Technical Report for the Implementation of the Restart-based Framework

1 Introduction

This article is intended to document the implementation of the restart-based framework on a realistic platform. The implementation mainly consists of two parts: *(i)* a main controller platform and *(ii)* a Root of Trust (RoT) module. The main controller runs tasks for user's application. Functions and tasks for the secure execution interval (SEI) are also handled on the same platform. The RoT module acts as a trustworthy hardware that can provide the security guarantees offered by the restart-based framework. An high level overview diagram that shows the connection between the main controller and the RoT module is given in Figure 1.

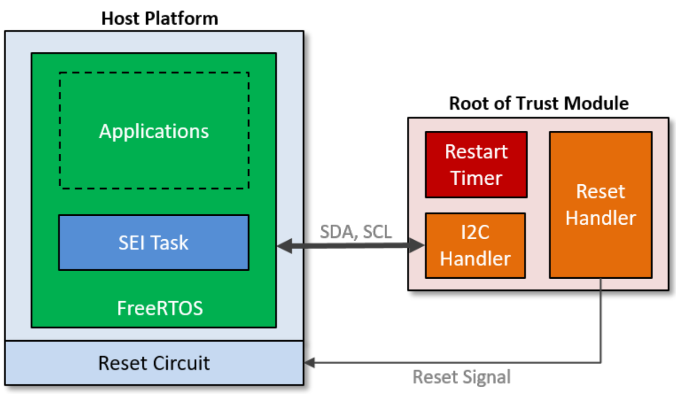

Figure 1: A high level overview of the connection between the main controller platform and the RoT module.

In the following content, §2 and §3 provide the details of the implementation for RoT module and the main controller respectively. §4 talks about the wiring between the RoT module and the main controller. §6 describes a demonstrative application that we have implemented to demonstrate the use of the proposed restart-based protection.

2 Root of Trust (RoT) Module

The main function of the RoT is to act as a trustworthy hardware that generates a configurable reset signal and enforces the secure execution interval. What follows below introduces the details of the RoT module we have implemented.

2.1 Hardware (MSP-EXP430G2)

A MSP-EXP430G2 board is used to realize the RoT module. The MSP-EXP430G2 board is a development board specifically designed for MSP430 series micro-controllers developed by *Texas Instruments* (TI). It is equipped with a MSP430G2452 [5], an instance of the MSP430 micro-controllers. The board is operated under 3.3V power which drives the MSP430G2452 micro-controller as well as its inputs/outputs. Figure 2 displays the board and its pinout.

The *Timer A* in the micro-controller is used to build the restart timer. It is a 16-bit timer that is configured to run at a clock rate of 1MHz (*i.e.*, 1us per timer count) with using its integrated

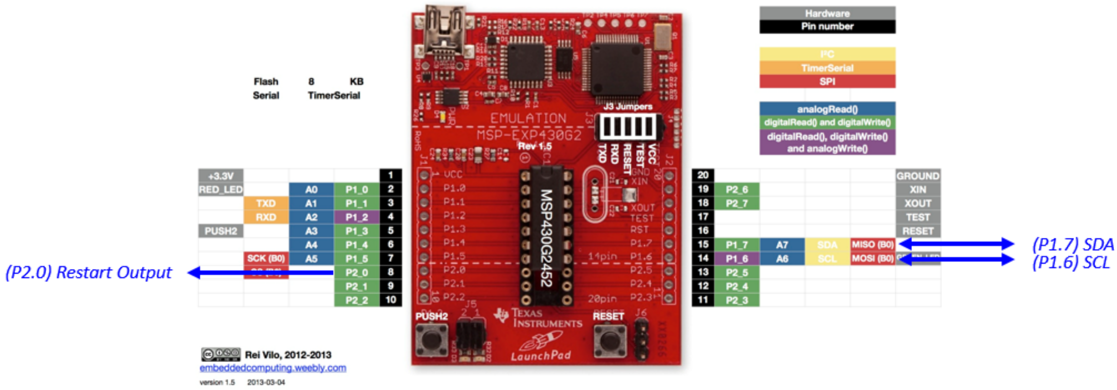

Figure 2: MSP-EXP430G2 board pinout.

digitally controlled oscillator (DCO). That is, the minimum restart time supported by the RoT module is $1us$. We use a counter inside the interrupt handler of *Timer A* to extend the timer with an adjustable factor, so the restart timer can count up to the range based on the application's needs.

2.2 I^2C Interface

To make the timer configurable to the host (the platform that uses the RoT module), a communication interface is provided. We choose I^2C as the interface in our design since I^2C is commonly adopted in many passive components (*e.g.,* sensors, memory modules). On the MSP430G2452 micro-controller, pin *P1.7* and *P1.6* can be configured as *SDA* and *SCL* for I^2C respectively, as shown in Figure 2.

2.3 RoT Control Flow

The RoT timer module listens incoming commands from the I^2C interface connected to the host. The RoT timer module maintains two timers: *(i)* a secure execution interval timer and *(ii)* a restart timer.

The restart timer enforces the duration between each restart of the system. When the restart timer is due, a reset signal is issued and is intended to trigger a reset for the host system. The secure execution interval timer is activated when a reset signal is issued (*i.e.,* right after the restart timer is due). The secure execution interval is designed for the host system to run security checks to determine the system's security level and to configure the next restart time. Once the system exits the secure execution interval (either the secure execution interval timer is due or the host actively tells the RoT module to exit the interval), the secure execution interval timer is terminated and the restart timer is activated. The control flow that runs in the RoT module is shown in Figure 3 and Figure 4.

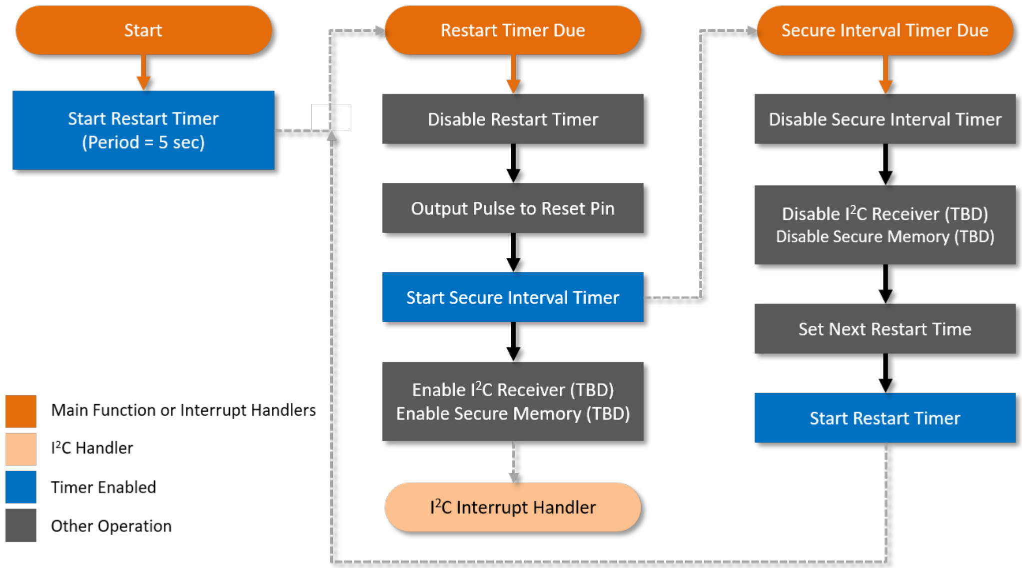

Figure 3: Flow chart of the RoT timer (1^{st} part).

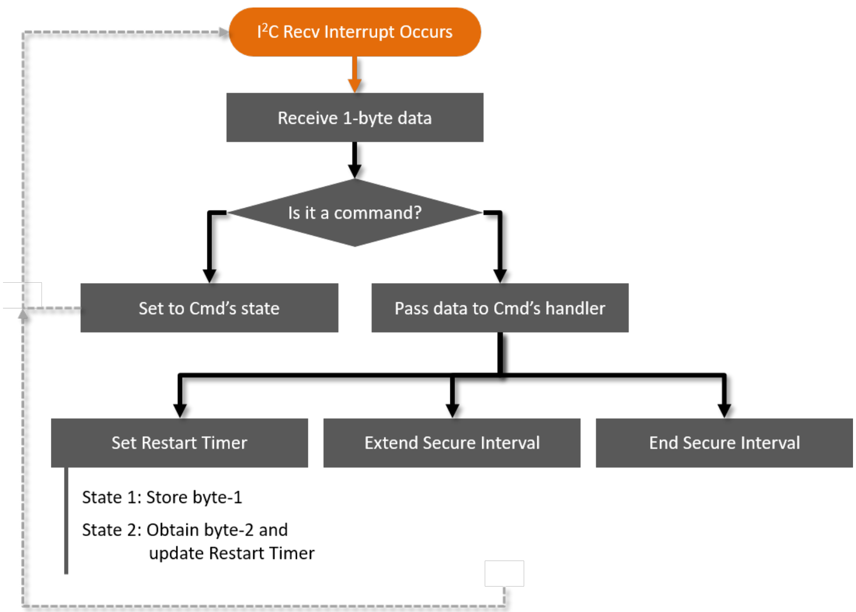

Figure 4: Flow chart of the RoT timer (2^{nd} part).

3 Main Controller Platform

3.1 Zedboard

A Zedboard [2] is used as an application platform in this implementation. It includes a XC7Z020 SoC, 512MB DDR3 memory and an on-board 256MB QSPI Flash. The XC7Z020 SoC consists of a processing system (PS) with dual ARM Cortex-A9 cores and a 7-series programmable logic (PL). The processing system runs at 667MHz. Note that only one ARM core is used in our implementation. The programmable logic is programmed to connect Zedboard's basic functions (*i.e.*, LEDs, switches, buttons). Figure 6 shows the circuit design in the programmable logic.

3.2 Boot Options

There are several boot options available on Zedboard: *(i)* boot via JTAG, *(ii)* boot via on-board flash and *(iii)* boot via external SD card. The boot mode can be configured by adjusting the

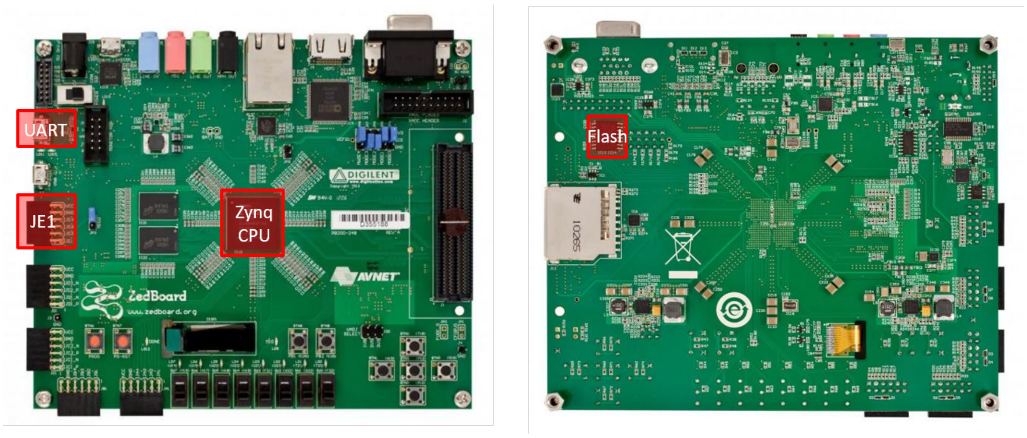

Figure 5: Top and bottom view of Zedboard. The *JE1* header is used to connect RoT module via I^2C interface.

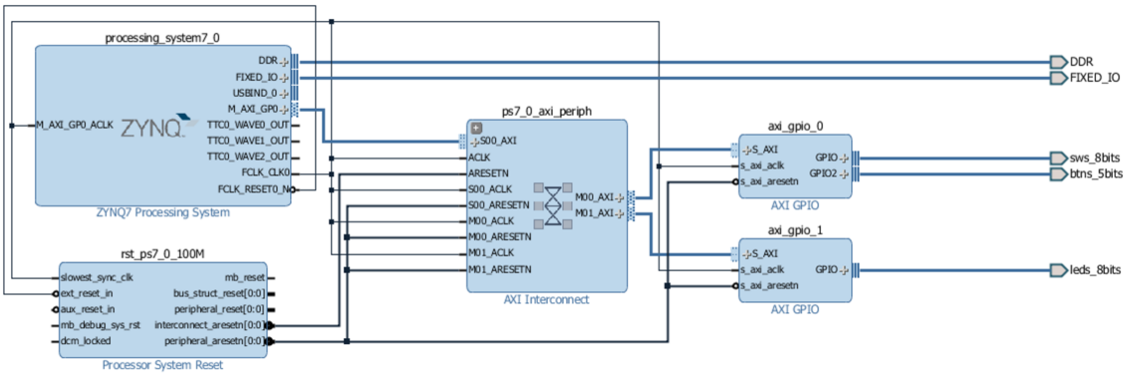

Figure 6: Programmable logic design in Zynq-7000 CPU on Zedboard.

positions of the jumpers on Zedboard as shown in Figure 7.

Figure 7: Boot options on Zedboard.

For an efficiency reason, we choose to boot the system via on-board flash. This option yields the fastest boot time among the three. A boot time measurement is given in §5.

3.3 SEI Task and Operating System

The main controller runs *FreeRTOS* [1], a preemptive real-time operating system, for both SEI tasks and application tasks. During SEI, only SEI tasks are created and executed when *FreeRTOS* starts. The SEI tasks set the next restart time to RoT module via I^2C interface. When SEI ends, the SEI tasks are terminated and the application tasks are created.

4 Interfacing Host Platform and RoT Timer

4.1 I^2C Interface

As we have introduced earlier, RoT timer provides I^2C for a host to configure its timer. In this case, Zedboard acts as a I^2C master while RoT timer acts as a I^2C slave. On Zedboard, ARM CPU's *MIO14* and *MIO15* are configured as *SCL* and *SDA* for I^2C respectively. As shown in Figure 8, ARM CPU's *MIO14* and *MIO15* are available on Zedboard as *JE9* and *JE10*. Therefore, Zedboard's *JE9* is connected to MSP430G2452's *P1.6* and Zedboard's *JE10* is connected to MSP430G2452's *P1.7*.

