EEE3094S - Controls Lab 3 Report

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EEE3097S

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Contents

I. Introduction and Model Summary

This project is based on constructing a proportional controller for a hovering helicopter model. The controller will be designed to control the altitude of the flying helicopter. The controller must be designed according to the requirements and specifications of the client. The characteristics of the controller will be determined using simulations and will then be tested using a circuit built on a breadboard. The step response as well as the frequency response of the entire system will be used as a tool to identify the different components and parameters needed to build an adequate controller. Using MATLAB Simulink, these responses can be simulated and the parameters easily changed to meet the necessary requirements. However, it is important to note that the simulations work in an ”ideal” environment where uncertainties such as component tolerances or noise are not taken into account. This means the aim of this experiment is to build a controller onto a breadboard (using the simulations as a tool) that will meet the requirements in a ”real” environment. This circuit for the controller will then be tested and changed to meet those requirements and account for the possible uncertainties.

The model of the system is first being analysed in open loop configuration. The input of the model is a voltage which is then transformed into a change in the position of the helicopter. This input voltage goes through and powers different systems that affect the angle, the speed and the force that the system will have. These different systems together, allow for a change in position of the helicopter. These systems include the Voltage to Angle System, the Rotor System and the Mass System. The helicopter will then be able to fly upwards depending on the voltage value. However, there is a factor that acts in the opposite direction - gravity. The gravitational force of the helicopter will result in a minimum input voltage needed for it to lift off the ground. This minimum input voltage value is 2.5V and is an essential value for this experiment. The problem encountered is that when the input voltage is greater or equal to 2.5V, the helicopter will fly upwards at a constant speed without stopping at a particular position. The helicopter is therefore not hovering but travelling upwards indefinitely which is highly undesirable in ”real-life” circumstances. This can however be fixed using a controller which (with the correct parameters) will allow the helicopter to hover at a certain position (in meters) in mid-air. The mathematical model of the open loop system is made more clear in Figure 1.

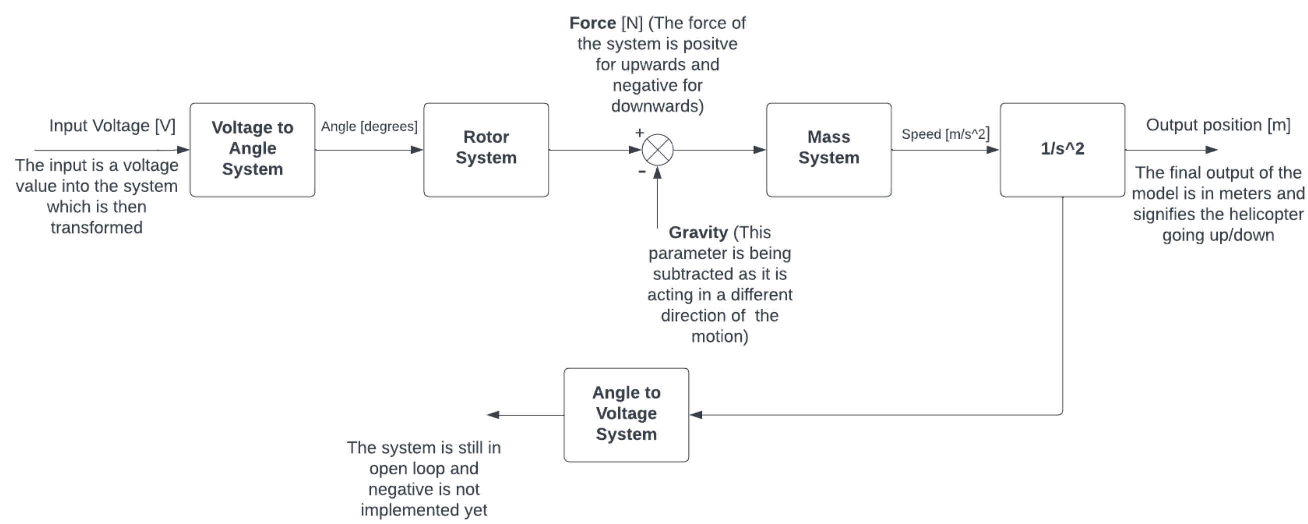

Fig. 1: Block diagram showing the mathematical model of the **Open-loop** system

The goal of this experiment is to design and implement a controller which is capable of making the helicopter hover at a certain position. This controller must meet the specified requirements by the client. The controller system will be placed before this mathematical model such that the input voltage will first go through the controller and then the plant. The system will also be placed in closed loop with negative feedback which will allow for the output to be adjusted to the desired position.

II. Specifications and Systematic

The specifications imposed need to be taken in consideration in the design of the controller for the system. The specifications are related to the characteristics of the transfer function of the plant. For this experiment the following characteristics were used: the gain of the plant's transfer function was **A = 11.3729**, the time constant was **T = 10.889** and the sensor component was **S = 0.51**. The specifications were tabulated to make it easier to distinguish between them.

