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LABORATORY GUIDE

3 DOF Helicopter Experiment for MATLAB®/Simulink® Users

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1 PRESENTATION

1.1 Description

The 3 DOF Helicopter plant is depicted in Figure 1.1. Two DC motors are mounted at each end 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 an instrumented joint mounted at the end of a long arm and is free to pitch about its centre. The arm is installed on an additional 2-DOF instrumented joint which allows the helicopter body to move in the elevation and yaw directions. 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. The system is analogous to a tandem rotor helicopter oriented perpendicular to the support arm, as shown in Figure 3.2.

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. 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 slip ring. Electrical signals to and from the arm and helicopter are channelled through the slip ring to eliminate tangled wires, reduce friction, and allow for unlimited and unhindered travel.

Figure 1.1: 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 1.2, 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.

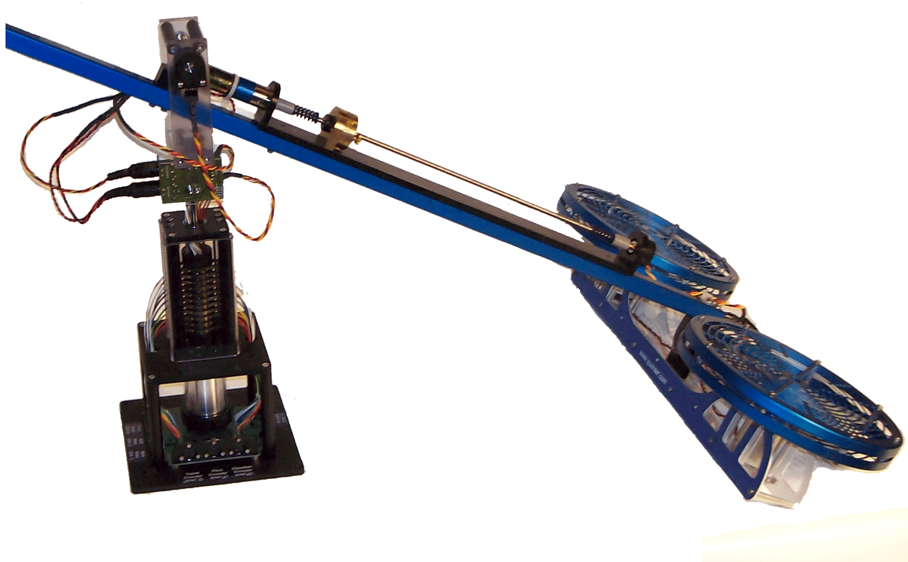

Figure 1.2: Active Disturbance System on the 3 DOF Helicopter .

1.2 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-USB), and the power amplifier (e.g. VoltPAQ), as described in [2].
- Wiring the 3 DOF Helicopter plant with the amplifier and DAQ device, as discussed in [2].
- Designing a state-feedback control using Linear-Quadratic Regulator (LQR).
- Using QUARC®to control and monitor a plant in real-time and in designing a controller through Simulink®.

2 EXPERIMENT FILES OVERVIEW

Table 2.1 below lists and describes the various files supplied with the 3 DOF Helicopter experiment.

File Name #	Description
3 DOF Helicopter User Manual.pdf	Contains information about the hardware components, specifications, and the information to setup and configure the hardware.
3 DOF Helicopter Laboratory Manual.pdf	The laboratory manual goes through the 3 DOF Helicopter system modeling, state-feedback control design, as well as the experimental procedures used 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_heli3d.mdl	Simulink file that implements the real-time state-feedback LQR controller for the 3 DOF Helicopter system.

Table 2.1: Files supplied with the 3 DOF Helicopter experiment.

3 MODELING

The mathematical model developed for the 3 DOF Helicopter system is summarized in Section 3.1. In Section 4, the feedback system used to control the position of the helicopter is described.

3.1 Dynamics

The free-body diagram of the 3 DOF Helicopter is illustrated in Figure 3.1 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.

