ISSN No:-2456-2165

Prototype of a Functioning Urban Firefighting Drone

Adib Ahnaf
Chief Operations Officer
Socian Ltd Dhaka, Bangladesh
adib@socian.ai

Faisal Hossain
Planning Engineer
Mir Trading Company Dhaka, Bangladesh
Faisal.dfx@gmail.com

Abstract:- This paper presents the design, development, and evaluation of a primary prototype of an Unmanned Aerial Vehicle (UAV) in urban firefighting. It includes the project purpose, mechatronic designs, system architecture, hardware explanation, software simulation, and performance evaluations. The paper focuses on implementing a UAV that can reach high altitudes to spot and extinguish urban fires and reduce the risks to human life. The prototype is mainly centered around firefighting purposes operated by officials in firefighting departments. We discover decent success with novel additions like tethering and throwing mechanisms in our primary prototype, with opportunities for further research in a properly simulated environment.

Keywords:- *firefighting drone, urban firefighting, prototype, evaluation, octacopter*

I. INTRODUCTION

A. *Project Background:*

Fires have destroyed countless lives and properties throughout history. The destruction is observed across a wide range of countries around the globe. In 2020, the United States faced 860,000 residential fire incidents (Hall & Evarts, 2022), China lost assets worth 620 million USD (State Council of People's Republic of China, 2022), and Europe lost over 5000 lives (European Fire Safety Alliance, 2022). Among different types of fires in 2021, urban fires constituted 20% of the incidents in the United States; However, they accounted for nearly 64% of all fatalities (Hall & Evarts, 2022). The most accepted solution for large fires has been deploying firefighters to the incident through fire trucks. However, considerable risks remain to human life while ever-increasing traffic significantly delays operations. In many low-developed and developing countries, ladders used by firefighters have limitations to specific heights. For example, this range is usually up to twenty-two floors in Bangladesh (Rahman, 2019); using helicopters to drop water at the exact places is also challenging due to urban architecture, process delays, and elevated expenses.

Unmanned Aerial Vehicles already have widespread uses in surveillance and filming (Giones, F., & Brem, A. 2017). The constant increase in payload, range, and flight time allowed the adaptation of drones in the military, healthcare, and delivery. Capitalizing on accessibility, UAVs can be a possible solution for controlling and even extinguishing flames in urban areas.

We developed a semi-autonomous UAV that flies to spots firefighting ladders fail to reach. We consider the use of sphere-shaped standard Fire extinguishing balls, as well as water pipe, known as hose. The UAV thus holds both a water-spraying and ball-throwing mechanism. It can further send in-real-time updates to the concerned firefighting team on the ground.

B. *State-of-the-Art:*

Research on using drones in firefighting has been widespread in recent times. Abinash, D.V., alongside his team from Shri Krishna College of Engineering and Technology, demonstrated the capabilities of UAVs in transmitting significant in-real-time data during fire occurrences (2017). Another article indicated impressive performances of UAVs in forest fire monitoring - far more accurate than satellite systems (Merino, L. 2011). Manuj (2019) published an article about a semi-autonomous drone designed to locate fire sources. There, Manuj utilized carbon fiber, coated with nylon, to resist fire more than the general alternatives like plastic.

UAVs and Artificial Intelligence are being combined in fire prediction as well.The new research "Early Forest Fire Detection Using Drones and Artificial Intelligence" (Kinaneva et. al), involved use of computer vision in smoke recognition and analysis.

Owing to the convenience and cost-efficiency of firefighting balls, they have also been widely researched on as a mechanism in firefighting drones. Patil et al. (2020) of Dept. of EXTC Engineering, BVCOE published an article titled, 'Firefighting Drones Using Extinguisher Bomb'. She utilized Arduino based systems to integrate thermal camera in fire detection, and a mechanism for manually dropping the ball.

For countries with traffic congestion and limited budget, an affordable and efficient firefighting drone holds immense potential. While standard firefighting ladders reach 12 storied buildings and current TurnTable Ladders (TTL) reach a maximum of 24 floors, taller buildings remain at risk with no widespread alternative. Fire extinguishing ball can be a suitable resource but it is not as effective in large fires or in the case of smaller window-spaces. The limitation of flight time and disturbance in live video feedback by smoke can hinder the firefighting capabilities of a drone. We consider solving these aspects in our prototype.

C. Project Objective:

Payload of a drone corresponds to the capabilities of its rotors and battery. A LiPo battery-powered drone ensures a maximum flight time of 55 minutes (Burns, 2020). The recharging period required afterward can be problematic in firefighting. To solve this challenge, we implement tethering method in our design.

While most forest firefighting drone projects demonstrate firefighting ball drops, our goal include creation of a throwing mechanism instead. We emphasize the creation of balls with lesser weight as the 1.3kg balls manufactured by AFO can cause significant reverse force while throwing. Furthermore, the throwing mechanism of customized smaller AFO balls is far more suitable in congested cities unlike open forest areas.

Smoky environment can hinder data collection greatly. Reading temperature scale can identify regions of lower disruptions, for which we use a thermal sensor. Since AFO firefighting balls are not suitable for massive fires, water hoses can be a viable alternative.

We are also integrating GPS (Global Positioning System) guided autonomous flights. This system removes the necessity of simultaneous manual control with the help of collected intelligence via different systems.

II. MATERIALS AND METHODS

A. Functional Requirements:

Drones can have various configurations like co-axial, quadcopter, octacopter etc. To achieve higher efficiency and stability, we will design an octacopter with eight brushless DC motors and eight propellers. Custom aluminum frames are suitable for operation for light-weight, affordability, and temperature resistance.

A 6-axis gyro, barometer, and accelerometer will be vital in stabilizing the drone during heavy weight lifting. With a GPS identifying 3-axis (latitude, longitude, and altitude), and a microcontroller, the drone will be capable of holding its position and automated flying up to a great extent. Temperature sensors, gas sensors, humidity sensors, infrared sensors, UV sensors, barometric pressure sensors, etc., are all crucial in collecting data during a fire. These data will be in real-time to ground stations.Six directional ultrasonic sensors will work as obstacle avoidance systems in the drone to reduce potential accidents.

We will build a spring mechanism for manual and automated ball throwing through a servomotor. The use of tethering can remove pressure on the LiPo battery, offering extended flight time.

We shall use a thermal camera for video capture. Live video feed (basic, thermal, infrared), and telemetry data (temparature, gas presence, humidity etc.) will be displayed in real-time in ground stations consisting of a radio transmitter, telemetry module, video receiver, and other components.

B. Project Methodology:

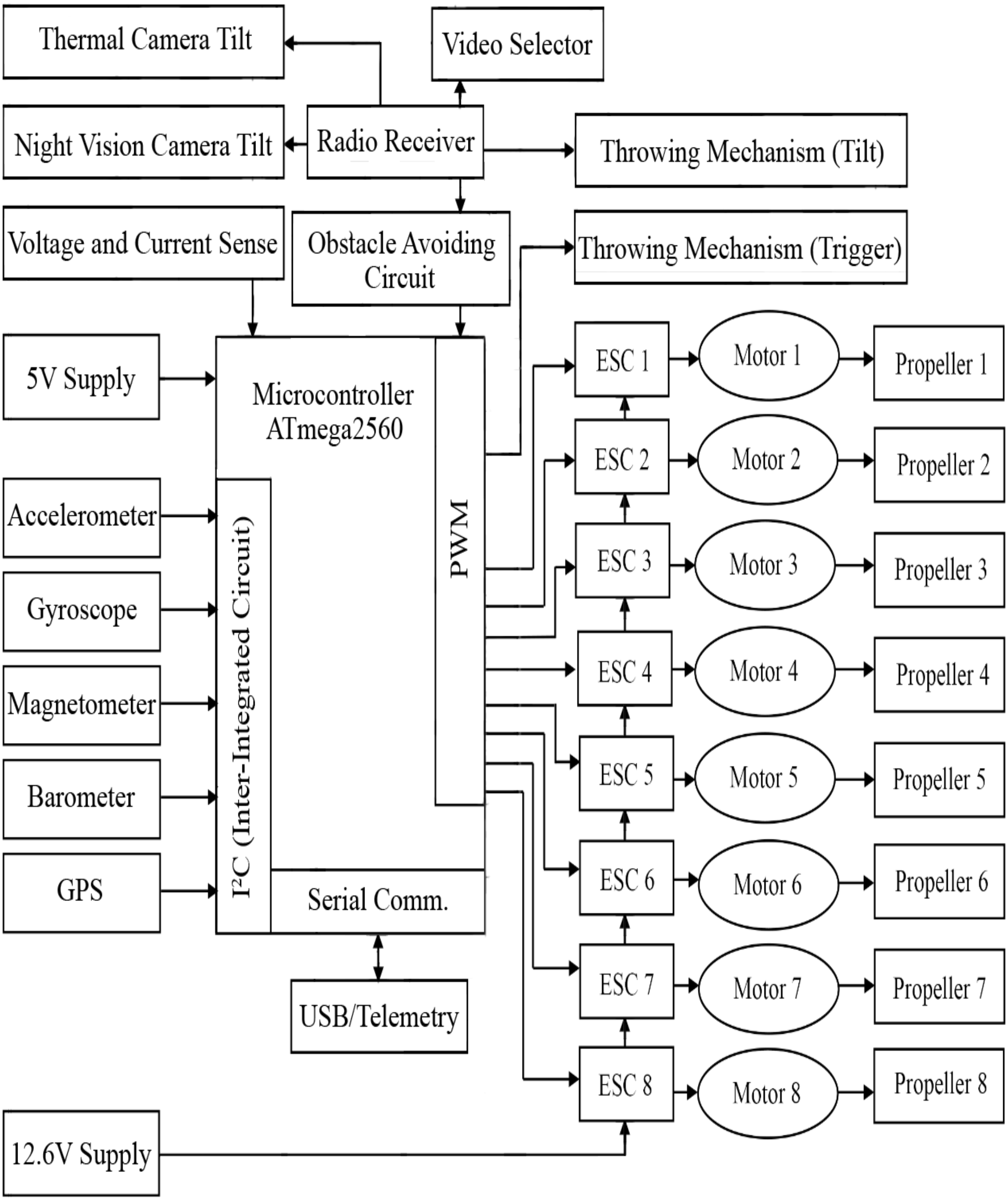

Fig. 1: Block diagram of the drone flying system

As displayed in Figure 2, the six ultrasonic sonar sensors in six directions are connected with ATmega328 microcontroller with the whole circuit powered through 5V supply.