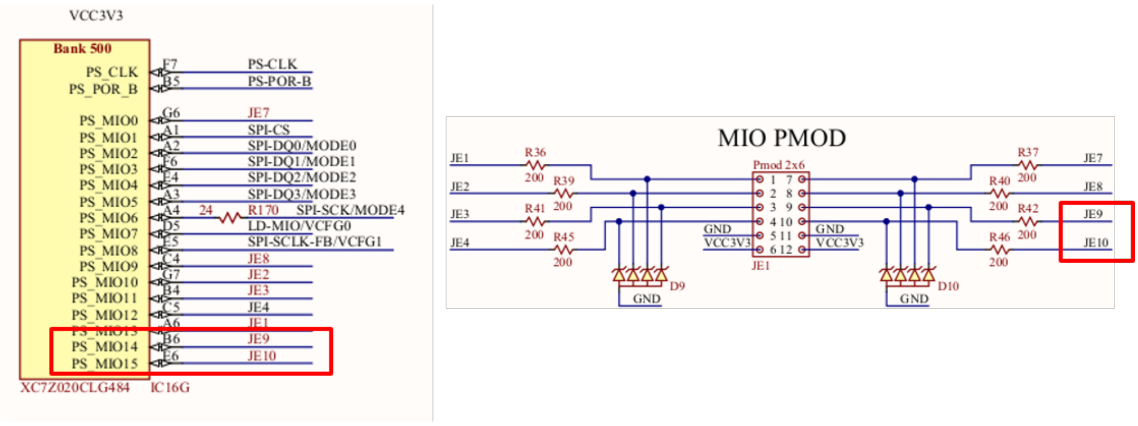

Figure 8: *MIO14* and *MIO15* pin locations on Zedboard.

To make I^2C interface work properly, a pull-up resistor is required on both *SDA* and *SCL* pins. Here, we use internal 3.3V pull-ups provided by the ARM core on *MIO14* and *MIO15*. Figure 9 shows the pull-up configurations for *MIO14* and *MIO15* in *Vivado*.

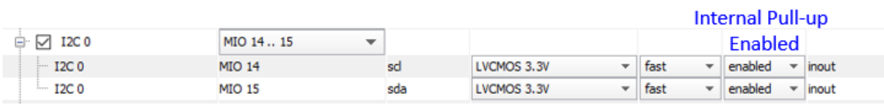

Figure 9: Configuration details for *MIO14* and *MIO15* in *Vivado*. The internal pull-ups for *MIO14* and *MIO15* are enabled.

4.2 Reset Signal

The main issue we have when connecting the reset output from the RoT module to Zedboard is the inconsistency of the I/O voltage. On Zedboard, the reset input uses 1.8V which is lower than RoT module's output voltage 3.3V. To avoid any damage caused by the voltage surcharge, a level shifter that converts 3.3V signal from RoT module to 1.8V signal for Zedboard is necessary. We use a BSS138, a N-channel logic level enhancement mode field effect transistor, to build a 3.3V to 1.8V level shifter (this is a bidirectional level shifter). Figure 10 shows the circuit design of the level shifter and Figure 11 shows the captured waveform of the reset signals on both 1.8V and 3.3V sides.

5 System Restart

The restart procedure activates by sending out a low state signal from RoT to Zedbaord. Upon restart, several things happen:

1. RoT triggers the reset pin. A complete reset signal include pulling the reset signal from high to low and then release it from low to high.
2. Zedboard is reset. Both PS and PL in the XC7Z020 SoC are reset. Note that, upon reset, the image for PL is cleared.

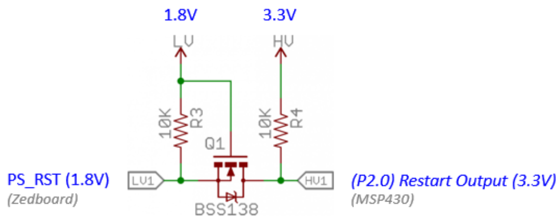

Figure 10: Converting 3.3V output signal from RoT module to 1.8V signal for Zedboard's reset input.

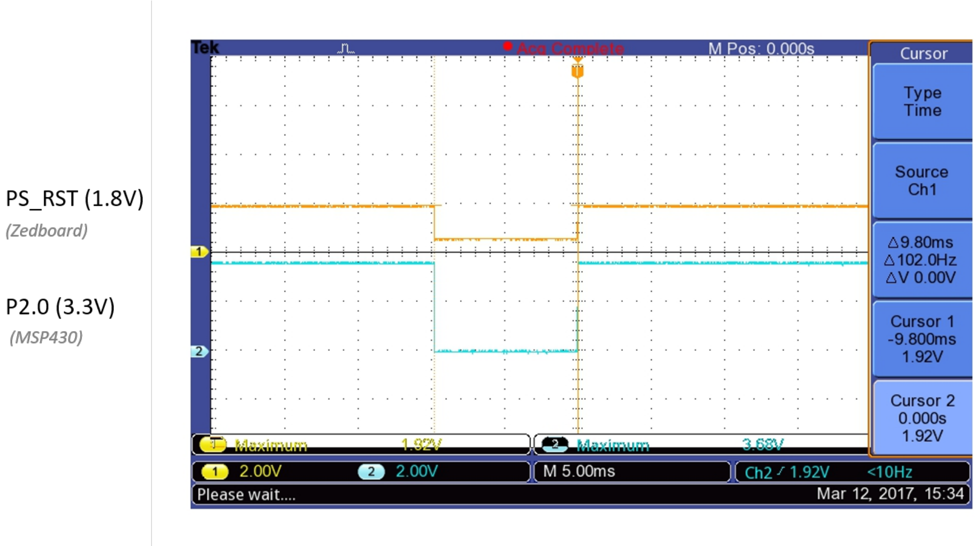

Figure 11: Waveform of the reset signals on RoT side and Zedboard side.

3. XC7Z020 loads a bootloader from the on-board Flash via QSPI to PS (it is configurable as described in §3.2).

4. The bootloader then loads an image from the on-board Flash to program PL. Note that configuring PL is necessary for PS to run correctly for following applications.

5. Once PL is ready, the bootloader loads the application image from the on-board Flash. The control of PS is handed to the loaded image once the loading is done.

From an experiment on the implemented system, the restart time (booting from the on-board QSPI Flash) measures 390ms as shown in Figure 12. As a side note, the restart time for booting from an external SD card (mentioned in §3.2) measures 680ms.

6 Demonstrative Application

In this section, we describe the use of restart-based framework under a more realistic configuration. Note that we leave the detail of the methodology in the main paper. We only focus on the implementation in this report.

6.1 3DOF Helicopter

3DOF helicopter (displayed in figure 13) is a simplified helicopter model, ideally suited to test intermediate to advanced control concepts and theories relevant to real world applications of flight dynamics and control in the tandem rotor helicopters, or any device with similar dynamics [3]. It is equipped with two motors that can generate force in the upward and downward direction, according to the given actuation voltage. It also has three sensors to measure elevation, pitch and travel angle as shown in Figure 13. We use the linear model of this system obtained from the

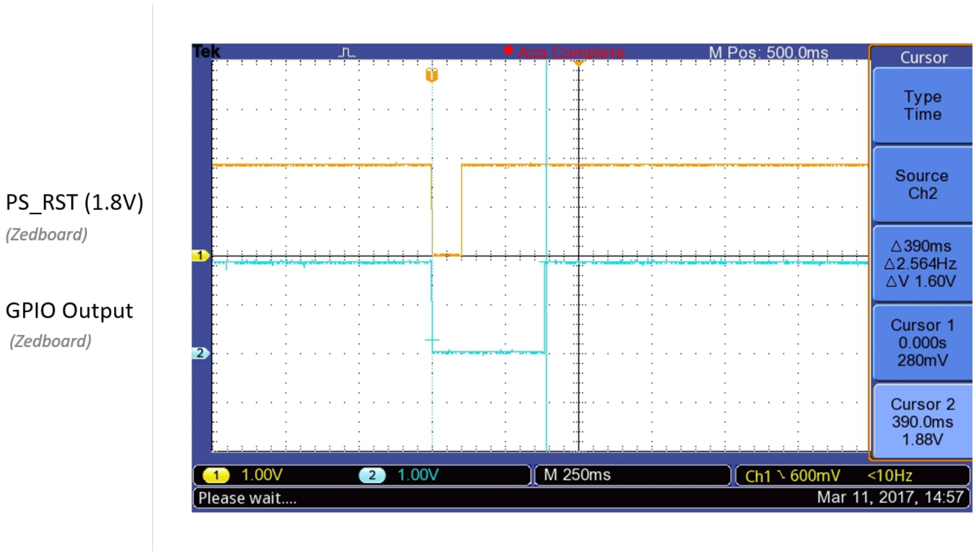

Figure 12: Measurement of the reboot time via on-board flash. It measures 390ms, from the triggering of the reset signal to the first executed instruction.

manufacturer manual [3] (manual is attched to the end of this document) for designing the BC and the DM and test the designed controller on the real system.

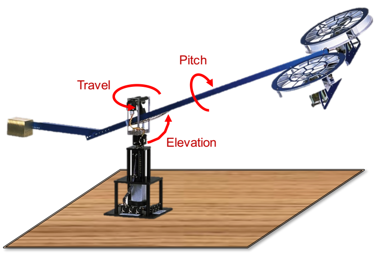

Figure 13: 3 Degree of freedom (3DOF) helicopter.

For 3DOF helicopter, the safety region is defined in such a way that the helicopter fans do not hit the surface underneath, as shown in Figure 13, while respecting the maximum angular velocities. The linear inequalities describing the safety region are given in (1) which is in the form of $H_x \cdot x \leq h_x$. In equation (1), the first two rows of the matrix H_x and vector h_x specify the set of pitch and elevation angles such that the helicopter does not contact with the surface.

$$\begin{bmatrix} -1 & -0.33 & 0 & 0 & 0 & 0 \\ -1 & 0.33 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \epsilon \\ \rho \\ \lambda \\ \dot{\epsilon} \\ \dot{\rho} \\ \dot{\lambda} \end{bmatrix} \leq \begin{bmatrix} 0.3 \\ 0.3 \end{bmatrix} \tag{1}$$

Here, variables ϵ, ρ, and λ are the elevation, pitch, and travel angles of the helicopter. Equation (2) describes the limits on the motor voltages of the helicopter in the form of $H_u \cdot u \leq h_u$.

$$\begin{bmatrix} 1 & 0 \\ -1 & 0 \\ 0 & 1 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} v_l \\ v_r \end{bmatrix} \leq \begin{bmatrix} 1.1 \\ 1.1 \\ 1.1 \\ 1.1 \end{bmatrix} \tag{2}$$

Here, v_l and v_r are the voltage for controlling left and right motors. Using the model and these linear safety requirements, we utilized the approach discussed in [6] to design the safety controller. The resulting safety controller is a gain feedback controller that runs on the system.

6.2 Interfacing 3DOF Helicopter and Zedboard

The main controller unit interfaces with the 3DOF helicopter through a PCIe-based *Q8 High-Performance H.I.L. Control and data acquisition unit* [4] and an intermediate Linux-based PC. The PC communicates with the ZedBoard through the serial port. At every control cycle, a task on the controller communicates with the PC to receive the sensor readings (elevation, pitch, and travel angles) and send the motors' voltages. The PC uses a custom Linux driver to send the voltages to the 3DOF helicopter motors and reads the sensor values.

6.3 Main Controller Design

6.3.1 SEI Tasks

Immediately after the reboot, `SafetyController` and `FindRestartTime` tasks are created and executed when the *FreeRTOS* starts. `SafetyController` is a periodic task with a period of $20ms$. It implements a simple 3DOF flight control function that keeps the flight in a safe state during SEI. And, `FindRestartTime` is a single task that returns before the end of SEI. Length of the SEI is set to $30ms$. `FindRestartTime` task is executed in a loop, and it only breaks out when a positive restart time is found. At this point, the restart time is sent to the RoT module via I^2C interface, `SafetyController` and `FindRestartTime` tasks are terminated and the main control application tasks are created.

6.3.2 3DOF Tasks

A periodic task is used to control 3DOF. The task implements a `ComplexController` with PID algorithm that controls 3DOF. It is similar to the controller used in `SafetyController` except that `ComplexController` controls 3DOF to make it move toward the configured set points.

References

[1] FreeRTOS. http://www.freertos.org/.

[2] Xilinx Zedboard. http://zedboard.org/.

[3] Quanser inc., 3 dof helicopter, 2016. http://www.quanser.com/products/3dof_helicopter, accessed: September 2016.

[4] Quanser inc., q8 data acquisition board, 2016. http://www.quanser.com/products/q8, accessed: September 2016.

[5] T. Instruments. Msp430x2xx family user's guide. 2013.

[6] D. Seto and L. Sha. A case study on analytical analysis of the inverted pendulum real-time control system. Technical report, DTIC Document, 1999.

Aerospace Plant: 3-DOF Helicopter

Position Control

3-DOF Helicopter

Reference Manual

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1. Introduction

The 3-DOF Helicopter plant is depicted in Figure 1. Two DC motors are mounted at the two ends of a rectangular frame and drive two propellers. The motors axes are parallel and the thrust vector is normal to the frame. The helicopter frame is suspended from in instrumented joint mounted at the end of a long arm and is free to pitch about its centre. The arm is gimbaled on a 2-DOF instrumented joint and is free to pitch and yaw. The other end of the arm carries a counterweight such that the effective mass of the helicopter is light enough for it to be lifted using the thrust from the motors. A positive voltage applied to the front motor causes a positive pitch while a positive voltage applied to the back motor causes a negative pitch. A positive voltage to either motor also causes an elevation of the body (i.e., pitch of the arm). If the body pitches, the thrust vectors result in a travel of the body (i.e., yaw of the arm) as well. The vertical base is equipped with an eight-contact slipring. Electrical signals to and from the arm and helicopter are channeled through the slipring to eliminate tangled wires, reduce friction, and allow for unlimited and unhindered travel.

Figure 1 3-DOF Helicopter when running.

The objective of this experiment is to design a control system to track and regulate the elevation and travel angles of the 3-DOF Helicopter. The system is supplied with a complete mathematical model, the system parameters, and a sample state-feedback controller.

As shown in Figure 2, the 3-DOF Helicopter can also be fitted with an Active Mass Disturbance System (ADS). The ADS is comprised of a lead-screw, a DC motor, an encoder, and a moving mass. The lead-screw is wound through the mass such that when lead is rotated the mass moves along the helicopter arm linearly. One end of the lead-screw is connected to a DC motor and the other end has an encoder. As the motor is driven, the lead-screw rotates and causes the mass to move. Using the encoder measurement and a position controller, the user can move the mass to a desired position and actively disturb the helicopter.

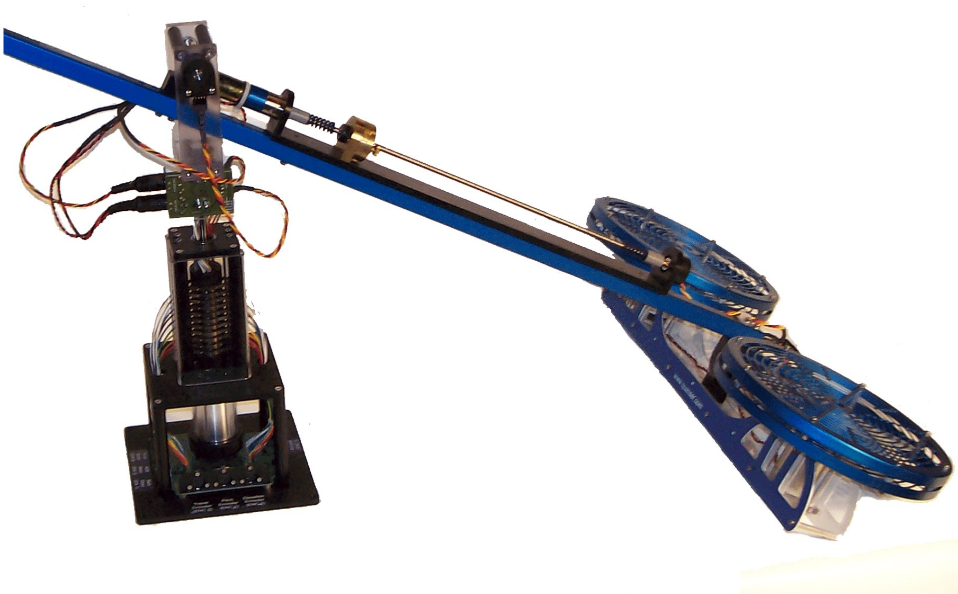


Figure 2: Active Disturbance System on the 3-DOF Helicopter.

