# EE 402 - GRADUATION PROJECT II
# TERM REPORT

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**PROJECT TITLE: EXPERIMENTAL TILTROTOR AIRCRAFT**

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# ABSTRACT

Tiltrotor is a term given to aircraft which have tilting rotors on the tip of their fixed wings. They have helicopter-like vertical take-off and landing (VTOL) capabilities and benefit from fixed-wing aircraft advantages such as higher cruise speeds and stable flight. Therefore, tiltrotors are becoming more crucial every day for both civilian and military use. It is aimed to design and build an experimental tiltrotor setup in this project. The angel position control of the setup will be achieved with a PID controller. A graphical user interface (GUI) with cross-platform compatibilities will be created for interaction with the system. Once built, the system will be used for research and experimentation on tiltrotor-related topics.

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# 1. INTRODUCTION

In recent years, there have been great breakthroughs in the aerospace and defense industry in Turkey and accordingly, unmanned aerial vehicles (UAVs) development has flourished. UAVs can be classified as 2 main groups: fixed-wing and rotary-wing. Although fixed-wing UAVs have the advantage of speed, factors such as difficult take-off and landing and the need for a runway limit their usage areas. Although rotary-wing UAVs seem to be advantageous due to their easy take-off and landing ability and their lack of need for a runway, their limited speed grounds their usage areas. The obvious advantages and disadvantages of these 2 types of UAVs gave rise to the idea of tiltrotor aircraft. By addressing the shortcomings, these multi-functional aircraft, known as tiltrotor vehicles, are effectively utilized in both military (war, patrolling, target search, reconnaissance, etc.) and civil (transportation, search-and-rescue, firefighting, etc.) application fields. Tiltrotors can behave like a helicopter when take-off and landing in a tight space without the need for a runway is needed and transform into an airplane by altering the pitch of the propeller in the air, when necessary, thanks to their propellers that can tilt between 0-90 degrees.

The aim of this project is to design a ground platform in accordance with scientific methodology and to develop a Tiltrotor by examining important vehicle-related parameters on both a theoretical and experimental basis. In this context, multi-disciplinary studies that require structural, control and electrical-electronic science such as the calculation of horizontal and vertical thrust forces with the use of sensors, the relationship between propeller speed and inclination and these forces, the control of slope and speed will be carried out. This scientific study will be used as an important experimental setup for the university’s Faculty of Aeronautics and Space Science. The project, which is planned to be developed for use in engineering studies, will serve mechanical, control, and electrical-electronic applications as well as aviation applications. The project is directly related to the Faculty of Aeronautics and Space Science’s infrastructural courses such as dynamics, strength, materials science, aerodynamics, flight mechanics, and system dynamics.

The project will include the structure of a VTOL and inclined rotor aircraft. This type of aircraft is included in the literature as "Tiltrotor aircraft". The movable rotor has 90° movement. Thus, it can take off vertically in a fixed plane. If it provides sufficient altitude during flight, it can switch from helicopter mode to airplane mode and therefore has faster movement capability compared to helicopters. In addition, the fuel consumed during the flight is more economical than helicopters. In order to develop the aircraft, which is advantageous in areas such as search and rescue, reconnaissance, and transportation, an experimental infrastructure such as the relevant project is needed.

In the experimental set, a ground platform representing aircraft with inclined rotor mechanism will be created and the system will consist of two tilting rotors in the form of a desktop fixed platform. The load cells to be placed on the test set will measure the lifting force created by the propellers; There will be a ground setup for aerodynamics and flight mechanics applications. In addition to these, the system responses will be measured by giving inputs to the engine speed and rotor angle values, The lift force generated by different types of propellers will be compared with the experimental results, Platform will be tested with various control applications in transition mode, The accuracy of the mathematical model obtained by theoretical calculations will be checked under real experimental conditions and the results obtained will be evaluated, Simulation data will be verified through experimentation by measuring the lift forces occurring in the helicopter, transition and airplane modes. Experiment set control will be provided via a cross-platform capable Graphical User Interface (GUI).