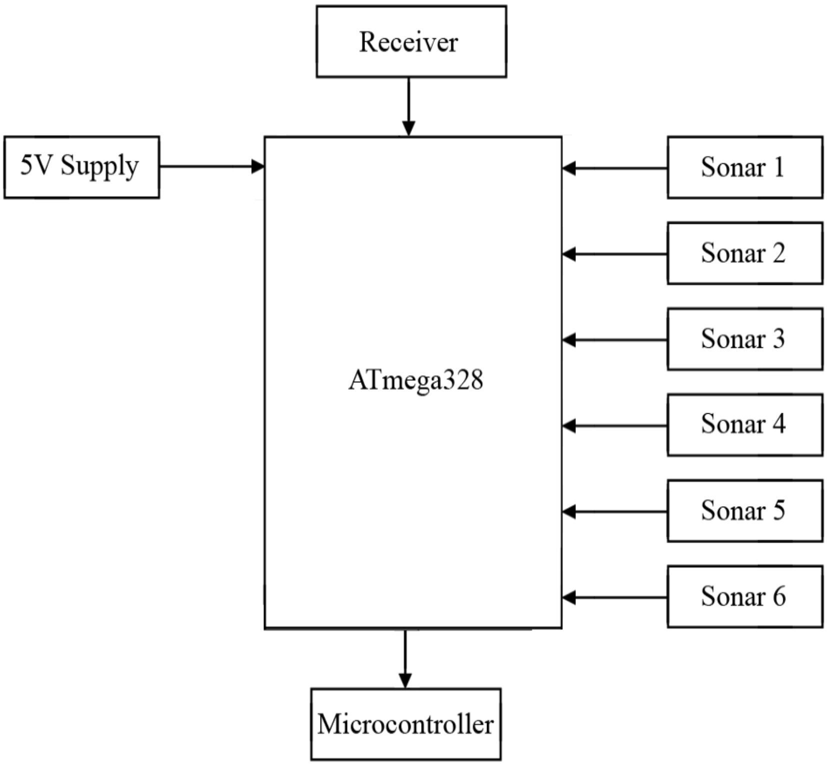

Fig. 2: Block diagram of obstacle avoiding system

We will connect Raspberry Pi with a number of sensors to get environmental reading, Through basic image processing, we shall also analyze the camera data, which is directly sent to ground station.

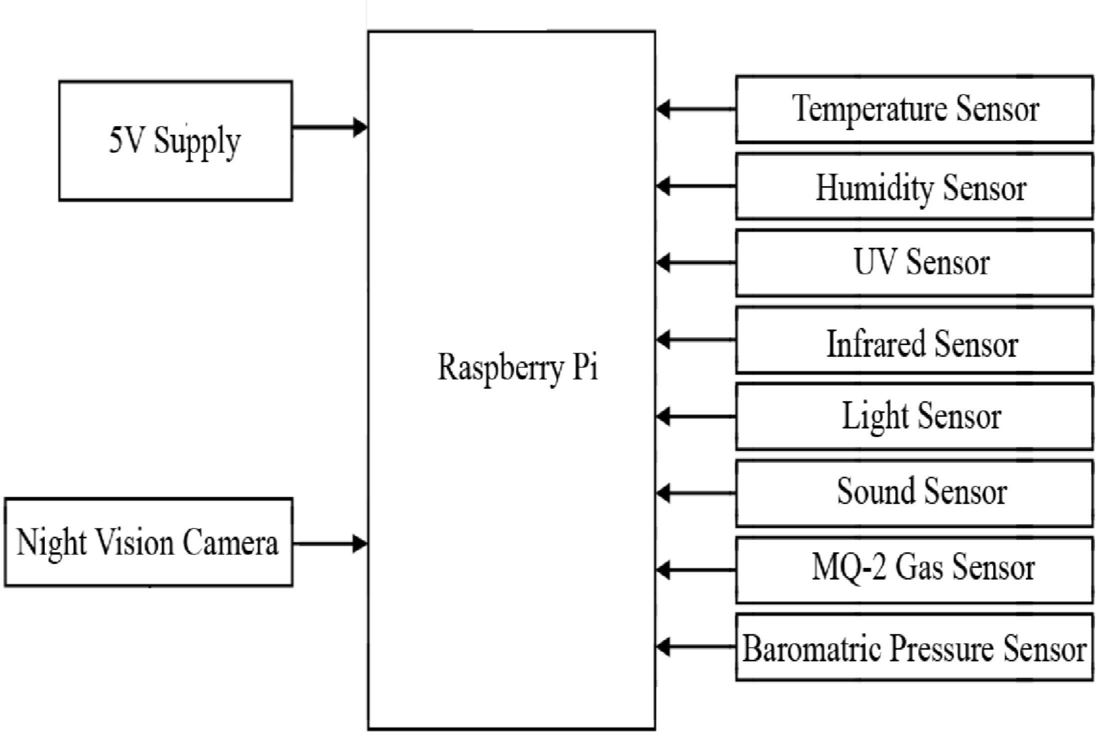

Fig. 3: Block diagram of the environment sensing circuit

Since our selected video transmitter can transmit one video at a moment, we utilize a selector during feeding the thermal and night vision camera outputs to the transmitter. This enables the user to ground station attendant to switch camera as per necessity.

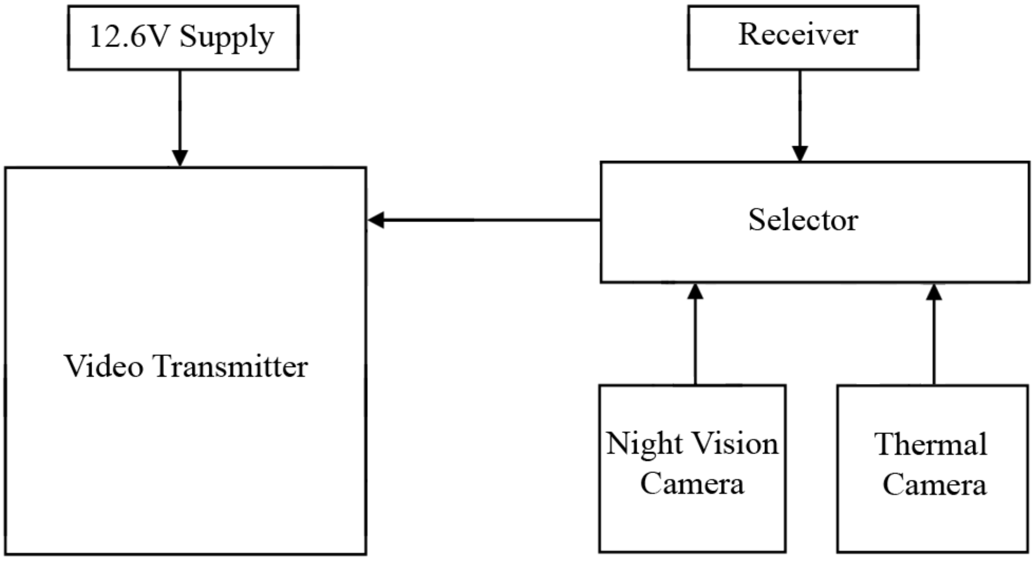

Fig. 4: Block diagram of the video transmitting circuit

a) Ground Station:
This project's design segments include Ground Station and Air Unit.

