Imperial College London - Department of Aeronautics

$3^{rd}/4^{th}$ Year Laboratory Handout

The Twin Rotor Multivariable System: Feedback Control of a Pseudo-Helicopter Main-lab Instructions

Academic year 2018/19

- **You have to finish the pre-lab tasks and submit the pre-lab report before the laboratory session in order to complete the exercise successfully**
- **Remember to take the controller designed in pre-lab to this session for testing, Write down the numbers now on the next page**
- **Read this document thoroughly before the session**
- **This main-lab report accounts for *70%* of the overall mark**
- **Important Notes on Safety:**
  - Never start the experiment without someone holding the setup at the initial position (-27.5° elevation and 0° pitch)
  - The helicopter can travel covering a quite large space, stand clear of this region when the device is in operation
  - Always have somebody near the power switch so that the power can be cut in case of danger (e.g. unstable controller)

Version 3 (20190111)

Designed Weights

- **Slightly improved:**
  - **Q:**____ **R:**____________
- **Best elevation:**
  - **Q:**____ **R:**____________
- **Best travel:**
  - **Q:**____ **R:**____________
- **Best overall:**
  - **Q:**____ **R:**____________

Contents

1 In-Lab Modelling and Simulation

1.1 Linear System Modelling

In order to design controller we first need to generate the linear state-space model for the 3 DOF Helicopter. For this purpose follow these steps:

1. Load the LabVIEW 2015 software.

2. Open the LabVIEW project called 3D HELI LAB.lvproj, shown in Figure 1.

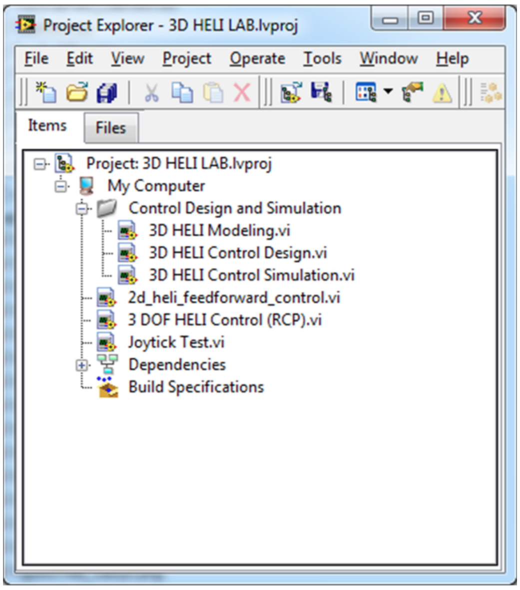

Figure 1: LabVIEW project used for the 3 DOF Helicopter provided by Quanser.

3. Under the `Control Design and Simulation` directory in the project explorer, open the 3D HELI Modelling VI[1] and run it by clicking the icon. All the parameters within the VI should be set to the values shown in Table 1 in the Appendix.

4. While the VI is running, click the OK button on the front panel to save the model to a file named `HeliLinearModel`. This file is to be used throughout the control design and simulation stages.

1.2 Controller Design

In order to design a PID-LQR controller follow these steps:

1. From the project explorer, open the 3D HELI Control Design VI.

2. Click on the LQR tab and modify the weight matrices accordingly to your desired values (based on the outcome of your Pre-Lab tasks, but remember to make one for the default values also). The values of the weights in Q represent quantitatively the amount of restriction applied to the controller such that the system follows more strictly the desired state trajectories. Both values in matrix R should always be set to 0.05 for this experiment.

3. Add the file path for the `HeliLinearModel` and run the 3DHELI Control Design VI by clicking the icon.

4. By navigating through all three tabs verify that the system is controllable and that the controller will stabilise the system. If this is the case, click on the `Save` button to record the LQR feedback gain K for its use in the simulation and implementation of the controller in the next sections.

[1]VI stands for Virtual Instrument.