The 3 DOF Helicopter modeling conventions used are:

1. The helicopter is horizontal when the elevation angle equals $\epsilon = 0$.
2. The travel angle increases positively, $\dot{\lambda(t)} > 0$, when the body rotates in the counter-clockwise (CCW) direction.
3. The pitch angle is positive, $\rho(t) > 0$, when the front motor is higher than the back motor.

The 3 DOF Helicopter model that is used in this laboratory is analogous to a tandem rotor helicopter such as the Boeing HC-1B Chinook illustrated in Figure 3.2. As described in the FBD shown in Figure 3.1, the pitch of the helicopter, ρ, is the rotation of the helicopter about a line perpendicular to the length of the body located at the centre of gravity. For example, the illustration in Figure 3.2 would have a positive pitch given that the nose of the helicopter is above the horizon. The elevation axis is defined as a line parallel to the length of the body, at the base coordinate frame. Therefore, a change in the elevation angle, ϵ, translates into a change in the "altitude" of the helicopter as it rotates about the base frame. For example, if the helicopter shown in Figure 3.2 were rotating about an imaginary elevation axis, it might have a slightly negative elevation since the base of the helicopter is visible. Finally, the travel axis is defined as a vertical line at the base coordinate frame perpendicular to the elevation axis. A change in the travel angle, λ, translates into forward flight about the travel axis. For example, if the helicopter shown in Figure 3.2 were attached to an imaginary travel axis limiting its mobility, forward flight would result in a circular trajectory about the base frame.

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 3.1. 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.

$$V_{op} = \frac{1}{2}\frac{g(L_w m_w - L_a m_f - L_a m_b)}{L_a K_f} \tag{3.1}$$

where the parameters are defined in [2].

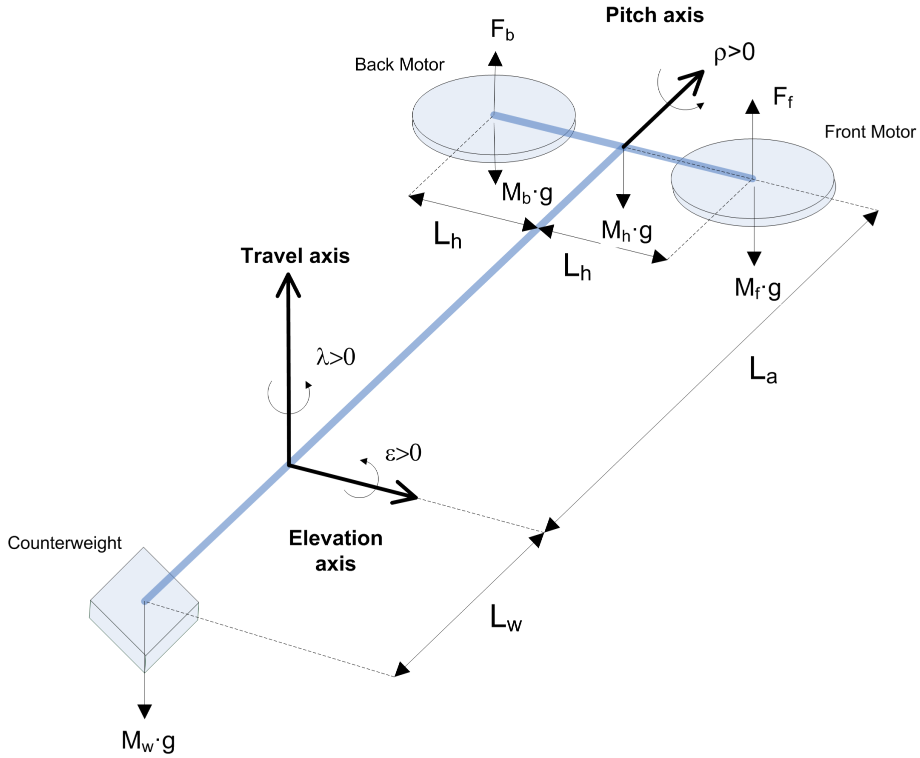

Figure 3.1: Free-body diagram of 3 DOF Helicopter.