Specification	Acceptable value	Details and importance
Peak Overshoot	Overshoot must be within 20%	The overshoot of the step response is how much the step response go over the final value before going into steady state
Set-point tracking	Controller must track within 0.4 m of the final value	The controller must be able to hover at the specified position accurately. This means that the tracking of what was set must be within the specified range
Settling time	Settling time must be less than 9 seconds (determined from characteristics of the plant i.e time constant)	The settling time of the response is how long the step response takes to reach steady state. This signifies how long it will take for the controller to track the set-point and allow for the helicopter to hover
Output Disturbance rejection	The disturbance rejection must be within the settling time of 9 seconds.	If disturbance is added to the system, the controller must be able to recover and reach steady state within the settling time
Sinusoidal tracking	Controller must tracking 0.4 m of the final when there is a sinusoidal input	If a the input voltage of the plant is sinusoidal, the controller must still be able to correctly track the set-point

TABLE I: Table showing the different specifications and their importance

From these specifications, the controller can be designed. The design of the controller was done by getting the parameters of the controller's transfer function using simulations. The two most important aspects of this design is the gain of the controller and the phase change that the controller will bring to the system. The poles and the zeroes of the controller's transfer function will play a critical role in the validation of the specifications. The position of the poles and zeroes will change the response and must therefore be adjusted to meet the specifications.

The circuit for the controller is made up of three op-amp circuits which are connected together in series. The first op-amp circuit is used to produced a gain. This will be the gain of the controller and can be changed by altering the resistor ratio between the two resistors as it can be seen in following figure 2.

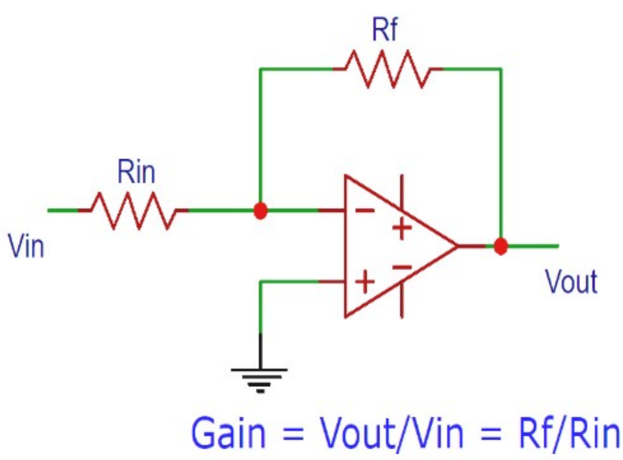

Fig. 2: Figure showing how to get the gain from the op-amp circuit

The second op-amp circuit is used to implement the poles and the zeroes of the controllers. In order to implement a lead circuit in the controller there must be a lag that is implemented as well. This results in both a pole and a zero parameter that need to be simulated and designed. This lead circuit is made up of capacitors and resistors. The first RC pair will dictate the position of the zero. The RC pair in the feedback will dictate the position of the zero. The following lead lag circuit 3 shows how to get the pole and zero values from the relationship between the resistors and the capacitors. This will be used in conjunction with the simulations to get the adequate parameters for the controller.

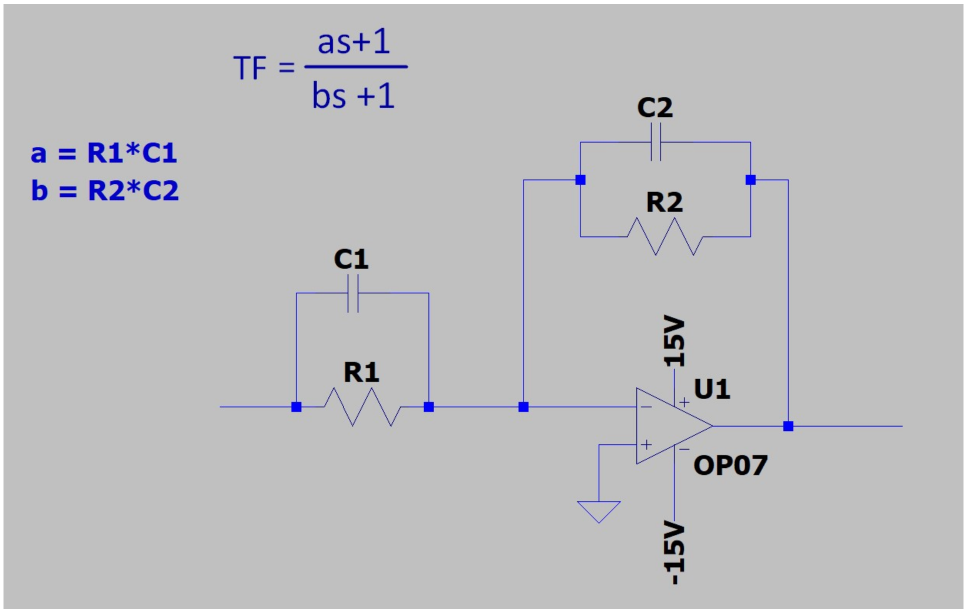

Fig. 3: Figure showing the lead lag circuit used for the pole and zero of the controller