# 2. LITERATURE REVIEW

## 2.1.THEORY REVIEW

### 2.1.1. Tiltrotor

Tilt rotors are generally aircrafts that generate lift and thrust through rotating rotors at the tips of a fixed wing. Generally, a transverse rotor design is used. The Tiltrotor combines a helicopter's VTOL capability with the speed and range of a traditional fixed-wing aircraft. The rotors are tilted for vertical flight so that the axis of rotation is horizontal, providing lift in the same way as a typical helicopter rotor does. The rotors increasingly lean forward as the aircraft speeds up, and the plane of rotation finally becomes vertical. In this mode, the rotors act as propellers, and the airfoil of the fixed wings takes on the role of providing lift as the aircraft moves ahead. The tiltrotor can attain higher cruising speeds and takeoff weights than helicopters because the rotors may be arranged to be more efficient for propulsion, eliminating the problem of a helicopter retracting blade stalling. In Figure 2.1.1.1 the three flight modes are shown.

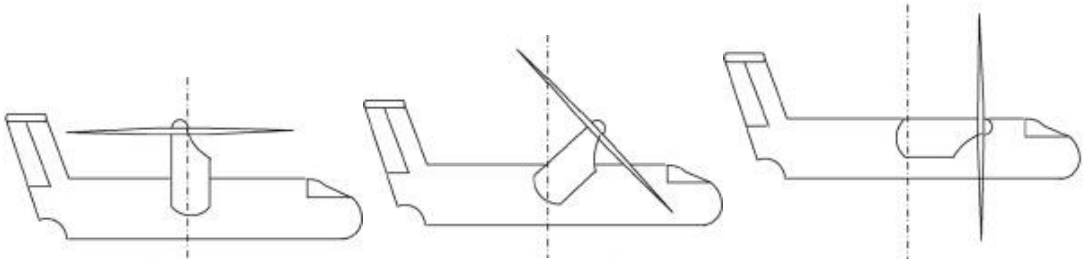

**FIGURE 2.1.1.1 – FLIGHT MODES OF THE TILTROTOR**
***(FROM LIFT TO RIGHT: HELICOPTER, TRANSITION, AND AIRPLANE)***

For this project’s twin tilting rotors system, in order to obtain the roll motion, both rotors must rotate in the opposite direction, or one must rotate faster or slower than the other according to the rotation axis to exert opposite forces. To obtain the pitch movement, it is sufficient to change the angle of both rotors synchronously. And finally, to obtain the yaw motion, the angle between the 2 rotors must be increased or decreased. A detailed representation of the procedure is given in Figure 2.1.1.2.

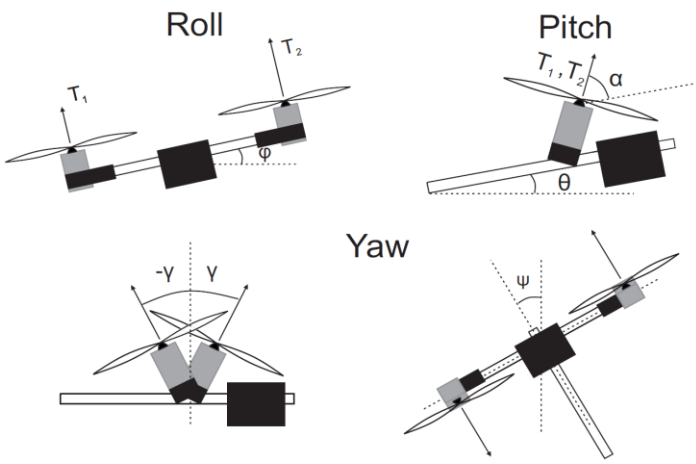


FIGURE 1.1.1.2 – BIDIRECTIONAL MOVEMENTS OF THE TILTROTOR

### 2.1.2. PID Controller

The PID algorithm controls three separate constant parameters to reduce the error value, so it is sometimes called three-stage control: proportional, (denoted by P), integral (denoted by I), and derivative (denoted by D). As for what the values stand for; P is the current error, I is the sum of past errors, and D is an estimate of future errors. The system is brought to the desired state by controlling it through the weighted sum of these three values. The controller applies a correction that includes proportional, integral, and derivative terms. This correction aims to minimize the error by adjusting a control variable. For example, in our system, it is possible to increase or decrease the tilt angle of the rotors according to the weighted sum of the PID terms.