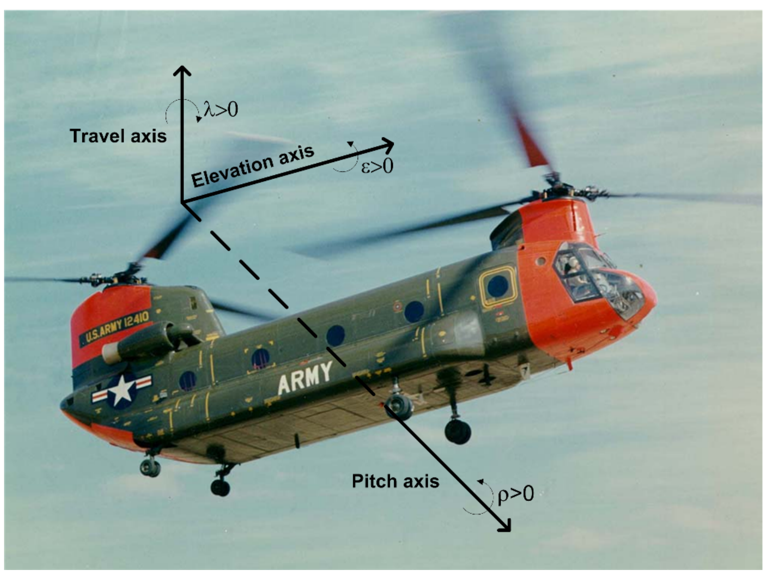

Figure 3.2: Translation of the free-body diagram onto a Boeing HC-1B Chinook.

3.2 State-Space Model

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

$$\frac{d}{dt}x = Ax + Bu$$

and

$$\frac{d}{dt}y = Cy + Du$$

the state vetor for the 3 DOF Helicopter is defined

$$x^T = \left[\epsilon, \rho_d, \lambda, \frac{d}{dt}\epsilon, \frac{d}{dt}p, \frac{d}{dt}\lambda\right] \quad (3.2)$$

where the output vector is

$$x^T = [\epsilon, \rho_d, \lambda]$$

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

$$A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{(L_w m_w - 2L_a m_f)g}{m_w L_w^2 + 2m_f L_h^2 + 2m_f L_a^2} & 0 & 0 & 0 & 0 \end{bmatrix}, \quad (3.3)$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{L_a K_f}{2m_f L_a^2 + m_w L_w^2} & \frac{L_a K_f}{2m_f L_a^2 + m_w L_w^2} \\ \frac{1}{2}\frac{K_f}{m_f L_h} & -\frac{1}{2}\frac{K_f}{m_f L_h} \\ 0 & 0 \end{bmatrix}, \quad (3.4)$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}, \text{and}$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

The model parameters used in the (A,B) matrices in Equation 3.3 and Equation 3.4 are defined in [2].

4 CONTROL DESIGN

4.1 State-Feedback

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

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

where

$$K_{PD} = \begin{bmatrix} K_{1,1} & K_{1,2} & K_{1,3} & K_{1,4} & K_{1,5} & K_{1,6} \\ K_{2,1} & K_{2,2} & K_{2,3} & K_{2,4} & K_{2,5} & K_{2,6} \end{bmatrix}$$

is the proportional-derivative control gain,

$$x_d^T = \begin{bmatrix} \epsilon_d & p_d & \lambda_d & 0 & 0 & 0 \end{bmatrix}$$

is the desired state, x is the state defined in Equation 3.2,

$$V_i = \begin{bmatrix} \int k_{1,7}(x_{d,1} - X_1)\,dt + \int k_{1,8}(x_{d,3} - X_3)\,dt \\ \int k_{2,7}(x_{d,1} - X_1)\,dt + \int k_{2,8}(x_{d,3} - X_3)\,dt \end{bmatrix}$$

is the integral control, and V_{op} is the operating point voltage defined in Equation 3.1. The variables ϵ_d, ρ_d, and λ_d, are the elevation, pitch, and travel setpoints (the desired angles of the helicopter). In the control the pitch command is set to zero, thus ρ_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.

