A Mini Project Report on

1 Degree-of-Freedom Copter Control

Submitted to the

DEPARTMENT OF
ELECTRONICS AND INSTRUMENTATION ENGINEERING

In partial fulfillment of the requirements of the course

Bachelor of Engineering in Electronics and Instrumentation Engineering

By

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CERTIFICATE

This is to certify that the project work entitled **"1 Degree-of-Freedom Copter Control"** is carried out by **Ketan Anand 1MS18EI020, Nitish Bhat 1MS18EI029, Pavan N 1MS18EI031, Shreyas RK 1MS18EI050** who are bona fide students of **Ramaiah Institute Of Technology, Bangalore** in partial fulfillment for the award of Bachelor of Engineering in **Electronics and Instrumentation Engineering** by Visvesvaraya Technological University, Belagavi during the year **2020-21**. It is certified that all corrections/suggestions indicated for Internal Assessment have been incorporated in the report deposited in the department library. The project report has been approved as it satisfies the academic requirements in respect of Project work prescribed for the said degree.

Project Guide	**Head of the Department**
Ms. K. M. Vanitha	**Dr. M. K. PUSHPA**

External Examiners

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1.	
2.	

ACKNOWLEDGEMENT

The development of complex controls in the domain of flight control system initially begins on a simplified system with fewer degrees of freedom (DoF) and less intricate manoeuvrability. In this project we have undertaken the simulation and construction of a single DoF Copter, a system that often finds application vertical take-off and landing systems.

We take this excellent opportunity to sincerely thank our HoD, Dr. M. K. Pushpa, Electronics and Instrumentation Engineering, RIT and project co-ordinator Dr. A. Saravanan, Assistant Professor, Electronics and Instrumentation Engineering, RIT for letting us proceed with the idea of 1 Degree-of-Freedom Copter Control. We are very thankful to our project guide Ms. K. M. Vanitha for helping us shape and conceive this project, to guiding us through nuances in development, all in the midst of a year with challenging circumstances.

We also wish to express our heartfelt gratitude to the project panel for their constant support and encouragement.

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ABSTRACT

This report presents the design, implementation, and analysis of a modified PID controller to stabilize the angular position of a 1-DOF copter system. A dynamic model of the system was obtained using classical mechanics. Simulation was performed to showcase the effectiveness of feedback control in stabilizing the system. The control algorithm was implemented on the ESP32 microcontroller. The controller performed well within the linear operating region of ±30° but showed increased oscillations, settling times and overshoot beyond that range. However, the controller could not guarantee stabilization for hover angles beyond 50°

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CHAPTER 1: INTRODUCTION

INTRODUCTION

The degrees of freedom (DOF) of a mechanical system essentially encompasses information of how many parameters are required to define the position of a rigid body in n-dimensional space. In this project, we have implemented a 1-DoF copter system which allows the movement of an object in only one way which is rotation about the pitch axis. Since the analysis and development of a 1-DoF system is relatively simple, it makes it easier to understand system integration and control strategies utilized for flight control systems.

Control algorithms such as PID help in achieving stability, and is employed by many industries to achieve optimized, automatic control of systems. Hence, understanding a relatively simple controller such as PID gives more insights into how control strategies can be developed and improved.

A motor is an electrical machine that converts electrical energy into mechanical energy and is widely used in modern devices from washing machines to printers. Motors are a fundamental part of our system and knowledge of how to drive them effectively can prevent damage of system elements.

Real-time applications that need strict timing deadlines and reliability often need fast processing of real-time data and determinism in execution. Due to the advent of powerful embedded systems, performing multiple tasks concurrently is possible and gives courage to build computationally intensive systems.

1.1 LITERATURE SURVEY

In literature, there have been several implementations of the 1-DoF copter system. [11] focuses on simulation of vertical take-off and landing systems (VTOL) to simplify characterization of a complex aircraft system and determine hover characteristics of systems such as helicopters, quad-rotor and tilt-rotor aircrafts. They use a cascaded feedback loop consisting of a PI inner feedback loop and PID for the outer loop. Tuning the feedback loop resulted in an overshoot of 20% with a peak time of 1s. [12] focuses on the implementation of a 1-DoF copter system utilizing a custom machined mechanical laboratory setup and control of BLDC motors using an electronic speed controller (ESC). Implementation of the closed loop structure uses the PID algorithm and the Arduino Uno. In [13] an adaptive neural network backstepping control design has been employed to control a 3-DoF helicopter. The helicopter is described by a state-space model and Lyapunov stability criterion has been used to show the effectiveness of the control strategy. [14] proposes the control of a highly non-linear twin-rotor MIMO system using a 1-DoF and 2-DoF PID algorithm. Simulation and verification for the stabilization of the system has been performed using MATLAB. [15] focuses on the physical implementation of a 1-DoF VTOL system utilizing BLDC motors. Simulation of the system has been performed on LabVIEW and system identification toolkit has been used to obtain the transfer function of the system. The PID controller was implemented within LabVIEW and the effect of parameter changes were investigated by plotting the step response.