## 2.2. PRACTICE REVIEW [1]

- ✓ The first work on the tiltrotor was done in 1902 by the Franco-Swiss brothers Henri and Armand Dufaux.
- ✓ Building VTOL aircrafts using helicopter-like rotors was taken further in the early 1930s and the first design resembling modern tiltrotors was patented by George Lehberger in May 1930, but the concept was not developed any further.
- ✓ Platt and LePage patented the PL-16, the first American tiltrotor aircraft in 1946.
- ✓ In 1954 The two flight-capable prototypes were the single-seated Transcendental Model 1-G and the two-seat Transcendental Model 2, each

powered by a single-piston engine. The Transcendental 1-G was the first tiltrotor aircraft to fly and perform most of the transition from a helicopter to an airplane in 10 degrees of true horizontal airplane flight

- ✓ In 1981 Bell and Boeing Helicopters began developing the V-22 Osprey, a twin-turboshaft military tiltrotor aircraft for the US Air Force and US Marine Corps.
- ✓ Around 2005–2010 Bell and Boeing reunited to undertake conceptual work on a larger Quad Tiltrotor (QTR) for the US Army's Joint Heavy Lift (JHL) program.
- ✓ In 2013, Agusta Westland announced that they were free-flying a manned electric tiltrotor called Project Zero with rotors in the wingspan.
- ✓ In 2014, the Clean Sky 2 program (by the European Union and industry) awarded $328 million to Agusta Westland and partners to develop a "next-generation civilian tiltrotor design for the offshore market, with the Critical Design Review in late 2016. They aim to achieve a maximum take-off weight of 11 tons, 19 to 22 passenger seats, cruising speed of 300 knots, top speed of 330 knots, a ceiling of 25,000 feet, and a range of 500 knots in their first flight which was planned to take place in 2021.

# 3. CONCEPTUAL DESIGN

## 3.1. DESIGN CRITERIA

Tilt-rotor aircrafts can have two or four rotors, as described in the literature overview. Although certain parametric data might alter in this context, the objects to be evaluated will essentially remain the same. Depending on the scenario, the number of motors and propellers to be employed in the system might range from 2 to 4 rotors. However, since the project is in its first stage, a twin-rotor design is going to be implemented. As a result, the system will have two propellers and two motors. Rather than being propelled by a single motor, the propellers will be powered by individual motors. As a result, mathematical models of the Brushless DC (BLDC) motors will be generated, and the forces generated by propellers will be approximated. The motors are aimed to be fed directly from the power line instead of a battery. Nevertheless, a battery system can be added to the existing system to create a portable platform in line with the needs.

The propellers will include different mechanical safeguards for the researchers' safety during the experiment. Load cells will accumulate the overall lifting force generated in the system by the numerous variations of motors and propellers and utilize the data for optimization. The vertical and lateral forces exerted by the propellers will be computed and validated using the aerodynamic calculations test kit.

In all, the system will have three modes: helicopter (vertical take-off and flight), transition, and aircraft. The input parameters for the controller will be calculated in each mode state by collecting data from the load cells installed in the system. Forces in the vertical and lateral planes will vary based on the tilt angle in helicopter and aircraft modes, while in the transition mode, forces in the vertical and lateral planes will change depending on the tilt angle. Dynamic equations and a mathematical model of the system will be built for these computations. The experimental set and simulation findings will be converged using a simulation developed in the MATLAB Simulink environment.

The experimental system will be controlled with a controller card through a computer. That being the case, a GUI design is another subsystem of this study. Since this is the first stage, the input parameters of the experimental setup will be just the rotor angle and the motor speed. But, in the following stages, it is planned that the rotor angle and motor speed will be controlled by the system according to the orbital planning of the system.

Usage of a separate motor and gear mechanism for the tilt mechanism is chosen for the system. The tilt mechanism, which is one of the control parameters, should work sensitively and the gap should be minimized. If the backlash in the gears increases the instability of the system, backlash reduction by using springs may come to the fore. As for controlling the rotor pitch, the use of a PID controller has been considered. Also, it is planned to provide feedback for the controller via sensors stationed at the rotor tilt regions.

Due to the necessity of knowing the characteristic features of propellers and engines, it is planned to obtain the parts from off-the-shelf products either from domestic providers or from abroad. Alternatively, using our university resources, various propeller types can be printed with a 3D printer and subjected to performance evaluations.

In Figure 3.1.1, a preliminary design of the system prototype drawn in SolidWorks is presented.

