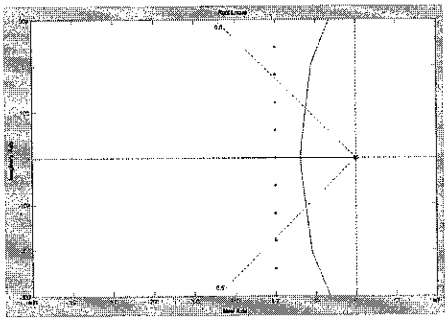


FIGURE 53 • ROOT LOCUS PLOT

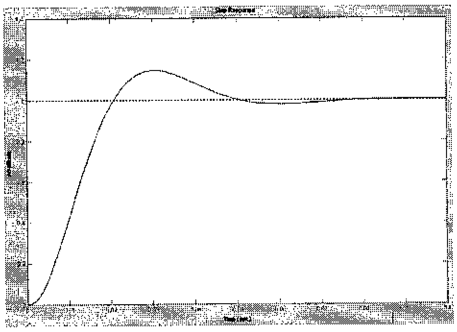


FIGURE 54 • STEP RESPONSE

FIGURE 55 and FIGURE 56 below shows the real simulation using smaller value of z. As the results, the robot is able to balance for a longer period of time, for nearly 14 seconds, before entering uncontrolled region. The results shows a very stable reading, showing the attempt to balance, and a very fast response for the motor voltage

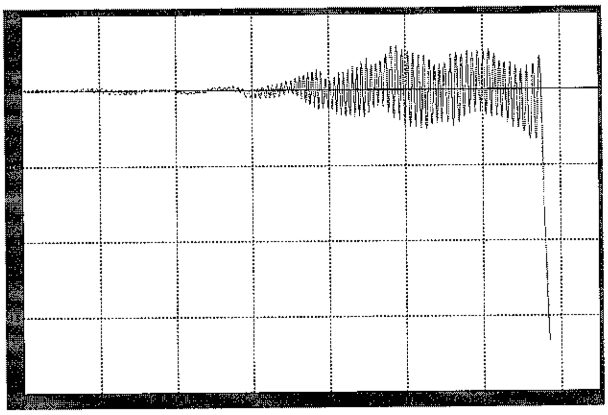


FIGURE 55 • ENCODER RESPONSE

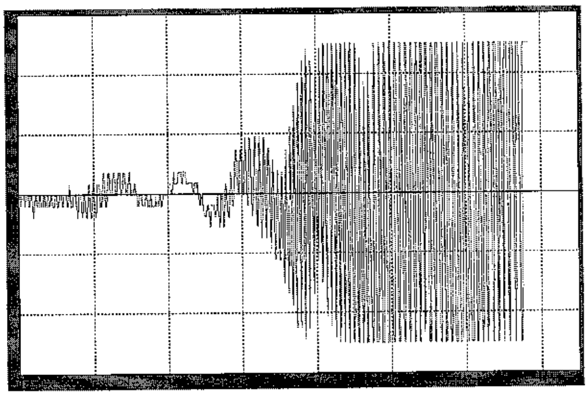


FIGURE 56 • MOTOR VOLTAGE RESPONSE

CHAPTER 5

CONCLUSION

The first requirement of this project is to develop a good structure of robot, which is successfully completed by student in this semester. The structure is designed so it is able to withstand some changes done due to weight distribution and additional equipment.

Second requirement of this project is to complete the system by connecting it to the Quanser interface systems, which is completed by student in this semester. The system is using MATLAB as its user interface, which is easy. Student has undergone several experiment and study on the complete system to test the reliability and the range of operation.

The third requirement of this project is to study and design a controller based on the control system concept. After series of experiments conducted, student has concluded that using PI controller has the best results of all, referring to the robot balancing duration and error control.

As a conclusion, the project is successfully done.

CHAPTER 6

RECOMMENDATION

The current project can be used for laboratory experiment for Control System I and II subject, regarding the system controllability, design and application of root locus and the effects of various types of compensators.