Regarding the selection of the op-amp, it was decided to use 3 inverting op-amps. An additional requirement from the client was to not have more than 4 op-amps used in the circuit for the controller. Having additional op-amp circuits would not be useful and the circuit would not be optimized. However, it is important to notice that the final output will come out as a negative value due to the odd number of inverting op-amps. The input voltage must therefore be negative in order for the system to output a positive value and function adequately.

Using the MATLAB software, the root locus, the bode plots and the Nyquist diagram of the controller transfer function can be simulated. The simulations were first tested on the ”sisotool” using the root locus to determine the position of the zero and the pole of the controller that would keep the system within the design specifications: a settling time of two seconds lower than the time constant - in this case it was calculated to be a settling time of 8.89 seconds, and the other specification was the overshoot which could not be larger than 20% of the step applied at the set-point. From this root locus simulations and the frequency responses, different positions for the pole and zero were tried while still fitting within the specifications. When the specifications were met, the value for the positions were gathered from the root locus. This can be seen in figure 4 which shows the positions of the pole, zero and the gain which were calculated to be **-10, -0.47 and 10 respectively**. The bode plot in figure 5 and the Nyquist diagram in figure 6 were all used to confirm these values were realizable and met the specifications.

columnwidthcolumnwidth

Fig. 4: Root Locus of controller on sisotool

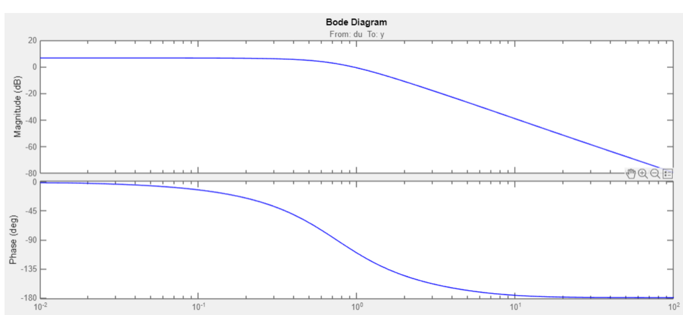

Fig. 5: Bode plots of controller on sisotool

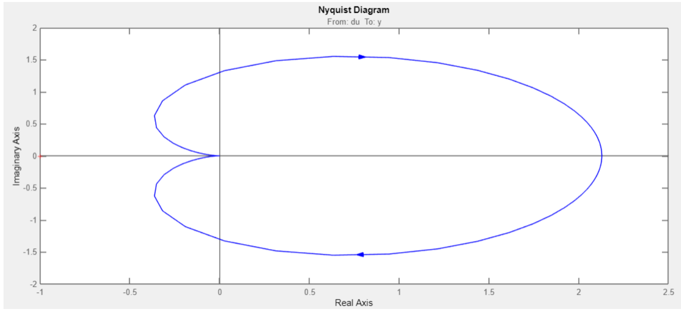

Fig. 6: Nyquist plot of controller on sisotool

The block diagram for the entire system is then designed in order to do the simulations and gather the parameters for the controller. This block diagram is displayed in Figure 7.