5. Repeat the process for the weights obtained by all group members.

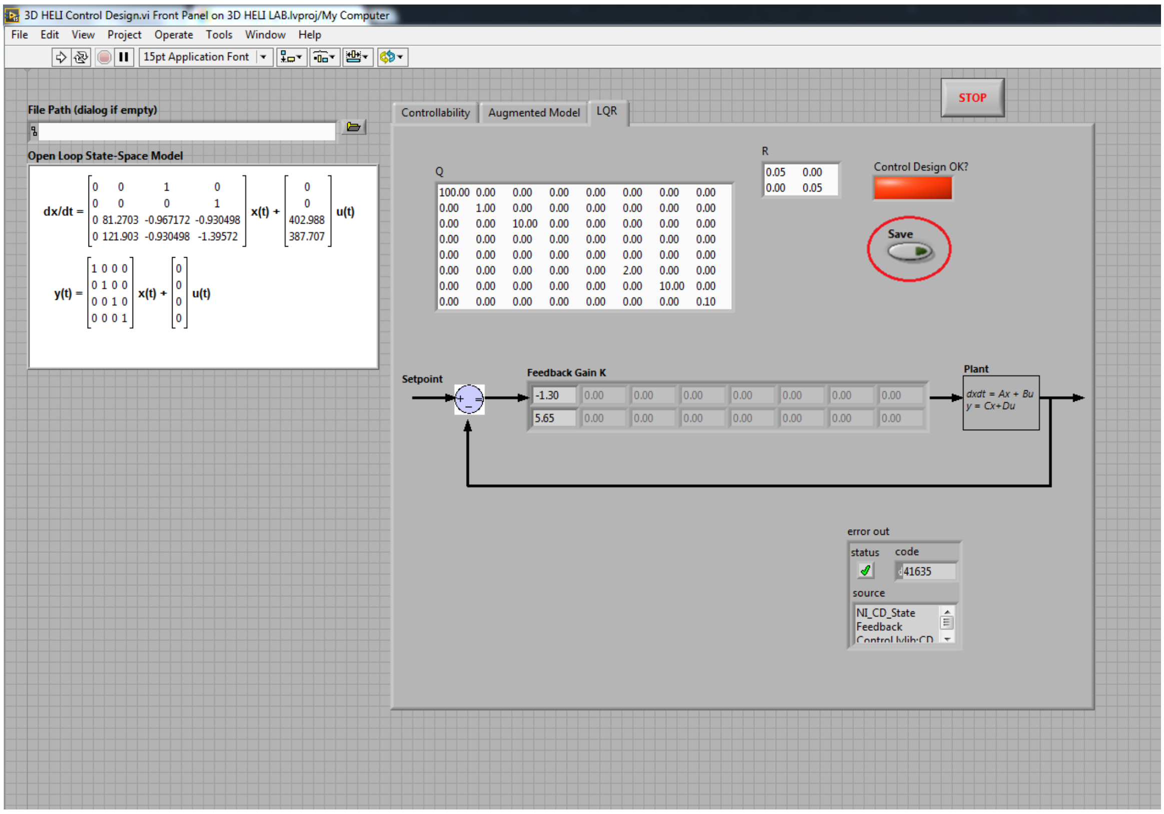

Figure 2: PID-LQR controller design.

6. If needed, you can return to this VI to regenerate new feedback gains after testing the performance of the closed-loop controller.

2 In-Lab Experiments

Now you are ready to precede to the experiments. Please read again the **Important Notes on Safety** of the handout cover.

To prevent damages to the setup, protection systems similar to flight envelop protection is in place and will be automatically activated when a predefined operational boundary has been reached.

If this happens in the openloop manual control experiment (section 2.3.1), the green `Safety Open-Loop` light will illuminate (see figure 4). Do not worry as you will be given back the control authority after the light goes off momentarily.

However, if the protection system kicks-in in the closed-loop control experiments (section 2.2 and 2.3.2), the red `Safety Override` light will go on with the elevation and pitch angles of the helicopter being brought to zero. You will need to have someone grab the helicopter and click the `STOP` button of the VI.