1.2 SCOPE OF WORK

The system we develop can be used to understand and demonstrate the control strategies of flight control systems such as drones, quadcopters, hovercraft, planes and underwater vehicles. Also, this system will help learners to study and validate essential components of control systems like modelling, driving motors along with sensor interfacing and building an embedded system. The system has the ability to accept custom control parameters to evaluate how parameter changes affect the system stability.

1.3 OBJECTIVES

- To build a simple mechanical setup for the copter system
- To build the data acquisition system and interface motor driver and display peripherals.
- To create an interactive hover angle input that is maintained constant under external disturbances using feedback control with minimal settling time and overshoot.
- To implement an embedded system that can achieve concurrency with multiple tasks effectively.

1.4 ORGANISATION OF THE REPORT

This report gives a basic description about how we are going to implement our project and the literature survey included here gives us an idea on how to implement various innovations and overcome the problems that are faced in the development process.

In order to provide an easier understanding of the following project it has been organized into the particular categories. Following are the categories:

- Chapter 1: It includes the basic idea behind selecting the project, literature survey, objectives and scope of work.
- Chapter 2: It consists of basic introduction to the project and the basic block diagram of the overall system and subsystems.
- Chapter 3: It explains the hardware and software subsystems with implementation details.
- Chapter 4: It explains about the results obtained from the existing model of the project.
- Chapter 5: This chapter has the conclusion of the project.

CHAPTER 2: METHODOLOGY

METHODOLOGY

- **2.1 INTRODUCTION:**

- The methodology can be split into two parts:
  - ➢ The hardware subsystem which essentially comprises the data acquisition system, the OLED display system and the motor driver system.
  - ➢ The software subsystem which consists of an RTOS running on a microcontroller.

- **2.2 SYSTEM BLOCK DIAGRAM:**

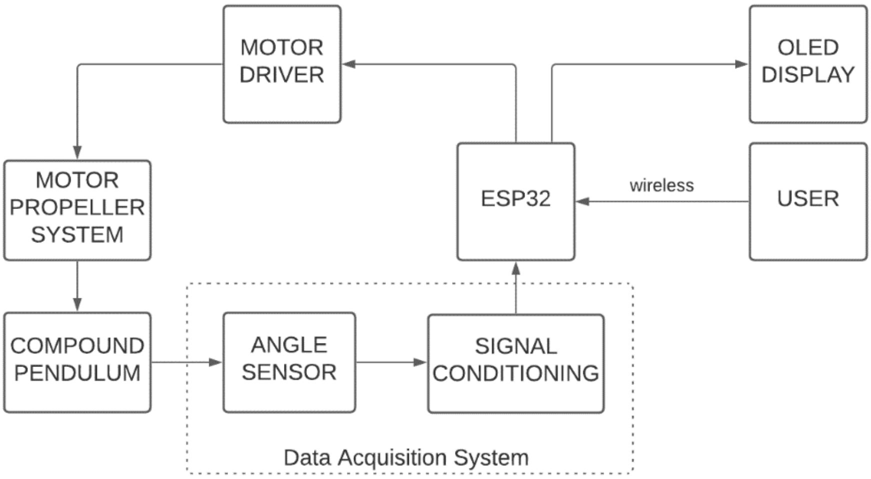

Figure-2.1- Block Diagram of 1-DoF Copter system

- ➢ The microcontroller (ESP32) is central to the system architecture and is used to control the motor driver, OLED display, communicate with the user wirelessly and sample the current angle.
- ➢ The user can input the desired hover angle and perform "on the fly" tuning parameter (Kp, Ki, Kd, B) changes via the Bluetooth serial interface
- ➢ The current angle given by the angle sensor is sampled by the microcontroller after passing through a signal conditioning circuit
- ➢ Based on user input and current angle sensed, the microcontroller controls the motor driver by generating an appropriate control signal.
- ➢ The motor driver drives the motor based on the control signal which in turn propels the compound pendulum system to hover at the desired angle.
- ➢ The copter parameters such as current angle, desired angle and control parameters are displayed on the OLED display by the microcontroller.