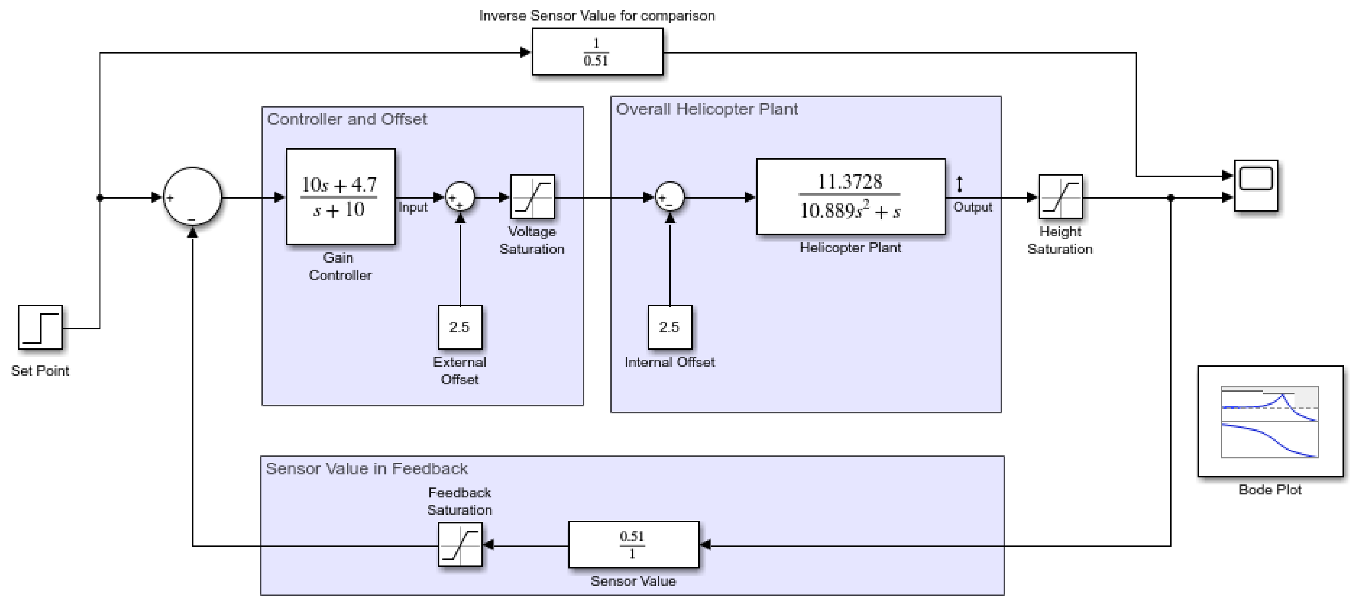

Fig. 7: Block diagram of the entire system used for the simulations

The final circuit for the controller can now be designed. This circuit is displayed in figure 8.

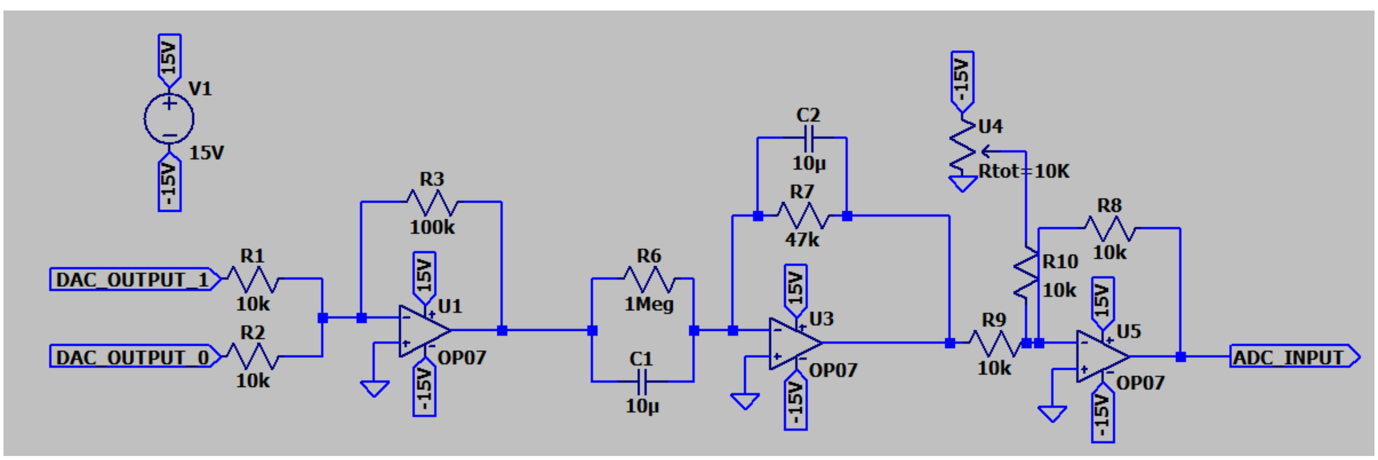

Fig. 8: Circuit Diagram of the controller

III. Simulation Results and Comparison

The figure below, Figure 9, shows the step response when the continuous time-lead controller has been implemented in the system. The transfer function of this controller was refined in order to comply with the settling time and overshoot specifications.