For future upgrade, the tilt sensor can be replaced by using a proper inclinometer, or a Gyroscope. Using this high precision sensor can eliminate current problems of deviation and environmental disturbance to the pole. For controller design in the future, it is recommended to include the robot weight, wheel and friction between the wheel and the base floor, to achieve perfect control.

CHAPTER 7

REFERENCES

WEB PAGE AND INTERNET SEARCH

1) www.geology.smu.edu/~dpa-www/robo/nbot/
2) www.barello.net/Papers/Balancing%20Robot%20Seminar.pdf
3) www.engin.umich.edu/group/ctm/examples/motor2/motor/html
4) www.pittmannet.com/122100.html
5) www.quanser.com
6) http://www.engin.umich.edu/group/ctm/examples/motor/

MANUALS

7) Control System II Inverted Pole Laboratory Manual
8) Quanser System Experiment Manual
9) UPM User Manual
10) 9232S001 Pittman Technical Data Sheet

BOOKS

11) Norman S. Nise. 2000. Control Systems Engineering. Wiley, USA.

APPENDICES

APPENDIX A

MATLAB ROOT LOCUS M-FILE

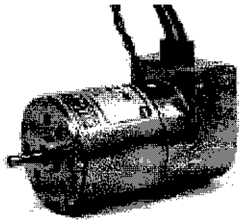
```
J=1.9E-6;
b=1.3E-4;
K=1.55E-2;
R=1.93;
L=1.16E-3;

num=K;
den=[(J*L) ((J*R)+(L*b)) ((b*R)+K^2) 0];


rlocus(num,den)
sgrid(0.5,0)
sigrid(100)
axis([-1000 1000 -300 300])

[k,poles]=rlocfind(num,den)
[numc,denc]=cloop(k*num,den,-1);
t=0:0.001:1;
step(numc,denc,t)
```

```
J=1.9E-6;
b=1.3E-4;
K=1.55E-2;
R=1.93;
L=1.16E-3;

num=K;
den=[(J*L) ((J*R)+(L*b)) ((b*R)+K^2) 0];

numcf=conv([1 140], [1 150]);
dencf=[1 0];
numf=conv(numcf,num);
denf=conv(dencf,den);

rlocus(numf,denf)
sgrid(.5,0)
sigrid(100)
axis([-400 100 -300 300])

[k,poles]=rlocfind(numf,denf)
[numc,denc]=cloop(k*numf,denf,-1);
t=0:0.001:.1;
step(numc,denc,t)
```

APPENDIX B

PITTMAN 9232S001 DATA SHEET

PittmanExpress™



9232S001

Lo-Cog® DC Servo Motor

Assembly Data	Symbol	Units	Value	
Reference Voltage	E	V	12	
No-Load Speed	S_{NL}	rpm (rad/s)	7,016	(735)
Continuous Torque (Max.)[1]	T_C	oz-in (N-m)	2.4	(1.7E-02)
Peak Torque (Stall)[2]	T_{PK}	oz-in (N-m)	14	(9.7E-02)
Weight	W_M	oz (g)	10	(283)
Motor Data				
Torque Constant	K_T	oz-in/A (N-m/A)	2.20	(1.56E-02)
Back-EMF Constant	K_E	V/krpm (V/rad/s)	1.63	(1.56E-02)
Resistance	R_T	Ω	1.93	
Inductance	L	mH	1.16	
No-Load Current	I_{NL}	A	0.32	
Peak Current (Stall)[2]	I_P	A	6.22	
Motor Constant	K_M	oz-in/√W (N-m/√W)	1.62	(1.14E-02)
Friction Torque	T_F	oz-in (N-m)	0.50	(3.5E-03)
Rotor Inertia	J_M	oz-in-s² (kg-m²)	2.7E-04	(1.9E-06)
Electrical Time Constant	τ_E	ms	0.63	
Mechanical Time Constant	τ_M	ms	14.4	
Viscous Damping	D	oz-in/krpm (N-m-s)	0.027	(1.8E-06)
Damping Constant	K_D	oz-in/krpm (N-m-s)	1.9	(1.3E-04)
Maximum Winding Temperature	θ_{MAX}	°F (°C)	311	(155)
Thermal Impedance	R_{TH}	°F/watt (°C/watt)	72.9	(22.7)
Thermal Time Constant	τ_{TH}	min	7.2	
Gearbox Data				
Encoder Data				
Channels			3	
Resolution		CPR	500	