- **2.3 SUB-BLOCK EXPLAINATION:**

- **2.3.1 COMPOUND PENDULUM**

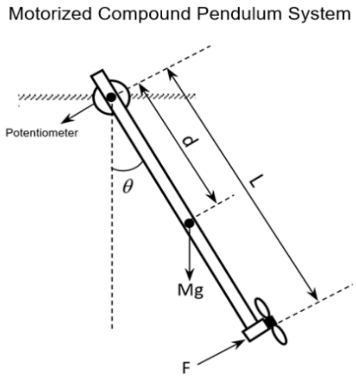

Figure-2.2- Compound Pendulum

- It consists of a wooden beam with a coreless DC motor attached to one end and a potentiometer knob attached to the other.
- A 45mm propeller is attached to the motor shaft which generates thrust when the motor rotates clockwise.
- The end that is connected to potentiometer acts like a pivot and when the copter rotates about the pivot, it changes the resistance of the potentiometer which gives an indirect measurement of angle.

- **2.3.2 OLED DISPLAY:**

Figure-2.3- OLED Display

- The OLED display is used to monitor real-time system information such as control parameters (Kp, Ki, Kd, B), control signal (PWM) duty cycle, current angle and desired angle

- **2.3.3 ANGLE SENSOR:**

Figure-2.4- 10k Potentiometer

- A 10k potentiometer is used as an angle sensor for the copter system
- A change in potentiometer resistance occurs due to the rotation of the wooden beam about the pivot, which produces a corresponding voltage change that is processed by the signal conditioning circuit.
- This change in voltage is sampled by the microcontroller ADC after signal conditioning

- **2.3.4 SIGNAL CONDITIONING:**

The signal conditioning circuit is used to filter out noise and provide a clean voltage signal for the microcontroller ADC to sample

- **2.3.5 ESP32:**

Figure-2.5- ESP32

The ESP32 is a dual core, low-power microcontroller with integrated Bluetooth functionality. It is a powerful microcontroller capable of performing multiple tasks such as handling user input and controlling peripherals concurrently

- **2.3.6 MOTOR DRIVER:**

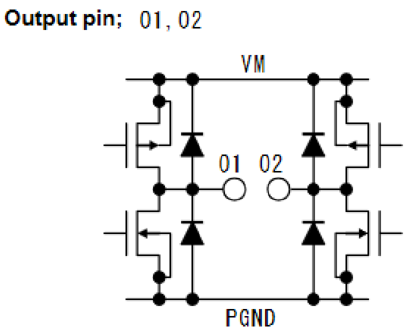

Figure-2.6- Internal H bridge circuit of TB6612

- ➢ The motor driver controls the motor voltage and direction based on the inputs from the microcontroller.
- ➢ It has a H-bridge topology but the motor is made to rotate in a single direction (clockwise)
- ➢ A breakout board houses the motor driver IC and has power supply decoupling capacitors installed.

- **2.3.7 MOTOR PROPELLER SYSTEM**
  - ➢ A 45mm propeller is attached to the motor shaft which generates thrust when the motor is energized and rotates clockwise.

- **2.4 SOFTWARE USED:**
  - ➢ Serial Bluetooth Terminal
  - ➢ Visual Studio Code

  - Serial Bluetooth terminal is a mobile application used to send information using Bluetooth between 2 paired devices. Here angle information is sent from mobile to ESP32.

- The entire programming of the microcontroller was done on Visual Studio Code due to its user friendly interface, relative ease of programming and at the same time, the versatility it provides.

- **2.5 HARDWARE AND SOFTWARE SELECTION:**

All the hardware for the project was designed and selected due to the following reasons.

- The selection of the ESP32 was due to the availability of integrated Bluetooth, extensive number of GPIO pins, availability of integrated ADC, DAC channels and ability to provide high performance concurrency between multiple threads.
- The selection of TB6612 motor driver IC was due to it meeting the ratings of the coreless DC motor with a max current handling capacity of 1 A, support of low motor voltages and higher efficiency due to the usage of MOSFETs as opposed to L298N that uses BJTs.
- The selection of the OLED display was due to less number of pins that are needed to control it since it uses the I2C protocol.