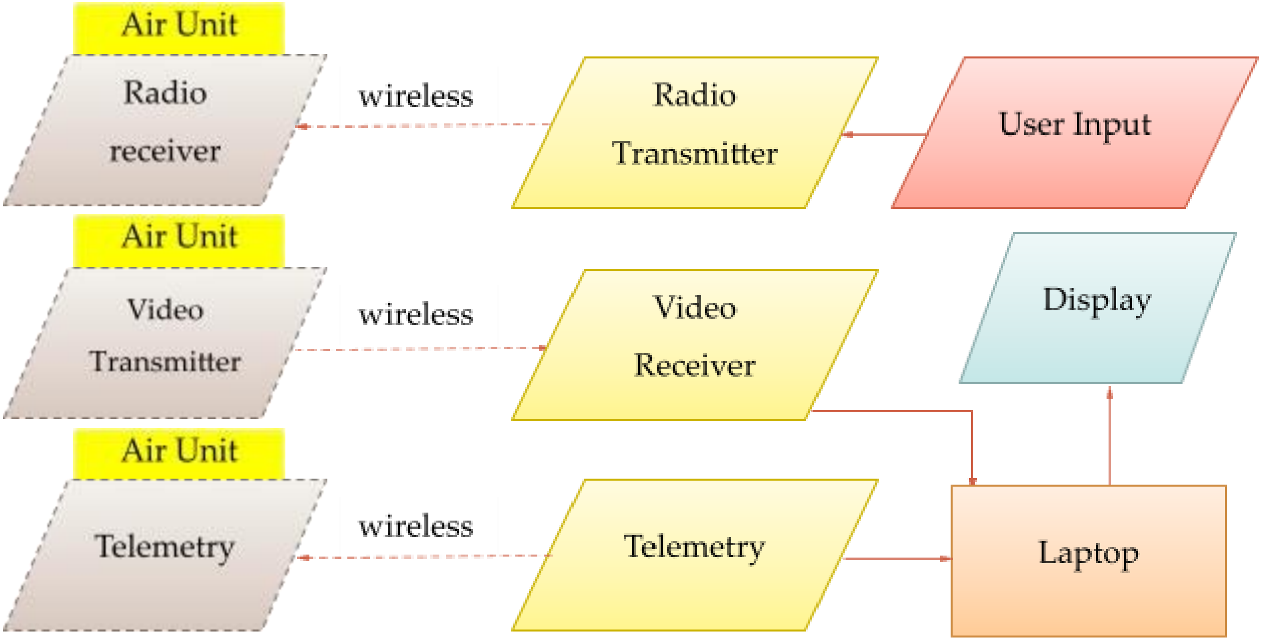

Fig. 5: Flow diagram of ground station

Ground panel will act as the control panel powered by a 12V battery. Discharge rates are not very important, since current consumption is less. A lead acid batter will be utilized in the station consisting of radio transmitter, analog video receiver and telemetry. All received data can be observed via a laptop.

- **Radio Transmitter:**
10 separate PWM signals are broadcasted by the radio receiver utilizing 2.4GHz radio signal. The first four controls roll, pitch, yaw, and throttle. Dedicating a channel for failsafe allows the drone to return to initial position in emergency situations. The remaining channels will control the tilt of throwing mechanism and camera. The used transmitter model, Flysky FS-i6x, operates at 12V.

- **Analog Video Receiver:**
Analog video is received at 5.8GHz frequency and video data is transmitted to laptop by a TV card. RS832 model video receiver is used, which operates at 12V.

- **Telemetry:**
A pair of trans-receivers, one on the ground station and another on air unit, will communicate two-way at 433MHz frequency. This allows simultaneous

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information exchange including coordinate guidance and telemetry data.

b) Air Unit:
The unit is controlled by Arduino 2560. Sensors like accelerometer, gyroscope, magnetometer, GPS sense the position of the vehicle and feed it to the microcontroller. 8 PWM signals as output control the speed of the motors.

- **Power System:**
Owing to the high current consumption (~3.5A per motor at 12.6 volt), the amperage requirement for eight motors is roughly 28A. All other circuits' amperage are negligible. Three 4.2 volt cell (nominal 3.7 volt) 8400mAh Li-Po battery connected in series, will power unit, causing a total voltage of (4.2v*3 cell) = 12.6 V. All ESCs will connect to the terminal. Several 5-volt buck converter will be there to power the microcontrollers and other elements.

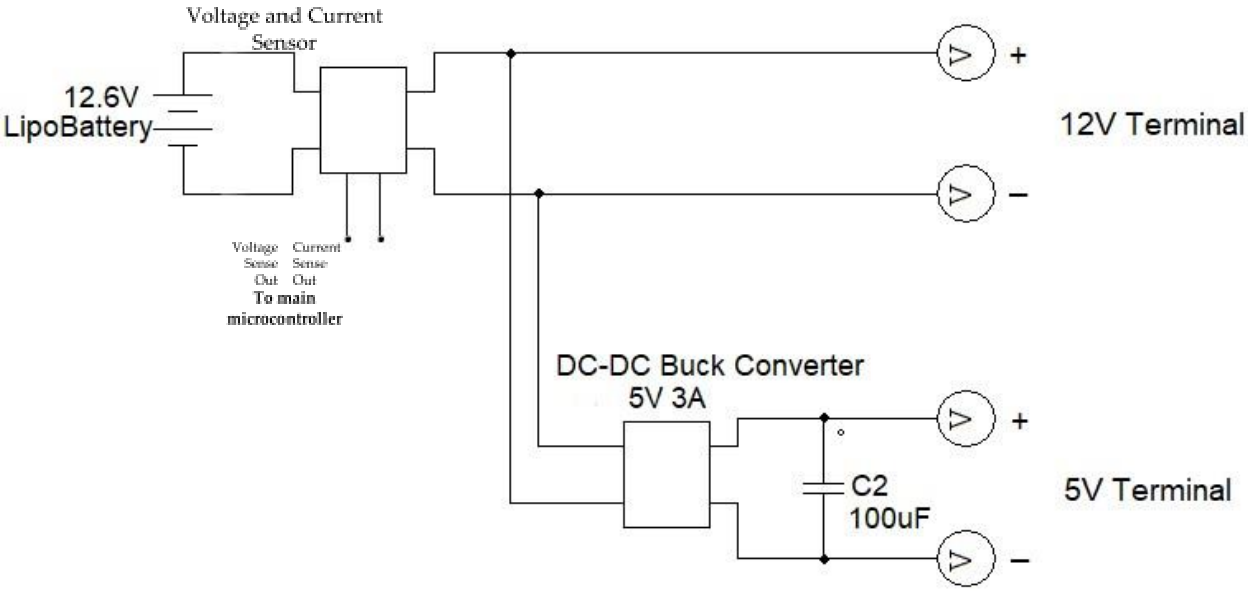

Fig. 6: Power system of the air unit (when powered by battery)

- **Tethering:**
The drone will optionally gain power from the ground. Powered directly from an AC outlet from the ground, the drone can have uninterrupted flight time. This, however, requires facility creation in high buildings. We will use 15 feet of both positive and negative 14 AWG wire (thick due to higher ampere requirements) to power our UAV.

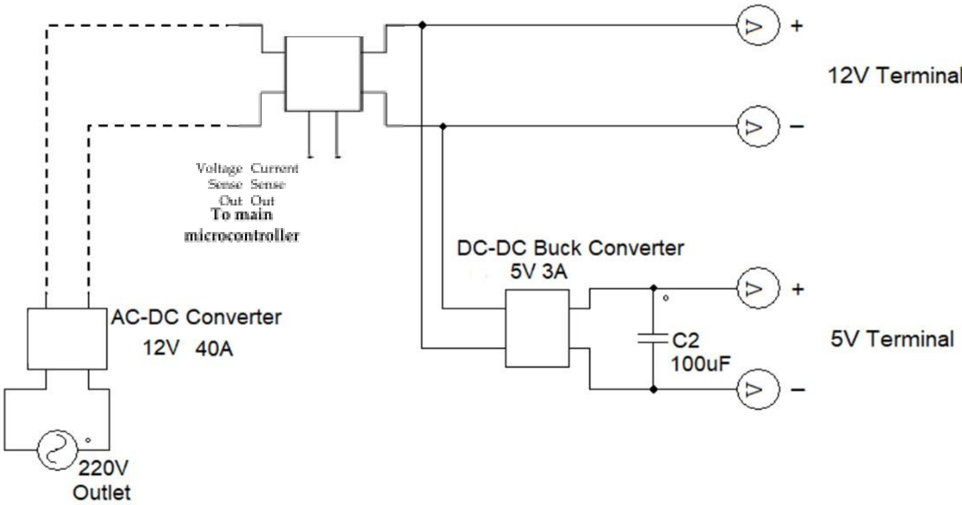

Fig. 7: Power system of the air unit (when tethering is active)

- **Motors, Propellers, and ESCs:**
  Brushless 2312 800KV motors will be used owing to more extended durability. This motor can generate approximately 980g thrust at 12.6V. Plastic 10-inch two-blade propellers with a 4.5-inch pitch are suitable for these motors. The ESC will receive the PWM signal and convert the input voltage into three-phase voltage for the motors.

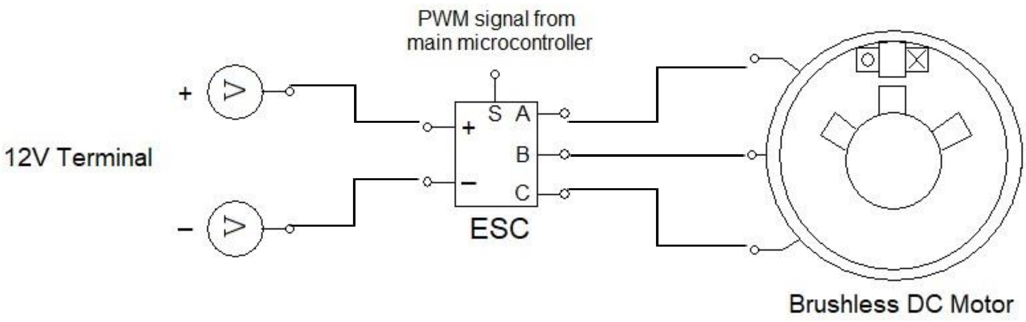

Fig. 8: Electronic Speed Controller (ESC) connection

- **Radio Receivers and Telemetry:**
  The unit receives ten PWM signals, five of which are fed to the microcontroller to control the roll, pitch, yaw, throttle, and failsafe trigger of the drone. Other signals control the throwing mechanism and camera. Flysky FS-iA10 model, operating at 5V, is used here.