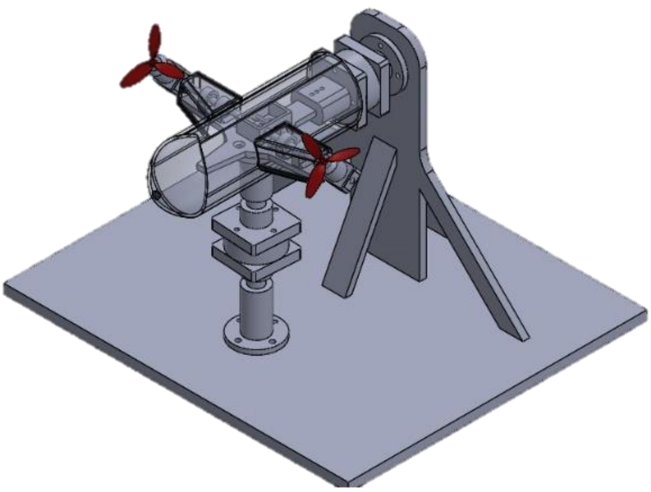

FIGURE 3.1.1 - PRELIMINARY DESIGN OF THE SYSTEM

In conclusion, the design criterion can be summarized as follows.

The system must have:

- Two BLDC motors and two propellers due to the twin-rotor configuration.
- A step motor and a tilting-mechanism for rotor control.
- At least one load cell in horizontal and vertical planes for the twin-rotor configuration
- A PID controller for rotor angle and motor speed control.
- An aluminum chassis structure.
- Depending on the budget, either composite (carbon fiber, fiberglass, aramid, …etc.) or PLA+ outer body design.

## 3.2. METHOD & SYSTEM MODEL

As stated before, the inner structure of the system is planned to be built from aluminum and the outer body will be manufactured from either a composite material or PLA+. The method for powering the system is directly feeding the system from an outer power source. The system consists of two BLDC motors and two propellers for thrust generation. As for the tilting method, it is achieved as a result of the gears rotating the shaft connected to the rotors. The gear will be rotated by a separate motor. As stated in the section before, the system has three modes: vertical take-off & landing, transition, and horizontal flight. Said modes will be initiated by adjusting the tilt angle of the rotor. And a PID controller will be used as the position control method. Input parameters and system commands will be sent from a computer-based GUI. The GUI will be designed in Python with the help of the Kivy library. The Kivy library is preferred for its ability to produce cross-platform compatible applications. Meaning that control of the system control is not limited to a computer only, but it can be achieved even via a smartphone or a tablet.

## 3.3. THEORETICAL ANALYSIS

Let us briefly discuss the theory behind the PID controller that is going to be used in the system. The overall PID control function’s block diagram is demonstrated in Figure 3.3.1.

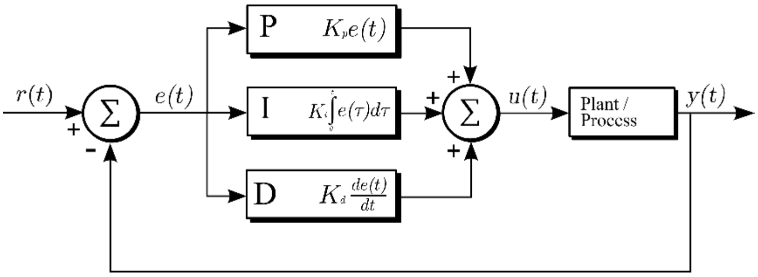


**FIGURE 3.3.1 - BLOCK DIAGRAM OF THE PID CONTROLLER**

The mathematical representation of the overall PID control function can be presented as the following:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\mathrm{d}\tau + K_d \frac{\mathrm{d}e(t)}{\mathrm{d}t} \qquad (1)$$

Where e(t) is the error function, and it is obtained by subtracting the process variable from the desired setpoint The Kp coefficient represents the proportional value of the current error for the control function. Ki represents the cumulative sum of the system's previous errors in the control function. And lastly, Kd represents the optimum approximation of the future errors with respect to the error's rate of change.

# 4. PRELIMINARY DESIGN

## 4.1. FIRST RESULTS

As for now, our goal is to design and build a preflight experimental setup to verify and test the capabilities of the chosen equipment. The experimental setup will consist of only one BLDC motor and one propeller. As for measurement purposes, two digital load cells will be used. One for measuring the thrust generated in the vertical axis and the other for the horizontal axes. Additionally, the tilting motion will be achieved manually in the first prototype, and if satisfactory results are obtained the system will be changed into an automated one. Figure 4.1.1 demonstrates the 3D model for the experimental setup.