- **2.6 HARDWARE INTERFACING:**

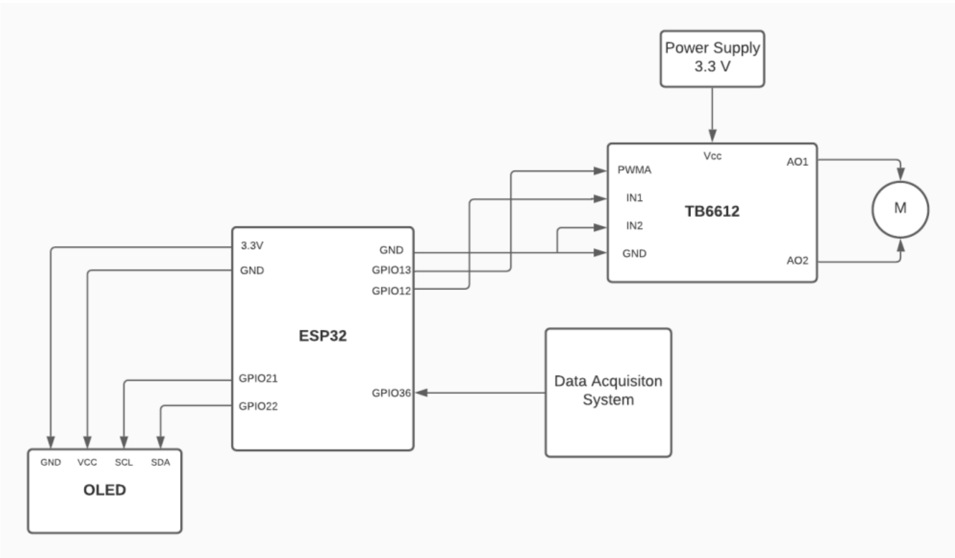

Figure-2.7- Hardware Interfacing Diagram

- As shown, the ESP32 is central to the architecture and controls the other peripherals. The GPIO pins 12, 13 are used to control the motor driver where pin 12 determines whether the motor turns clockwise or turns off completely and pin 13 controls the PWM input to the driver.

- The OLED uses the I2C protocol and is powered by the internal regulator of the ESP32 and the SCL and SDA pins are controlled by GPIO22 and GPIO21 respectively
- GPIO36 of the ESP32 is used to acquire angle information from the data acquisition system.

- **2.7 SOFTWARE ARCHITECTURE:**

- A Real-Time Operating System (RTOS) is an operating system that is designed to provide a deterministic execution pattern intended to be used in real-time applications having strict timing deadlines.
- An RTOS provides the illusion of simultaneous execution by rapidly switching between multiple threads.
- Therefore, an RTOS provides a platform for a microcontroller to perform several tasks such as handling user input and controlling peripherals concurrently.

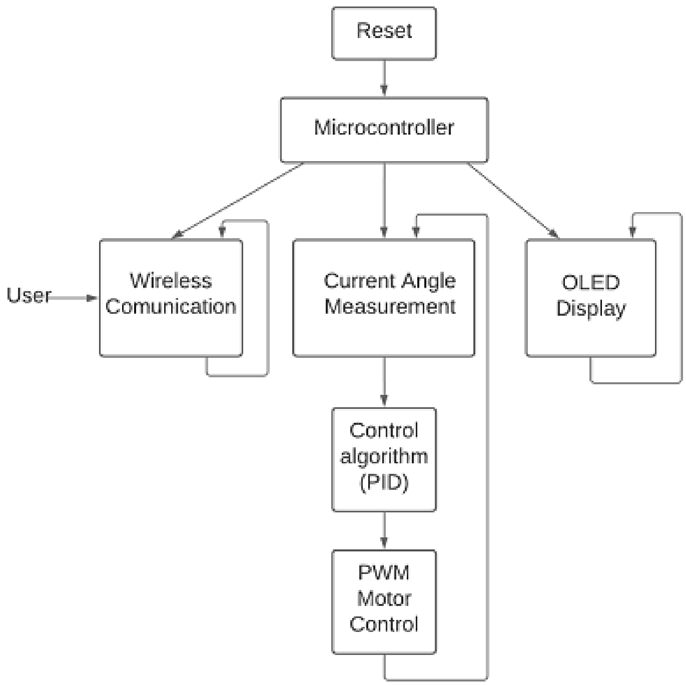

Figure 2.8 – RTOS Setup

- RTOS in this system performs mainly 3 tasks concurrently.
  - Getting input from the user
  - Getting the current angle of the copter, running the PID algorithm and updating the PWM duty cycle to drive the motor.
  - Update the OLED display with current angle, setpoint and copter parameters.

- **2.8 CONTROL ARCHITECHTURE**

- **PID Controller**

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt}$$

where,

K_p is the proportional gain

K_i is the integral gain

K_d is the derivative gain

e(t) = SP – PV (t) is the error (SP is the setpoint, and PV (t) is the process variable), t is the time or instantaneous time (the present)

τ is the variable of integration (takes on values from time 0 to the present

- We modify the PID algorithm in the following ways
  - Clamping (limiting) integrator output to prevent integral windup
  - $K_d \frac{de(t)}{dt} \; = \; -K_d \frac{dPV(t)}{dt}$ when setpoint is constant. This eliminates derivative kick
  - $K_i \int_0^t e(\tau)\, d\tau \;\rightarrow \int_0^t K_i e(\tau)\, d\tau$ eliminates bump during "on the fly" parameter (K_i) change
  - Utilization of a weighting factor B (between 0 and 1) to obtain a ratio between proportional on error and proportional on PV to reduce proportional kick

CHAPTER 3: IMPLEMENTATION

3.1 INTRODUCTION

The system comprises two essential parts: The user interface and the copter system.
The user can communicate with the system via the Bluetooth serial terminal as per the list of commands.