4.2 Linear Quadratic 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,

$$x_i^T = \left[\epsilon, \rho, \lambda, \frac{d}{dt}\epsilon, \frac{d}{dt}\rho, \frac{d}{dt}\lambda, \int \epsilon\,dt, \int \lambda\,dt \right]$$

Usign the feedback law

$$u = -Kx_i,$$

the weighting matrices

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

and

$$R = \begin{bmatrix} 0.05 & 0 \\ 0 & 0.05 \end{bmatrix}$$

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

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

is calculated by minimizing the cost function

$$J = \int_0^\infty x_i^T Q x_i + u^T R u \, dt.$$

In terms of the PID control gains described earlier, the full control gain is expressed

$$K = \begin{bmatrix} K_{1,1} & K_{1,2} & K_{1,3} & K_{1,4} & K_{1,5} & K_{1,6} & K_{1,7} & K_{1,8} \\ K_{2,1} & K_{2,2} & K_{2,3} & K_{2,4} & K_{2,5} & K_{2,6} & K_{1,7} & K_{1,8} \end{bmatrix}$$

5 LAB PROCEDURE

5.1 Main Components

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

- **Power Amplifier**: Quanser VoltPAQ-X2, or equivalent.
- **Data Acquisition Board**: Quanser Q8-USB, QPID, 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 QUARC-Simulink configuration.

5.2 Controller Simulation

5.2.1 Objectives

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

5.2.2 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 5.1.

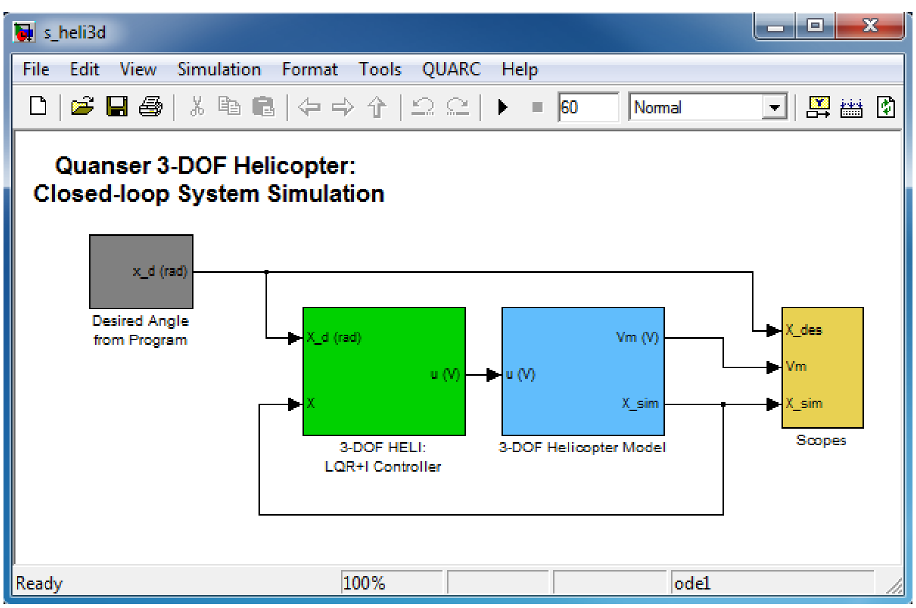

Figure 5.1: Simulink model $s\_heli3d.mdl$ used to simulate closed-loop response of 3 DOF Helicopter.

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 is $\pm$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.

5.3 Controller Implementation

5.3.1 Objectives

Implement the controller designed in Section 4 using QUARC to control the position 3 DOF Helicopter .

5.3.2 Procedure: 3 DOF Helicopter

Before beginning the closed-loop simulation procedure, ensure the helicopter has been setup and all the connections have been made as instructed in the 3 DOF Helicopter User Manual [2].

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. Load MATLAB

2. Open Simulink model $q\_heli3d.mdl$ shown in Figure 5.2 that implements a sample LQR controller. The model runs your actual 3 DOF Helicopter plant by directly interfacing with your hardware through the QUARC blocks, described in [1].

