Imperial College London - Department of Aeronautics

Laboratory Handout for AERO96002 Control Systems

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

January 14, 2021

- **You have to finish the pre-lab tasks and submit Matlab Grader assignment 1 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**
- **Oral assessment will be arranged after the lab sessions. Knowledge of both pre-lab and main-lab tasks, all lecture materials and Matlab Grader assignments to date, will be examined. The grade account for 20% of the mark for AERO96002 Control Systems**
- **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 4 (20200109)

Designed Weights

- **Slightly improved:**
  - **Q:**______________________________ **R:**__________
- **Best elevation:**
  - **Q:**______________________________ **R:**__________
- **Best travel:**
  - **Q:**______________________________ **R:**__________
- **Best overall:**
  - **Q:**______________________________ **R:**__________

Contents

1 Testing of the Pre-lab Controller Design (Recommended Time: 20 min)

1.1 Linear System Modelling

We will first test the pre-lab controller designs to see how do they perform in practice. For that, we 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.

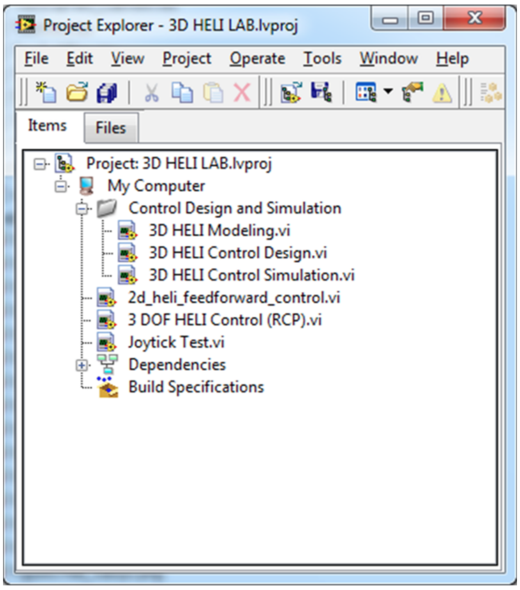

Figure 1: LabVIEW project used for the 3 DOF Helicopter provided by Quanser.

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 Generation

In order to generate the PID-LQR controller you have designed in pre-lab, 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.

[1] VI stands for Virtual Instrument.

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.