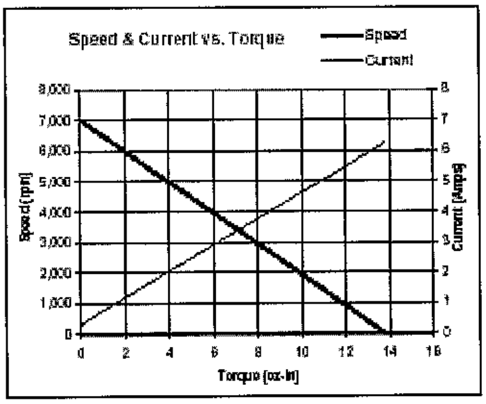
1 - Specified at max. winding temperature at 25°C ambient without heat sink. 2 - Theoretical values supplied for reference only.

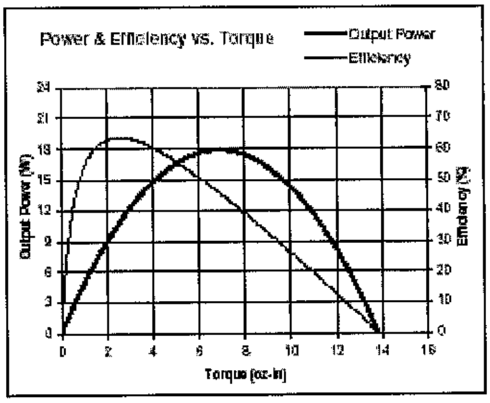
Included Features

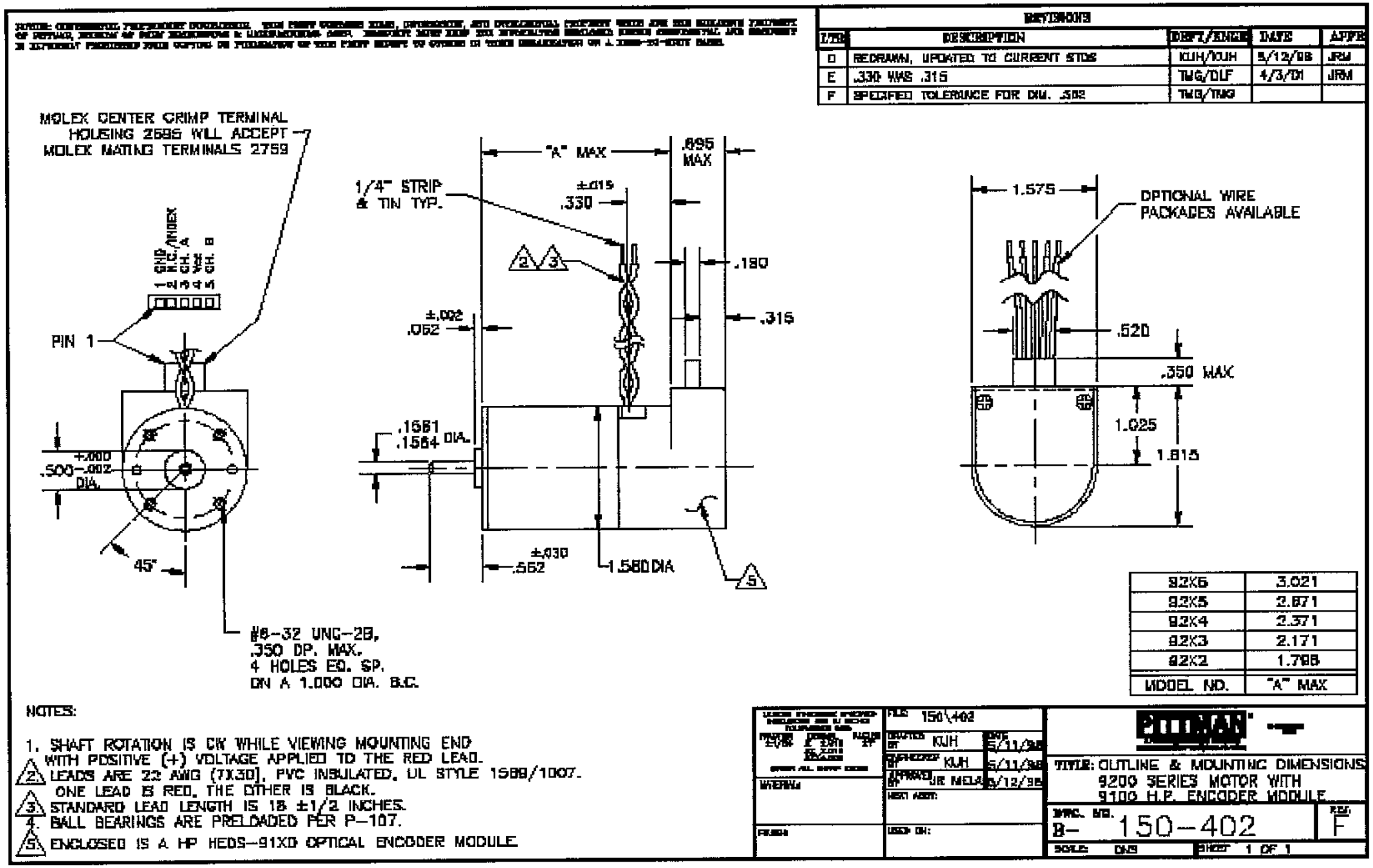
- 2-Pole Stator
- Ceramic Magnets
- Heavy-Guage Steel Housing
- 7-Slot Armature
- Silicon Steel Laminations
- Stainless Steel Shaft
- Copper-Graphite Brushes
- Diamond Turned Commutator
- Motor Ball Bearings