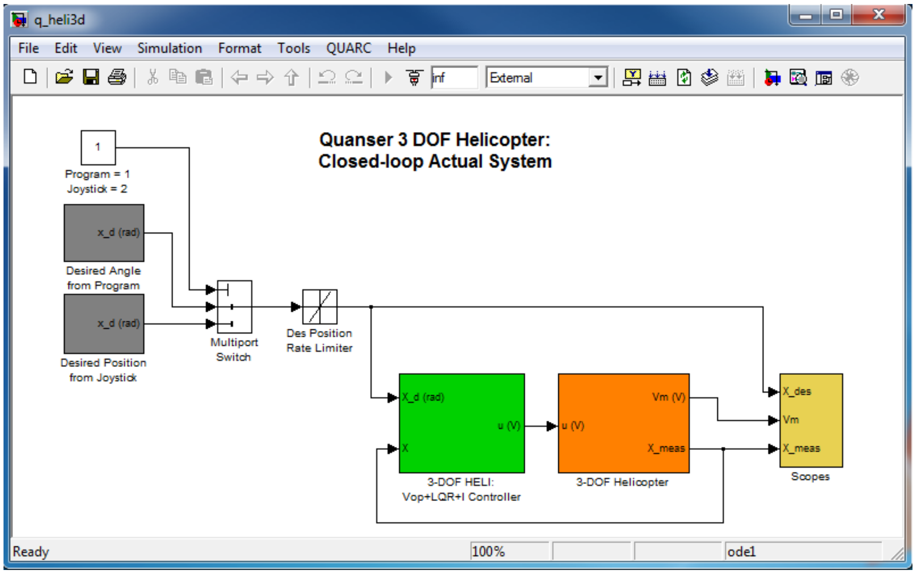

Figure 5.2: Simulink model q_heli3d implements the LQR controller on actual 3 DOF Helicopter system.

3. **Configure setup script**: 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.

4. Execute the $setup\_lab\_heli\_3d.m$ MATLAB script to setup the workspace before compiling the diagram and running it in real-time with QUARC. 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 gains, and voltage limits.

5. Open the 3 DOF Helicopter subsystem shown in Figure 5.3. It contains the QUARC blocks that interface with the hardware of the actual plant. The Analog Output block outputs the voltage computed by the controller to the DACB and the Encoder Input block reads the encoder measurements.

6. **Configure DAQ**: Double-click on the *HIL Initialize* block in the Simulink diagram and ensure it is configured for the DAQ device that is installed in your system. By default the block shown in Figure 5.3 is setup for the Quanser Q8 hardware-in-the-loop board.