3.2 FLOW DIAGRAM:

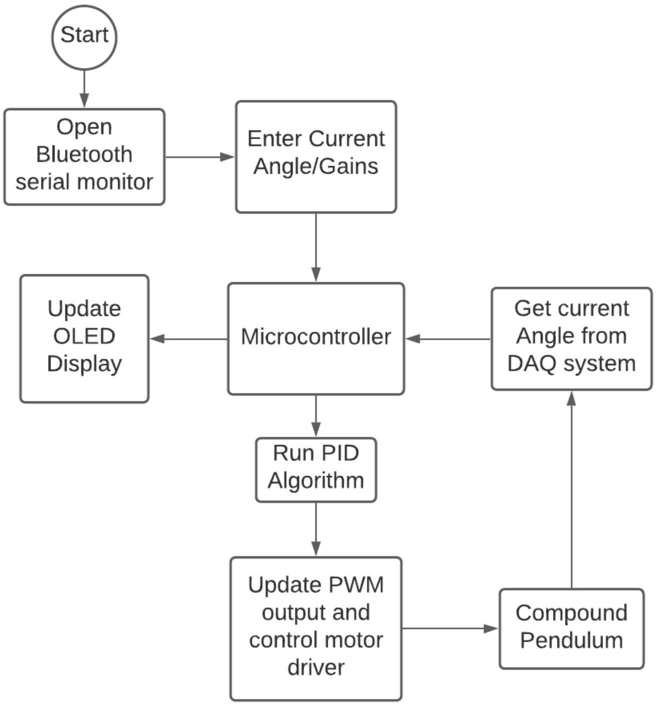

Figure-3.1- Flow Chart of the System

3.2.1 FLOW DESCRIPTION

1. START
2. “Pair” is pressed to pair the microcontroller and the user’s device.
3. Setpoint angle/gains are entered in Bluetooth serial monitor.
4. The current angle of compound pendulum is continuously monitored for any setpoint change or disturbance applied to the system.
5. The microcontroller evaluates the PID algorithm using the user set parameters and current angle and updates the PWM duty cycle output.
6. The PWM duty cycle is then used to control the speed of the motor which in turn changes hover angle of the system accordingly.
7. The current angle and the control parameters are updated to the OLED Display.
8. STOP

3.3 COMPONENTS INTERFACED:

1. The microcontroller: ESP32 is utilized in this system to automate the process and communicate with external peripherals.
2. OLED Display: OLED Display is used to show the current angle and the control parameters via the I2C communication protocol.
3. TB6612: The motor-driver is interfaced with the ESP32 to control the motor.

3.4 USER-INTERFACE- Serial Bluetooth Terminal

- **KEYPOINTS:**

    1. The system communicates with the user through the Bluetooth serial terminal.

    2. Software used was developed by Kai Morich.

- **WORKING:**

Figure-3.2(a) – Pairing of the devices

First pair the two devices using Bluetooth. This can be done by turning ON Bluetooth in phone settings and pair the devices as shown in Figure 3.2(a). Once the devices are paired open the Bluetooth serial terminal application as shown below in figure 3.2(b). Select the '1 DoF copter' to connect with the system.

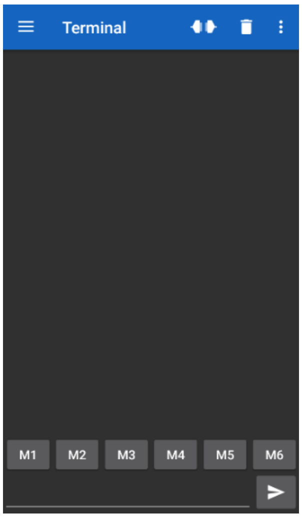

Figure-3.2(b) – Bluetooth Serial Terminal

Figure 3.2(c) displays the history of commands user entered by the user.

Figure-3.2(c) – Entering commands to 1 DoF System

- **COMMANDS:**

Instructions	**Description**
<number>	Any number entered is taken as setpoint angle to the system and is limited to -90 to 50 degrees.
kp <number>	Change the Proportional gain of the system
ki <number>	Change the Integral gain of the system
kd <number>	Change the Derivative gain of the system
beta<number>	Change the weighting factor (between 0 and 1) to determine percentage of proportional on error and proportional on PV the system.
off	Bring it back to the initial state.