2. Prerequisites

In order to successfully carry out this laboratory, the user should be familiar with the following:

- 3-DOF Helicopter main components (e.g. actuator, sensors), the data acquisition card (e.g. Q8), and the power amplifier (e.g. UPM), as described in Section 4, Reference [1], and Reference [4], respectively.
- Wiring the 3-DOF Helicopter plant with the UPM and DAC device, as discussed in Section 5.
- State-feedback control and the Linear-Quadratic Regulator, i.e. LQR, enough to design a controller.
- Using WinCon to control and monitor a plant in real-time and in designing a controller through Simulink. See Reference [2] for more detail and, in particular, ensure a few examples described in the *Model Examples* section are ran before running any of the 3-DOF Helicopter controllers.

3. Experiment Files Overview

Table 1 below lists and describes the various files supplied with the 3-DOF Helicopter experiment.

File Name	***Description***
3-DOF Helicopter Reference Manual.pdf	This manual is both the user and laboratory guide for the Quanser 3-DOF Helicopter specialty aerospace plant. It contains information about the hardware components, specifications, information to setup and configure the hardware, system modeling, control design, as well as the experimental procedure to simulate and implement the controller.
3-DOF Heli Equations.mws	Maple worksheet used to analytically derive the state-space model involved in the experiment. Waterloo Maple 9, or a later release, is required to open, modify, and execute this file.
3-DOF Heli Equations.html	HTML presentation of the Maple Worksheet. It allows users to view the content of the Maple file without having Maple 9 installed. No modifications to the equations can be performed when in this format.
quanser.ind and quanser.lib	The *Quanser_Tools* module defines the generic procedures used in Lagrangian mechanics and resulting in the determination of a given system's equations of motion and state-space representation. It also contains data processing routines to save the obtained state-space matrices into a Matlab-readable file.
setup_lab_heli_3d.m	The main Matlab script that sets the model, control, and configuration parameters. **Run this file only to setup the laboratory.**
setup_heli3d_configuration.m	Returns the 3-DOF Helicopter model parameters *Kf, m_h, m_w, m_f, m_b, Lh, La, Lw,* and *g,* the encoder calibration constants *K_EC_T, K_EC_P,* and *K_EC_E*.
setup_ads_configuration.m	Returns the various parameters associated with the Active Disturbance System (ADS).
HELI3D_ABCD_eqns.m	Matlab script file generated using the Maple worksheet *3-DOF Heli Equations.mws.* It sets the *A*, *B*, *C*, and *D* matrices for the state-space representation of the 3-DOF Helicopter open-loop system which is used in *s_heli3d.mdl* and to design an LQR-based controller.
s_heli3d.mdl	Simulink file that simulates the closed-loop 3-DOF Helicopter system using its linear equations of motion model and a position controller.
q_heli3dr_zz.mdl	Simulink file that implements the real-time state-feedback LQR controller for the 3-DOF Helicopter system. The *zz* suffix denotes the data acquisition board used, for example the *q4* or *q8*.

Table 1: Files supplied with the 3-DOF Helicopter experiment.

4. System Description

The following is a listing of the major hardware components used for this experiment:

- **Power Amplifier**: Two Quanser UPM-2405, or equivalent.
- **Data Acquisition Board**: Quanser Q8, Q4, or equivalent.
- **Helicopter Plant**: Quanser 3-DOF Helicopter aerospace experiment with or without the Active Disturbance System (ADS).
- **Real-time control software**: PC equipped with WinCon-Simulink-RTX configuration.

See the references listed in Section 8 for more information on these components.

4.1. Components

Section 4.1.1 lists the components on the 3-DOF Helicopter plant and Section 4.1.2 describes the components on the 3-DOF Helicopter device with the Active Disturbance System (ADS).

4.1.1. 3-DOF Helicopter Components

The components comprising the 3-DOF Helicopter system are labeled in figures 3, 4, and 5 are described in Table 2. The motors, propeller assemblies, and encoders are described in more detail below.

ID #	*Description*	*ID #*	*Description*
1	Helicopter body	11	Slip ring
2	Motor	12	Base
3	Front propeller assembly	13	Ball-bearing block
4	Back propeller assembly	14	Travel encoder
5	Pitch encoder	15	Front motor connector
6	Arm	16	Back motor connector
7	Elevation encoder frame	17	Travel encoder connector
8	Elevation encoder	18	Pitch encoder connector
9	Counterweight	19	Elevation encoder connector
10	Encoder/motor circuit		

Table 2: 3-DOF Helicopter component nomenclature.

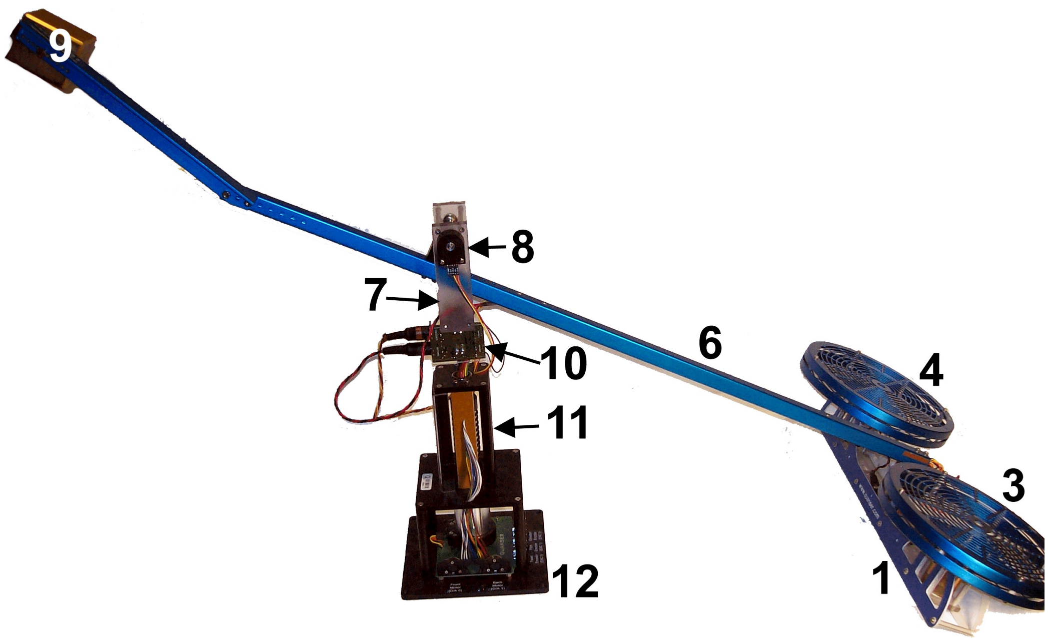


Figure 3: Components of 3-DOF Helicopter.

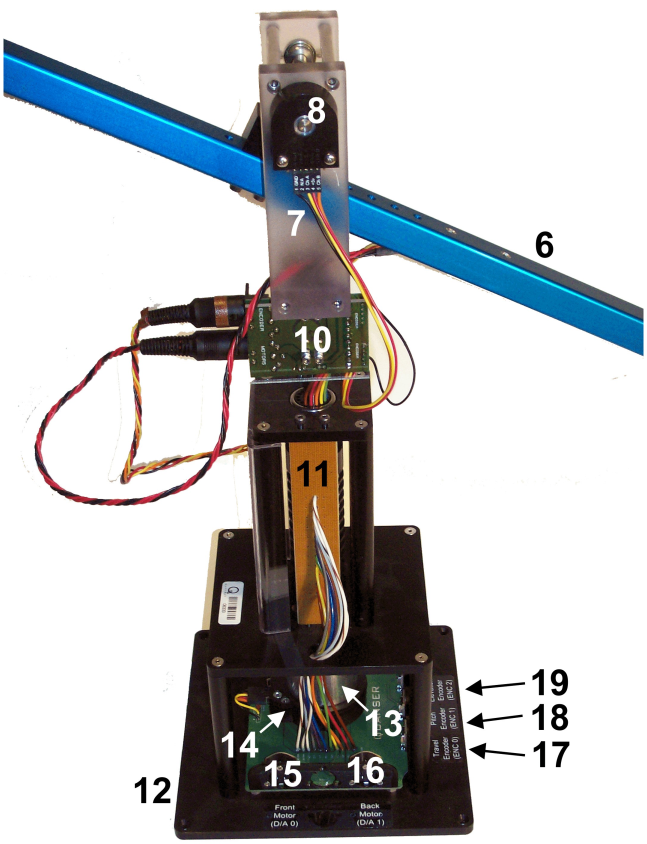


Figure 4: Components on 3-DOF Helicopter base.

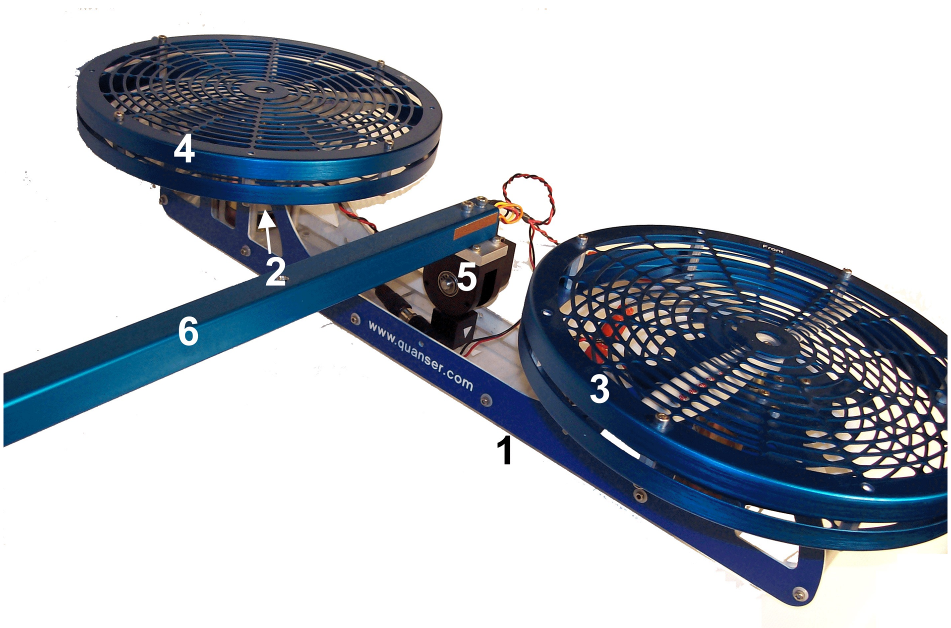


Figure 5: Components on the helicopter body of the 3-DOF Helicopter system.

4.1.1.1. DC Motors (Component #2)

The 3-DOF Helicopter has two DC motors: the front and back motors Each DC motor is a *Pittman Model 9234*. It has an electrical resistance of 0.83 Ω and a current-torque constant of 0.0182 N·m/A. The rated voltage of the motor is 12 V but its peak voltage can be brought up to 22 V without damage. See Reference [5] for the full specifications of this motor.

4.1.1.2. Propeller Assemblies (Component #3 and 4)

The front and back propeller assemblies are composed of the actual propeller, which is directly mounted to the motor shaft, and the aluminum propeller shield. The propellers used for both the front and rear motors are Graupner 20/15 cm or 8/6". They have an identified thrust-force constant of 0.119 N/V.

4.1.1.3. Encoders (Components #5, #8, and #14)

The 3-DOF Helicopter experiment has three encoders: the encoder measuring the pitch of the helicopter body, the encoder measuring the elevation of the body, and the encoder measuring the travel of the body. In quadrature mode, the pitch and elevation encoders have a resolution of 4096 counts per revolution and the travel encoder has a resolution of 8192 counter per revolution. Thus the effective position resolution is 0.0879 degrees about the pitch and elevation axes and 0.0439 degrees about the travel axis.

4.1.2. Active Disturbance System Components

The components of the Active Disturbance System (ADS) on the 3-DOF Helicopter system is labeled in figures 6, 7, and 8 and the described in Table 2 and Table 3.

ID #	Description	ID #	Description
20	ADS Motor	23	ADS Encoder
21	Active Disturbance Mass	24	ADS Motor Connector
22	Lead-screw	25	ADS Encoder Connector

Table 3: Additional components on the 3-DOF Helicopter ADS experiment.

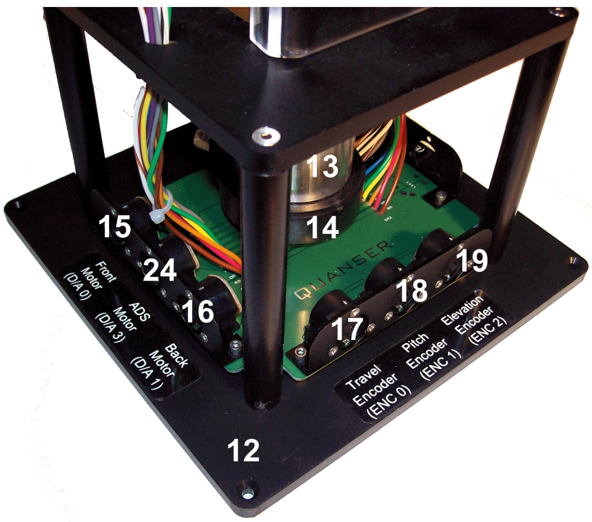


Figure 6: Connectors on base of 3-DOF Helicopter ADS experiment – ADS motor connector side view.

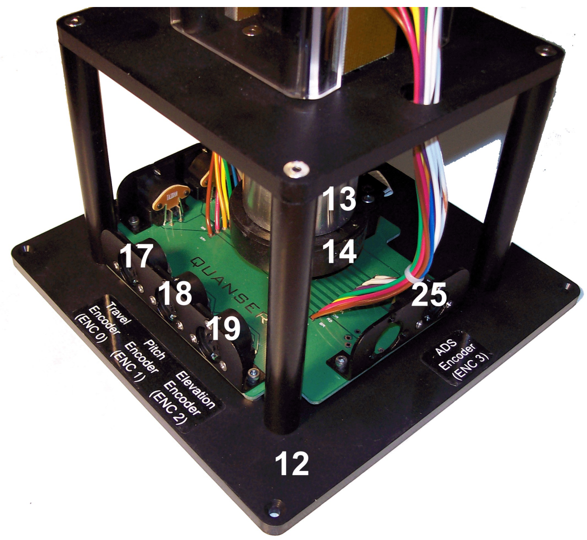


Figure 7: Connectors on base of 3-DOF Helicopter ADS experiment – ADS encoder side view.