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

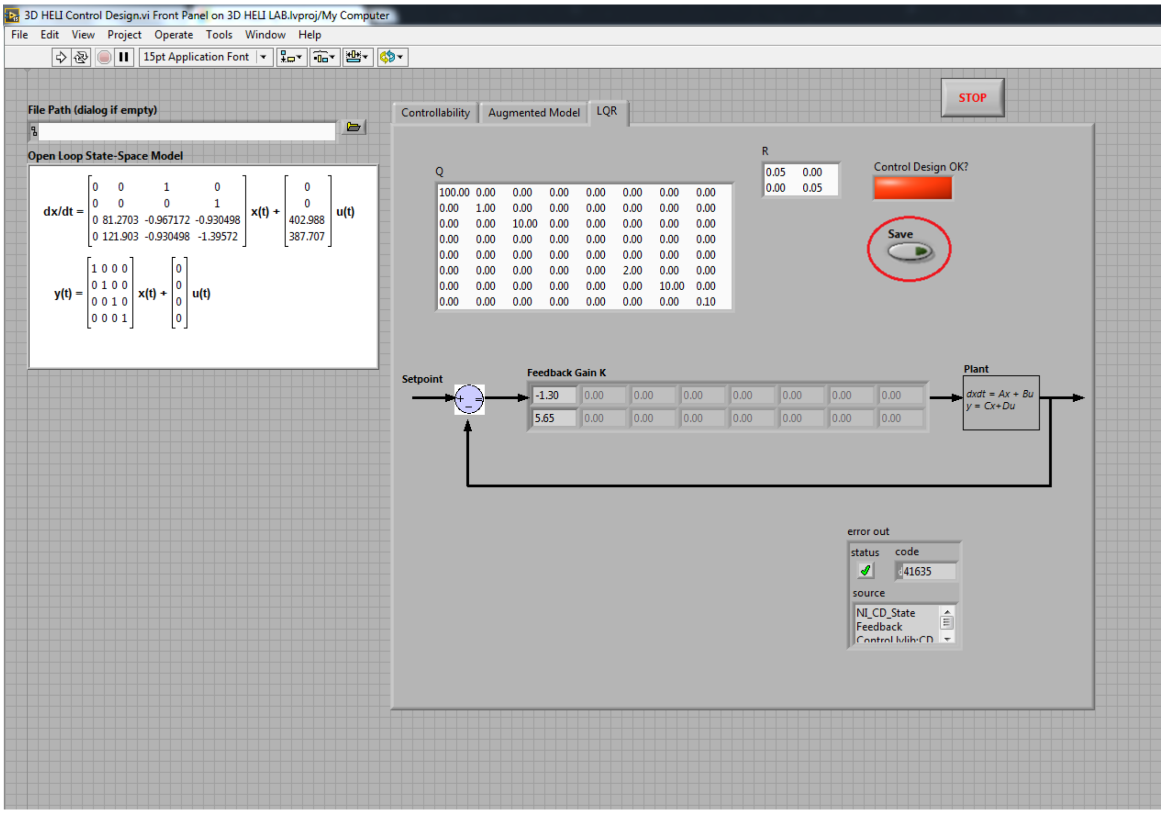

Figure 2: PID-LQR controller design.

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

1.3 Closed-Loop Lab Test with Pre-lab Design

In this section we will investigate the closed-loop performance of the PID-LQR controller running on the actual real 3 DOF Helicopter. 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 the protection system kicks-in in this closed-loop control experiment, 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.

Now you are ready to precede to the experiments. For this purpose follow these steps:

1. Open the `Main 3D HELI Control VI` (figure 3), 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 4.

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

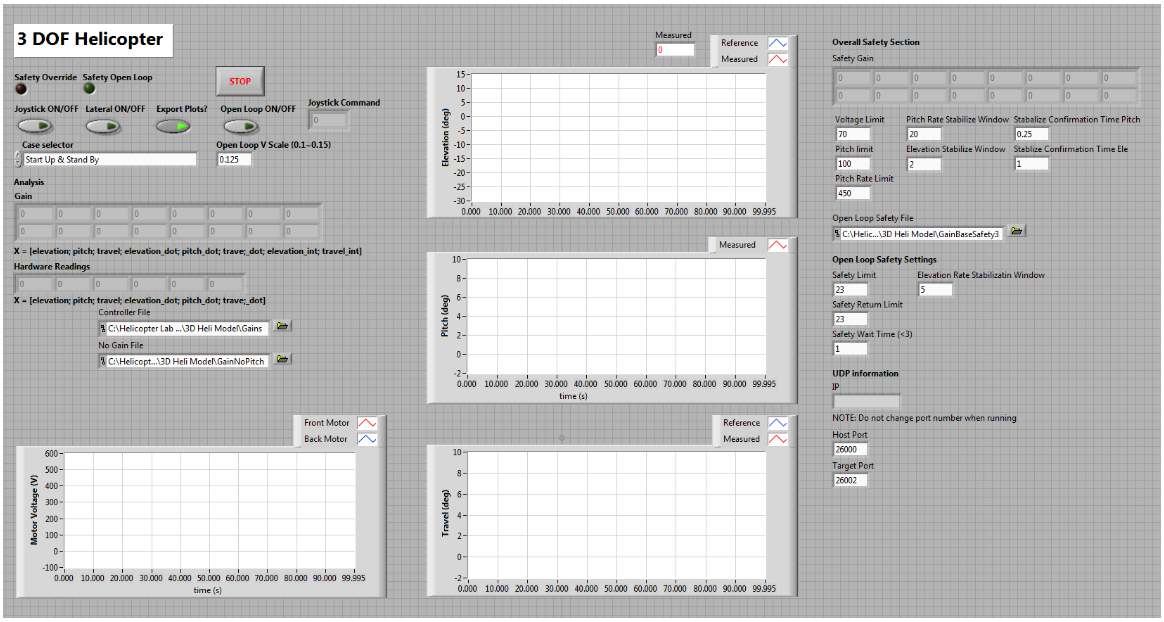

Figure 3: LabVIEW VI used to run the closed-loop controller on the 3 DOF Helicopter.

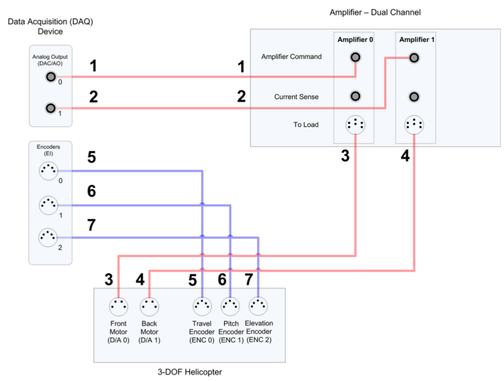

Figure 4: 3 DOF Helicopter system's wiring set up.

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 In-Lab Design and Testing (Recommended Time: 40 min)

Now you have tested all the pre-lab designs on the actual setup. Did they perform in the same way as you expected?

