ENGINEERING TRIPOS PART IIA

ELECTRICAL AND INFORMATION ENGINEERING TEACHING LABORATORY

MODULE EXPERIMENT 3F1

FLIGHT CONTROL

Objectives:

- Simulation of various aircraft models on the computer.
- Study real-time (manual) control and the limitations imposed by time delays.
- Design of a simple autopilot.
- Illustrate frequency response concepts in analogue and digital control systems, conditions for oscillation in feedback systems and stability.
- Gain familiarity with Python and Jupyter Notebooks.

Getting Started

- Log on to the teaching system. The computers in the EIETL should already be configured to log in to the Linux side of the teaching system, do not log in to the Windows side.
- Under `Activities`, select `Start 3F1 Flight Control`. This will create a `3F1_Flight_Control` directory in your home directory, and you will be able to access its contents later from any computer on the teaching system.
- Once the files are copied over, a Jupyter Notebook will launch automatically. All further instructions for the lab, including how to complete the worksheet, how to write your report, and how to submit your work, are contained within the notebook.
- The worksheet and report template are located at the end of this document.

Troubleshooting

If the Jupyter notebook does not launch from the `Start 3F1 Flight Control` shortcut, you can run it manually from within the `3F1_Flight_Control` directory via the following terminal commands:

```
source /usr/local/python-venv/bin/activate
jupyter notebook 3f1_lab.ipynb
```

Instructions for a Full Technical Report

Students not intending to submit a Full Technical Report on the 3F1 Lab may ignore this section. Guidance on the preparation of FTRs is provided in the CUED booklet *A Guide to Report Writing*, with which you were issued in the first year. If you are offering a FTR on this experiment, you should include a discussion section with seven subsections addressing the following points. Include your Laboratory Report as an appendix and refer to it where appropriate.

[1] The Stabilisation of Sinusoidal Disturbances

From §2.4: Use the results of your calculations to indicate $K(j\omega_1)G(j\omega_1)$, where $\omega_1 = 0.66 \times 2\pi$ rad/s, on an Argand diagram for suitable stabilising proportional gains and hence estimate $|(1 + K(j\omega_1)G(j\omega_1))|$. Does the theory predict that your feedback will help attenuate the sinusoidal disturbance for stabilizing gains? How does this compare to your experience given in your lab report?

[2] Unstable Aircraft

From §2.5: It turns out that if $D > T$ then no proportional gain exists to stabilise the system. Verify this claim analytically in your report.

[3] Broom Balancing

The problem of stabilizing an unstable aircraft is similar in many respects to the problem of balancing a broom.

Consider the question: "What is the shortest upside down broom I can balance on my hand?" The linearised equations of motion (assuming negligible handle weight, length L, horizontal position of your hand x, angle θ to vertical, and considering one dimension) are:

$$\ddot{x} + L\ddot{\theta} = g\theta$$

Suppose we measure the horizontal position of the top of the broom, $y = x + L\theta$ and then use the feedback signal, $z = y + T\dot{y}$ where $T^2 = L/g$. Calculate the transfer function from x to z under this arrangement.

This assumes the particular proportional-derivative action controller given, but this is a reasonable choice. Do you notice a similarity with the dynamics of the unstable aircraft?

Hence provide estimates of the minimum value of L based on your above results. Compare this with reality, and comment.

[4] PID Derivative Term Approximation

From §3.3: Review the code implementing the PID Controller. Which method was used to approximate the derivative? Calculate the transfer function of the discretised controller (z-domain) assuming that the simulation runs at a consistent 60 frames per second.

[5] Discretised Time Delays

Consider the discretisation of blocks with time-delays. Consider the continuous time plant $G(s) = e^{-D_1 s}/s$ placed in the arrangement illustrated in Figure ??. Find the discrete-time transfer function from $u(k)$ to $y(k)$. The DAC is a simple zero order hold, and you may assume that the ADC and DAC operate synchronously with sampling period T (Hint: You may find it useful to write $D_1 = nT + D_0$ where n is an integer and $0 \leq D_0 < T$).

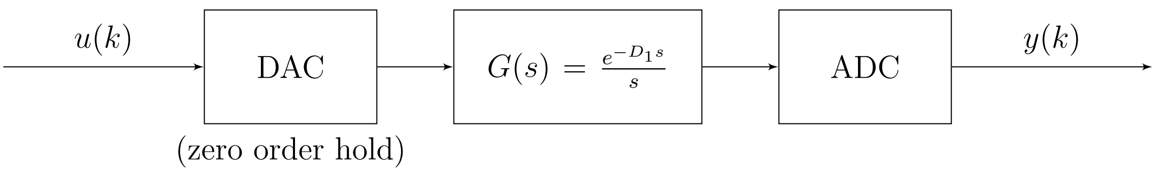


Figure 1: ADC/DAC arrangement for discretization

The plotting functions for producing Bode diagrams used by the lab obtains a time-delayed frequency response for the continuous system by first calculating the frequency response of the plant and then shifting it by a time delay corresponding to e^{-Ds}. However, the simulation runs in discrete time, and treats input as a zero-order hold. Discuss any changes in accuracy that might arise from using this scheme with a low sampling rate.