3.5 DATA ACQUISITION SYSTEM

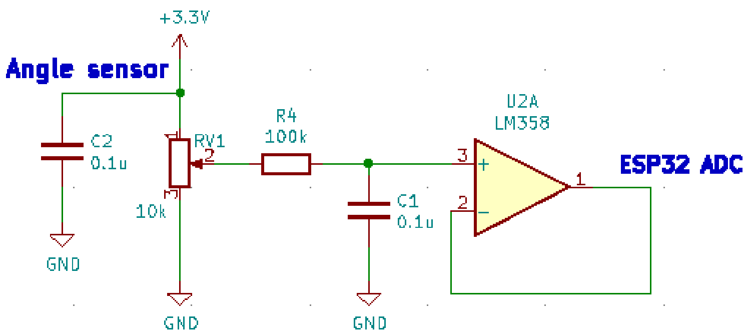

Figure 3.3 – Schematic of Data Acquisition system

- The data acquisition system consists of a 10k potentiometer that changes resistance when the copter system rotates.
- This change in resistance changes the voltage across the potentiometer wiper which is sampled by the ADC after passing through a low pass filter and a voltage follower.
- The voltage follower acts as an impedance matching device.

3.6 1-DoF COPTER SYSTEM

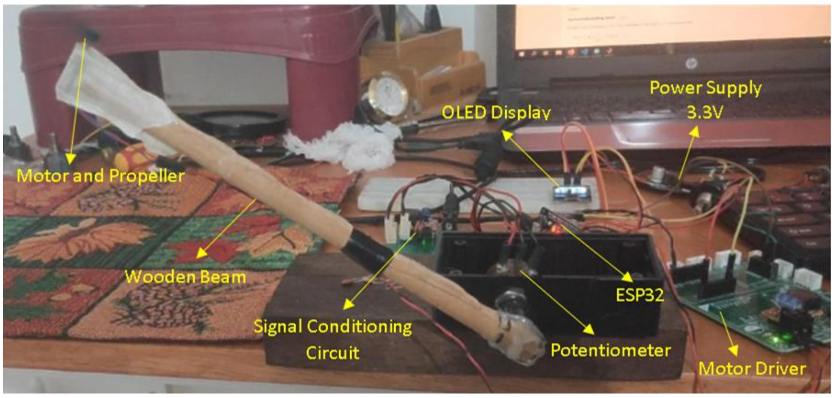

Figure 3.4 – 1 DoF Copter Setup

- Figure 3.4 shows the assembly of the system. Initially, the ESP32 is connected to the PC and the peripherals are interfaced to the ESP32. The microcontroller is programmed via USB.
- After all the connections are made, supply is turned on and system is let free for functioning.
- The closed loop control of the copter system is done using the PID algorithm modified as shown before.
- The required setpoint and K_p, K_i, K_d, B values are entered using the Bluetooth serial terminal.
- The current angle sampled by the microcontroller ADC and the setpoint entered by the user are used to compute the error signal
- The PID algorithm uses the error signal to produce a PWM duty cycle which is then sent to the motor driver to control the motor voltage
- The system parameters are updated continuously and displayed on the OLED display

CHAPTER 4: RESULTS

RESULTS

The hardware and the software subsystem for the 1 DoF Copter has been designed and implemented. The system was successful at hovering at any angle given by the user within the range -90° to 50°. The system was able to self correct and had satisfactory settling times and overshoot when disturbances were applied at various hover angles using the following gains.

PID Parameters	
K_p	0.8
K_i	0.45
K_d	0.08
B	0.55

A real time graph was plotted for different setpoint using the above gain values.