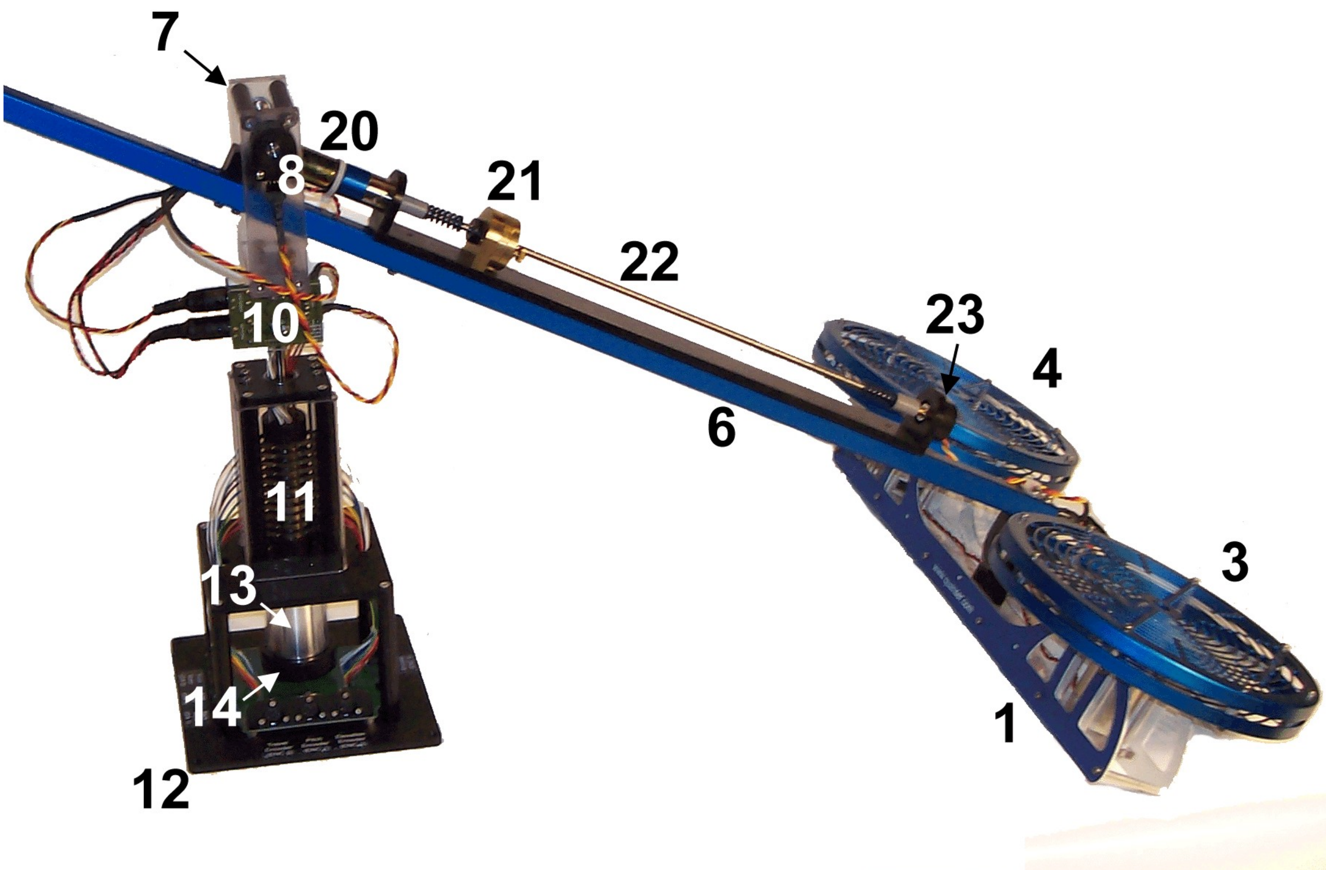


Figure 8: Components of the Active Disturbance System (ADS) on the 3-DOF Helicopter.

4.2. System Specifications

The 3-DOF Helicopter system specifications are given in Section 4.2.1 and the Active Disturbance System specifications are listsed in Section 4.2.2.

4.2.1. 3-DOF Helicopter Parameters

Table 4 below lists the main parameters associated with the Quanser 3-DOF Helicopter experiment. The parameters that are *not* used in the mathematical model of the system or in the lab files given are shaded.

Symbol	*Matlab Notation*	*Description*	*Value*	*Unit*
R_m	Rm	Motor armature resistance.	0.83	Ω
K_t	Kt	Motor current-torque constant.	0.0182	N.m/A

Symbol	Matlab Notation	Description	Value	Unit
J_m	Jm	Motor rotor moment of inertia.	1.91E-006	$kg.m^2$
K_f	Kf	Propeller force-thrust constant (found experimentally).	0.1188	N/V
M_h	Mh	Mass of the helicopter (body, two propellers assemblies, encoders, etc.).	1.15	kg
M_w	Mw	Mass of the counterweight.	1.87	kg
M_f	Mf	Mass of front propeller assembly (includes motor, shield, propeller, and half helicopter body).	0.713	kg
M_b	Mb	Mass of back propeller assembly.	0.713	kg
L_a	La	Distance between travel axis to helicopter body.	0.660	m
L_h	Lh	Distance between pitch axis to each motor.	0.178	m
L_w	Lw	Distance between travel axis to the counterweight.	0.470	m
g	g	Gravitational constant.	9.81	m/s^2
$K_{EC,LN,T}$	K_LN_EC_T	Travel encoder resolution (in quadrature mode).	8192	counts/rev
$K_{EC,LN,P}$	K_LN_EC_P	Pitch encoder resolution (in quadrature mode).	4096	counts/rev
$K_{EC,LN,E}$	K_LN_EC_E	Elevation encoder resolution (in quadrature mode).	4096	counts/rev
$K_{EC,T}$	K_EC_T	Travel encoder calibration gain.	7.67E-04	rad/counts
$K_{EC,P}$	K_EC_P	Pitch encoder calibration gain.	1.50E-03	rad/counts
$K_{EC,E}$	K_EC_E	Elevation encoder calibration gain.	-1.50E-03	rad/counts

Table 4: 3-DOF Helicopter system specifications.

4.2.2. ADS Parameters

Table 5 below describes the specifications of 3-DOF Helicopter Active Disturbance System.

Symbol	*Matlab Notation*	*Description*	*Value*	*Unit*
V_{nom}	Vnom	Motor nominal input voltage.	6.0	V
R_m	Rm	Motor armature resistance.	2.6	Ω
L_m	Lm	Motor armature inductance.	0.18	mH
K_t	Kt	Motor current-torque constant.	0.00767	N.m/A
K_m	Km	Motor back emf constant.	0.00767	V.s/rad
J_m	Jm	Motor rotor moment of inertia.	3.90E-007	$kg.m^2$
K_g	Kg	Internal gearbox gear ratio.	3.71	
P_b	Pb	Lead-screw pitch	1/3	in/rev
x_{max}	X_MAX	Maximum travel limit of disturbance mass.	0.264	m
v_{max}	V_MAX	Maximum speed of disturbance mass.	0.25	m/s
$K_{EC,LN,X}$	K_EN_LN_X	ADS encoder resolution (in quadrature mode).	4096	count/rev
$K_{EC,X}$	K_EC_X	Calibration gain for linear position of disturbance mass.	-2.067E-006	m/count

5. System Setup and Wiring

Section 5.1 describes how to assemble and setup the Quanser 3-DOF Helicopter specialty plant. The cables used to connect the helicopter system are summarized in Section 5.2 and the standard wiring procedure is given in Section 5.3. Section 5.4 features the additional connections needed if using the Active Disturbance System. Lastly, the joystick that can be used to control the helicopter is discussed in Section 5.5.

5.1. System Setup

Follow these steps for the mechanical setup of the Quanser 3-DOF Helicopter device:

1. Place the support base, component #12 shown in Figure 3, on a table or on the floor.
2. Install the elevation encoder frame, component #7 in Figure 3, on the top of the base. Ensure the white arrow labels on the circuit, ID #10 in in Figure 3, and on the frame are aligned. Once fitted, tighten the two thumb screws.
3. Guide the long blue arm, ID #6 in Figure 3, through the elevation encoder frame. Tighten the cap screw maintaining perpendicularity to the elevation encoder frame wall.

CAUTION: Never apply extreme loads in the vertical direction!

4. There are two cables protruding from the main arm: the 6-pin-DIN to 6-pin-DIN motor connector and the 5-pin-DIN to 5-pin-DIN encoder connector. Connect the motor cable to the connector labeled “MOTOR” on the helicopter circuit, component #10, shown in Figure 10.
5. Connect the encoder cable to the connector labeled “ENCODER” on the helicopter circuit (ID #10 in Figure 10). Make sure there is sufficient slack in the wiring harness to accommodate the total travel of the arm.

CAUTION: Never lift the system using the blue arm. Always carry from the base with one hand and stabilize the blue arm with the other hand.

6. Connect the flat 5-pin encoder connector from the helicopter circuit to the elevation encoder, ID #8 in Figure 4. Make sure the GND pin on the cable is wired to the connector labeled GND on the elevation encoder.
7. Attach the helicopter body, ID #1 in Figure 5, to the T-fitting of the pitch encoder (ID #5 in Figure 5). Ensure the white arrow labels on the helicopter body and the T-Fitting are both aligned and tighten the screw from the bottom of the helicopter body. Adjust the helicopter body such that it is perpendicular to the arm
8. As illustrated in Figure 9, attach the secondary arm to the end of the main arm, ID #6 in Figure 3, and tighten two screws through the nuts. The angle of the secondary arm relative to the main arm has been selected such that the effective mass at the helicopter end is relatively constant.
9. Once the secondary arm is securely fastenned, attach the counterweight to the hole marked 71 g and tighten the thumb screw to secure the weight.

NOTE: When using the Active Disturbance System, set the counterweight to the 0 g position, as depicted in Figure 9.

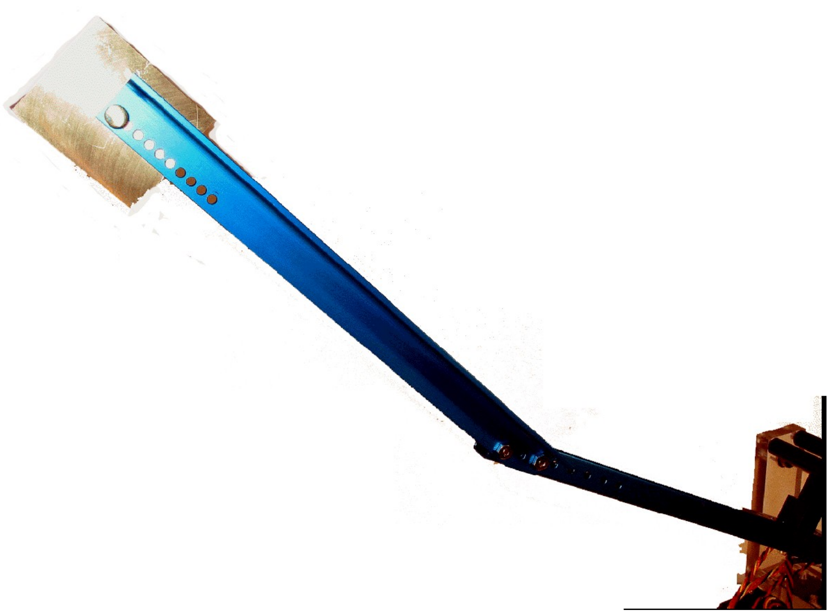


Figure 9: Counterweight and secondary arm setup.

10. Using a weigh scale, measure the weight of the helicopter body with the counterweight attached at the other end. The desired mass differential is approximately 70 g. If the body does not weigh

70 g, adjust the position of the counterweight (i.e. forward or backward) until the body weighs approximately 70 g. Once in place the weight adjustment does not have to be repeated. If you do not have a scale, leave the mass at marked position.

11. The standard setup, in the default configuration, and starting position for the 3-DOF Helicopter system is depicted in Figure 10.

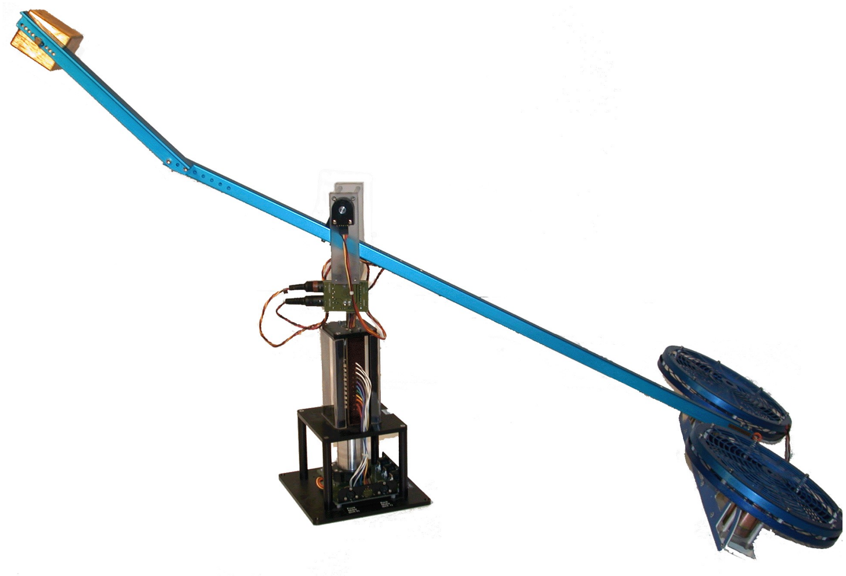


Figure 10: Starting position of the 3-DOF Helicopter system.

12. Ensure all obstructions that may interfere with the complete 360-degree axial motion of the helicopter are removed before performing any experiment.

5.2. Cable Nomenclature

Table 5, below, provides a description of the standard cables used in the wiring of the 3-DOF Helicopter system.

Cable	Designation	Description
 *Figure 11 "From Digital-To-Analog" Cable*	5-pin-DIN to RCA	This cable connects an analog output of the data acquisition terminal board to the power module for proper power amplification.
 *Figure 12 "To Load" Cable Of Gain 5*	4-pin-DIN to 6-pin-DIN	This cable connects the output of the power module, after amplification, to the desired actuator (e.g., propeller motor). One end of this cable contains a resistor that sets the amplification gain. When carrying a label showing "5", at both ends, the cable has that particular amplification gain.
 *Figure 13 "Encoder" Cable*	5-pin-stereo-DIN to 5-pin-stereo-DIN	This cable carries the encoder signals between an encoder connector and the data acquisition board (to the encoder counter). Namely, these signals are: +5VDC power supply, ground, channel A, and channel B.
 *Figure 14 "From Analog Sensors" Cable*	6-pin-mini-DIN to 6-pin-mini-DIN	This cable carries analog signals (e.g., from joystick, plant sensor) to the UPM, where the signals can be either monitored and/or used by a controller. The cable also carries a ±12VDC line from the UPM in order to power a sensor and/or signal conditioning circuitry.