2.1 Open-Loop Step Response

Before implementing the designed controller, it is recommended to test the real system in open-loop configuration in order to gain a greater understanding of the dynamic behaviour of the system. For safety purposes only the open-loop elevation step response will be analysed in the real system. Further open-loop analysis can be carry out in the simulated linear and nonlinear models. To test the open-loop elevation step response follow these steps:

1. Open the `3D Heli Control open-loop Elevation` VI in LabVIEW.

2. In the front panel a slider can be seen, as that shown in Figure 3. This is used to control both motors' voltages. [2]

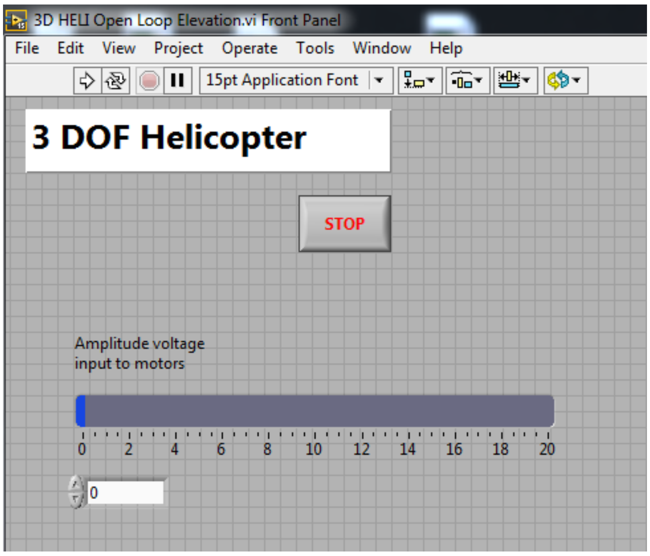

Figure 3: LabVIEW VI used to run the real system in open-loop configuration.

3. Allow the lab demonstrator to set up the helicopter (with tape) to prevent it from pitching due to the presence of a mass mismatch between the front and back motors.

4. Check that the voltage slider is set to zero and run the VI.

5. Type 5 in the numeric input dial, next to the slider, to apply a voltage step input of such amplitude.

6. Allow the system to run for 40 seconds, then ramp the voltage slowly back to zero. Click on the `STOP` button and export your data in the same way as in the previous parts.

This data can be used to identify a more accurate model describing the uncoupled elevation dynamic behaviour of the real system.

2.2 Closed-Loop Position Control Implementation

In this section we will investigate the closed-loop performance of the PID-LQR controller running on the actual real 3 DOF Helicopter. For this purpose follow these steps:

1. Open the `Main 3D HELI Control VI` (figure 4), that is used to run the 3 DOF Helicopter experiment.

2. Configure the panel with `Joystick OFF`, `Lateral ON`, `Export Plots ON` and `Open-Loop Off`. Make sure the `Case selector` is at `Start Up & Stand By`

3. Open the 3D HELI Control VI block diagram. Do this by pressing `ctrl+e`. Double click on the HIL Initialise control and ensure it is configured for the Data Acquisition (DAQ) device that is installed in your system. In our case select PCIe-6351. Press `ctrl+e` again to return to the VI.

4. Ensure that the helicopter has been setup (tape removed) and all the connections have been made as shown in Figure 5.

[2] The same voltage is applied to both motors to achieve a safe elevation by trying to prevent the helicopter from pitching.

> **Important Safety Note:**
>
> - **You should only use the feedback gain that has proven to perform well in the simulation**