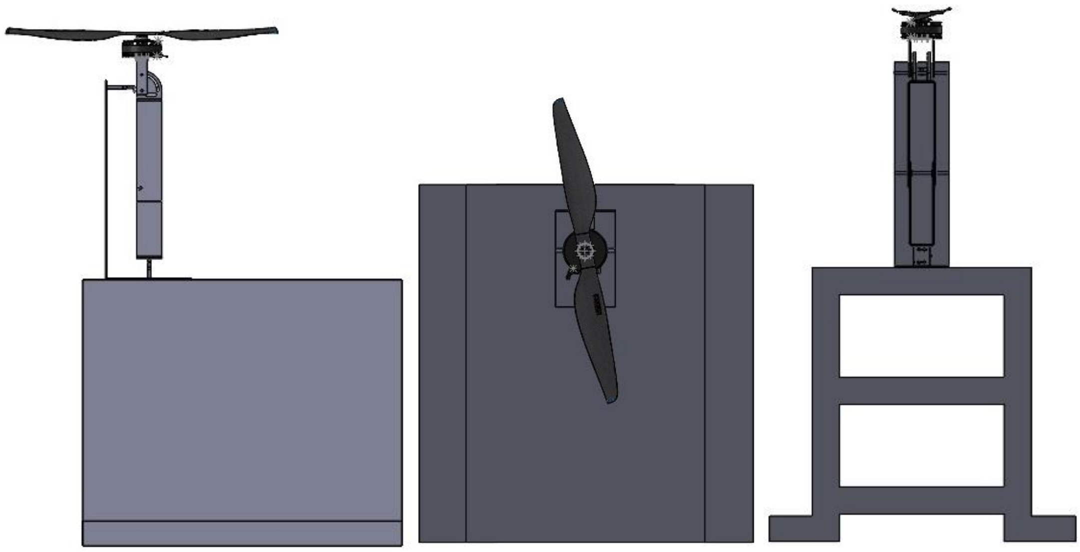

FIGURE 4.1.1 – 3D MODEL OF THE EXPERIMENTAL SETUP
*(FROM LIFT TO RIGHT: SIDE-VIEW, TOP-VIEW, AND FRONT-VIEW)*

The model was drawn using the SOLIDWORKS software. Since the motor will be generating thrusts as high as 36 kg, the chassis will be built from stainless steel for its durability and weight.

As of now, research on the necessary electronic components is made and the BLDC motors, Electronic Speed Controller (ESC)s, propellers, and load cells have been purchased and received. The stepper motors are to be purchased yet. A list of the main components is shown in Table 4.1.1.

| Purchased Components | | | |
|---|---|---|---|
| Product | Amount | Unit Price ₺ | Total Price ₺ |
| U15II KV80 BLDC Motor [2] | 2 | 689.90 $ | 1,397.8 $ |
| U15II KV100 BLDC Motor [3] | 2 | 689.90 $ | 1,397.8 $ |
| FLAME 180A 12S V2.0 [4] | 4 | 259.99 $ | 1,039.96 $ |
| G40*13.1 Prop-2PCS/PAIR [5] | 2 | 448.90 $ | 897,80 $ |
| STC S Type Load Cell [6] | 2 | 119.00 € | 238.00 € |
| PWI-D Desktop Indicator [7] | 1 | 133.00 € | 133.00 € |
| Data Logger Data Transfer Software | 1 | 105.00 € | 105.00 € |
| Component to be purchased | | | |
| NEMA 34 – 12 Nm Step Motor 86Hs120 [8] | 1 | 1,542.68 ₺ | 1,542.68 ₺ |
| CWD 860 Step Motor Driver [9] | 1 | 1,336.99 ₺ | 1,336.99 ₺ |
| Step Motor Power Supply 60V 6A Transformer [10] | 1 | 604.17 ₺ | 604.17 ₺ |
| Dark USB 2.0 - RS232 Serial Port Converter [11] | 2 | 244.93 ₺ | 489.86 ₺ |

**TABLE 4.1.1 – MAIN COMPONENT LIST**

By observing Table 4.1.1 we can say that most of the main components have been purchased. Only the step motor for the automated system and the RS232-to-USB converter remains to be purchased. The chosen BLDC motor has a maximum power consumption of 10 kilowatts, and it can generate a maximum thrust of almost 36 kg. The load cells can weigh a maximum of 200 kilograms, and they have a sensitivity of 20 grams.

The load cells were successfully tested, and data was obtained on the indicator. Currently, we are working on sending the data to the user interface. The BLDC motors and the ESCs were tested with low currents using PWM drivers. The results were satisfactory, and the components seemed to work flawlessly. The figures below show the purchased main components.