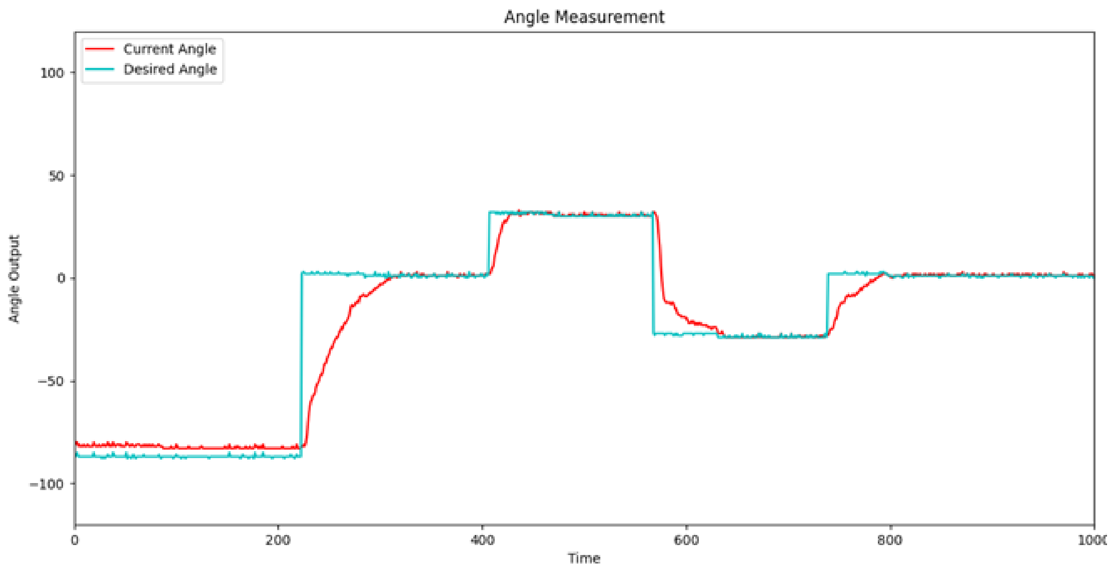

Figure 4.1 – PID Tuned Response

The following images show the system at different operating regions.

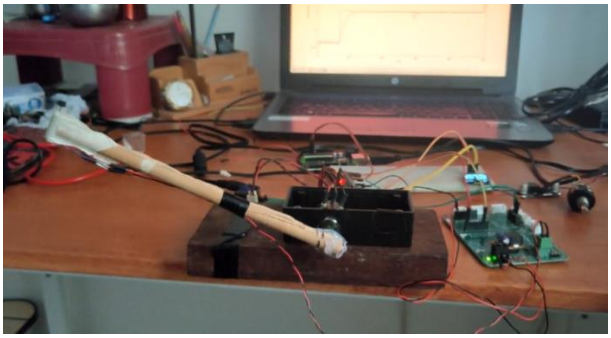

Figure 4.2(a) – at 30°

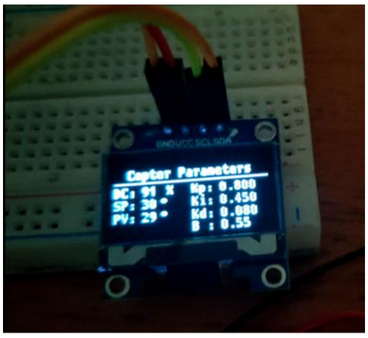

Figure 4.2(b) – OLED Display at 30°

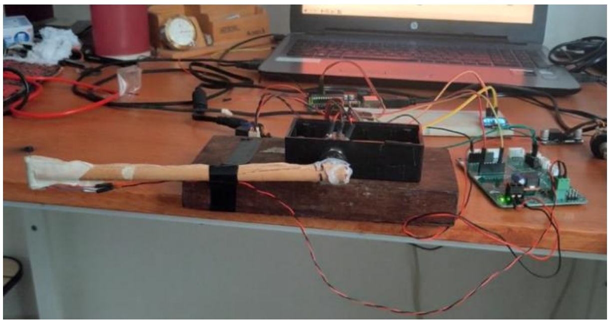

Figure 4.3 – at 0°

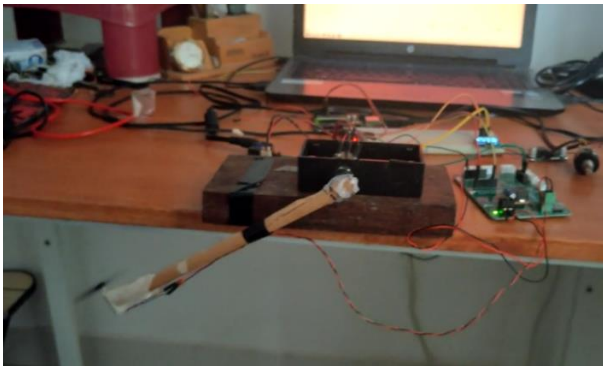

Figure 4.4 – at -30°

Figure 4.5 – Commands give to the system

- Figure 4.1 shows the tuned step response of the system at different setpoints.
- Figure 4.2(a) shows the system hovering at 30°
- Figure 4.2(b) shows the OLED Display when the system is at 30° and also shows the system parameters.
- Figure 4.3 shows the system hovering at 0°.
- Figure 4.4 shows the system hovering at -30°.
- Figure 4.5 shows the commands given in Bluetooth serial terminal.

CHAPTER 5: CONCLUSION

CONCLUSION

The 1-DoF copter system was modelled using classical mechanics and a linearized model was obtained. The mechanical setup, data acquisition system, display system and motor driver system were designed and implemented in hardware. The microcontroller was programmed to run an RTOS architecture to control the hardware subsystem. The PID algorithm was modified and implemented within the RTOS architecture.