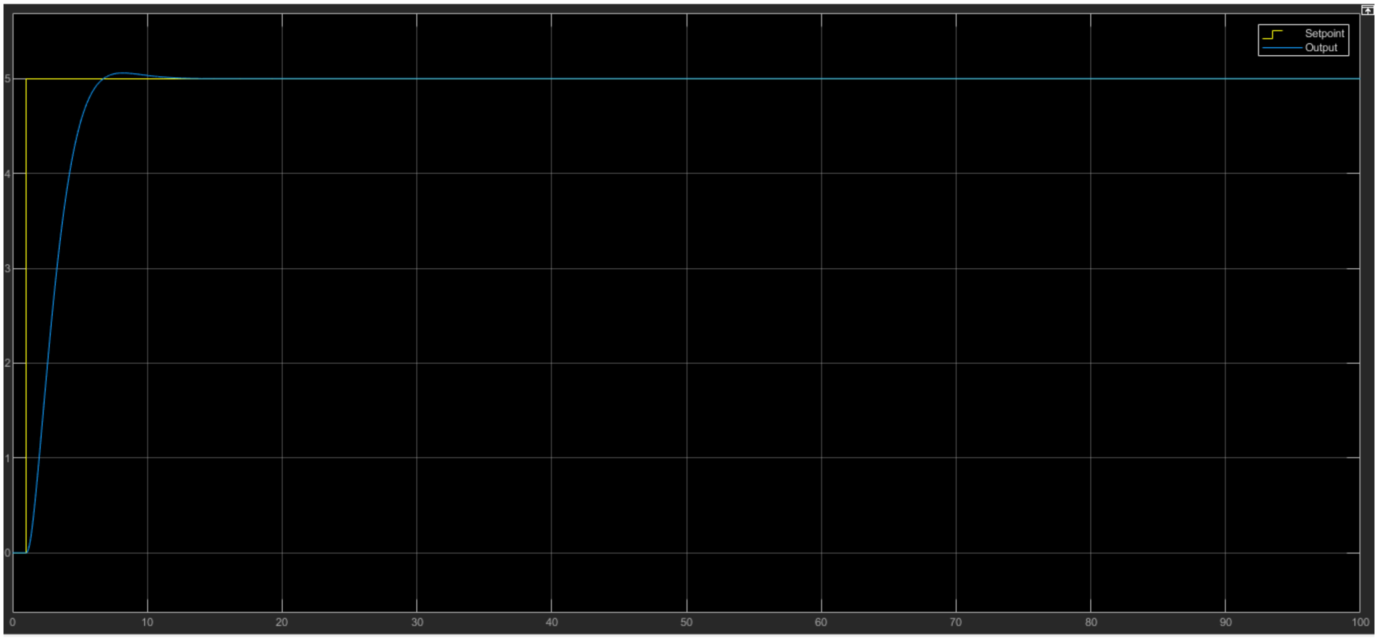

Fig. 9: Step Response on Simulink

In Figure 10, shows the sinusoidal tracking that the system is capable of producing when the continuous time-lead controller is implemented. The transfer function of this controller was refined in order to comply with the sinusoidal tracking specifications.

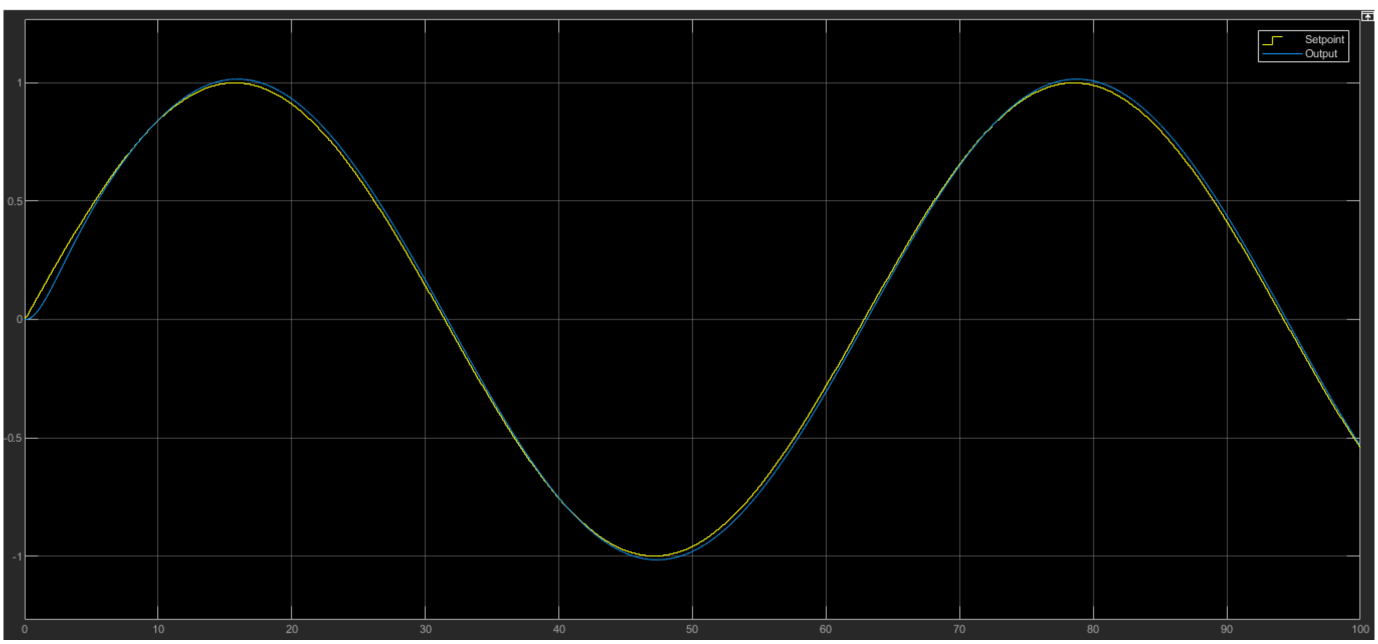

Fig. 10: Sinusoidal Tracking on Simulink

In the figure labeled as Figure 11, the simulation software is shown which was used to test the physical version built based on the circuit diagram shown in Figure 8.