[6] Discrete Systems

Complete **§4: Discrete Systems** in the lab notebook, including answers to the questions and requested figures.

3F1 Lab Worksheet

2.1 Simplified Aircraft Model

Transfer function =

`num =` `den =`

2.2 Modelling Manual Control

Controller transfer function =

$k =$ $D =$

Phase margin =

Amount of extra time delay which can be tolerated =

2.3 Pilot Induced Oscillation

Period of oscillation (observed) =

Period of oscillation (theoretical) =

2.4 Sinusoidal disturbances

Maximum stabilising gain =

Gain at 0.66 Hz = Phase at 0.66 Hz =

2.5 Unstable Aircraft

Fastest pole at $T =$

3.2 Autopilot with Proportional Control

Proportional gain $K_c =$ Period of oscillation $T_c =$

3.3 Autopilot with PID Control

Transfer function of PID controller =

PID constants: $K_p =$ $T_i =$ $T_d =$

Adjusted value of $T_d =$

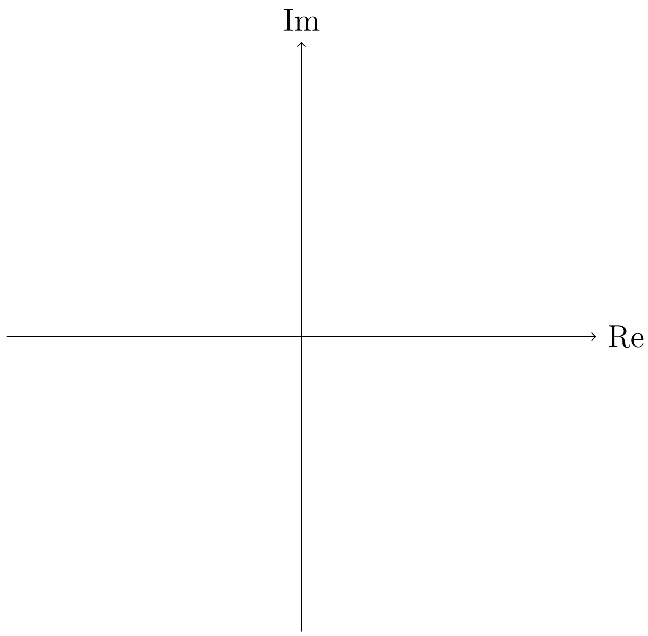
3.4 Integrator Wind-up

Integrator bound $Q =$

Report Template (3F1 Flight Control Lab)

This report template contains **9 questions** spread over **4 pages**.

1. (§2.2 Modelling Manual Control) Nyquist diagram (from Bode diagram) for controller in series with plant.



Nyquist diagram

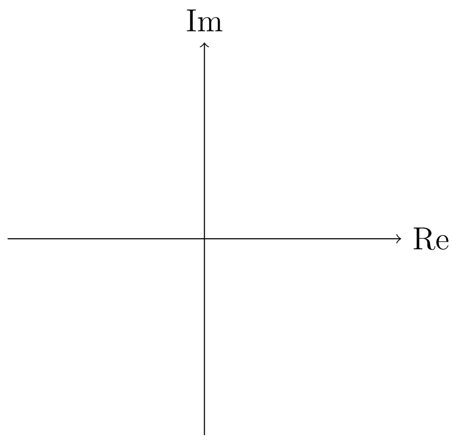
2. (§2.2 Modelling Manual Control) Are you using any integral action? Give a brief explanation. What does this imply about the accuracy of the model of the human controller?

3. (§2.3 Pilot Induced Oscillation) Explain the oscillation of the feedback loop. How does your observed period of oscillation compare to the theoretical prediction?

4. (§2.3 Pilot Induced Oscillation) Can you give a rough guideline to the control designer to make PIO less likely?

5. (§2.4 Sinusoidal Disturbances) Was your manual input able to reduce the error (as compared to providing no input)?

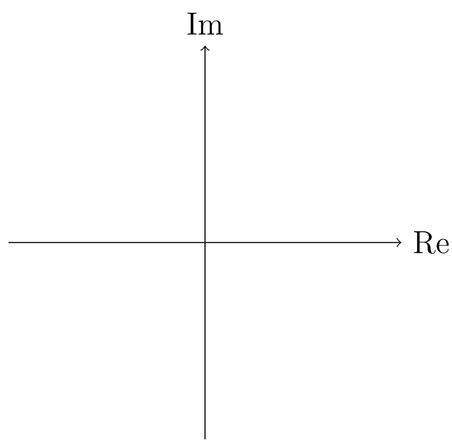
6. (§2.5 An Unstable Aircraft) Nyquist diagram for $G_2(s)$.



Nyquist diagram of $G_2(s)$

7. (§2.5 An Unstable Aircraft) Explain, using the Nyquist criterion, why the feedback system is stable with a proportional gain greater than 0.5.

8. (§2.5 An Unstable Aircraft) Sketch of a Nyquist diagram for $G_2(s)$. with a small time delay D.



Nyquist diagram with small time delay

9. (§3.4 Integrator Wind-up) Explain how you calculated the bound on Q.