The designed system performed well in the linear region of operation (± 30°) and could stabilize between -90° and 50° and "on the fly" tuning parameter changes can be performed on the system. The system was found to stabilize quickly under external disturbances with an average settling time of 3s (within 5% of final value). The system was observed to attain stability with an average overshoot of 2° within the linear region of operation.

CHAPTER 6: FUTURE WORK

FUTURE WORK

As the 1-DoF copter is a non-linear system, to achieve better control outside the region of linearity, non-linear control techniques such as gain scheduling, adaptive control or MPC can be used. Superior control can also be achieved by evaluating the PID algorithm at a faster rate. Interfacing an external ADC can be done to achieve faster sampling rates, attain stable readings and obtain better accuracy while acquiring real-time sensor data.

CHAPTER 7: APPENDIX

APPENDIX

- **7.1 ESP32 Specifications:**

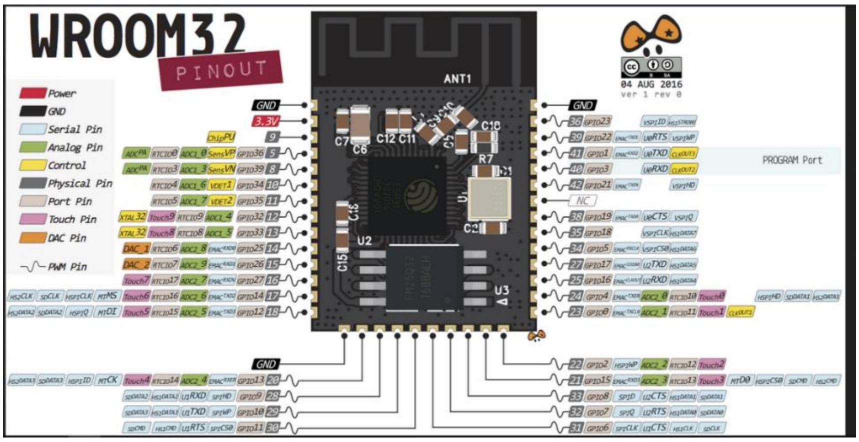

Figure 7.1- ESP32 Pin Diagram

- ➢ Processor is Dual Core Tensilica Xtensa 32-bit LX6
- ➢ Operating Voltage is 2.3 – 3.6 V
- ➢ Operating current is 80 mA
- ➢ Clock Frequency is 240 MHz
- ➢ Flash memory is 4 MB
- ➢ Data Rate is 54 Mbps
- ➢ It has BT/ BLE and WiFi support
- ➢ It has 18 ADC Channels
- ➢ 3 SPI interfaces
- ➢ 3 UART interfaces
- ➢ 2 I2C interfaces
- ➢ 2 Digital-to-Analog Converters (DAC)

- **7.2 OLED Display (SSD1306)**

Module pinout

VCC	Power Pin (3.3 V/ 5 V)
GND	Ground Pin
SCL	Serial Clock Line
SDA	Serial Data Line

Table 7.2- SSD1306 Pinout

<u>Specifications:</u>

- ➢ Display Size is 0.96”
- ➢ Uses I2C Protocol

- Resolution is 128x64px
- Uses 7 bit address for I2C

- **7.3 Motor Driver IC (TB6612FNG)**

Specifications:

- Supply Voltage (Vcc) is 2.7 - 5.5 V
- Supply Voltage (VM) is 2.2 - 13.5 V
- Output Current (Max) is 1 A
- Switching frequency (PWM) is 100kHz

Pin Label	Function	Power/Input/Output	Notes
VM	Motor Voltage	Power	This is where you provide power for the motors (2.2V to 13.5V)
VCC	Logic Voltage	Power	This is the voltage to power the chip and talk to the microcontroller (2.7V to 5.5V)
GND	Ground	Power	Common Ground for both motor voltage and logic voltage (all GND pins are connected)
STBY	Standby	Input	Allows the H-bridges to work when high (has a pulldown resistor so it must actively pulled high)
AIN1/BIN1	Input 1 for channels A/B	Input	One of the two inputs that determines the direction.
AIN2/BIN2	Input 2 for channels A/B	Input	One of the two inputs that determines the direction.
PWMA/PWMB	PWM input for channels A/B	Input	PWM input that controls the speed
A01/B01	Output 1 for channels A/B	Output	One of the two outputs to connect the motor
A02/B02	Output 2 for channels A/B	Output	One of the two outputs to connect the motor

- **7.4 COMPOUND PENDULUM SPECIFICATIONS**
  - Coreless DC Motor – Rated at 3.7V and 0.8 A
  - Propeller span is 45 mm
  - Length of the wooden beam is 20 cm

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