Customization Options

- Alternate Winding
- Sleeve or Ball Bearings
- Modified Output Shaft
- Custom Cable Assembly
- Special Brushes
- EMI/RFI Suppression
- Spur or Planetary Gearbox
- Special Lubricant
- Optional Encoder
- Fail-Safe Brake







LTR	DESCRIPTION	DEPT/ENGR	DATE	APPR
D	REDRAWN, UPDATED TO CURRENT STDS	KJH/KJH	5/12/98	JRM
E	.330 WAS .315	TMG/DLF	4/3/01	JRM
F	SPECIFIED TOLERANCE FOR DIA. .502	TMG/TMG		

MODEL NO.	"A" MAX
92X6	3.021
92X5	2.871
92X4	2.371
92X3	2.171
92X2	1.796

NOTES:

1. SHAFT ROTATION IS CW WHILE VIEWING MOUNTING END WITH POSITIVE (+) VOLTAGE APPLIED TO THE RED LEAD.
2. LEADS ARE 22 AWG (7X30), PVC INSULATED, UL STYLE 1569/1007. ONE LEAD IS RED, THE OTHER IS BLACK.
3. STANDARD LEAD LENGTH IS 18 ±1/2 INCHES.
4. BALL BEARINGS ARE PRELOADED PER P-107.
5. ENCLOSED IS A HP HEDS-91XD OPTICAL ENCODER MODULE.

FILE 150\402
DRAWN BY KJH DATE 5/11/98
ENGINEER BY KJH 5/11/98
APPROVED BY JR MELA 5/12/98

TITLE: OUTLINE & MOUNTING DIMENSIONS
9200 SERIES MOTOR WITH
9100 H.P. ENCODER MODULE

DWG. NO. B- 150-402 REV. F

SCALE: DNS SHEET 1 OF 1

APPENDIX C

UPM DATA SHEET

QUANSER
INNOVATE. EDUCATE

Universal Power Module

1503,1506,2405,2405-PWM

User Manual

1. Description

The Universal Power Module is a power amplifier that is required to drive each Quanser actuator. The UPM consists of:

- [1] ±12 Volt Power Supply.
- [4] Analog Sensor Inputs.
- [1] Power Amplified Analog Output (the gain is set by the choice of cable).

The above mentioned ports all provide test points alongside the standard connections to provide complete access to the inherent signals. These test points can be monitored externally if the user wishes (i.e. through an oscilloscope).