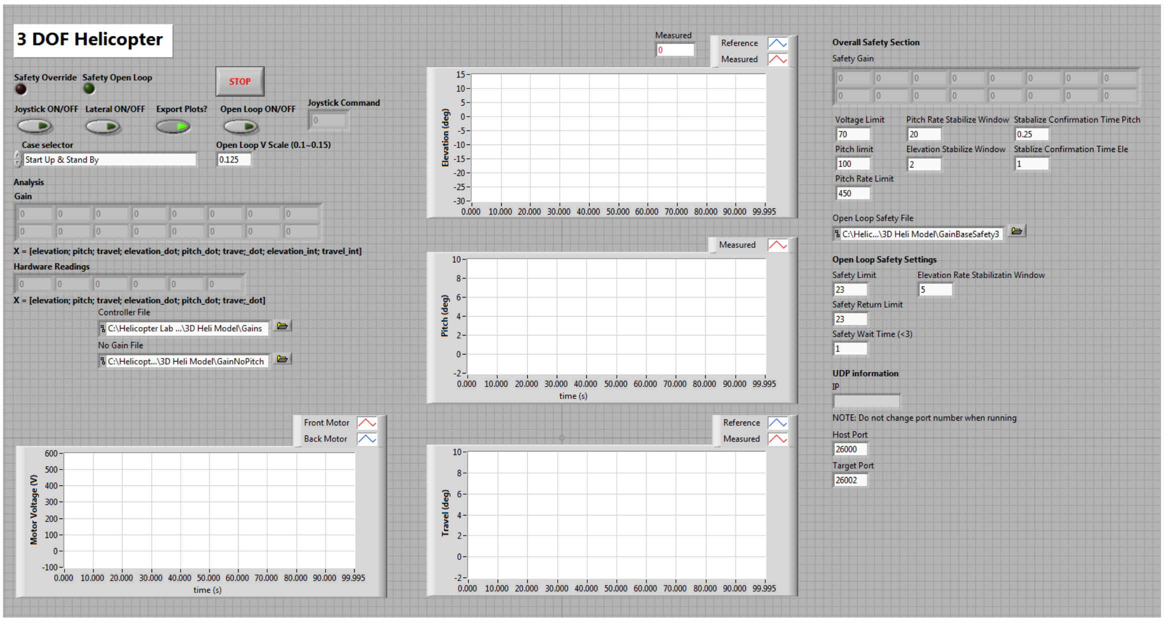

Figure 4: LabVIEW VI used to run the closed-loop controller on the 3 DOF Helicopter.

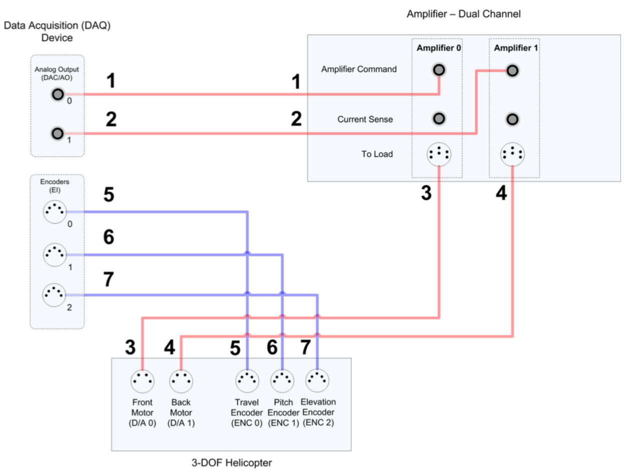

Figure 5: 3 DOF Helicopter system's wiring set up.

5. Have someone holding the setup at the initial position (-27.5° elevation and 0° pitch), then run the VI by clicking the icon.
6. In the pop up window, select the first feedback gain K generated earlier.
7. Once you hear the propellers running, release the helicopter and you will see the helicopter elevates itself. After the helicopter stabilises, select `Elevation and Travel Amplitude 10` in the case selector, and observe the response of the system to the combined desired trajectories. A good controller should allow the helicopter to track both trajectories quite accurately.

8. Before stopping the system set the case selector back to `Start Up & Stand By`. Have someone ready to grab the helicopter as it falls, then click `STOP`. **NB: Data beyond 100 seconds might got overwritten, so if you need to collect more data, stop and run the experiment again.**

9. Export the system's response data for posterior analysis in your report. Several Excel files will be generated and automatically pop up for each graph's data. Save the Excel files and make sure they are clearly named. For clarity, you may also merge the sheets into one file for each test cases. **NB: Make sure you close all Excel windows before each measurement. In case the pop up failed, open the task manager and kill the Excel process.**

10. Re-do steps 2 to 9 for the other gains you have computed.

2.3 Manual Control

In this part of the lab, we would like you to experience in person on how the knowledge and theories you have acquired in the courses and the labs can be utilized in real-world aerospace applications to improve performance and reduce the workload of human operators.