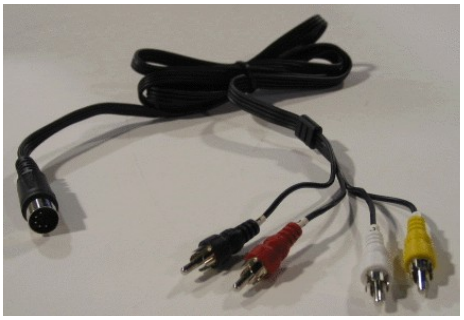
Cable	*Designation*	*Description*
 *Figure 15 "To Analog-To-Digital" Cable*	5-pin-DIN to 4xRCA	This cable carries the analog signals, unchanged, from the UPM to the Digital-To-Analog input channels on the data acquisition terminal board.

Table 5 Cable Nomenclature

5.3. Typical Connections For The 3-DOF Helicopter

The travel, pitch, and elevation encoders are connected directly to the data-acquisition board. This provides the position feedback necessary to control the helicopter. The data-acquisition board, i.e. DACB, outputs a control voltage that is amplified and drives the front and back motors. Both motors are driven by a Quanser Universal Power Module 2405, i.e. UPM-2405, or equivalent. The UPM-2405 is capable of delivering a maximum voltage of ±24V to the motors

This section describes the typical cabling connections that are used by default for the Quanser 3-DOF Helicopter system. Figures 16, 17, 18, and 19 below illustrate, respectively, the wiring of the UPM driving the front motor, the UPM driving the back motor, the Q8 Terminal Board, and the Helicopter base. The connections are described in detail in the procedure below and summarized in Table 6.

Follow these steps to connect the 3-DOF Helicopter system:

1. It is assumed that the Quanser Q4 or Q8 board is already installed as discussed in the Reference [1]. If another data-acquisition device is being used, e.g. NI M-Series board, then go to its corresponding documentation and ensure it is properly installed.
2. Make sure everything is powered off before making any of these connections. This includes turning off your PC and the UPMs.
3. Connect the 5-pin-DIN to RCA cable from the *Analog Output Channel #0* on the DAC board to the *From D/A Connector* on a UPM-2405. See cable #1 shown in Figure 16 and Figure 18. This carries the attenuated **front** motor voltage control signal, V_f/K_a, where K_a is the UPM-2405 amplifier gain.
4. Connect the 5-pin-DIN to RCA cable from the *Analog Output Channel #1* on the DAC board to the *From D/A Connector* on a UPM-2405. See the cable #2 shown in Figure 17 and Figure 18. This carries the attenuated **back** motor voltage control signal, V_b/K_a.
5. Connect the 4-pin-stereo-DIN to 6-pin-stereo-DIN that is labeled **Gain 5** from *To Load* on the

UPM-2405 to the *Front Motor* connector. See connection #3 shown in Figure 16 and Figure 19. This cable sets the gain of the amplifier to 5 and the connector on the UPM-side is gray in colour. The cable transmits the amplified voltage that is applied to the **front** motor, denoted V_f.

ATTENTION: The Quanser **UPM-2405** is capable of providing the required power to the 3-DOF Helicopter motors. However, it should be used in conjunction with a ***"To Load"*** **cable of gain 5** (i.e. 4-pin-DIN-to-6-pin-DIN cable), as described in Table 5, above. See Reference [4] for more detail.

6. Connect the 4-pin-stereo-DIN to 6-pin-stereo-DIN that is labeled **Gain 5** from *To Load* on the UPM-2405 to the *Back Motor* connector. See connection #4 shown in Figure 17 and Figure 19. The cable carries the amplified **back** motor voltage and is represented by the variable V_b.
7. Connect the 5-pin-stereo-DIN to 5-pin-stereo-DIN cable from the *Travel Encoder* connector on the 3-DOF Helicopter base to *Encoder Input # 0* on the terminal board, as depicted by connection #5 in Figure 18 and Figure 19. This carries the travel angle measurement and is denoted by the variable λ..

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!**

8. Connect the 5-pin-stereo-DIN to 5-pin-stereo-DIN cable from the *Pitch Encoder* connector on the 3-DOF Helicopter base to *Encoder Input # 1* on the terminal board. See connection #6 in Figure 18 and Figure 19. This carries the pitch angle measurement which is represented by the variable p.
9. Connect the 5-pin-stereo-DIN to 5-pin-stereo-DIN cable from the *Elevation Encoder* connector on the 3 DOF Helicopter base to *Encoder Input # 2* on the terminal board. This connection is illustrated in Figure 18 and Figure 19 by ID #7. It carries the elevation angle measurement, ε.
10. **If you are using the analog joystick shown in** Figure 24 **go to Step 11**. If you are using are using the Logitech Attack 3 USB joystick shown in Figure 25, then connect the USB cable from the joystick to a USB port on the PC while it is running. The system should detect the joystick and automatically install the driver (you will be prompted). See the *Logitech Installation Manual* for more information on the setup procedure. Note that if the USB joystick is used then the analog connections shown in Figure 17 and the 5-pin-DIN to 4xRCA cable connection shown in Figure 17 and Figure 18 are not needed and these cables would not be supplied. Also, the shaded connections listed in Table 6 can be ignored. See Section 5.5 for more information on system requirements of the Logitech joystick and how to use the *Rate Command* knob.
11. To setup an analog joystick shown in Figure 24, connect its *X* analog cable to the **"S3"** socket and its *Y* analog cable to the **"S4"** socket on a UPM-2405, as shown in Figure 17 with cable #8 for *X* and cable #9 for *Y*. **Ensure the UPM is not powered when making this connection.**
12. Connect the **"To A/D"** socket on the UPM-2405 with the joystick connections to Analog Inputs #0-3 on the terminal board using the 5-pin-DIN to 4xRCA cable, as illustrated in Figure 17 and Figure 18. The RCA side of the cable is labeled with the channels. Note that the cable with label "1" is goes to *Analog Input Channel #0*. **Ensure UPM and PC are off when making this connection!** The X and Y signals that are connected to the **"S3"** and **"S4"** terminals on the UPM are read in as *Analog Input #2* and *Analog Input #3* in WinCon.

Figure 16 Front Universal Power Module (UPM-2405)

Figure 17 Back Universal Power Module (UPM-2405)

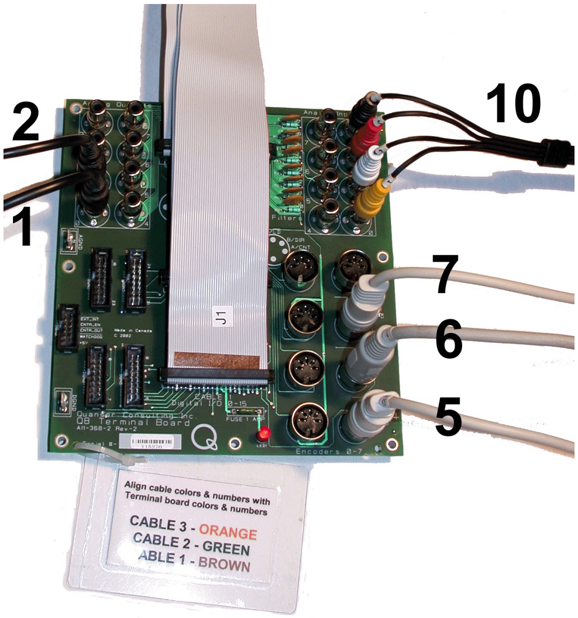


Figure 18 Q8 Terminal Board Connections

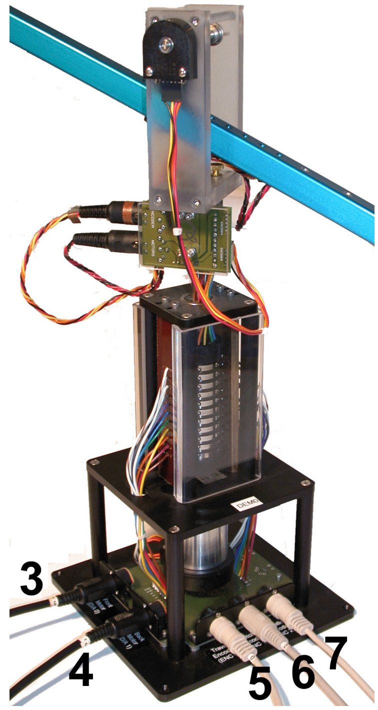


Figure 19 3-DOF Helicopter Connections

Cable #	From	To	Signal
1	Terminal Board: DAC #0	Front-UPM "From D/A" connector	Control signal to the front UPM
2	Terminal Board: DAC #1	Back-UPM "From D/A" connector	Control signal to the back UPM
3	Front-UPM "To Load" connector	3-DOF Helicopter "Front Motor D/A 0" connector	Power leads to the 3-DOF Helicopter's front DC motor (propeller). Cable of gain 5
4	Back-UPM "To Load" connector	3-DOF Helicopter "Back Motor D/A 1" connector	Power leads to the 3-DOF Helicopter's back DC motor (propeller). Cable of gain 5
5	3-DOF Helicopter "Travel Encoder ENC 0" connector	Terminal Board: Encoder Channel #0	3-DOF Helicopter's travel angle feedback signal to the data acquisition card
6	3-DOF Helicopter "Pitch Encoder ENC 1" connector	Terminal Board: Encoder Channel #1	3-DOF Helicopter's pitch angle feedback signal to the data acquisition card

Cable #	*From*	*To*	*Signal*
7	3-DOF Helicopter "Elevation Encoder ENC 2" connector	Terminal Board: Encoder Channel #2	3-DOF Helicopter's elevation angle feedback signal to the data acquisition card
8	Joystick "X" cable	Back-UPM "S3" connector	Joystick voltage signal (along the X-axis) to the UPM
9	Joystick "Y" cable	Back-UPM "S4" connector	Joystick voltage signal (along the Y-axis) to the UPM
10	Back-UPM "To A/D" connector	Terminal Board: S1 to ADC #0 S2 to ADC #1 S3 to ADC #2 S4 to ADC #3	Joystick voltage signals (along both X- and Y- axes) to the data acquisition terminal board, through the UPM

Table 6 3-DOF Helicopter system wiring summary

5.4. Additional Connections for the 3-DOF Helicopter w/ ADS

The additional wiring needed to operate the Active Disturbance System is detailed in the section. As before, figures 16 and 17 show, respectively, the front and back UPM connections. The cabling on the UPM used to drive the motor of the ADS is illustrated in Figure 20. See Figure 21 for the Q8 Terminal Board connections and figures 22 and 23 for the wiring on the Helicopter base. These connections are described in detail in the procedure below and summarized in Table 6.

Follow these steps to connect the 3-DOF Helicopter with the Active Disturbance System experiment:

1. Go through the 3-DOF Helicopter wiring as dictated in Section 5.3.
2. Connect the 5-pin-DIN to RCA cable from the *Analog Output Channel #2* on the DAC board to the *From D/A Connector* on the UPM-1503. See cable #11 shown in Figure 20 and Figure 21. This carries the attenuated ADS motor voltage control signal, V_{ads}/K_a, where K_a is the UPM-1503 amplifier gain.
3. Connect the 4-pin-stereo-DIN to 6-pin-stereo-DIN that is labeled **Gain 3** from *To Load* on the UPM-1503 to the *ADS Motor* connector. See connection #12 shown in Figure 20 and Figure 23. This cable sets the gain of the amplifier to 3. The connector on the UPM-side is black and should be labeled 3. The cable transmits the amplified voltage that is applied to the **ADS** motor, V_{ads}.

ATTENTION: The Quanser **UPM-1503** is capable of providing the required power to the 3-DOF Helicopter ADS motor. However, it should be used in conjunction with a ***"To Load"*** **cable of gain 3** (i.e. 4-pin-DIN-to-6-pin-DIN cable), as described in Reference [4].

4. Connect the 5-pin-stereo-DIN to 5-pin-stereo-DIN cable from the *ADS Encoder* connector on

the 3-DOF Helicopter base to *Encoder Input # 3* on the terminal board, as depicted by connection #13 in Figure 21 and Figure 22. This carries the angular measurement of the ADS lead screw. This measurement is then translated to give the linear position of the disturbance mass and is denoted by the variable *x*.

Figure 20: Connections on UPM-1503 used for ADS motor.

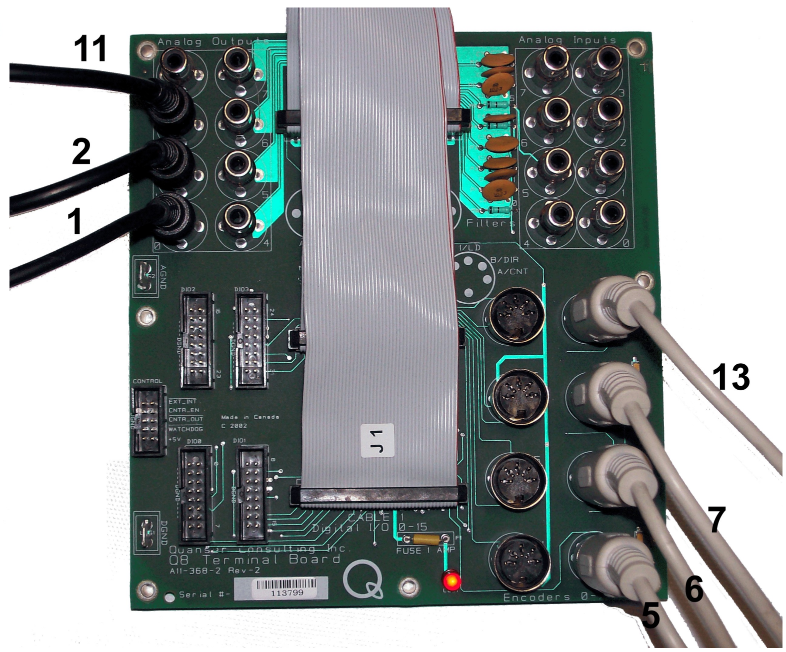


Figure 21: Q8 Terminal Board connections when using ADS.

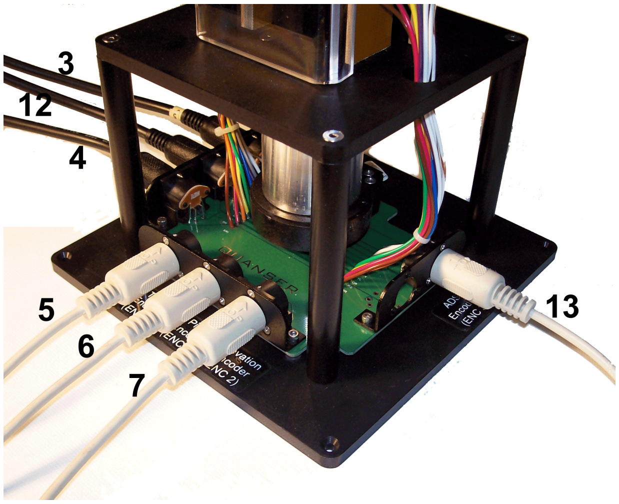


Figure 22: Connections on base of 3-DOF Helicopter ADS – ADS encoder side view.