2. Module Options

The following is a table of Universal Power Modules available from Quanser.

Power Modules					
Model	**Maximum Output Voltage**	**Maximum continuous Current**	**Output**	**Type**	**Number of Outputs**
UPM-15-03	15	3	Linear	Voltage	1
UPM-15-06	15	6	Linear	Voltage	1
UPM-15-03x2	15	3	Linear	Voltage	2
UPM-24-05	24	5	Linear	Voltage	1
UPM-24-15-PWM	24	15	*PWM*	Current	1

Table 1 Available UPM Options

3. Common UPM Connections

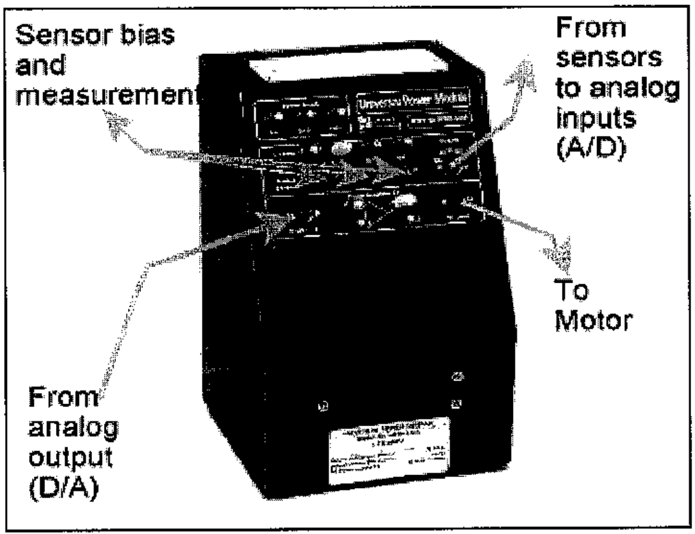


Figure 1 Typical UPM Connections

From...	*To...*	*Cable*	*Description*
D/A output Channel #0	'*From D/A*' on UPM	RCA to 5-pin DIN	This is your output signal that needs to be amplified.
Sensors	*S1,S2,S3,S4* on UPM	6-pin mini DIN	Connect all your analog sensors to the UPM (provides bias).
'*To A/D*' on UPM	A/D input Channels 0,1,2,3	5-pin DIN to 4 RCA cables	Routes all your sensor inputs to the DAC card
'*To Load*'	Motor	6-pin DIN to 4-pin DIN	This is the amplified signal used to drive your motor (or actuator).

Table 2 Most Common Configuration of UPM

**Note: Any Encoder inputs should be connected DIRECTLY to the DAC card. DO NOT Connect any Encoder signals to the UPM.*

4. Linear Power Modules

The following sections describes the majority of the Universal Power Modules available from Quanser. The UPM models that fall into the Linear category are:

- UPM 15-03
- UPM 15-06
- UPM 15-03x2
- UPM 24-05

The **motors** used in Quanser systems are DC motors. They may be either direct drive motors or geared motors. Geared motors have an internal gearbox which can be readily distinguished from the motor itself by examination. The motors are driven by the output of the amplifier (**UPM**). Voltage driven motors are driven using the ***UPM-XX-YY*** (NOT PWM). With the supplied cables, the circuit achieved is shown in Figure 2 below.The motor connector for motors that use the ***UPM-XX-YY*** power modules is a 4 pin DIN connector which is connected to the motor as shown.