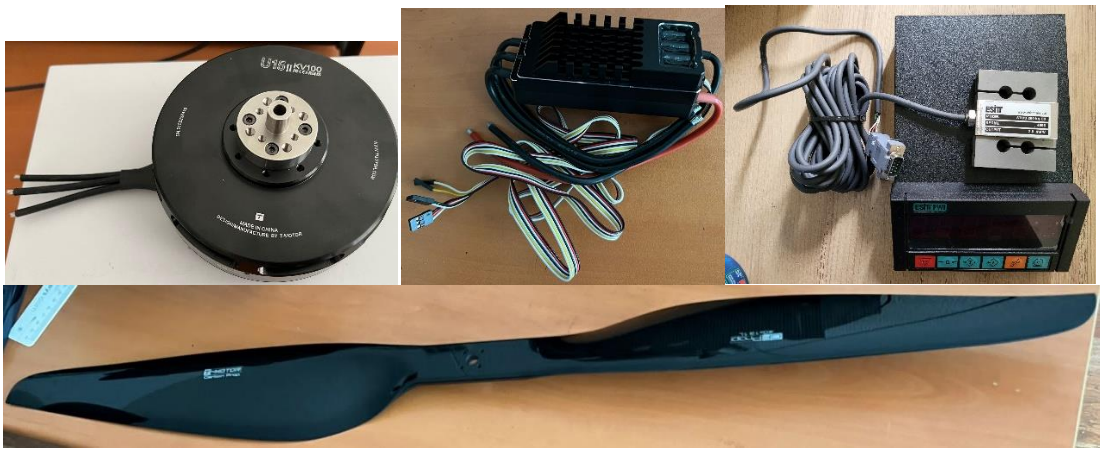

**FIGURE 4.1.2 – PURCHASED MAIN COMPONENTS**
***(FROM TOP LIFT TO RIGHT: BLDC MOTOR, ESC, LOAD CELL & INDICATOR, AND THE PROPELLER)***

Since the BLDC motor feeds on 10kW (50V-180A), there were debates on the feeding unit. The first choice was to build a battery pack but, since the system is currently going to be a nonflying ground-based system, it was decided to use an AC-to-DC voltage step-down (220V/50V) transformer. Currently, negotiations are being made with electric companies for the manufacturing of the said transformer.

As for the GUI, as stated in Section 3.2 the GUI was designed using the Python programming language with the help of the Kivy library. Figure 4.1.3 demonstrates the prototype for the GUI.