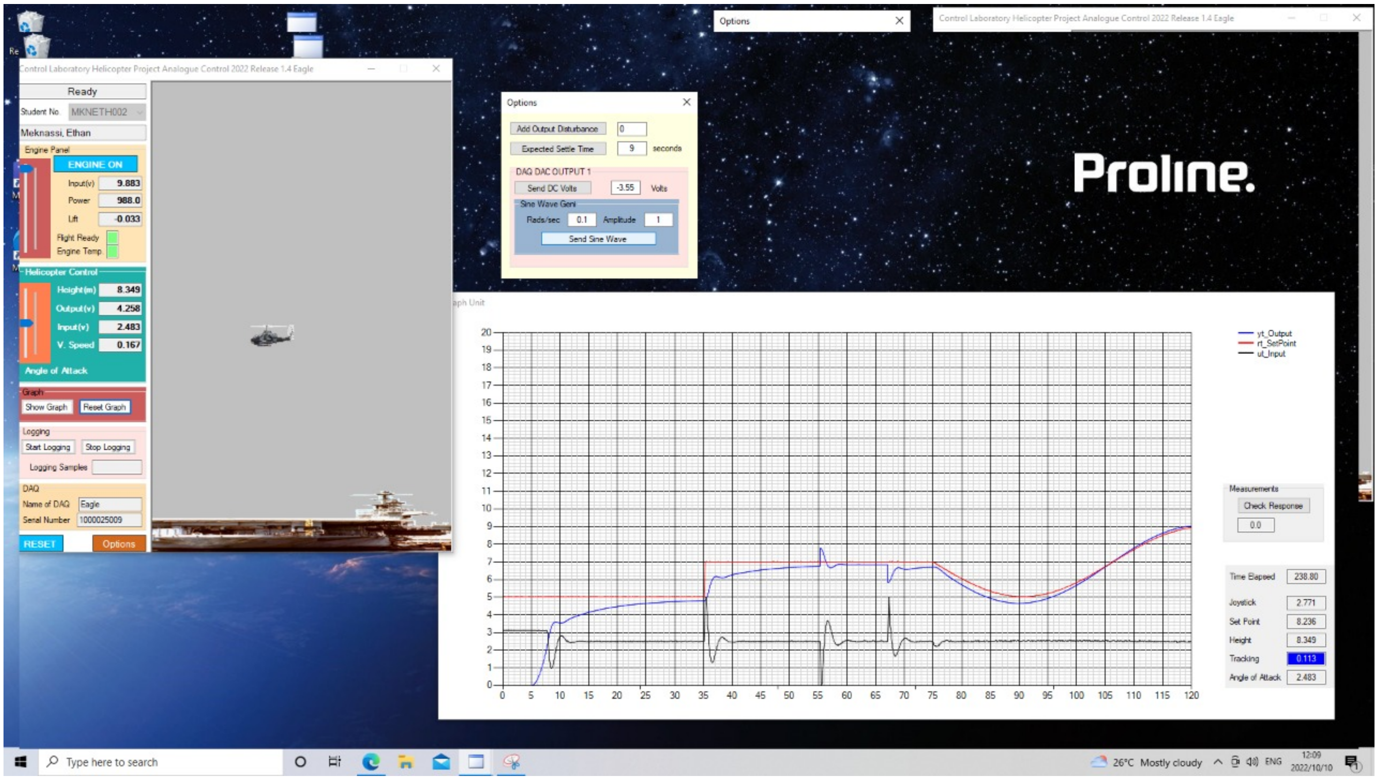

Fig. 11: Controller Physical Testing on Helicopter Software

The overshoot was measured as the maximum distance the output signal exceeded the set-point value. The specification was set to be less than 20% of magnitude of the set-point which in the above simulation was 1 meter and therefore the maximum height the helicopter was allowed to reach had to be below 6 meters. The simulation in Figure 10 shows that the ideal use of this transfer function has an overshoot which reaches a maximum value of 5.0625 meters and therefore has an overshoot of 0.0625 meters which is 1.25% of the magnitude of the set-point - which meets the specification. The practical experiment yielded an overshoot of 0.625 meters which equates to 12.5% as is shown by Figure 11. The difference in these two values can be attributed to the components used in the construction of the controller as well as the wires used to connect the circuit to the software. Each component used has its own uncertainty and when that applies to every component in use the total uncertainty results in a visual difference between the expected result and the achieved result.