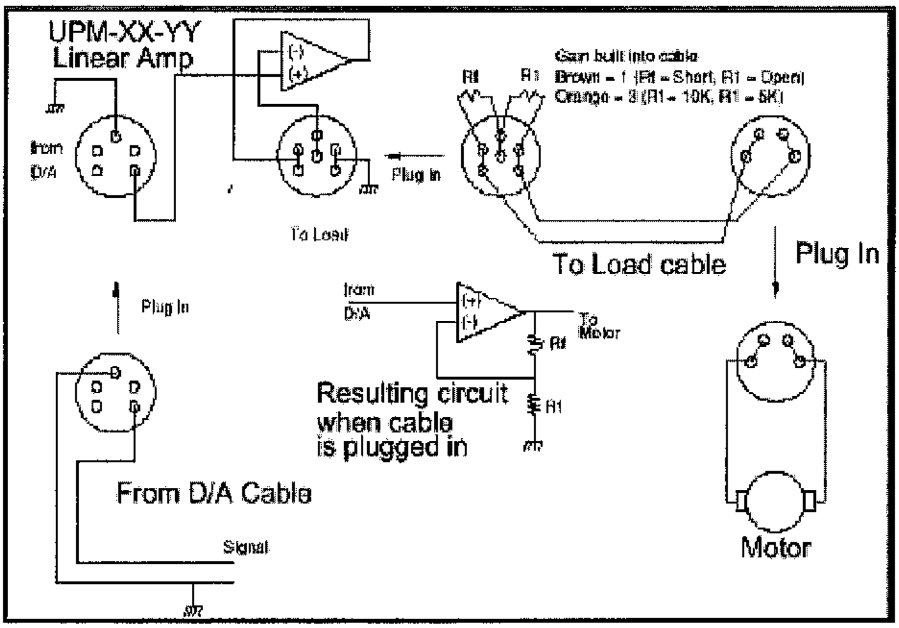


Figure 2 UPM XX-YY Schematic

**Note: Notice the resulting circuit is completed with the supplied cables. These cables are each calibrated to supply a specific gain and are clearly labeled. Always make sure that you are aware of the gain cable being used.*

5. PWM Power Amplifiers

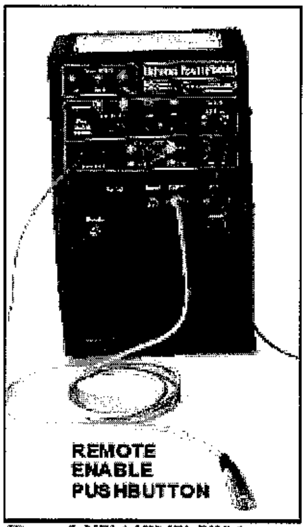


Figure 3 UPM-XX-YY-PWM

Motors that use the *UPM-XX-YY-PWM* have 6 pin connectors. The current gain in the amplifier is factory configured to output 2*YY amperes at 5 volts. The *output terminals are floating!* **DO NOT ATTACH A GROUND TO EITHER TERMINAL.** Furthermore, the PWM type amplifiers have the control panel shown in Figure 4.

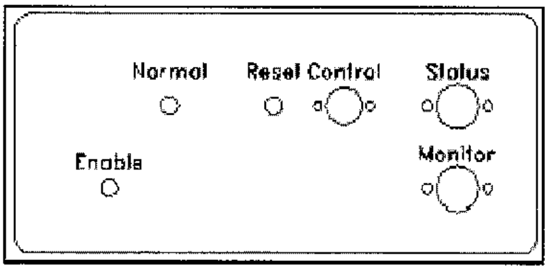


Figure 4 PWM Control Panel

The **Enable** switch along with the **Remote Pushbutton** enable the output of the amplifier. With the switch down or the pushbutton released,no power is delivered to the load. The **Normal** light indicates that the amplifier is enabled. In case of short circuit, the amplifier shuts off automatically and the **Reset** pushbutton must be used to re-initialize it.