- **Frame:**
  Both aluminum tubes and carbon fiber tubes are suitable for the operation. Carbon fiber tubes are more robust and light. However, they are comparatively costly. Aluminum tubes are cost-efficient alternatives to them. We are utilizing an H-configuration frame.

- **Sensors and Cameras:**
  Raspberry Pi will be the microprocessor for data collection from the sensors. Cameras will also be connected to the microprocessor, ensuring in-real-time broadcasting through a video transmitter.

Sensor/Camera	Model/Module Used
Temperature And Humidity Sensor	DHT11 Model
UV Sensor	CJMCU-GUVA-S12SD UV Detection Light Sensor Module
Infrared Sensor	IR Module
Light Sensor	LDR Module
Sound Sensor	Mini Microphone with LM393 op-amp
Barometric Pressure Sensor	BMP180 Model
Gas Sensor	MQ-2 Model
Thermal Camera	AMG3388 Model
Night Vision Camera	A Camera with Two Infrared LED

Table 1: Models of Sensors and Cameras Used

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- **Analog Video Transmier:**
  Analog video will be transmi ed from Raspberry Pi at 5.8GHz frequency to the video receiver by this unit, operating at 12 Volts. The TS832 Model is being used here.

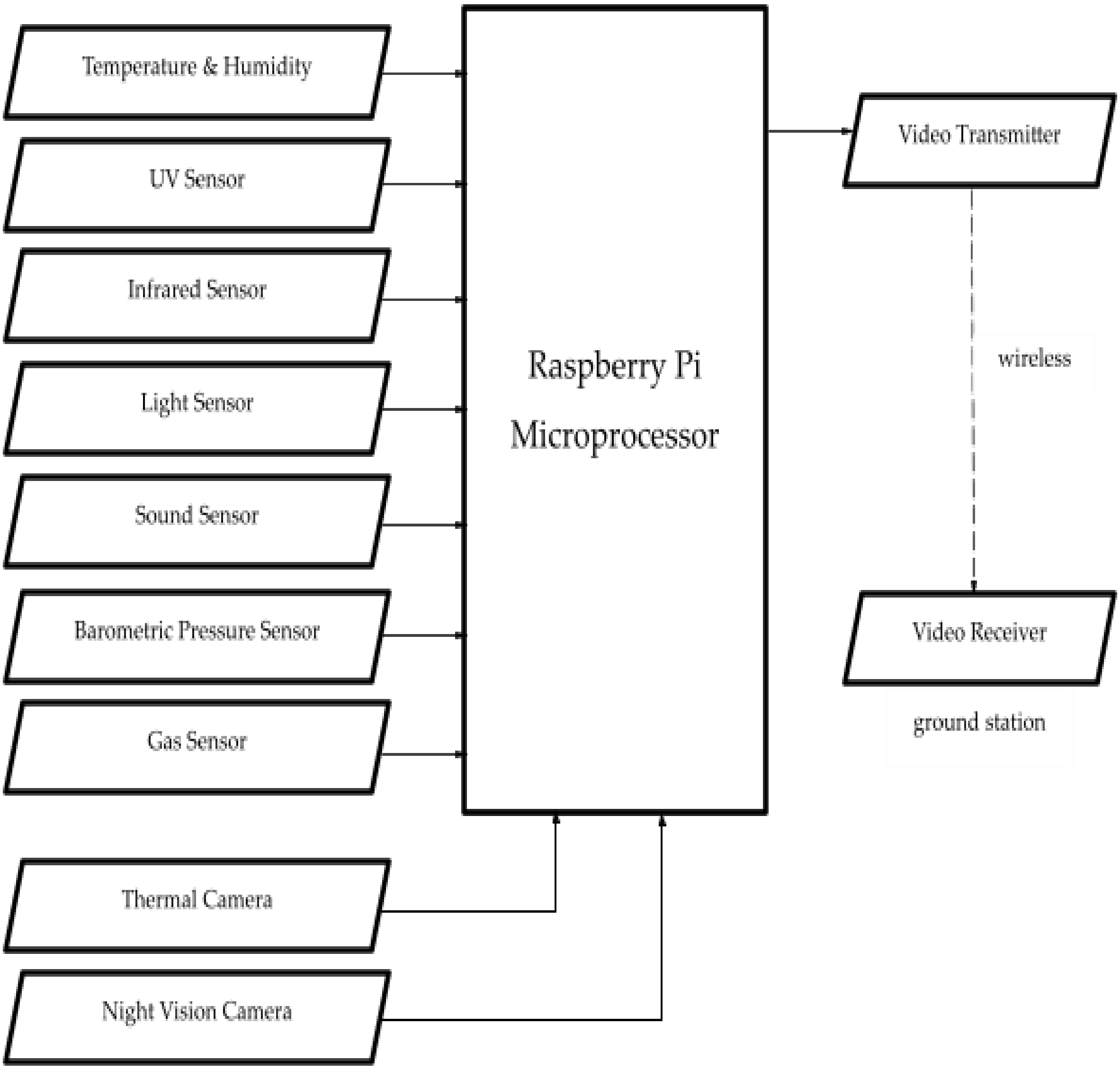

Fig. 9: Sensor data collection unit flow diagram

c) Obstacle Avoiding Technology:
   The unit ensures that the UAV will maintain a safe distance of approximately 3 meters from a particular object. A secondary Arduino 2560 microcontroller alongside 6 ultrasonic sensors facing 6 directions makes it functional. The 4 major PWM signals (roll, pitch, yaw, thro le) does not directly reach the main microcontroller but are fed into the secondary one. Arduino analyzes data from both ultrasonic sensors and receivers. Obstacle detection causes the technology to be forwarded to the main controller. We are using the HC-04 Sonar Sensor in this unit.

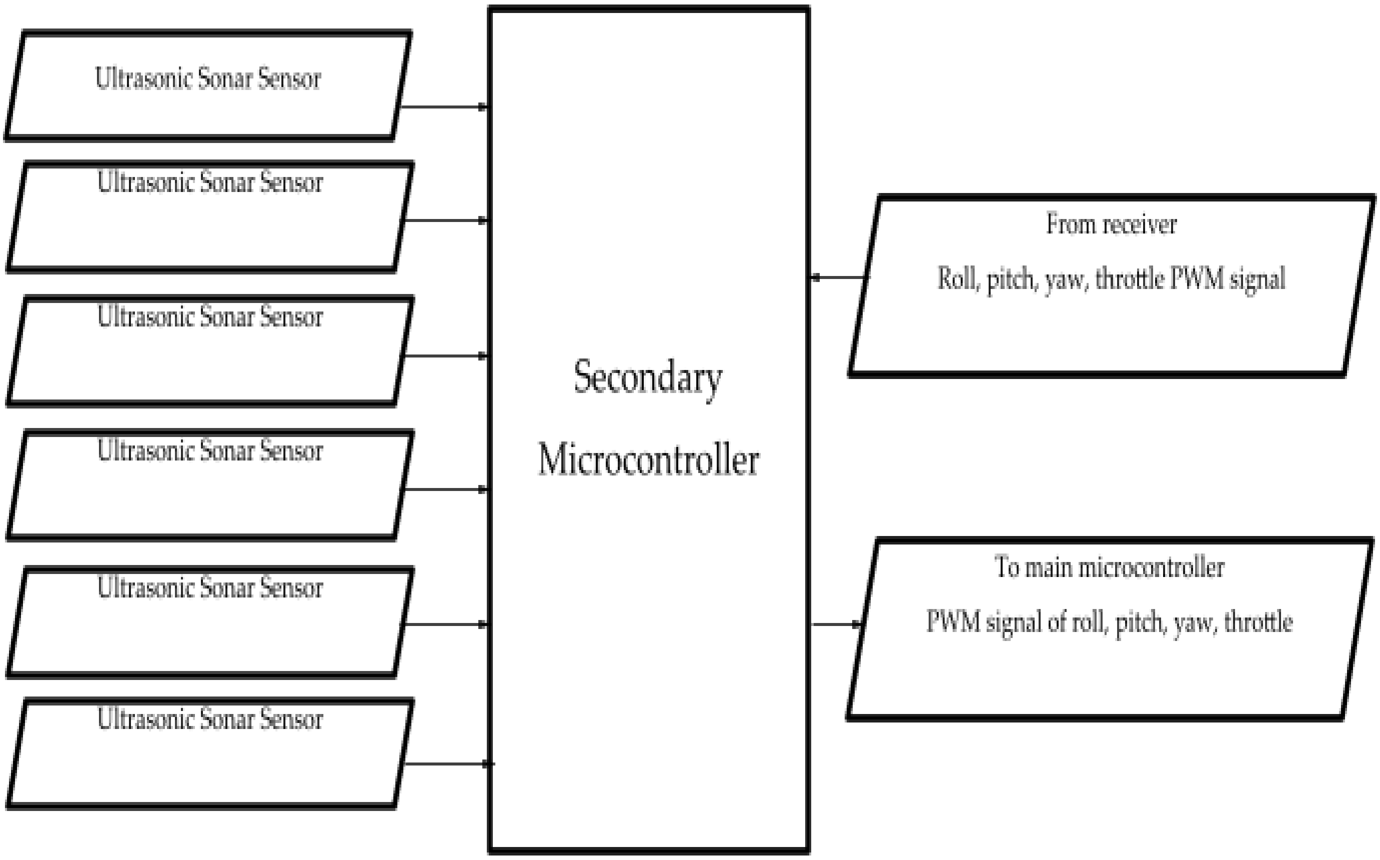

Fig. 10: Obstacle avoiding unit flow diagram

- **Hose Pipe Mechanism:**
  A hose pipe can be viable to lift only in absence of a heavy ba ery on the UAV, which can be achieved through tethering. The following hose mount can be 3D printed and a ached with a single screw. Water spraying at high altitudes can be made possible with long firefighting hoses.