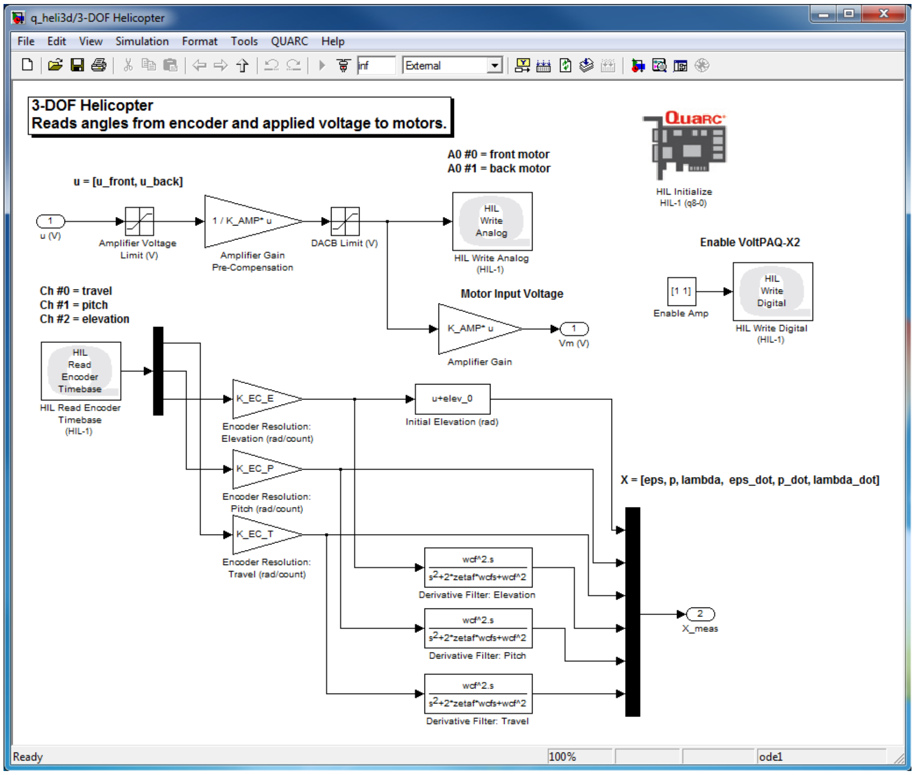

Figure 5.3: 3 DOF Helicopter subsystem used to interface with hardware.

7. The voltage sent to the Analog Output block is amplified by the amplifier and applied to the connected motor. Note that the control input is divided by the amplifier gain, K_AMP, before being sent to the DAQ board. 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 amplifier and data-acquisition board saturation blocks limit the amount of voltage that can be fed to the motor. In this case, since K_AMP = 3, the voltage is only saturated by the amplifier and not by the DAQ cards limits. The *Vm(V)* sink is the effective motor input voltage and shows when the amplifier is being saturated.

8. Click on QUARC | Build to compile the code from the Simulink diagram.

9. Open the *elevation (deg)*, *travel (deg)*, and *Vm (V)* scopes 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 0V line often can cause damage to the amplifiers.

10. Turn ON the amplifiers.

11. In the q_heli3d Simulink diagram, make sure the *Program/Joystick* block shown in Figure 5.2 is set to 1 in order to generate the desired angle from Simulink.

12. Select QUARC | Start to begin running the controller. The motors should begin running and the two propellers should start turning lightly.

    Note: Click on the **STOP** button on the Simulink tool bar at any time to stop running the controller.

13. 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.

14. 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 5.2. The helicopter body should be going up and down as the controller does the elevation tracking.

15. 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.

16. 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.

17. Figure 5.4 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.

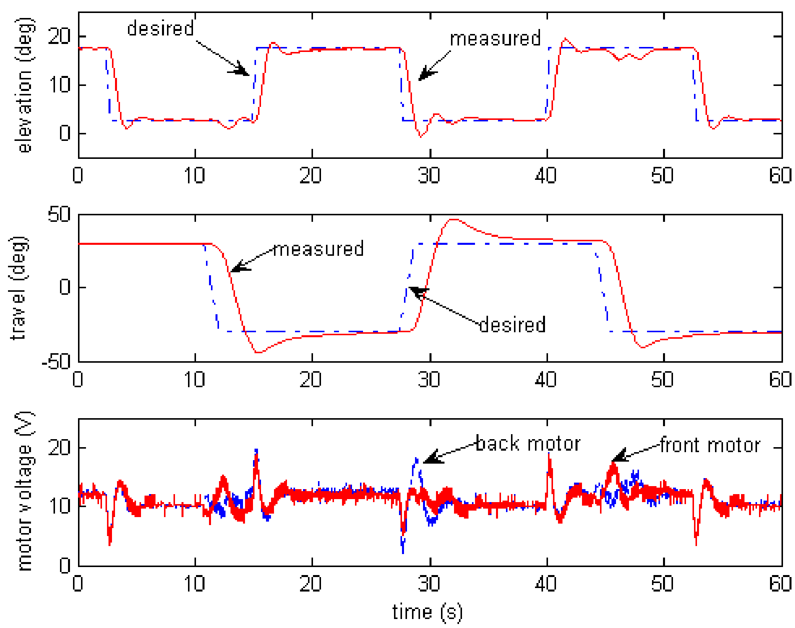

Figure 5.4: Typical closed-loop response of 3 DOF Helicopter system.

18. Alternatively, the desired angle can be generated using the joystick described in [2]. To use the joystick, set the *Program/Joystick* switch shown in Figure 5.2 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 QUARC if the joystick is to be used.

19. Click on the *Stop* button on the Simulink diagram tool bar (or select QUARC || Stop from the menu) to stop running the code.