The settling time was measured as the time taken for the system to be within 0.4 metres of the set-point. The settling time specification was determined to be 8.89 seconds, meaning that any time below that value would be acceptable for the settling time of the output signal. From Figure 9, it can be seen that the simulated settling time using the continuous time-lead controller transfer function results in a value of 5 seconds that can be considered the settling time for the ideal case. The settling time for the practical case is 15 seconds which is not an acceptable value for the settling time of the practical controller (from Figure 11). The settling time value increased to 3 times the simulated value and this can be attributed to the capacitor values chosen as well as how the gain value chosen interacts chosen op-amps because practical op-amps and therefore the op-amps used in this controller are limited in the maximum amount of gain can be applied to them.

The sinusoidal tracking accuracy was measured based on the point with the largest deviation between the sinusoidal set-point and the output signal. In the simulated model shown in Figure 10, the tracking of the sinusoidal with the maximum deviation occurs at each of the peaks. According to the specification, this value must remain lower than 0.4 metres at all times. The maximum deviation in the simulated model is 0.0625 metres. This difference is in some part due to the phase margin implemented within the controller. This phase margin is implemented due to the addition of a pole and zero to the system, which cause a shift in the output. The maximum deviation does meet the specification. The sinusoidal tracking measured on the practical circuit resulted in a maximum deviation in the tracking value from the set-point value of 0.48 metres, which does not meet the specification as it exceeds the threshold value by 0.08 metres. The value was measured at the first peak. The reason for this failure to meet the specification is in part due to the system not tracking exactly on the line on a straight line. Since the tracking was below the set-point line, the negative peaks were the points at which the highest deviations in the tracking occurred.

IV. Continuous Analog Design and Implementation

Using the transfer function of the continuous time lead controller designed, the controller can be approximated using the open loop gain cross-over frequency and the sampling time T. The sampling time chosen needs to meet the requirements that were set by the client. The sampling time must be at least be 20 times the gain cross-over frequency. For this controller, the gain cross-over frequency can be determined by the Bode plot in figure 5. The gain cross-over frequency was determined to equal to **w = 1 radian per second**. The sampling frequency is therefore 20 radians per second as a minimum value. Which leads to a sampling time of **0.008 seconds**. Approximation of the controller:

$$P(s) = \frac{11.3728}{s(10.889s+1)}$$

$$G(s) = \frac{10\left(\frac{s}{4.7}+1\right)}{\frac{s}{10}+1}$$

$$= \frac{50\left(\frac{2}{4.7}(z-1)+T(z+1)\right)}{z-1+5T(z+1)}$$

$$= \frac{U(z)}{E(z)}$$

$$50\left(\frac{2}{4.7}(z-1)+T(z+1)\right)E(z) = \big(z-1+5T(z+1)\big)U(z)$$

$$let\frac{1}{T} = 20 \times \frac{2\pi}{1\frac{rad}{s}} = 125.66\,Hz$$

$$T = 0.008s$$

$$\big(21.28(z-1)+0.4(z+1)\big)E(z) = \big(z-1+0.04(z+1)\big)U(z)$$

$$(1.04z-0.96)U(z) = (21.68z-20.88)E(z)$$

Giving an algorithm

$$u_{i+1} = 0.92u_i + 20.85e_{i+1} - 20.08e_i$$

For the Continuous analog design and implementation, the method discussed previously was used to get parameters of the controller. Using a value **k = 10** for the gain, the associated resistor ratio can be determined. Most of the resistors of the circuit were chosen to be 10kΩ resistors. This means a value of 10kΩ was chosen for Rin (or in the case of the experiment's circuit, R1). Therefore, in order to obtain a gain of k = 10, a value of 100kΩ needs to be chosen for Rf (or in the case of the experiment's circuit, R3).

R1 = 10kΩ

R3 = 100kΩ

The lead lag circuit needs to create a zero with a position of -0.47 and a pole with a position of -10. The capacitor values and the resistors values can then be determined using the same process shown in figure 3. The capacitor values were chosen to be with a low capacitance of 10μF. This is done because there must not be time wasted due to the capacitor charging. Using those capacitor values, the corresponding resistor values can be determined.

For the zero RF pair:

$C = 10\mu F$

$R = ?$

$a = 0.47$

$a = RC$

$R = \frac{a}{C} = \frac{0.47}{10\mu} = 47k$

For the pole RF pair:

$C = 10\mu F$

$R = ?$

$b = 10$

$b = RC$

$R = \frac{b}{C} = \frac{10}{10\mu} = 10\ M\Omega$

Therefore, the final transfer function of the controller with a gain of 10, a zero at -0.47 and a pole at -10 can be expressed as the following:

$$TF = \frac{10s + 4.7}{s + 10}$$

From these calculations, the circuit for the controller was built and the testing was done by comparing the step response of the system to the simulations. This was repeated for different potentiometer value until the controller was able to track the set-point adequately and meet all the requirements.

V. Conclusion

The controller that was designed met most of the specifications that were put in place by the client. The gain of the final controller design was **k=10** and also featured a phase-lead component which consisted of a zero with a position at **a=-0.47** and a pole with position at **b=-10**. These values were obtained using simulations on the MATLAB software. The controller was tested in a ”real” environment after being built on a breadboard.