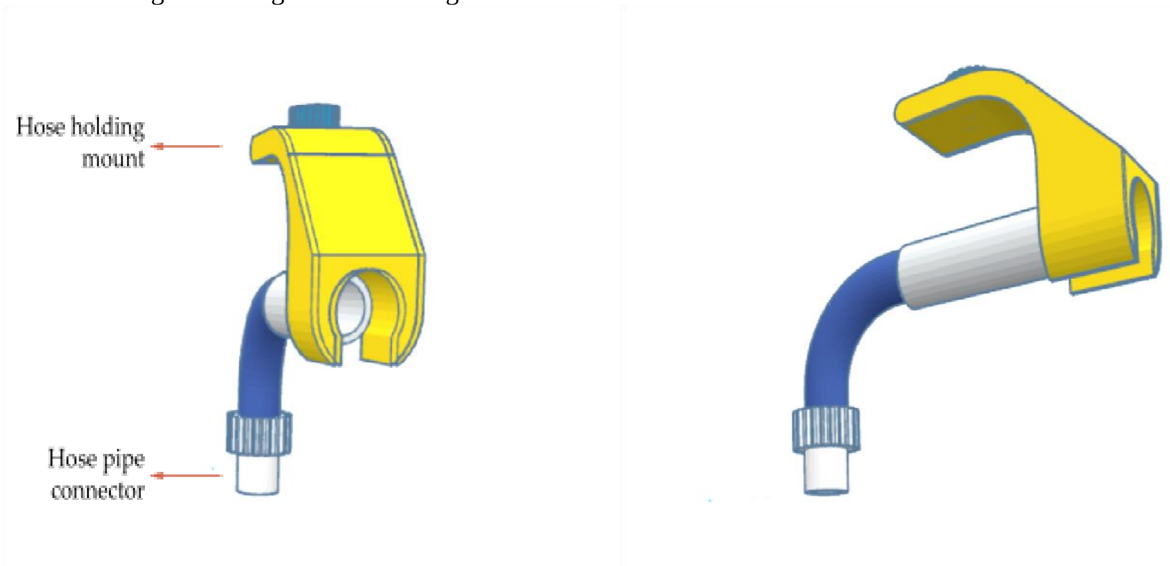

Fig. 11: Hose mount

- **Throwing Mechanism:**
Several AFO balls will be placed behind two wheels, separated by a servo-controlled barrier. The wheels connect to brushless motors which connect to separate ESCs. A 12.6V and a 5V terminal connect to the ESCs and servos respectively. PWM signals are transmi ed if triggered from the ground to the receiver of the air unit which controls the motor and servo speeds. On trigger, the servo-controlled barrier opens up while the wheels rotate and maximum speed. This allows projecting AFO balls at high velocity. We utilized TinderCAD software for the following 3D model.

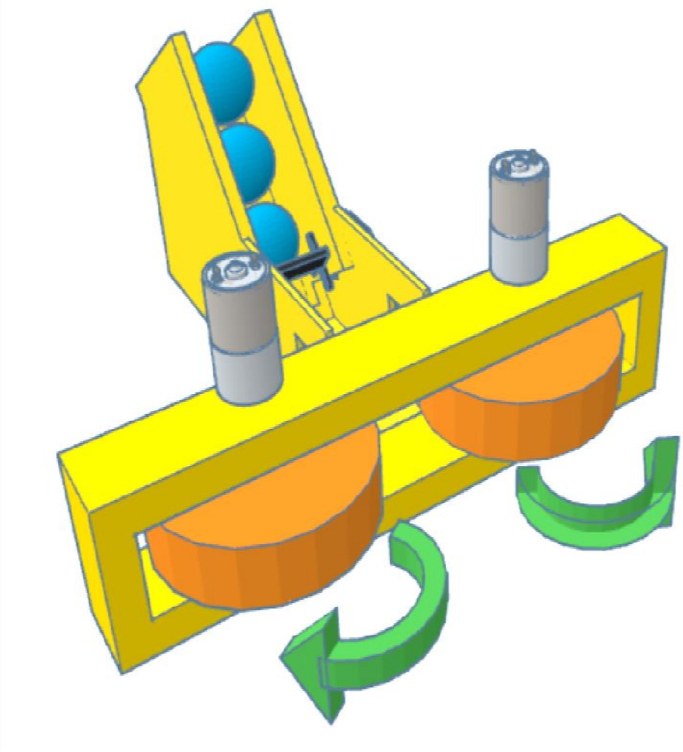

Fig. 12: Rotating wheel throwing mechanism

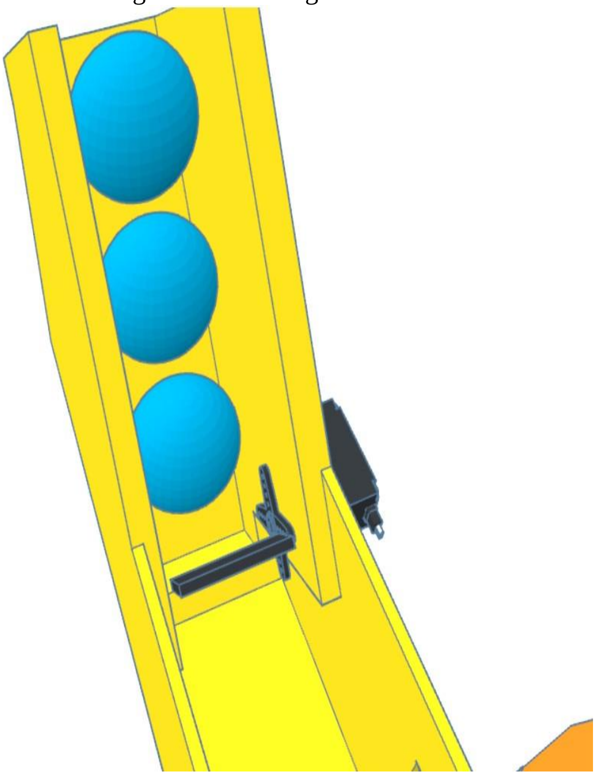

Fig. 13: Servo motor barrier of throwing mechanism

III. EXPERIMENTATION

Based on different levels of thro le, we collected motor data including power, thrust, efficiency, etc. The following table consists of the collected data at 29°C.

	Voltage (V)	Propeller	Throttle (%)	Ampere (A)	Power (W)	Thrust (g)	Efficiency (g/W)	Operating Temperature (°C)
2312 800KV	12.6V	10*4.5	20%	1.3	16.38	85	5.189255	29°C
			40%	2.2	27.72	198	7.142857	30°C
			50%	2.6	32.76	354	10.80586	32°C
			65%	4.5	56.7	480	8.465608	35°C
			75%	6.2	78.12	637	8.154122	38°C
			85%	8.9	112.14	791	7.053683	46°C
			100%	12.1	152.46	985	6.460711	55°C