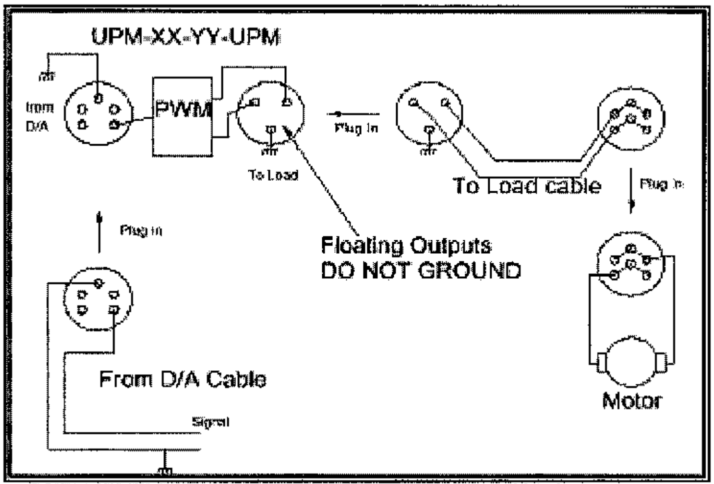


Figure 5 UPM-XX-YY-PWM Schematic when Operating in Normal Mode

The three **Control** signals should be grounded externally. All three enable lines must be tied low for the amplifier to operate normally. Floating any of the control signal results in disabling the amplifier output in one or both directions. The circuit on the left shows how the amplifier is used in normal operation. The **Enable** switch is tied in series with the **Remote** switch, the **Amplifier Enable** line and **Ground**. Both switches must be closed for the amplifier to operate normally. The Left Enable and Right Enable lines are tried low inside the Safety cable. You may use these lines to control the load in various manners.

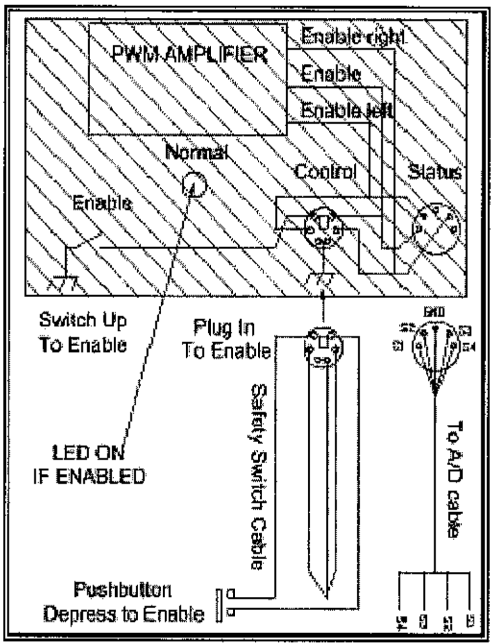


Figure 6 PWM Enable Signal Schematic

The Enable Status of the amplifier may be monitored through the signals available at the **Status** socket. If you use our standard 5 pin Din to 4 RCA cable, then the signals measured are as described in Table 3 below.

Status 5 Pin Din Socket	S1	Enable	S2	Enable Left	S3	Enable Right	S4
	Low = Enabled		Low = Enabled		Low = Enabled		N/A

Table 3 Signals available when connected to the STATUS socket

You may also monitor the amplifier related signals through the **Monitor** Socket. The signals you can monitor are the pre-amplifier voltage , the amplifier voltage and the **Current Monitor** signal which outputs a voltage proportional to the current being supplied. If you use our standard 5 pin Din to 4 RCA cable connected to the **Monitor** socket, the following signals can be measured.

Monitor 5 Pin Din Socket	S1	Pre-Amp	S2	Current Amplifier	S3	Current Monitor	S4
	1 Volt / volt		1 Volt / volt		(YY / 3) Ampere /volt		N/A

Table 4 Signals available when connected to the MONITOR socket

6. Recomended Power Modules

The following table is a reference to determine which Power Module should be used with each specific Quanser experiment. These following systems have been designed and tested with the specified configuration. Failure to adhere to these suggestions may result in unsatisfactory results and performance.