20. Power off the amplifiers.

5.3.3 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 $q\_heli3d\_w\_ads.mdl$ shown in Figure 5.5 that implements a sample LQR controller on the 3 DOF Helicopter with ADS plant. The model runs your actual 3 DOF Helicopter with the ADS plant by directly interfacing with your hardware through the QUARC blocks, as discussed in [1]. The 3 DOF Helicopter System subsystem is basically the Simulink model described in Figure 5.2. The helicopter controller is not engaged until the Active Disturbance is calibrated (i.e. 0 V is fed to the helicopter motor until the ADS is homed).

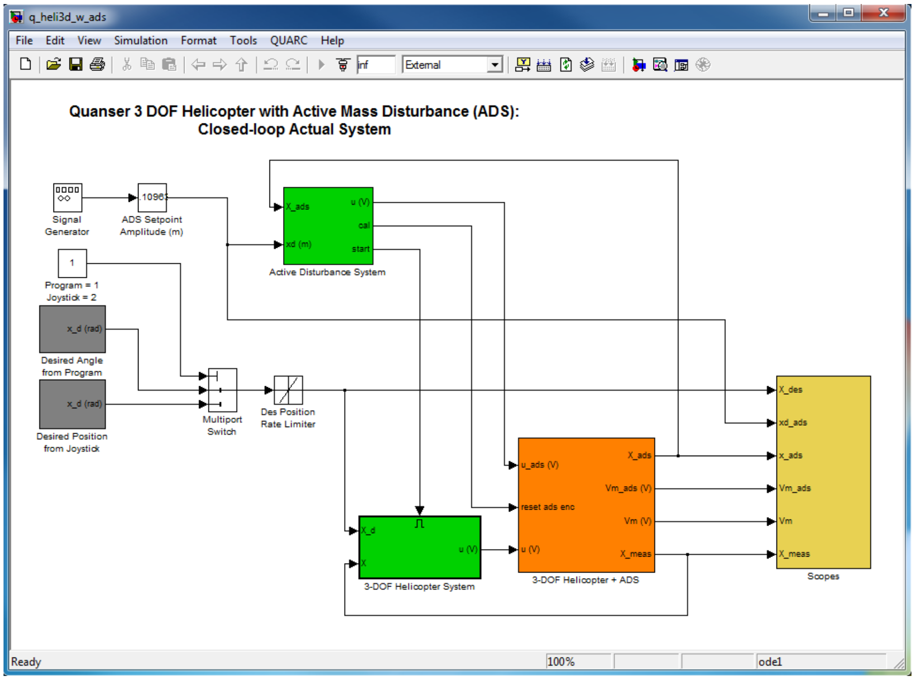

Figure 5.5: Simulink model $q\_heli3d\_w\_ads\_q8$ implements an LQR controller on the 3 DOF Helicopter with Active Disturbance system.

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 QUARC.

4. Click on QUARC | Build to compiled the Simulink diagram.

5. Open the *elevation (deg)*, *travel (deg)*, and *Vm (V)* scopes from 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 0V line often can cause damage to the amplifiers.

6. Turn ON the amplifiers.

7. In the q_heli3d_ads Simulink diagram, make sure the Program/Joystick block shown in Figure 5.5 is set to 1 in order to generate the desired angle from Simulink.

8. Click on QUARC || Start to begin running the controller. 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.

   Note: The controller can be stopped at any time by clicking on the **STOP** button located in the Simulink tool bar.

9. 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.

10. Set the *ADS Setpoint Amplitude (m)* slider gain block to 0.13 and *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.

11. 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 $\pm$25V and not go negative very often.

12. 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.

13. Figure 5.6, below, depicts the measured closed-loop position response of the 3 DOF Helicopter with the ADS when the disturbance mass is moving between $\pm$0.13 meters at 0.05 Hz.