Figure 6 is a schematic overview of the lab step. You will be directly controlling the elevation of the lab helicopter, of which the angle will be used as the pitch attitude of a Boeing V-22 Tilt-rotor aircraft inbound for landing in the Simulink simulation. You will need to complete the landing twice, one with open-loop control (also known as direct control law (DIR) in fly-by-wire systems) and one with the controller you have just designed.

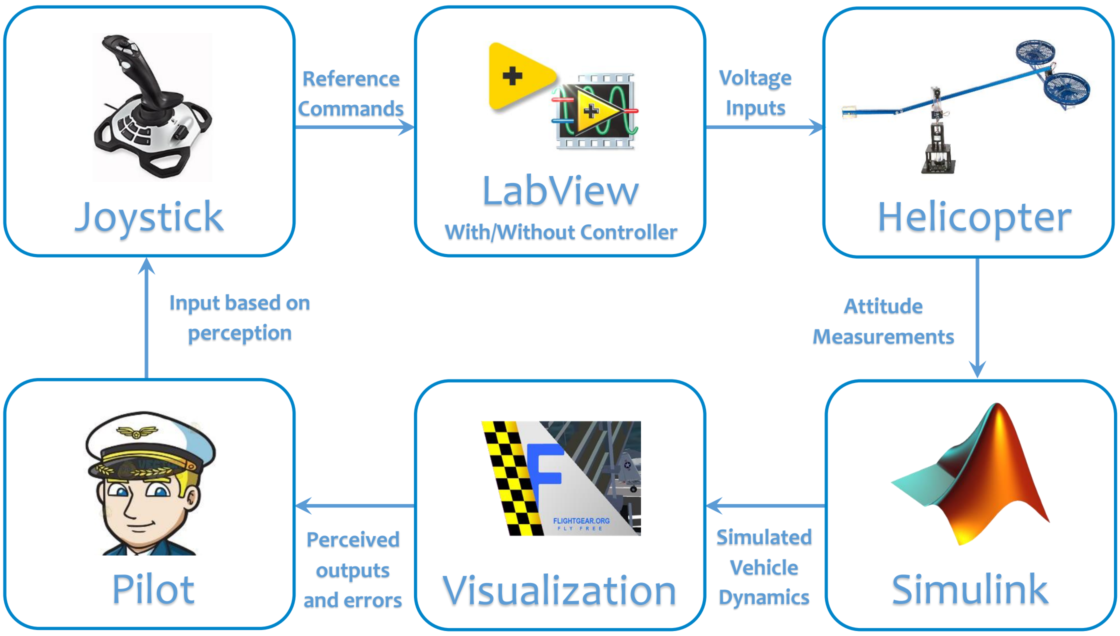

Figure 6: Experiment setup for the manual control exercise.

2.3.1 Open-loop Elevation Manual Control

In this part of the lab you will experience the difficulty of controlling the real open-loop system in its elevation trajectory alone. The joystick will be directly controlling the voltage sent to both motors directly. In order to carry out this part of the experiment carry out the following steps.

1. Let the lab demonstrator configure the FlightGear and Simulink environments, and put them aside first.

2. In the `Main 3D HELI Control VI` (figure 4), configure the panel with `Joystick OFF`, `Lateral OFF`, `Export Plots ON` and `Open-Loop Off`. Make sure the `Case selector` is at `Start Up & Stand By`
3. Have someone holding the setup at the initial position (-27.5° elevation and 0° pitch), then run the VI by clicking the icon.
4. In the pop up window, select the default feedback gain K generated earlier.
5. Once you hear the propellers running, release the helicopter and you will see the helicopter elevates itself.
6. After the helicopter stabilises, run the Simulink model. You should now be able to see the aircraft in FlightGear moving.
7. Select `Joystick ON` and `Open-Loop ON` in the LabView VI
8. Try use the joystick to land the aircraft smoothly at the aimed landing spot.
9. Once you have landed, the Simulink simulation will stop. Select `Open-Loop OFF` then `Joystick OFF`. With the assisting student ready to hold the helicopter, click on the `STOP` button.
10. Save relevant data (aircraft altitude and pitch angle) from the Matlab Workspace

2.3.2 Augmented Manual Control

As you have experienced, open-loop control is extremely labour-intensity and sometimes nearly impossible to a high precision and accuracy. For this reason, aircraft equip with modern fly-by-wire system will have its manual flight also implemented in a closed-loop manner.