The overshoot was measured to be 0.0625 meters, in the simulated version, which is 1.25% of the magnitude of the set-point - which meets the specification. The practical experiment yielded an overshoot of 0.625 metres which equates to 12.5% - which also meets the specification of a maximum of 20% overshoot. The difference in these two values can be attributed to the components used in the construction of the controller as well as the wires used to connect the circuit to the software. Each component used has its own uncertainty and when that applies to every component in use the total uncertainty results in a visual difference between the expected result and the achieved result.

The settling time specification was determined to be 8.89 seconds. It can be seen that the simulated settling time results in a value of 5 seconds that can be considered the settling time for the ideal case. The settling time for the practical case is 15 seconds which is not an acceptable value. The settling time value increased to 3 times the simulated value and this can be attributed to the capacitor values chosen as well as how the gain value chosen interacts chosen op-amps because practical op-amps and therefore the op-amps used in this controller are limited in the maximum amount of gain can be applied to them.

In the simulated model, the tracking of the sinusoidal with the maximum deviation occurs at each of the peaks. According to the specification, this value must remain lower than 0.4 metres at all times. The maximum deviation in the simulated model is 0.0625 metres. This difference is in some part due to the phase margin implemented within the controller. This phase margin is implemented due to the addition of a pole and zero to the system. The maximum deviation does meet the specification. The sinusoidal tracking measured on the practical circuit resulted in a maximum deviation in the tracking value from the set-point value of 0.48 metres, which does not meet the specification as it exceeds the threshold value by 0.08 metres. The value was measured at the first peak. The reason for this failure to meet the specification is in part due to the system not tracking exactly on the line on a straight line. Since the tracking was below the set-point line, the negative peaks were the points at which the highest deviations in the tracking occurred.

These uncertainties were caused by the tolerances of the resistors and the capacitors which causes the values to not be as accurate in a ”real” environment compared to the ”ideal” environment of the simulations. Another factor that is also affecting the results is noise. Noise is usually a cause of a high gain but can be caused by many other factors. This leads to the results differing from the simulations.

There are however a few ways to improve this experiments. The circuit of the controller could be optimized to reduce the noise as much as possible. The characteristics of the controller can be changed to get more accurate parameters. The gain could be reduced, reducing the noise and the position for the poles and zeros could be changed accordingly while still meeting the specifications. Furthermore, the settling time could be reduced for the system to be faster and improve its ability to track the set-point. Additionally, brand new components with lower tolerances could be used for the op-amps, capacitors, resistors and pentameters resulting in a reduced the effects of the aging of components. Finally, the final circuit could soldered together rather than being on a breadboard which would reduce the uncertainties greatly and make the final response more accurate and desirable.

VI. Appendices

EEE3094S Controller Demonstration 2022

Student Name	Ethan Meknassi	Student Number	MKNETH002
Student Name	Ethan Morris	Student Number	MRRETH003

Controller Demonstration Marking Guidelines (Total Marks 24)

Marks	0	1	2	3	4	MARK
Set Point Tracking	No Tracking or Large Error	Within 1m of Final Value	Within 0.8m of Final Value	Within 0.6m of Final Value	Within 0.4m of Final Value	4
Over/undershoot	Unlimited/ Very Large	Within 30%	Within 25%	Within 20%		3
Settling Time. No oscillations	$>t_{2\%}+7s$	$>t_{2\%}+4s$ $<t_{2\%}+7s$	$>t_{2\%}+2s$ $<t_{2\%}+4s$	$>t_{2\%}$ $<t_{2\%}+2s$	Within $t_{2\%}$ $t_{2\%}=$ 9	2
Output Disturbance rejection. Return to the previous final value	$>t_{2\%}+7s$	$>t_{2\%}+4s$ $<t_{2\%}+7s$	$>t_{2\%}+2s$ $<t_{2\%}+4s$	$>t_{2\%}$ $<t_{2\%}+2s$	Within $t_{2\%}$	4
Sinusoidal tracking slow-med-high speed	No Tracking or Large Error	Within 1m of Final Value	Within 0.8m of Final Value	Within 0.6m of Final Value	Within 0.4m of Final Value	3
Simulated Plot for an input Step of 5.	No Plot		Plot shown			2
Circuit diagram of your controller	No circuit diagram	Partial circuit diagram	Circuit diagram not fully labelled	Fully labelled circuit diagram		3
Penalty Marks	Controller Output: High amplitude oscillations of $>0.4v$ 2 Mark penalty	On/Off Bang-Bang Controller Type 8 Mark penalty	Using more than 4-Op Amps 3 Mark penalty	Other:		
					TOTAL MARKS	21

Assessor Name: **Signature:** **Date:** 10-10-2022

Fig. 12: Rubric of the demonstration