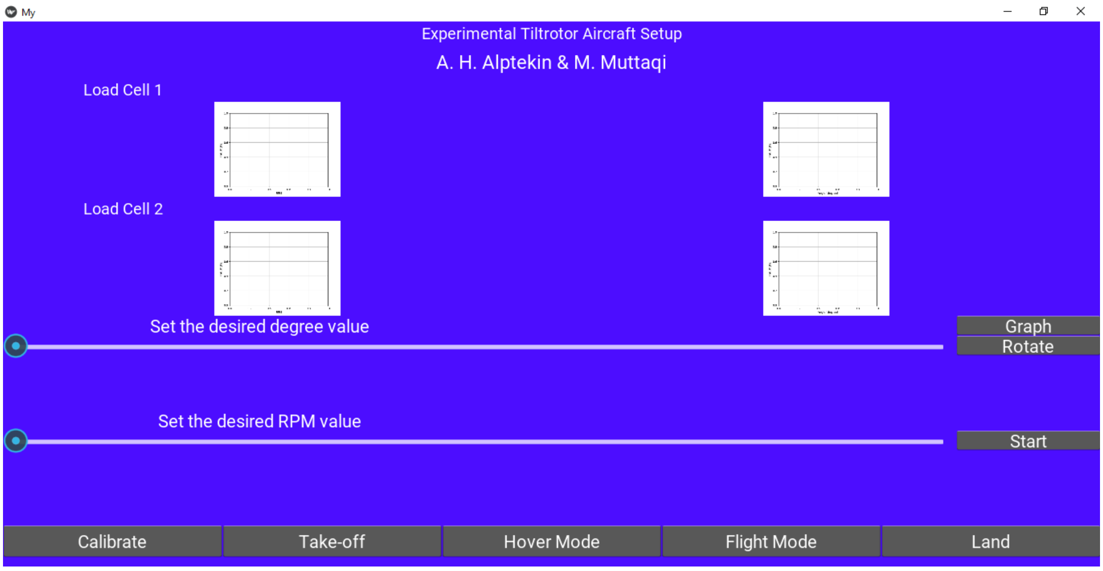


FIGURE 4.1.3 – PROTOTYPE OF THE GUI

The GUI includes four real-time graphs that will show the relation of the RPM and the tilt angle to the generated thrust for both the vertical and the horizontal axes. There are two sliders: one for RPM and one for angle control. Even though the actual tilt angle will be between 0 and 90 degrees, for experimental purposes the max value for the step motor slider was chosen as 360 degrees with increments of 5 degrees. Also, there is a calibration button and four buttons for preprogrammed flight modes. These modes are take-off, hover, flight, and landing. Since the components were just received, we were not able to establish communication with the actual component but, for demonstration reasons, an Arduino-based step motor setup was connected to the GUI and the angle was controlled successfully. As for the real-time graphs, to simulate the real-life application, a program was developed to generate random numbers and write them on a Comma Separated Excel (.csv) file and the values were called and graphed on the GUI. Here is a demo video of the GUI prototype [12]. The figures below show the prototype experimental setup.