Table 2:Motor data for different level of thro le

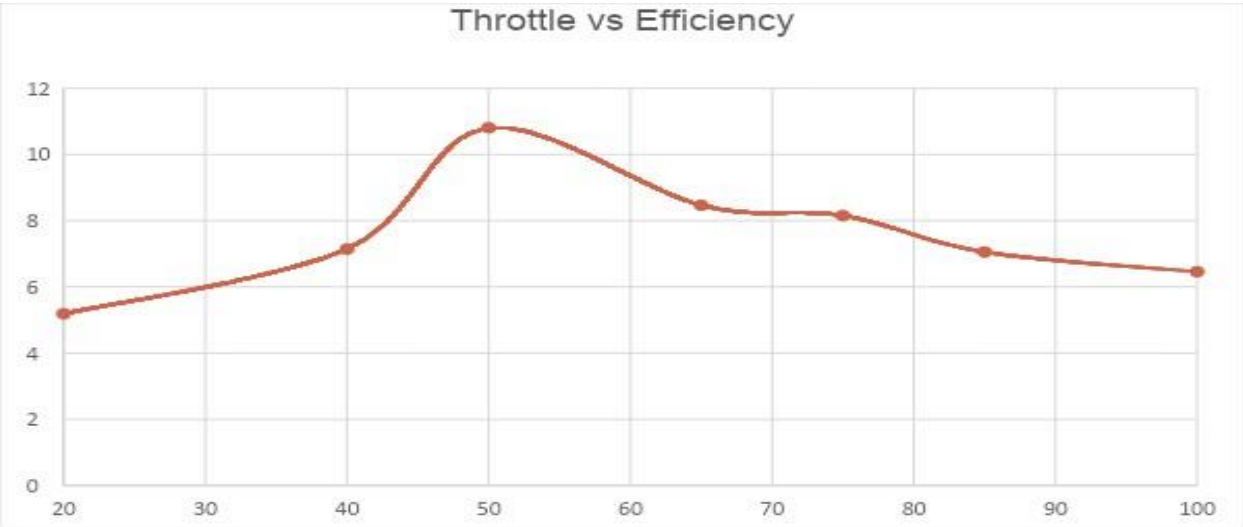

Fig. 14: Plot of motor throttle vs efficiency

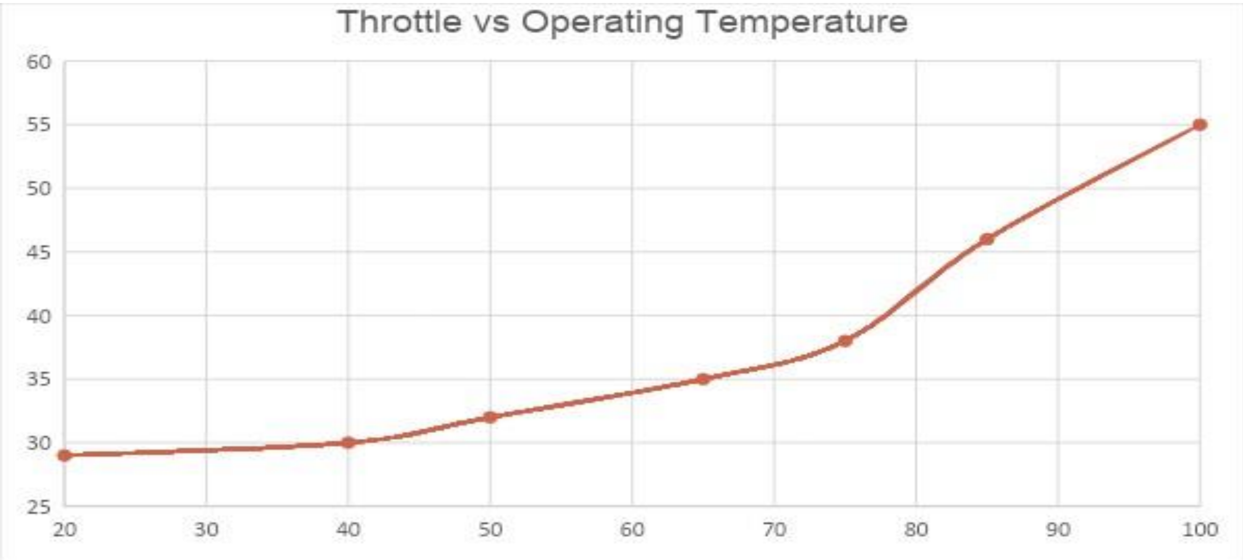

Fig. 15: Plot of motor throttle vs operating temperature

Maximum efficiency is obtained at 50% throttle when current consumption 2.6 A for 12.6V per motor. Individual

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motor thrust reaches 354 grams indicating total throttle of (8*354) = 2832 g. To maximize efficiency and flight time, the air unit should weigh close to 2832 g

To generate 2832g throttle, (2.64 per motor * 8) = 20.8A current is needed at 12.6 V. Rest of the components, operating at a low voltage of 5V, will approximately consume 2A at 12.6 V. Thus total current consumption in air unit amounts to (20.8A + 2A) = 22.8A.

In our design, we are using a 12.6 volt 8.4A battery.

The discharge time of the battery = $\underline{Current Supplied}\underline{capacity} amperage \underline{of} \underline{the battery}$
$= \underline{8.4A} \times 60 22.8 \underline{minutes} A = 22.1\ minutes$

So, the air unit will operate maximum 22.1 minutes on a single battery

- **Design Refinement:**
Based on our testing, our final schematic diagram has been modified and presented.

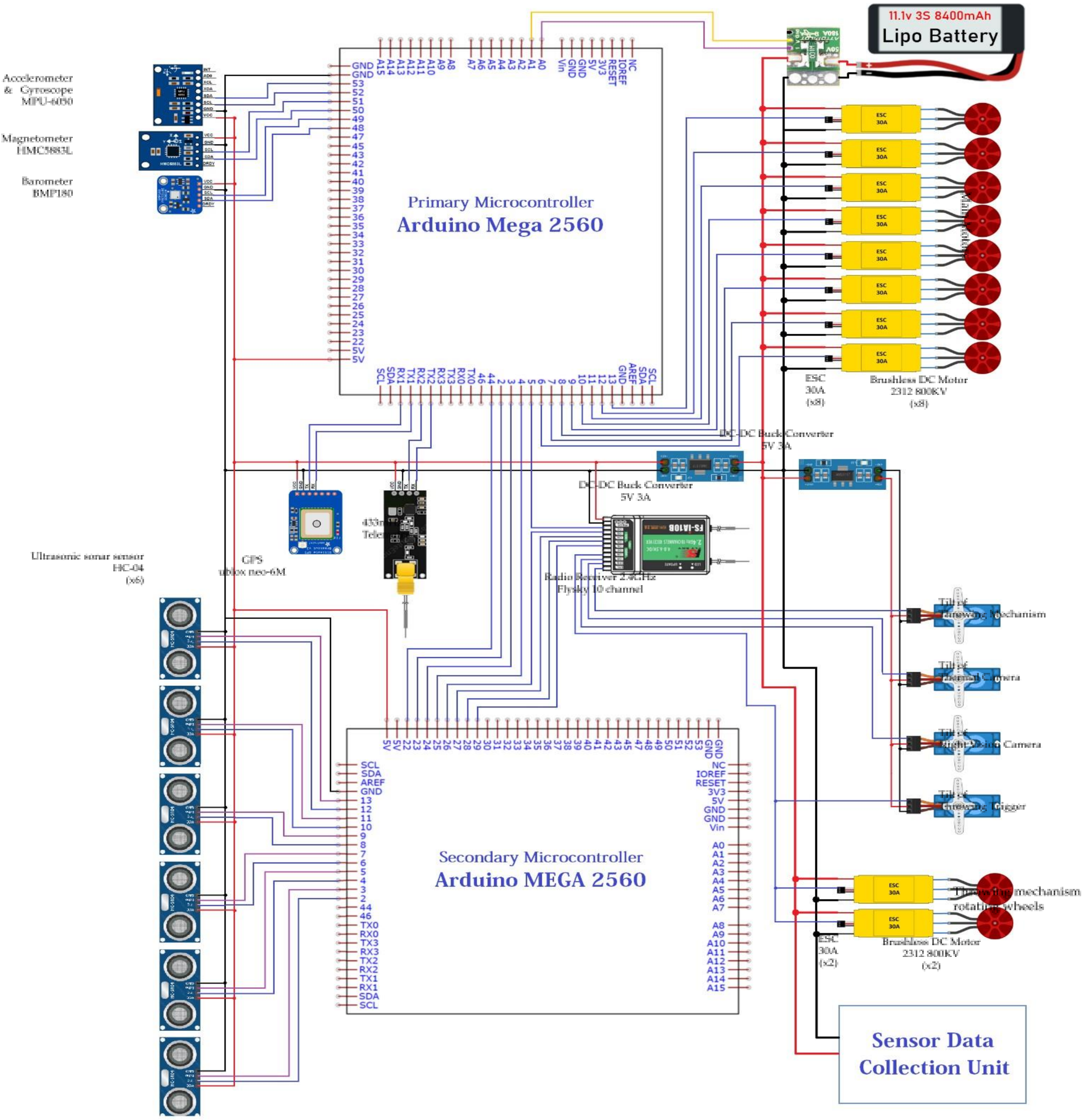

Fig. 16: Schematic diagrams of air unit final design

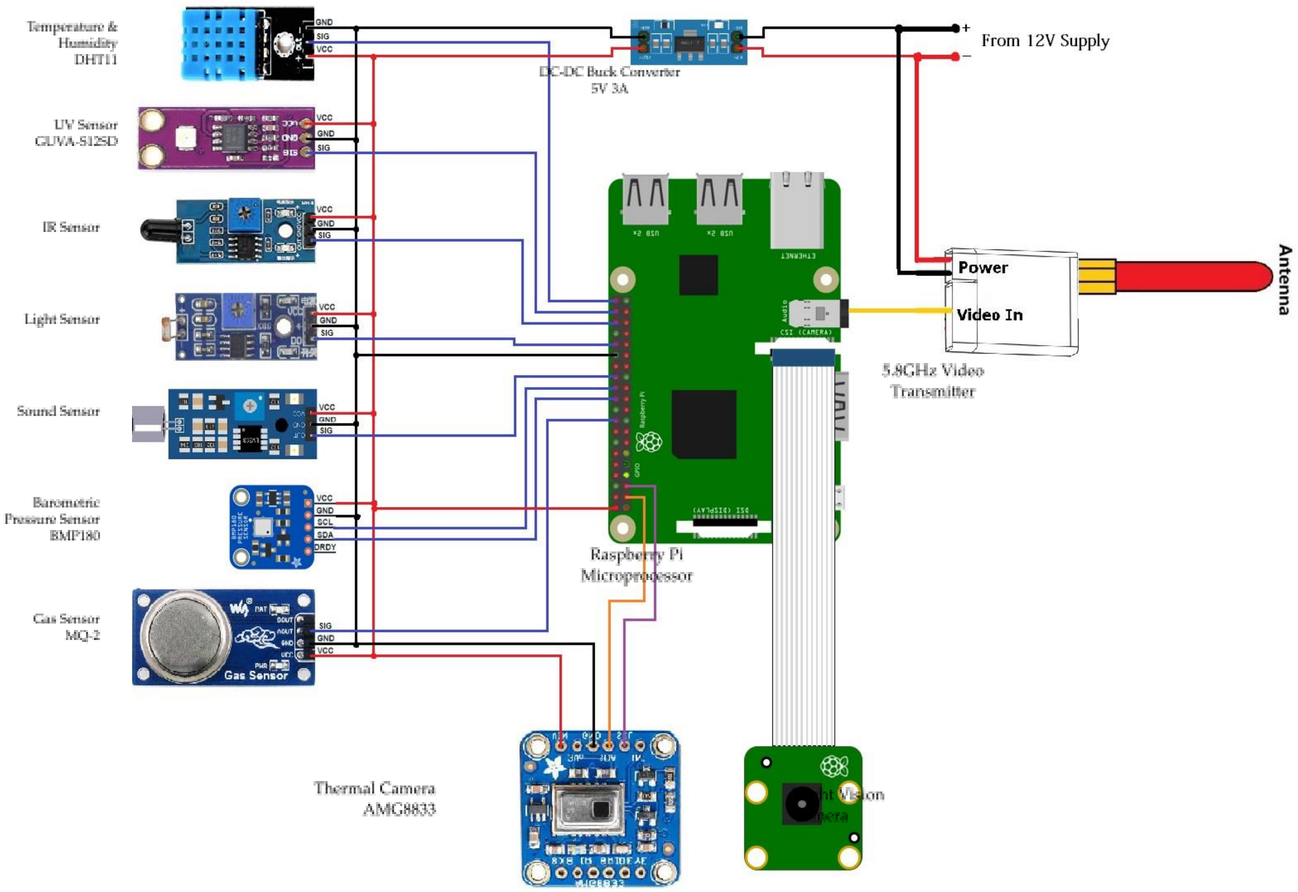

Fig. 17: Schematic diagrams of air unit final design (sensor data collection unit)