Based on the functionality, the system can be distinguished as the stability augmentation system (SAS) and the control augmentation system (CAS). SAS is essential in achieving an acceptable level of handling characteristics stipulated by the certification regulations, and it serves as the foundation which manual and autopilot flight tasks are accomplished.

A similar implementation can be done for our system. Use the joystick to set the desired pitch angle of the aircraft inbound for landing. Do this by following these steps.

1. Repeat step 1 to 6 of open-loop manual control.
2. In step 7, select `Joystick ON` only.
3. Try use the joystick to land the aircraft smoothly at the aimed landing spot.
4. Once you have landed, the Simulink simulation will stop, then select `Joystick OFF`. With the assisting student ready to hold the helicopter, click on the `STOP` button.
5. Save relevant data (aircraft altitude and pitch angle) from the Matlab Workspace

3 Report

A short individual report (**max 3 pages, 11pt font size, include all texts and figures, page margin no less than 20mm, Penalties will be applied!!!; Indicate your setup number on the report front page**) needs to be submitted, whose aim is to show that you have understood the laboratory. The full range (0-70%) will be used when marking the report.

The report should contain a brief summary of your main observations and present the main results. The following questions should be addressed and briefly discussed:

1. Open-loop System:

- Compare the simulated linear and nonlinear model step responses in elevation (generated with `OpenLoopLinearModel.slx` and `OpenLoopNonLinearModel.slx`), to that of the non-linear real system. Remember to have the same voltage step input as you have used in the lab, and show all elevation responses in the same figure and comment on any differences. [10%]

2. Closed-loop Position Control:

- Discuss the performance of the 4 pre-lab designs tested on the real setup (present figures only when necessary). Describe the observed differences between the predicted simulated performance of the closed-loop nonlinear system (in pre-lab) to that of the real system's, and try to explain the causes. [15%]
- Present the final controller design, and compare the simulated performance of the closed-loop nonlinear system (data can be generated after the lab) to that of the real system's. Support your discussion with figures comparing the reference signal, the simulated response and the measured ones from the real setup [15%]
- Compare the input voltage and output dynamic response of the system (i.e. change in the states of the system). With the support of a figure, discuss the level of saturation in the voltage input as the **desired** performance of your controller improves. [15%]

3. Manual Control:

- Compare the approach and landing performance using open-loop manual control and augmented manual control, by plotting the altitude and pitch angle data. Also comment on your different experiences as the pilot. [15%]

4 Appendix

Table 1: System parameters. [1]

Symbol	Description	Value	Units
K_f	Propeller force-thrust constant	0.119	NV^{-1}
m_f, m_b	Mass of front and back fans	0.654	kg
m_w	Mass of counterweight	1.924	kg
m_h	Mass of helicopter body		
L_a	Distance between travel axis to helicopter body	0.66	m
L_h	Distance between pitch axis to each motor	0.178	m
L_w	Distance between travel axis to the counterweight	0.47	m
g	Gravitational constant	9.81	ms^{-2}
F_f	Front motor thrust		
F_b	Back motor thrust		
V_f	Front motor voltage		
V_b	Back motor voltage		
ϵ, $\dot{\epsilon}$	Elevation angle and angular rates		
ρ, $\dot{\rho}$	Pitch angle and angular rate		
λ, $\dot{\lambda}$	Travel angle and angular rate		
K,K_{PD}	PID/PD gain		

References

[1] J. Apkarian, M. Levis, and C. Fulford, "Laboratory Guide - 3 DOF Helicopter Experiment for LabVIEW Users," *Quanser Inc.*, 2012.