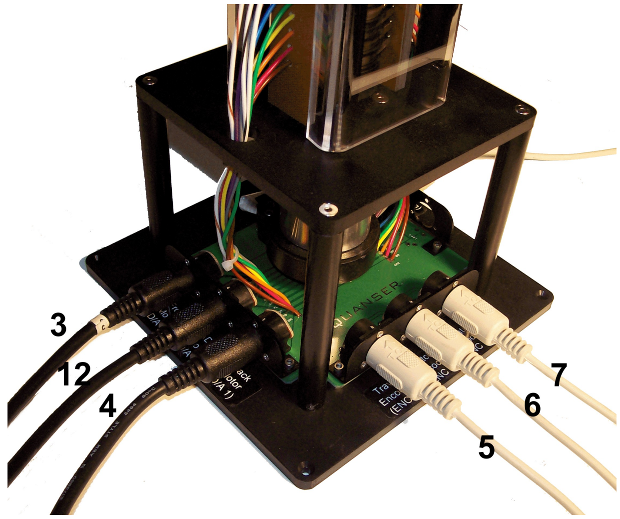


Figure 23: Connections on base of 3-DOF Helicopter ADS – ADS motor connector sidie view.

Cable #	*From*	*To*	*Signal*
11	Terminal Board: Analog Output #3	ADS UPM "From D/A" connector	Control signal to the ADS.
12	ADS UPM "To Load" connector	3-DOF Helicopter "ADS Motor (D/A 3)" connector	Power leads to the 3-DOF Helicopter's ADS DC motor. Cable of gain 3.
13	3-DOF Helicopter "ADS Encoder (ENC 3)" connector	Terminal Board: Encoder Channel #3	Active Mass Disturbance lead-screw angle feedback signal to the data acquisition card

Table 7: Additional wiring summary for 3-DOF Helicopter with Active Mass Disturbance system.

5.5. Joystick Description

The Quanser 3-DOF Helicopter experiment is supplied with either an analog joystick, shown in Figure 24, or a Logitech Attack 3 USB joystick, shown in Figure 25. They are used to generate a desired position instead of commanding it via the Simulink model blocks (see lab procedure later).

Figure 24: Analog joystick.

Figure 25: Logitech Attack-3 USB joystick.

The setup procedure for the analog joystick is described in steps 11-12 in Section 5.3. The setup procedure for the USB joystick is described in step 10 in Section 5.3. The rate command knob shown in Figure 25 changes the rate at which a command is generated by the joystick. The rate is at its greatest when the knob is turned fully toward the joystick handle.

The system requirements for the Logitech Attack-3 USB joystick are:

- PC with Pentium Processor or compatible
- 64 MB RAM
- USB port
- Windows 98, 2000, Me, or Xp

6. Modeling and Control Design

The mathematical model developed for the 3-DOF Helicopter system is summarized in Section 6.1. In Section 6.2, the feedback system used to control the position of the helicopter is described.

6.1. Modeling

The free-body diagram of the 3-DOF Helicopter is illustrated in Figure 26 and accompanies the Maple worksheet named *3-DOF Helicopter Equations.mws* or its HTML equivalent *3-DOF Helicopter Equations.html*. The equations can be edited and re-calculated by executing the worksheet using Maple 9.

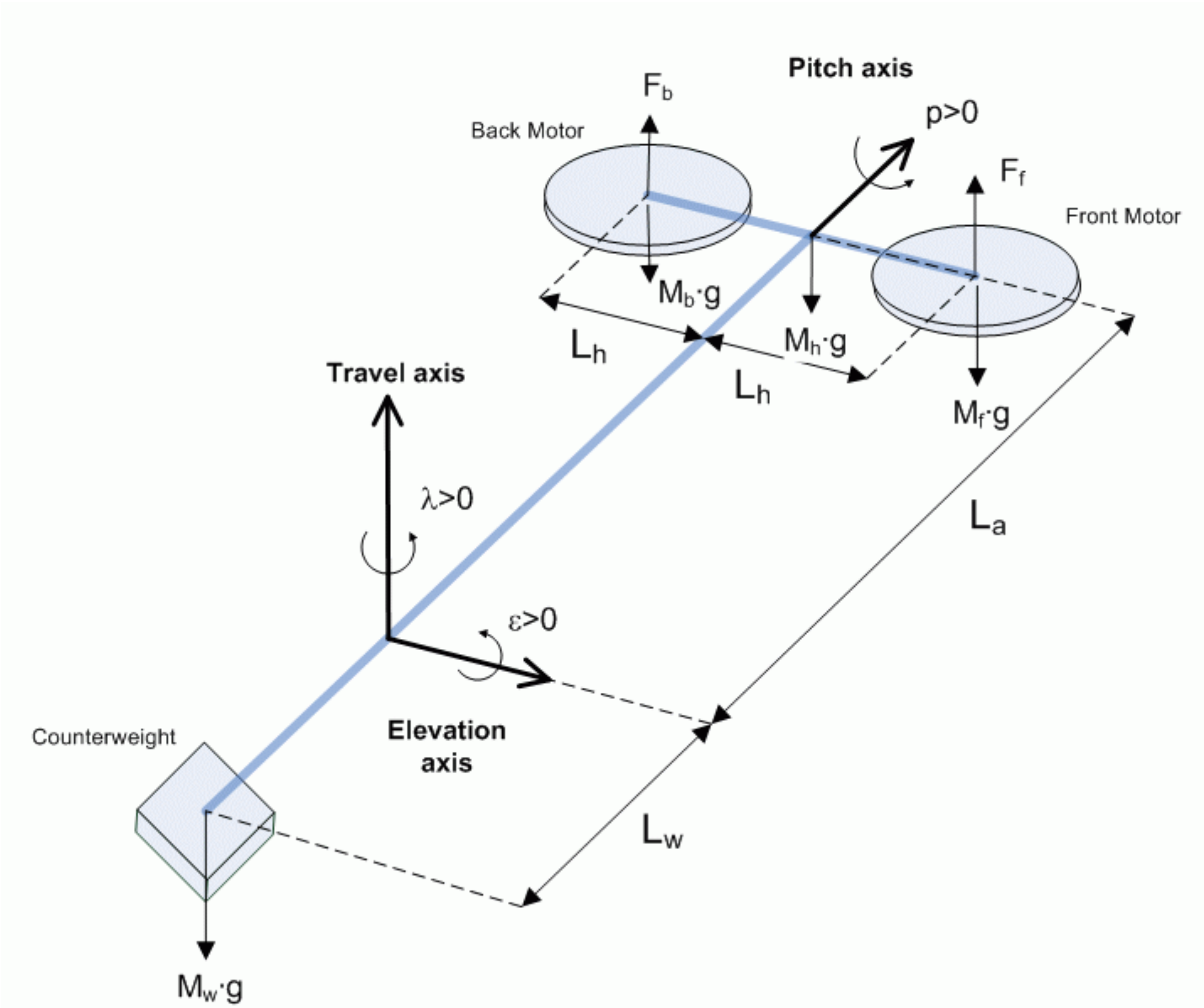


Figure 26: Free-body diagram of 3-DOF Helicopter.

The worksheet goes through the kinematics of the system. Thus describing the front motor, back motor, helicopter body, and counterweight relative to the base coordinate system shown in Figure 26. These resulting equations are used to find the potential energy and translational kinetic energy of the front motor, back motor, and counterweight of the system. The thrust forces acting on the elevation, pitch, and travel axes from the front and back motors are defined and made relative to the quiescent voltage or operating point

$$V_{op} := \frac{1}{2} \frac{g\,(L_w\,m_w - L_a\,m_f - L_a\,m_b)}{L_a\,K_f} \quad [1]$$

where all these parameters are defined in Table 4. Using the Euler-Lagrange formula, the nonlinear equations of motion of the 3-DOF Helicopter system are derived. These equations are linearized about zero and the linear state-space model (A,B,C,D) describing the voltage-to-angular joint position dynamics of the system is found. Given the state-space representation

$$\frac{\partial}{\partial t} x = A x + B u \qquad [2]$$

and

$$\frac{\partial}{\partial t} y = C y + \mathrm{D}\, u \qquad [3]$$

the state vector for the 3-DOF Helicopter is defined

$$x^T = \left[\varepsilon, p, \lambda, \frac{\partial}{\partial t}\varepsilon, \frac{\partial}{\partial t}p, \frac{\partial}{\partial t}\lambda \right] \qquad [4]$$

and the output vector is

$$y^T = [\varepsilon, p, \lambda] \qquad [5]$$

where the variables ε, p, and λ are the elevation, pitch, and travel angles. The corresponding helicopter state-space matrices (as derived in the Maple worksheet) are

$$A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\dfrac{(L_w m_w - 2 L_a m_f)\, g}{m_w L_w^2 + 2 m_f L_h^2 + 2 m_f L_a^2} & 0 & 0 & 0 & 0 \end{bmatrix}, \qquad [6]$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \dfrac{L_a K_f}{2 m_f L_a^2 + m_w L_w^2} & \dfrac{L_a K_f}{2 m_f L_a^2 + m_w L_w^2} \\ \dfrac{1}{2}\dfrac{K_f}{m_f L_h} & -\dfrac{1}{2}\dfrac{K_f}{m_f L_h} \\ 0 & 0 \end{bmatrix}, \qquad [7]$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}, \text{ and} \qquad [8]$$

$$\mathrm{D} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}. \qquad [9]$$

The model parameters used in the (A,B) matrices are defined in Table 4.

6.2. Control Design

In this section a linear proportional-integral-derivative, i.e. PID, controller is designed to regulate the elevation and travel angles of the 3-DOF Helicopter to desired positions. The PID control gains are computed using the Linear-Quadratic Regular algorithm. The state-feedback controller entering the front motor, V_f, and the back motor, V_b, is defined

$$\begin{bmatrix} V_f \\ V_b \end{bmatrix} = K_{PD}(x_d - x) + V_i + \begin{bmatrix} V_{op} \\ V_{op} \end{bmatrix}, \qquad [10]$$

where

$$K_{PD} = \begin{bmatrix} k_{1,1} & k_{1,2} & k_{1,3} & k_{1,4} & k_{1,5} & k_{1,6} \\ k_{2,1} & k_{2,2} & k_{2,3} & k_{2,4} & k_{2,5} & k_{2,6} \end{bmatrix} \qquad [11]$$

is the proportional-derivative control gain,

$$x_d^T = [\varepsilon_d \quad p_d \quad \lambda_d \quad 0 \quad 0 \quad 0] \qquad [12]$$

is the desired state, x is the state defined in Equation [4],

$$V_i = \begin{bmatrix} \int k_{1,7}(x_{d,1} - x_1)\,dt + \int k_{1,8}(x_{d,3} - x_3)\,dt \\ \int k_{2,7}(x_{d,1} - x_1)\,dt + \int k_{2,8}(x_{d,3} - x_3)\,dt \end{bmatrix} \qquad [13]$$

Is the integral control, and V_{op} is the operation point voltage defined in Equation [1]. The variables ε_d, ρ_d, and λ_d, are the elevation, pitch, and travel setpoints, i.e. the desired angles of the helicopter. In the control the pitch command is set to zero, thus $\rho_d = 0$. The gains $k_{1,1}$ through $k_{1,3}$ are the front motor control proportional gains and the gains $k_{2,1}$ through $k_{2,3}$ are the back motor control proportional gains. Similarly, $k_{1,4}$ through $k_{1,6}$ are the front motor control derivative gains and $k_{2,4}$ through $k_{2,6}$ are the back motor control derivative gains. The integral control gains used in the front motor control are $k_{1,7}$ and $k_{1,8}$ and the integral gains $k_{2,7}$ and $k_{2,8}$ are used in the back motor regulator.

The PID control gains are computed using the Linear-Quadratic Regular scheme. The system state is first augmented to include the integrals of the elevation and travel states,

$$x_i^T = \left[\varepsilon, p, \lambda, \frac{\partial}{\partial t}\varepsilon, \frac{\partial}{\partial t}p, \frac{\partial}{\partial t}\lambda, \int \varepsilon\, dt, \int \lambda\, dt \right]. \qquad [14]$$

Using the feedback law

$$u = -K x_i, \qquad [15]$$

the weighting matrices

$$Q = \begin{bmatrix} 100 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 10 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.1 \end{bmatrix} \qquad [16]$$

and

$$R = \begin{bmatrix} 0.05 & 0 \\ 0 & 0.05 \end{bmatrix}, \qquad [17]$$

and the state-space matrices (A,B) found previously, the control gain

$$K = \begin{bmatrix} 37.67 & 13.21 & -11.50 & 20.95 & 4.769 & -16.10 & 10.00 & -1.000 \\ 37.67 & -13.21 & 11.50 & 20.95 & -4.769 & 16.10 & 10.00 & 1.000 \end{bmatrix} \qquad [18]$$

is calculated by minimizing the cost function

$$J = \int_0^{\infty} x_i^T Q x_i + u^T R u \, dt \qquad [19]$$

with the Matlab *LQR* command. In terms of the PID control gains described earlier, the full control gain is expressed

$$K = \begin{bmatrix} k_{1,1} & k_{1,2} & k_{1,3} & k_{1,4} & k_{1,5} & k_{1,6} & k_{1,7} & k_{1,8} \\ k_{2,1} & k_{2,2} & k_{2,3} & k_{2,4} & k_{2,5} & k_{2,6} & k_{2,7} & k_{2,8} \end{bmatrix}. \qquad [20]$$

7. In-Lab Procedure

7.1. Controller Simulation

7.1.1. Objectives

- Investigate the closed-loop position control performance using a linear model of the 3-DOF Helicopter system.
- Ensure the controller does not saturate the actuator.