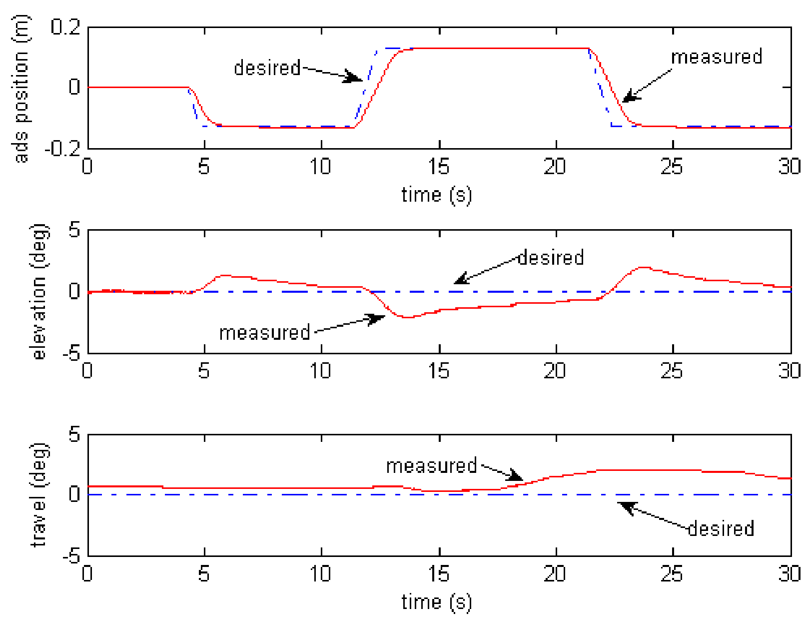

Figure 5.6: Closed-loop response of 3 DOF Helicopter ADS device.

14. Alternatively, the desired angle can be generated using the joystick described in [2]. To use the joystick, set the *Program/Joystick* switch shown in Figure 5.5 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 QUARC if the joystick is to be used.

15. Click on the *Stop* button on the Simulink diagram tool bar (or select QUARC || Stop from the menu) to stop running the code.

16. Power off the amplifiers.

6 TECHNICAL SUPPORT

To obtain support from Quanser, go to http://www.quanser.com/ and click on the Tech Support link. Fill in the form with all the requested software and hardware information as well as a description of the problem encountered. Also, make sure your e-mail address and telephone number are included. Submit the form and a technical support person will contact you.

REFERENCES

[1] Quanser Inc. *QUARC User Manual*.

[2] Quanser Inc. *3 DOF Helicopter User Manual*, 2011.

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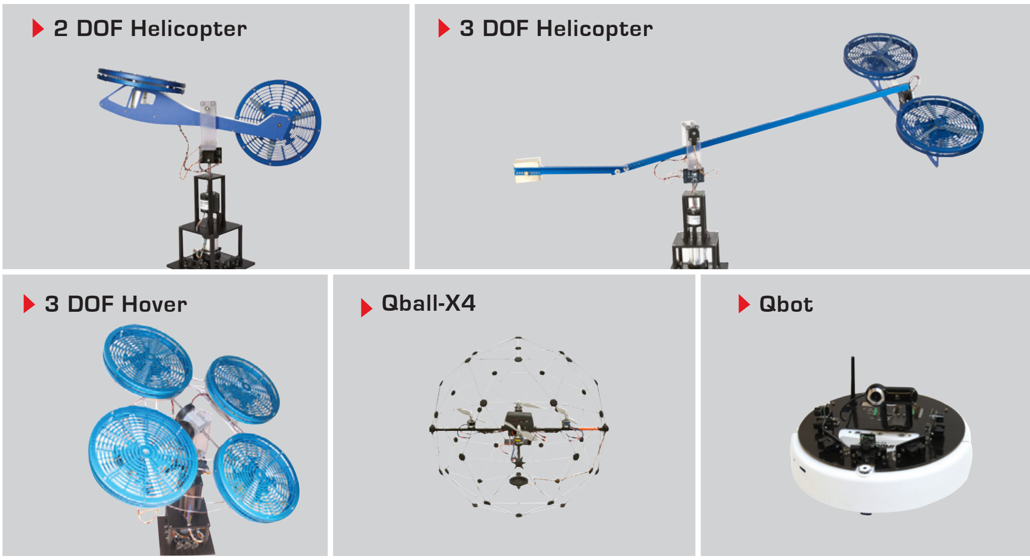

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