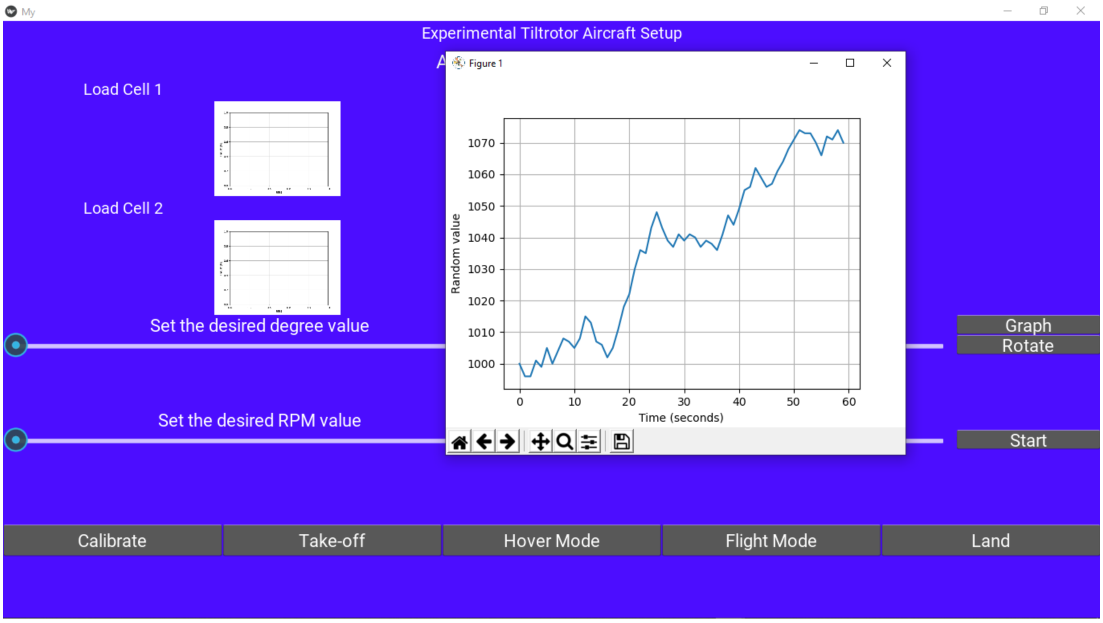

FIGURE 4.1.3 – SCREENSHOT OF THE REAL-TIME GRAPH

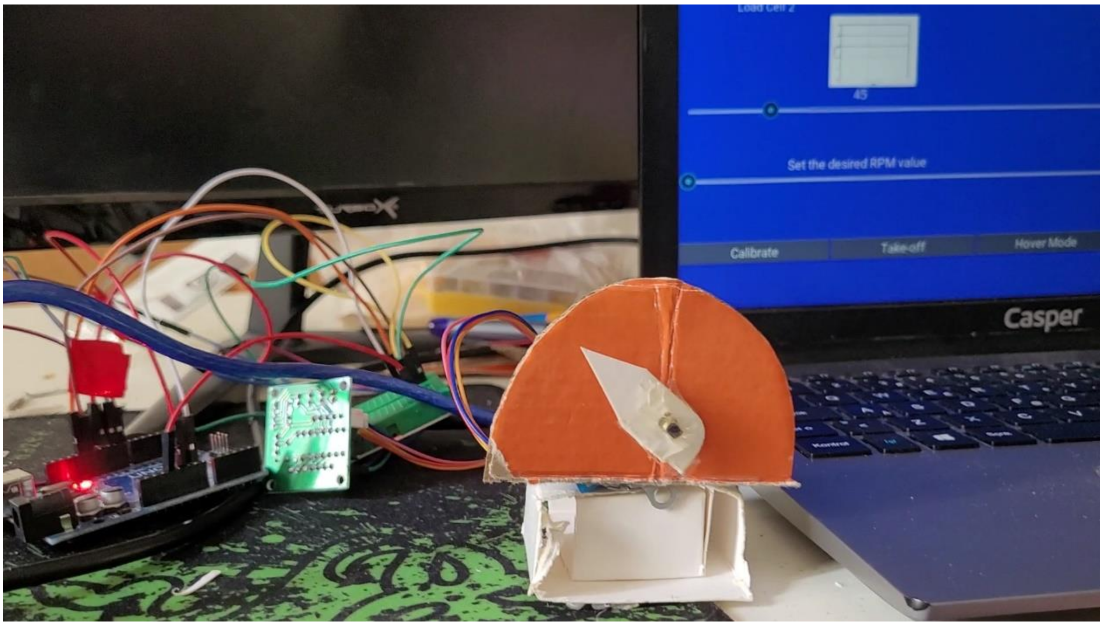

FIGURE 4.1.4 – CONTROLLING THE STEP MOTOR TO REACH AN ANGLE OF 45 DEGREES

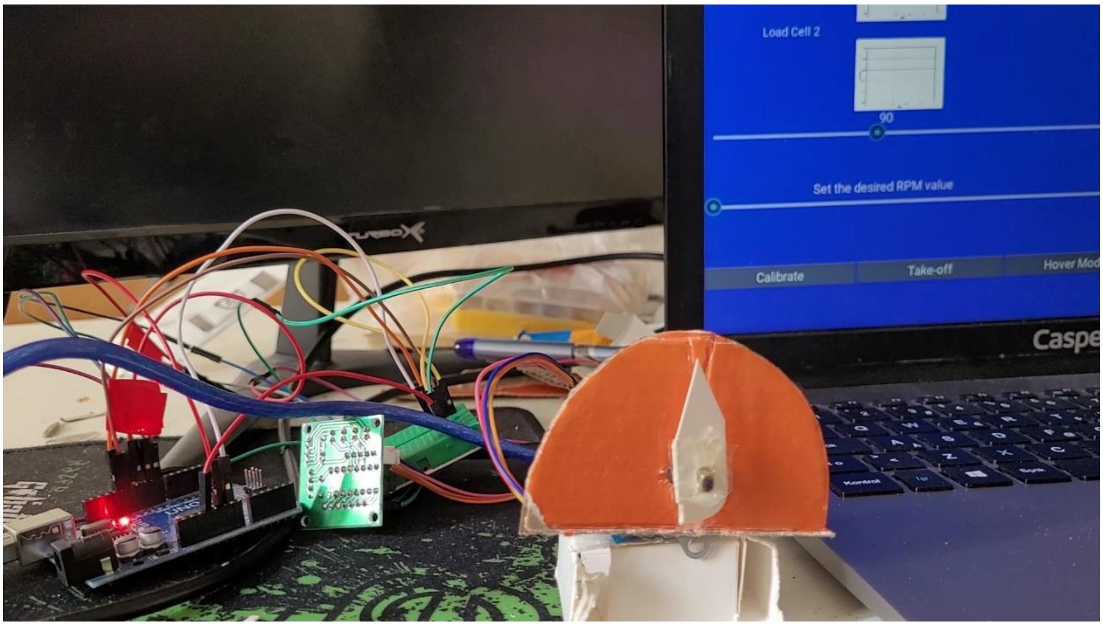


FIGURE 4.2 – CONTROLLING THE STEP MOTOR TO REACH AN ANGLE OF 90 DEGREES

# 5. COMMENTS AND CONCLUSIONS

Tiltrotors are starting to take a vital role in military and civilian applications since they combine the advantages of both airplanes and helicopters. They have the VTOL capabilities of a helicopter while also being able to reach high cruising speeds and fly like fixed-wing aircrafts. The goal of this project is to build and design an experimental setup that can be used for general research on tiltrotors. The project consists of a multidisciplinary study. Aeronautics knowledge will be utilized for aerodynamic analysis and design; mechanical knowledge will be utilized during the manufacturing process; and electrical-electronics knowledge will be utilized to power, control, and create a GUI for the system. A miniature tiltrotor UAV with flight capabilities can be designed and manufactured for future work.

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[5] https://store.tmotor.com/goods.php?id=493 [11.06.2022]
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