7.1.2. Procedure

Follow these steps to simulate the closed-loop response of the 3-DOF Helicopter:

1. Open Simulink model *s_heli3d.mdl* shown in Figure 27.

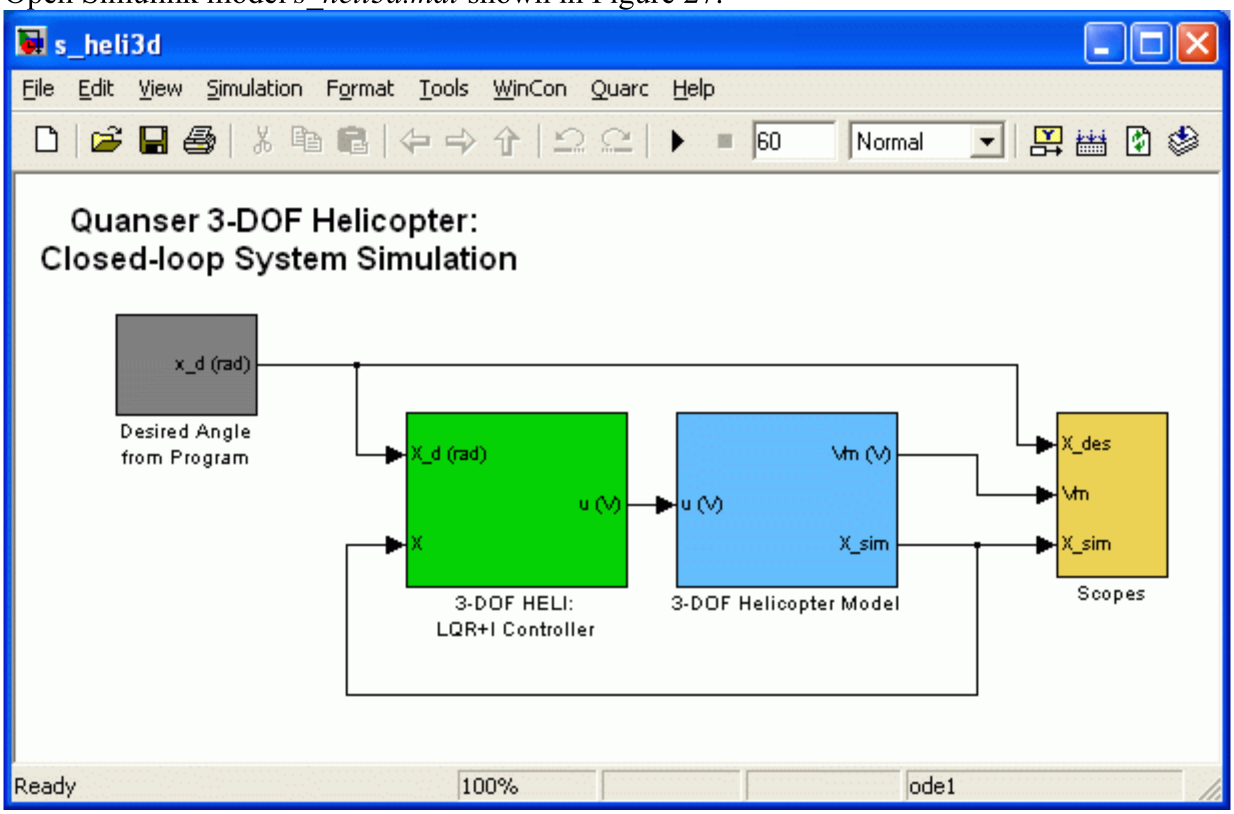


Figure 27: Simulink model s_heli3d.mdl used to simulate closed-loop response of 3-DOF Helicopter.

2. Run the Matlab script *setup_lab_heli_3d.m* to load the state-space model matrices and the control gain K.
3. To generate a desired elevation step of 7.5 degrees at 0.04 Hz frequency, open the *Desired Angle from Program* subsystem and set the *Amplitude: Elevation (deg)* gain block to 7.5 degrees and *Frequency* input box in the *Signal Generator: Elevation* block to 0.04 Hz.
4. To generate a desired travel step of 30 degrees at 0.03 Hz frequency set the *Amplitude: Travel (deg)* block to 30.0 degrees and the *Frequency* input box in the *Signal Generator: Travel* block

to 0.03 Hz.

5. In the *Scopes* subsystem, open the *elevation (deg)*, *pitch (deg), travel (deg)* and the *Vm (V)* scopes.
6. Click on start simulation to simulate the closed-loop response. The elevation and travel angles (purple trace) should track the corresponding desired position signals (yellow trace) in each scope. Examine the voltage in the *Vm (V)* scope and ensure the front (yellow plot) and back motor (purple plot) are not saturated. Recall that the maximum peak voltage that can be delivered to the motor by the UPM-2405 is ±24 V and that the controller implemented on the actual system includes the operation voltage, V_{op}. The operation voltage is approximately 7.5 V and this will be added to the resulting control output.
7. Try changing the desired elevation and travel angles to familiarize yourself with the controller. Observe that rate limiters are placed in the desired position signals to eliminate any high-frequency changes. This makes the control signal smoother which places less strain on the actuator.

7.2. Controller Implementation

7.2.1. Objectives

- Implement the controller designed in Section 6.2 using WinCon to control the position 3-DOF Helicopter.

7.2.2. Procedure: 3-DOF Helicopter

Follow the steps described below to implement the designed controller in real-time and observe its effect on the actual 3-DOF Helicopter plant:

1. Open the Simulink model *q_heli3d_zz.mdl* shown in Figure 28 that implements a sample LQR controller. The *zz* suffix denotes the type of data-acquisition board that is installed in your PC, such as *q4* or *q8*. The model runs your actual 3-DOF Helicopter plant by directly interfacing with your hardware through the WinCon blocks, as discussed in Reference [2].

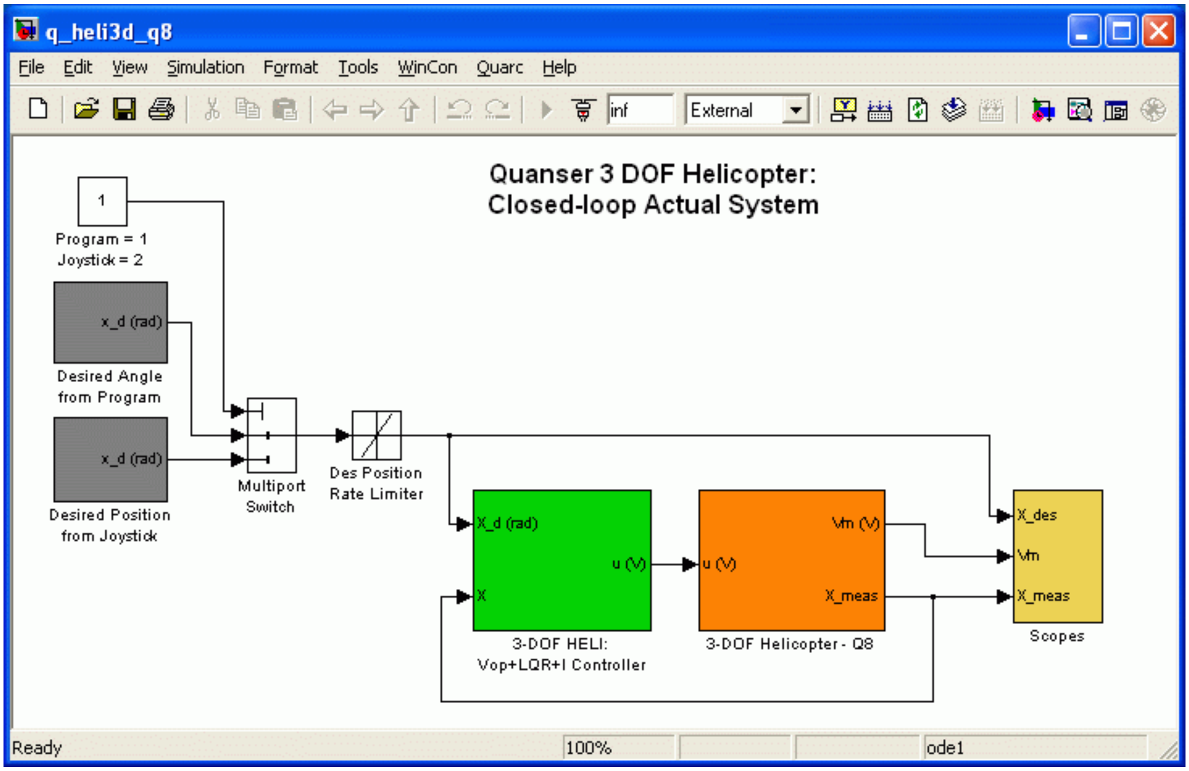


Figure 28: Simulink model q_heli3d_q8 implements the LQR controller on actual 3-DOF Helicopter system.

2. Open the design file *setup_lab_heli_3d.m* and ensure everything is configured properly.

⚠ **NOTE: Make sure the *WITH_ADS* parameter in the setup_lab_heli_3d.m file is set to *NO*.** This indicates to the automatically designed controller that the active disturbance is not being used.

3. Execute the *setup_lab_heli_3d.m* Matlab script to setup the workspace before compiling the diagram and running it in real-time with WinCon. This file sets the state-space model of the 3-DOF Helicopter system, calculates the feedback gain vector K, and sets various other parameters that are used such as the filter cutoff frequencies, amplifier gain, and the UPM and DACB limits.
4. Figure 29 illustrates the inside of the *3-DOF Helicopter - Q8* subsystem. It contains the WinCon blocks that interface with the hardware of the actual plant. The Analog Output block outputs the voltage computed by the controller to the Q8 DACB and the Encoder Input block reads the encoder measurements.

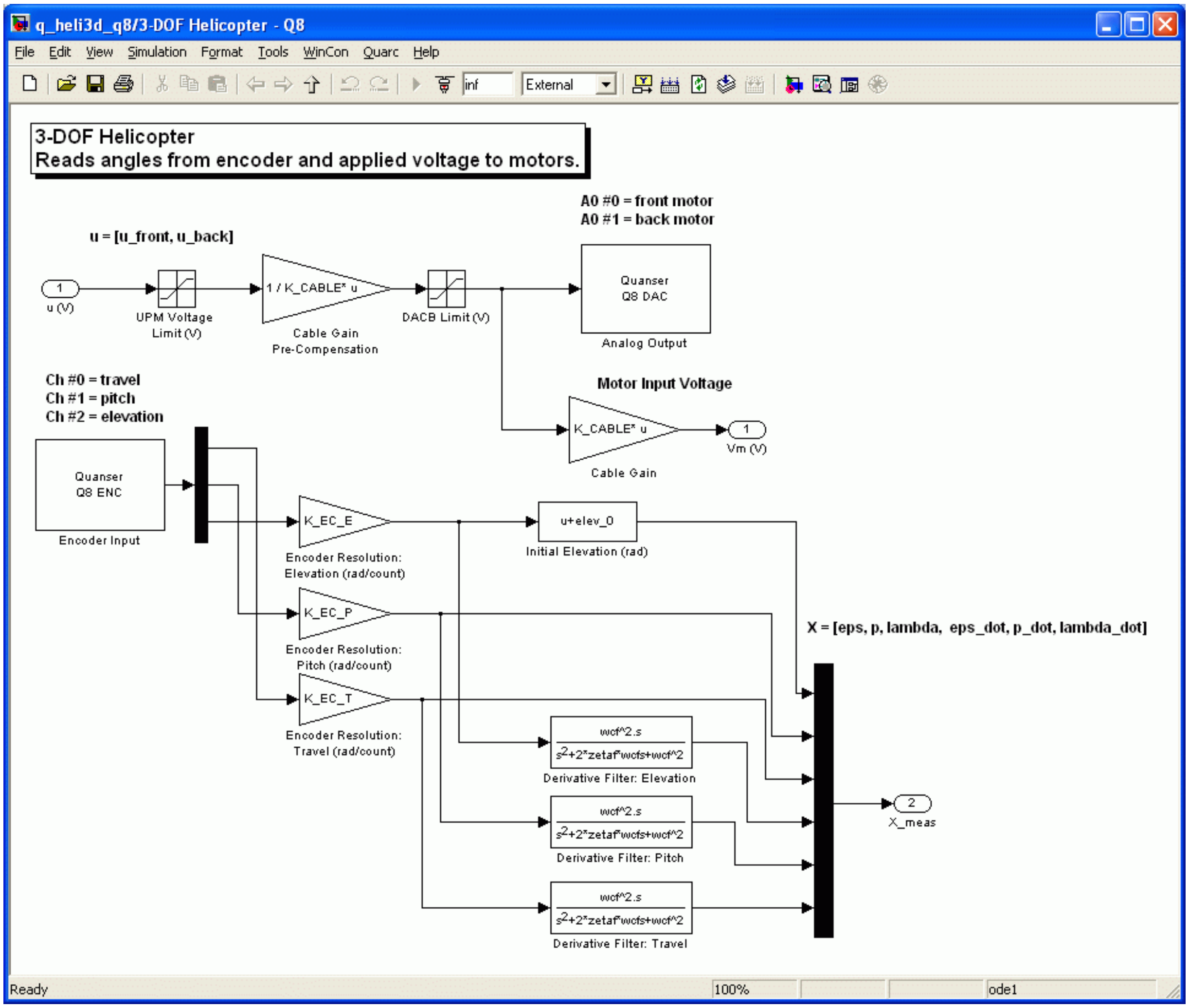


Figure 29: 3-DOF Helicopter - Q8 subsystem used to interface with hardware.

5. The voltage sent to the Analog Ouput block is amplified by the UPM-2405 and applied to the power amplifier's attached motor. Note that the control input is divided by the amplifier gain, K_CABLE, before being sent to the DACB. This way, the amplifier gain does not have to be included in the mathematical model as the voltage output from the controller is the voltage being applied to the motor. The UPM and DACB saturation blocks limit the amount of voltage that can be fed to the motor. In this case, since K_CABLE = 5, the voltage is only saturated by the UPM and not by the DACB. The *Vm (V)* sink is the effective motor input voltage and shows when the amplifier is being saturated.
6. The real-time code corresponding to the diagram can now be built by selecting the *WinCon | Build* item from the Simulink menu bar. After successful compilation and download to the WinCon Client, you should be able to use WinCon Server to run your actual system in real-time.
7. Click on the *Open plot* button in the WinCon Server window and select the variables *elevation (deg)*, *travel (deg)*, and *Vm (V)* in the *Scopes* folder. These scopes display both the desired and measured angles of the Helicopter as well as the voltages being applied to the front and back

motors.

CAUTION: Make sure the motor voltages do not switch between negative and positive often! Having the controller go across the 0 V line often can cause damage to the amplifiers.

8. Ensure the helicopter has been setup and all the connections have been made as instructed in Section 5.
9. Turn the power of the two Universal Power Amplifiers on. The red LED on the upper-left corner of the each UPM should be lit.
10. In the *q_heli3d_zz* Simulink diagram, make sure the *Program/Joystick* block shown in Figure 28 is set to 1 in order to generate the desired angle from Simulink.
11. Start the real-time controller by clicking on the green START button of the WinCon Server window. The motors should begin running and the two propellers should start turning lightly.

NOTE: Click on the red STOP button at any time to stop running the real-time controller. The Pause/Break key on the keyboard can also be used to stop the controller.

12. Initially the helicopter elevation angle is -27.5 degrees. Set the desired elevation angle to 10 degrees by setting the *Constant: Elevation (deg)* slider gain block, which is found in the *Desired Angle from Program* subsystem, to 10 degrees. The helicopter should now be stabilized slightly above its horizontal. The green plot in the *elevation (deg)* scope is the desired elevation angle and the red is the measured elevation angle.
13. Set the desired elevation angle to a constant of step wave with an amplitude of 7.5 degrees at a frequency of 0.04 Hz as discussed in Section 7.1. The helicopter body should be going up and down as the controller does the elevation tracking.
14. Set the *Amplitude: Travel (deg)* gain block to 30 degrees and the *Frequency* input box in the *Signal Generator: Travel* block to 0.03 Hz. The helicopter body should not be moving forwards and backwards as it tracks the desired travel angle. In the *travel (deg)* scope, the green trace is the desired travel angle while the red is the measured travel angle.
15. In the *Vm (V)* scope, the green line is the front motor voltage and the red trace is the back motor voltage. These should be within ±25V and not go negative very often.
16. Figure 30 below is a sample closed-loop position response of the 3-DOF Helicopter when commanding an elevation step of ±7.5 degrees at 0.04 Hz and a travel step ±30 degrees at 0.03 Hz.