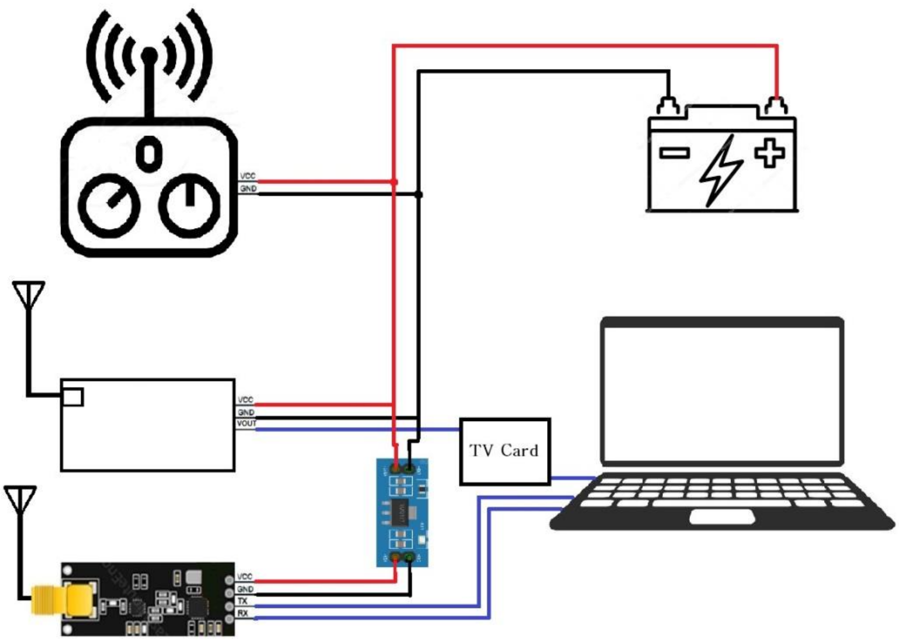

Fig. 18: Schematic diagram of ground station

IV. PROTOTYPE DEVELOPMENT

All the mentioned procedures and units were utilized in the creation of the prototype.

A. Hardware:

The frame is designed first with 38-inches long and 0.75-inches wide aluminium bars. 3D Mounts, each for one motor, connect the bars. Each of the two pair of bars shall maintain a 90-degree angle. The bars were tightened by 2.5 inch nuts and screws. A 3D 12/6 base is printed at the center. Motors are connected to the mounts and ESCs to the motors afterwards. 14AWG silicon wire was soldered to every ESC carrying 12V from LiPo battery. ESCs, and other components are connected to Arduino mega2560 by Signal wires. The weather station components were soldered to the veroboard. Positive and ground terminals are separated and supplied with 5V BEC.

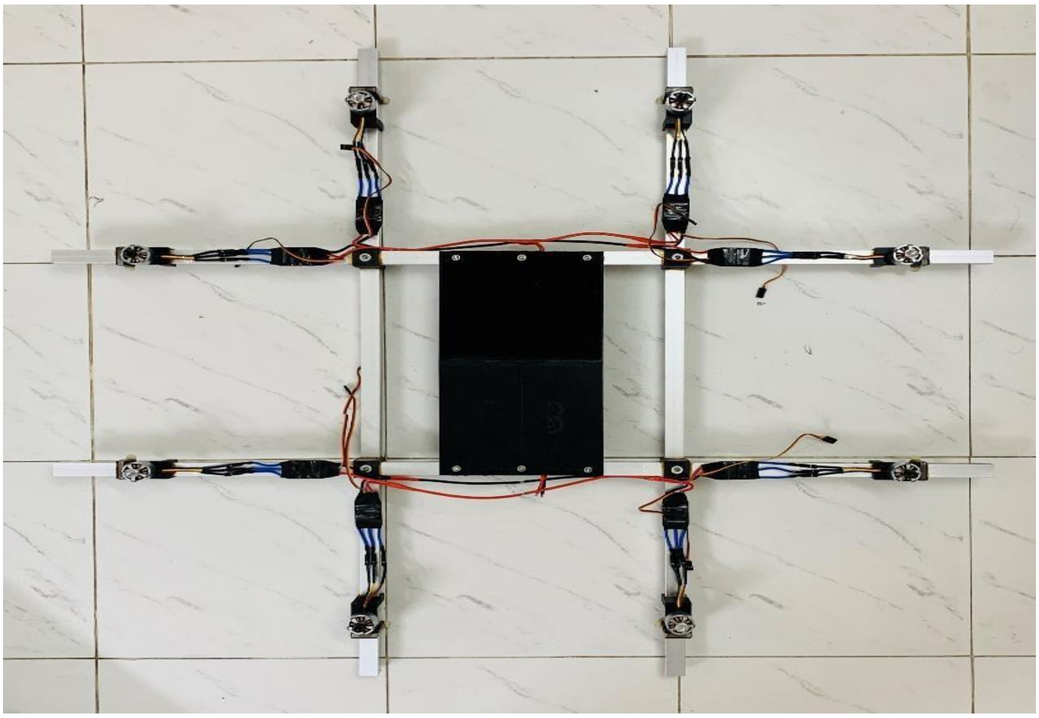

Fig. 19: Prototype of the flying unit

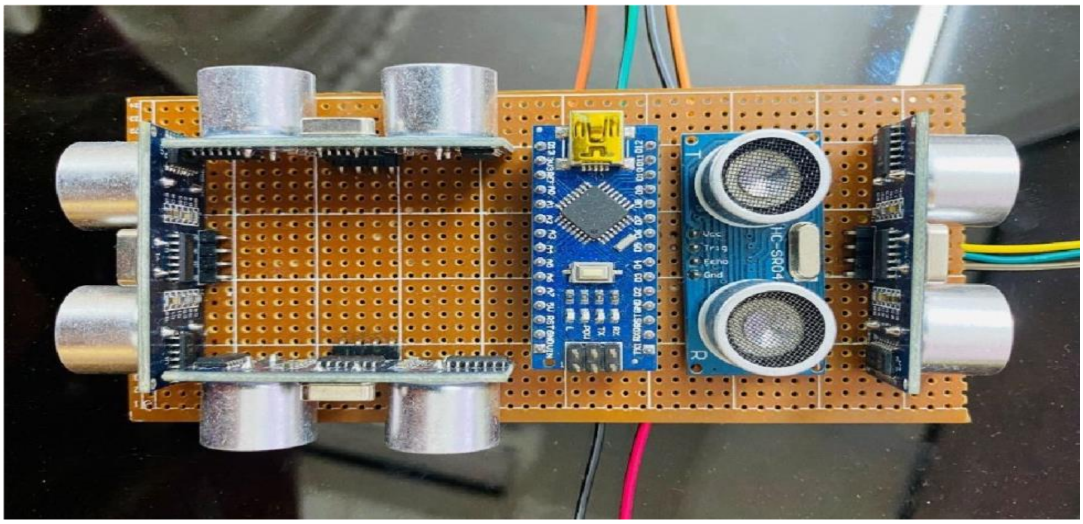

Fig. 20: Obstacle avoiding unit

Figure 21 demonstrates the 3D printed shooting mechanism. ESCs are connected with two brushless motors and corresponding shooting wheel. The ESCs take power from the main 12V rail. The signal pin of the ESC is directly connected to the main microcontroller.

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Fig. 21: Shooting mechanism

Sensors, all working on DC 5V, are soldered on a veroboard. Separate 5V BEC powers the positive and negative shorted terminals. The main 12V supply is connected with the input terminal. Jumper wires connect all 7 sensors through jumper wires.