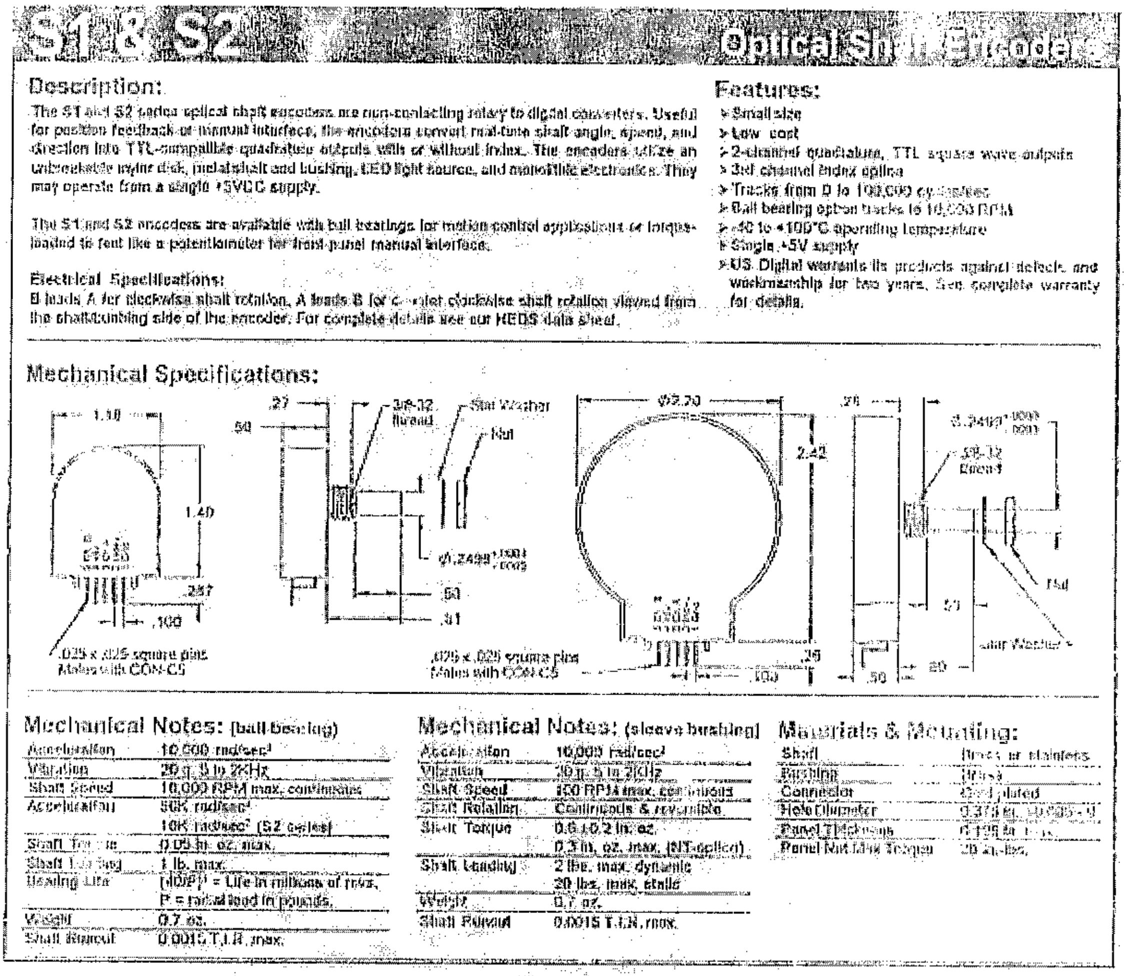
Actuator	Recommended Power Module
SRV02, SRV02-E	UPM-15-03
IP01,IP02	UPM-15-03
SRV03	UPM-24-15-PWM
Shaker Table Hi G AMD	UPM-24-15-PWM
2DOF Helicopter	Front Motor: UPM-24-05 Back Motor: UPM-15-03
3DOF Helicopter	UPM-12-03 x2
HiWire	UPM-15-03

Table 5 Recomended Power Modules for Quanser Actuators

APPENDIX d

ENCODER DATA SHEET

Appendix E. IP02 Encoder Specification Sheet



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:

.025 x .025 square pins
Mates with CON-C5

.025 x .025 square pins
Mates with CON-C5

Mechanical Notes: (ball bearing)

Acceleration	10,000 rad/sec²
Vibration	20 g, 5 to 2KHz
Shaft Speed	10,000 RPM max. continuous
Acceleration	50K rad/sec² 10K rad/sec² (S2 series)
Shaft Torque	0.05 in. oz. max.
Shaft Loading	1 lb. max.
Bearing Life	(40/P)³ = Life in millions of revs, P = radial load in pounds.
Weight	0.7 oz.
Shaft Runout	0.0015 T.I.R. max.

Mechanical Notes: (sleeve bushing)

Acceleration	10,000 rad/sec²
Vibration	20 g, 5 to 2KHz
Shaft Speed	100 RPM max. continuous
Shaft Rotation	Continuous & reversible
Shaft Torque	0.6 ±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.