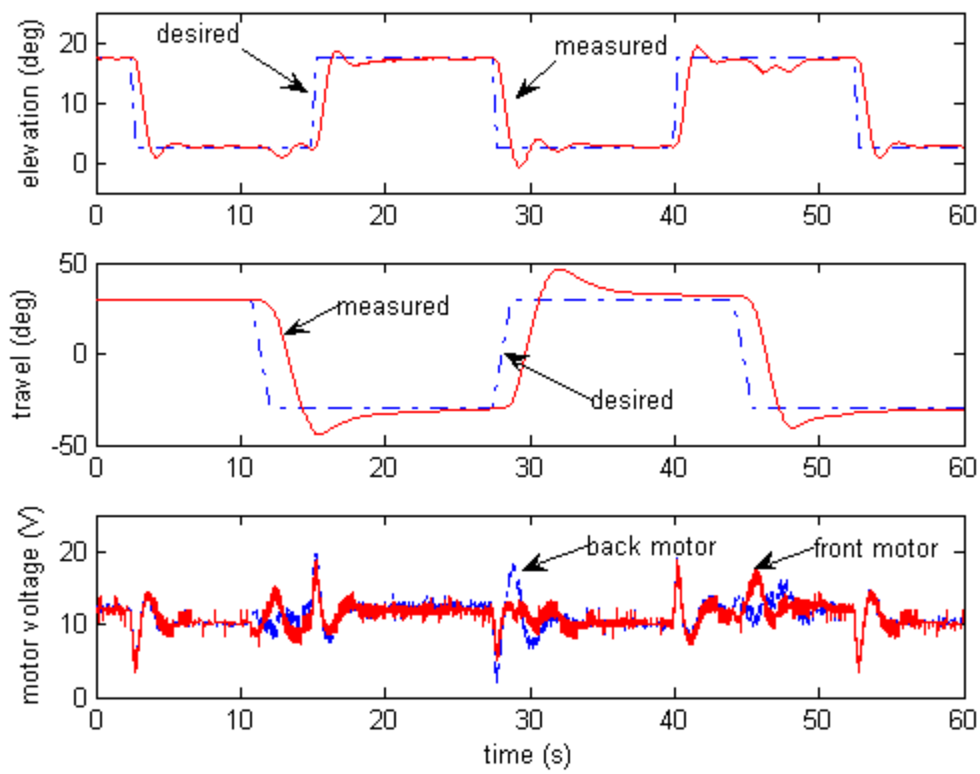


Figure 30: Typical closed-loop response of 3-DOF Helicopter system.

17. Alternatively, the desired angle can be generated using a joystick - either the analog or USB described in Section 5.5. To use the joystick, set the Program/Joystick switch shown in Figure 28 to 2. The rate at which the desired angle increases or decreases given a joystick position can be changed using the K_JOYSTICK_X and K_JOYSTICK_Y variables that are set in the setup_lab_heli_3d.m script file.

⚠ **CAUTION: Do not switch from the Program to the Joystick (from 1 to 2) when the controller is running.** Set the program/joystick switch to 2 before starting WinCon if the joystick is to be used.

18. Stop the WinCon controller when the experiment is complete by clicking on the red STOP button.
19. Power off the two UPMs.

7.2.3. Procedure: 3-DOF Helicopter with ADS

Follow the steps described below to implement the designed controller in real-time and observe its effect on the 3-DOF Helicopter with Active Disturbance System (ADS) plant:

1. Open Simulink model *q_heli3d_w_ads_zz.mdl* shown in Figure 31 that implements a sample LQR controller on the 3-DOF Helicopter with ADS plant. The *zz* suffix denotes the type of data-acquisition board that is installed in your PC, such as *q4* or *q8*. The model runs your actual

3-DOF Helicopter w/ ADS plant by directly interfacing with your hardware through the WinCon blocks, as discussed in Reference [2]. The *3-DOF Helicopter System* subsystem is basically the Simulink model described in Figure 28. The helicopter is not engaged until the Active Disturbance is calibrated.

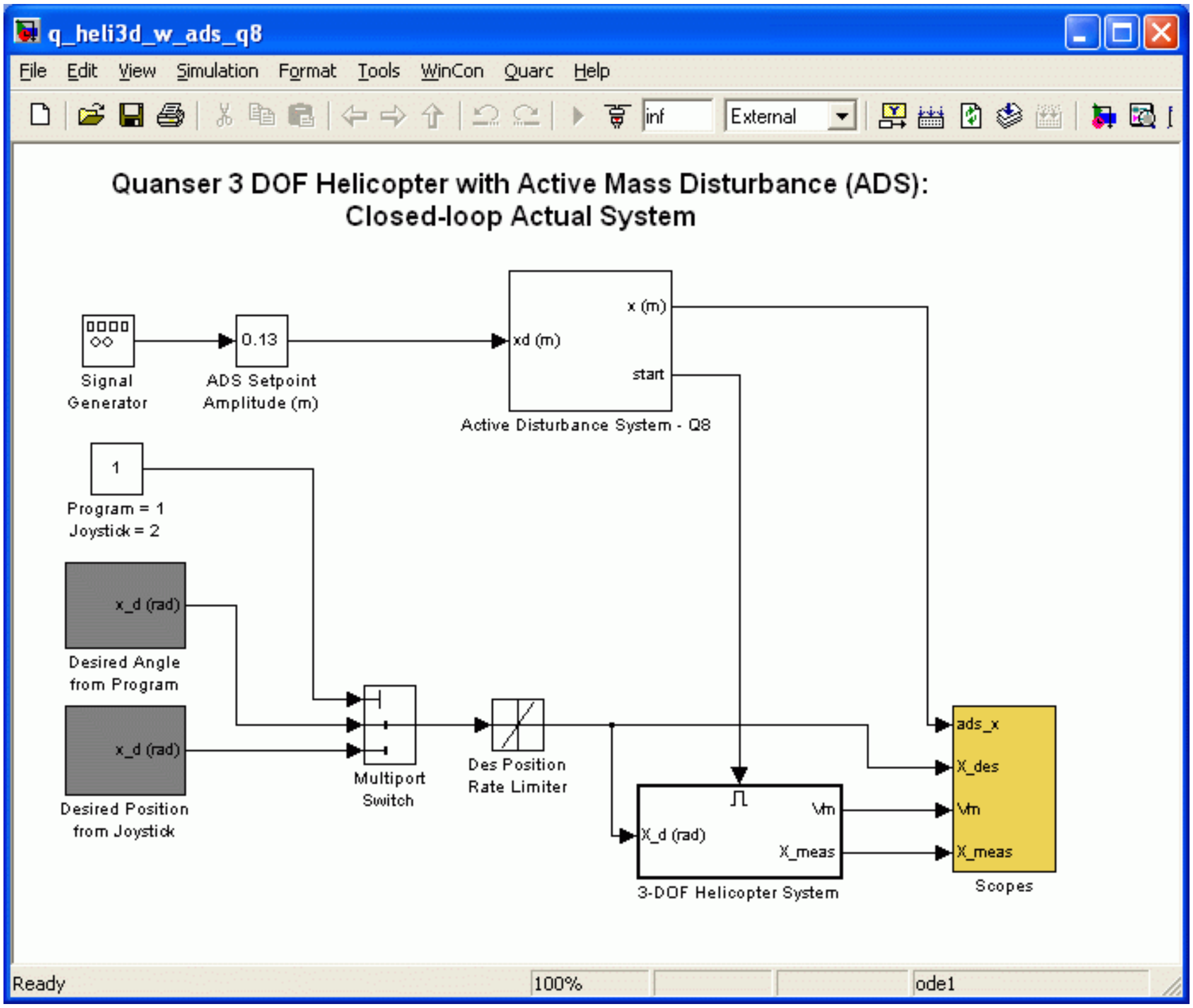


Figure 31: Simulink model q_heli3d_w_ads_q8 implements an LQR controller on the 3-DOF Helicopter with Active Disturbance system.

2. Open the design file *setup_lab_heli_3d.m* and ensure everything is configured correctly.

NOTE: Make sure the *WITH_ADS* parameter in the setup_lab_heli_3d.m file is set to *YES*. This indicates to the automatically designed controller that the active disturbance is being used.

3. Execute the *setup_lab_heli_3d.m* script to setup the workspace before compiling the diagram and running it in real-time with WinCon.
4. The real-time code corresponding to the diagram can now be built by selecting the *WinCon | Build* item from the Simulink menu bar. After successful compilation and download to the WinCon Client, you should be able to use WinCon Server to run your actual system in real-time.

5. Click on the *Open plot* button in the WinCon Server window and select the variables *elevation (deg)*, *travel (deg)*, and *Vm (V)* in the *Scopes* folder. These scopes display both the desired and measured angles of the Helicopter as well as the voltages being applied to the front and back motors.

CAUTION: Make sure the motor input voltage does not go between negative and positive very often! Having the controller go across the 0 V line often can cause damage to the amplifiers.

6. Ensure the helicopter hardware is setup as discussed in Section 5.1 and all the connections have been made as instructed in Section 5.4.
7. Turn the power of the two Universal Power Amplifiers on. The red LED on the upper-left corner of the each UPM should be lit.
8. In the *q_heli3d_zz* Simulink diagram, make sure the *Program/Joystick* block shown in Figure 31 is set to 1 in order to generate the desired angle from Simulink.
9. Start the real-time controller by clicking on the green START button of the WinCon Server window. The active disturbance is first calibrated. The mass is moved back towards the helicopter base until contact with the spring is made. It is then moved to the middle lead-screw position, i.e. the *home* position. Once calibrated, the front and back motors on the helicopter should begin running.

The real-time controller can be stopped at any time by clicking on the STOP button located in the WinCon Server window. Alternatively, the Pause/Break key on the keyboard can be used to stop the controller.

10. The helicopter elevation angle is initially -27.5 degrees. Set the desired elevation angle to 0 degrees by setting the *Constant: Elevation (deg)* gain block, which is found in the *Desired Angle from Program* subsystem, to 0 degrees. The helicopter should now be stabilized above its horizontal.
11. Set the *ADS Setpoint Amplitude (m)* slider gain block to 0.13 and the *Frequency* inside the *Signal Generator* block to 0.05 Hz. The disturbance mass will move 0.13 meters at 0.05 Hz about the middle of the slide.
12. In the *Vm (V)* scope, the green line is the front motor voltage and the red trace is the back motor voltage. These should be within ±25V and not go negative very often.
13. The response in the *elevation (deg)* scope shows elevation angle as the position of the disturbance mass is varied. Recall that the green plot in the *elevation (deg)* scope is the desired elevation angle and the red is the measured elevation angle. As the mass is brought to the base the elevation increases. However the integrators in the position controller begin to compensate for the shifted weight and the elevation begins to drift back to 0 degrees. Similarly, the elevation goes down when the mass if moved forward (towards the helicopter) and the controller integration begins to reject the disturbance.
14. Figure 32 below depicts the measured closed-loop position response of the 3-DOF Helicopter with the ADS when the disturbance mass is moving between ±0.13 meters at 0.05 Hz.

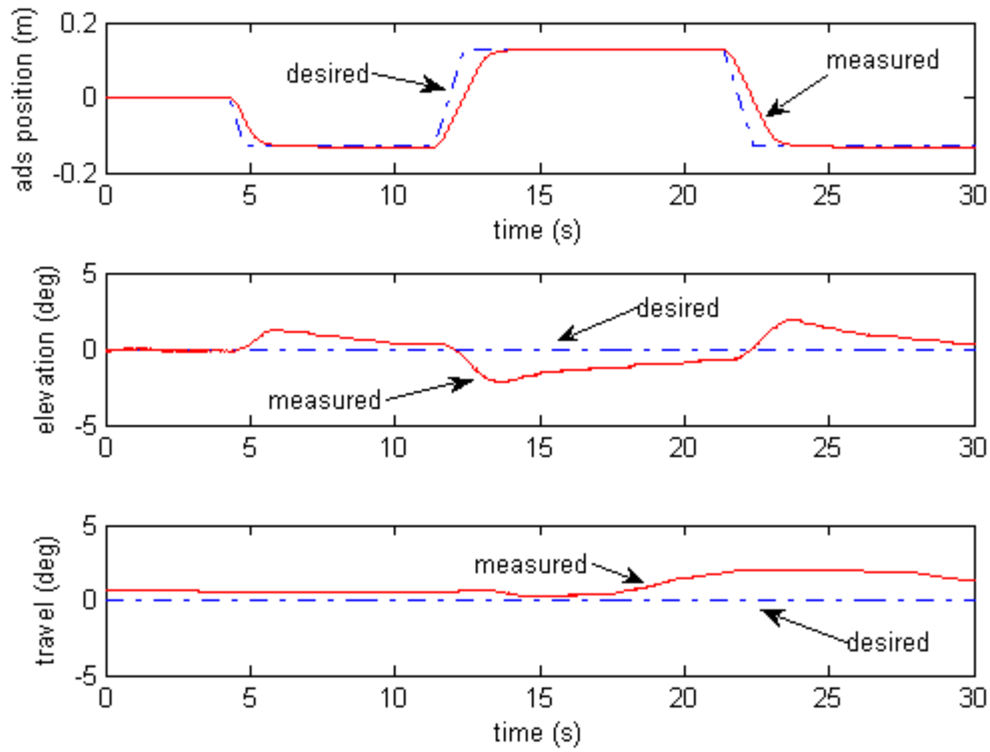


Figure 32: Closed-loop response of 3-DOF Helicopter ADS device.

15. Alternatively, the desired angle can be generated using a joystick - either the analog or USB described in Section 5.5. To use the joystick, set the Program/Joystick switch shown in Figure 31 to 2. The rate at which the desired angle increases or decreases given a joystick position can be changed using the K_JOYSTICK_X and K_JOYSTICK_Y variables that are set in the setup_lab_heli_3d.m script file.

⚠ **CAUTION: Do not switch from the Program to the Joystick (from 1 to 2) when the controller is running.** Set the program/joystick switch to 2 before starting WinCon if the joystick is to be used.

16. Stop the WinCon controller when the experiment is complete by clicking on the red STOP button.
17. Power off the two UPMs.

8. References

[1] Quanser. *Q4/Q8 User Manual*.
[2] Quanser. *WinCon User Manual*
[3] Quanser. *WinCon Installation Manual*.

[4] Quanser. *UPM User Manual*.
[5] Pittman. *Pittman LO COG DC Servo Motor Series 8000, 9000, and 14000*.