Now you will be given a chance to improve your control design on the site. Starting from a pre-lab control design that you think having the best performance (or the default design), repeat the tasks in Section 1.2 and 1.3 with new designs of weights Q until you are all happy with the final design. Note that the actual setup only physically capable of delivering a maximum voltage of 24V.

While doing this, pay special attention on the relationship between the actual tracking performance and the desired performance as the weights changes. Also try to identify different trade-offs in designing controllers for such multiple input multiple ouput (MIMO) system. You will not be evaluated based on the performance of the final design, but rather, the understanding of the theory and the connections to real-world practices.

3 Manual Control: Pilot Landing Simulation (Recommended Time: 20 min)

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.

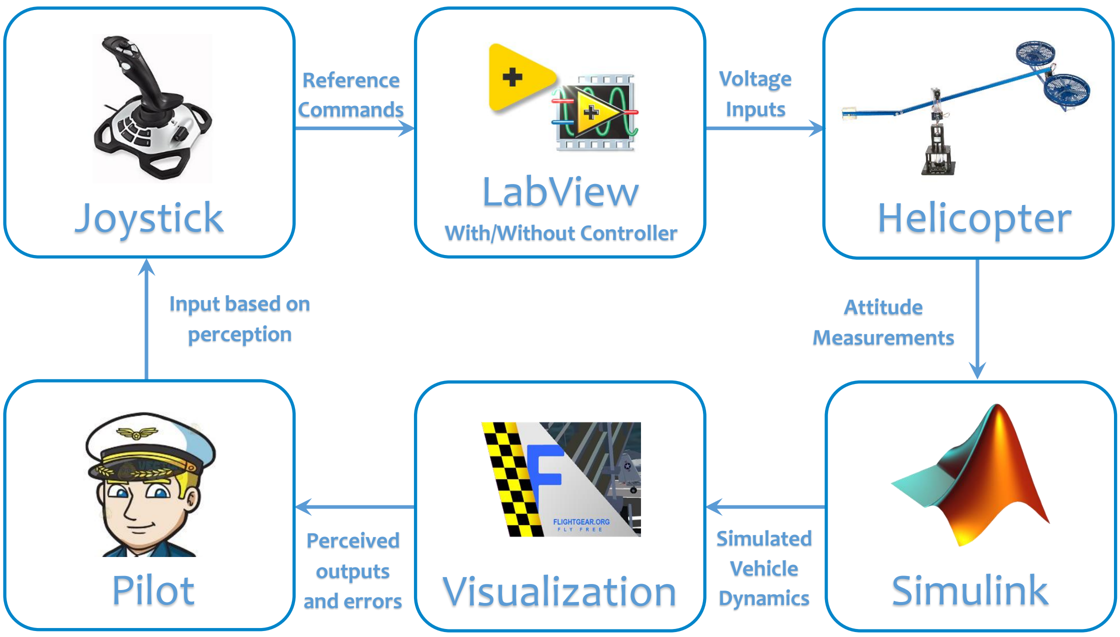

Figure 5: Experiment setup for the manual control exercise.

Figure 5 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.

3.0.1 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 3), 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

3.0.2 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

4 Oral Assessment

Shortly after the lab, an oral assessment will be arranged with the group together. ***Failure to attend the oral assessment* or *arrival delay of more than ONE minute* will lead to a mark of ZERO for the corresponding part. If you are more than ONE minute late, do not enter the exam room nor knock on the door, as we do not have the authority to assist you. Contact UG teaching office immediately and they will provide instructions.**

Here are some information to help you prepare for the oral assessment:

- The oral assessment lasts approximately 30 min. Your final grade will be based on your individual performance as well as the performance as a group.
- In the first 5 min, one of the group members will orally present the main learning outcomes of the lab, representing the group. You have full flexibility on this but the focus should be on the main 'take-home' messages for the lab, i.e. what have you learned today regarding control design for real-world physical systems. Presentation of the lab results is not necessary.
- This is followed by a number of individual questions, directed to selected group members. The answer to each question will directly affect his/her grade as an individual as well as the group grade. Your overall mark will be computed as a weighted sum of those two grades. Therefore, it will be your responsibility to make sure all group members properly prepare for the lab, get involved in the lab exercises, and share knowledge with each other before the oral exam, to ensure an overall good understanding of lab tasks across all group members.
- Knowledge of both pre-lab and main-lab tasks, all lecture materials and Matlab Grader assignments to date, will be examined. The questions will be regarding, but not limited to, the following aspects:
  - Jacobian linearisation
  - PID control design
  - LQR control design
  - Limitations of linear modelling and controller design
  - Criteria for good closed-loop design
  - Trade-offs in control design
  - Beauty and danger of feedback
  - Factors limiting closed-loop performance of a real-world system.

5 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.