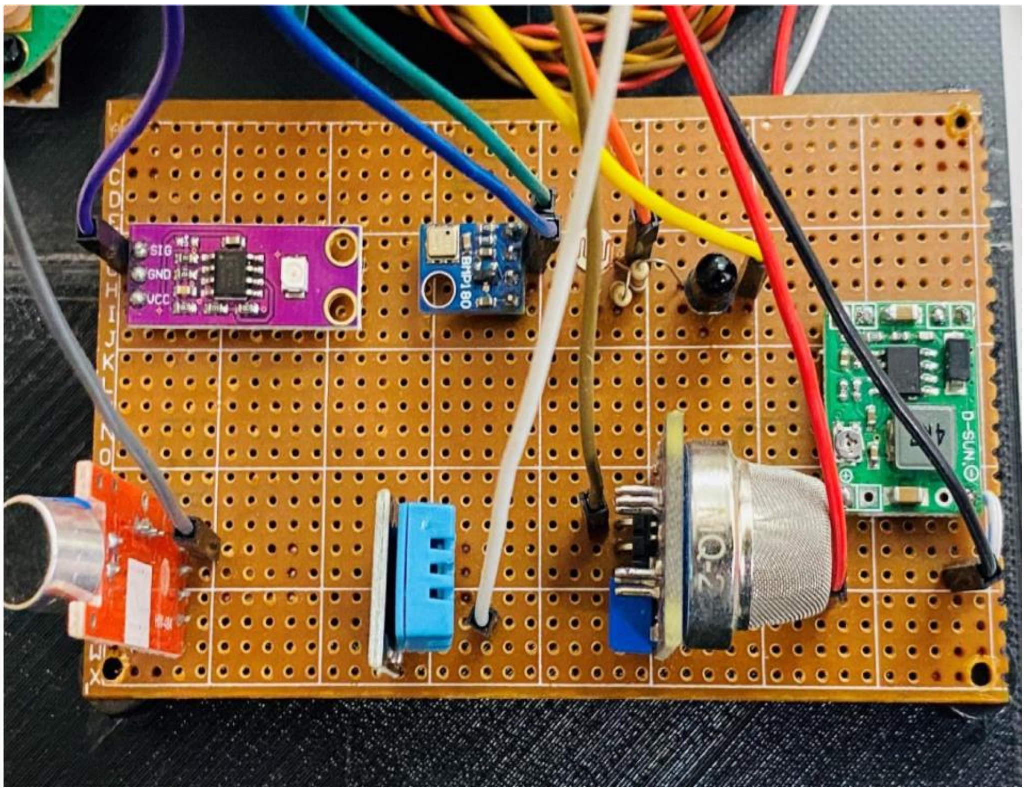

Fig. 22: Weather data sensing unit

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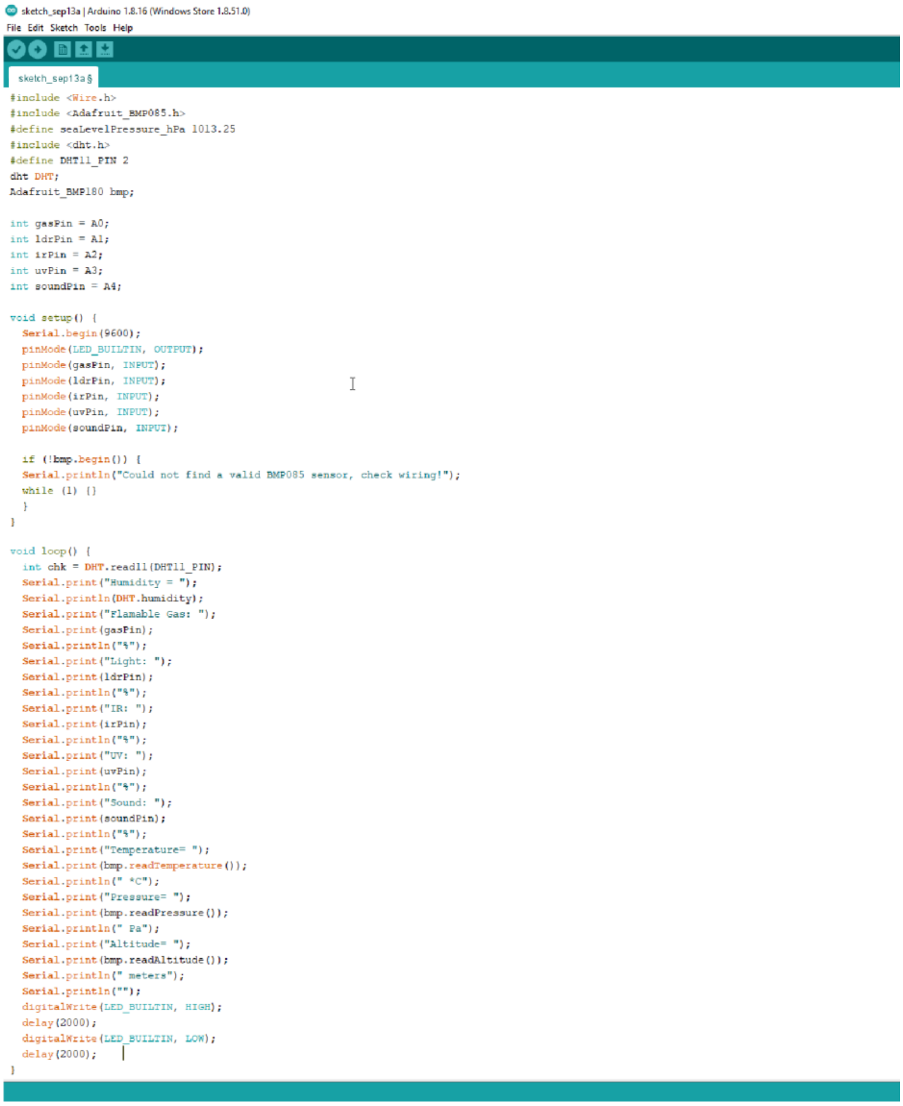


```
#include <Wire.h>
#include <Adafruit_BMP085.h>
#define seaLevelPressure_hPa 1013.25
#include <dht.h>
#define DHT11_PIN 2
dht DHT;
Adafruit_BMP180 bmp;

int gasPin = A0;
int ldrPin = A1;
int irPin = A2;
int uvPin = A3;
int soundPin = A4;

void setup() {
  Serial.begin(9600);
  pinMode(LED_BUILTIN, OUTPUT);
  pinMode(gasPin, INPUT);
  pinMode(ldrPin, INPUT);
  pinMode(irPin, INPUT);
  pinMode(uvPin, INPUT);
  pinMode(soundPin, INPUT);

  if (!bmp.begin()) {
  Serial.println("Could not find a valid BMP085 sensor, check wiring!");
  while (1) {}
  }
}

void loop() {
  int chk = DHT.read11(DHT11_PIN);
  Serial.print("Humidity = ");
  Serial.println(DHT.humidity);
  Serial.print("Flamable Gas: ");
  Serial.print(gasPin);
  Serial.println("%");
  Serial.print("Light: ");
  Serial.print(ldrPin);
  Serial.println("%");
  Serial.print("IR: ");
  Serial.print(irPin);
  Serial.println("%");
  Serial.print("UV: ");
  Serial.print(uvPin);
  Serial.println("%");
  Serial.print("Sound: ");
  Serial.print(soundPin);
  Serial.println("%");
  Serial.print("Temperature= ");
  Serial.print(bmp.readTemperature());
  Serial.println(" *C");
  Serial.print("Pressure= ");
  Serial.print(bmp.readPressure());
  Serial.println(" Pa");
  Serial.print("Altitude= ");
  Serial.print(bmp.readAltitude());
  Serial.println(" meters");
  Serial.println("");
  digitalWrite(LED_BUILTIN, HIGH);
  delay(2000);
  digitalWrite(LED_BUILTIN, LOW);
  delay(2000);
}
```

Fig. 23: Code for weather data sensing unit

Thermal camera is mounted at the front of the frame. Both thermal and night vision camera are connected to Raspberry Pi which transmits these data to ground stations.

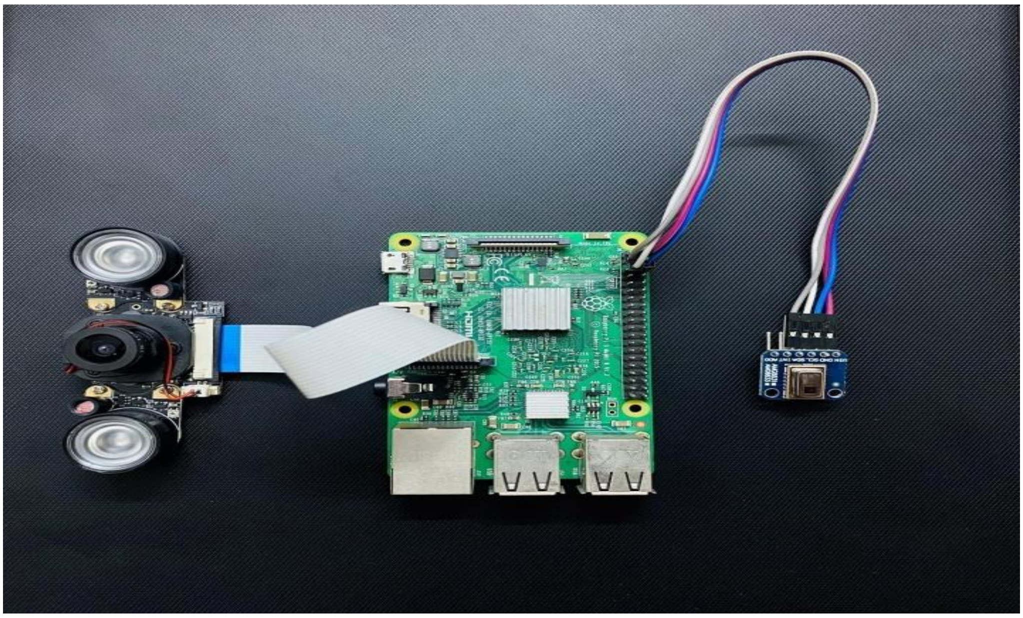

Fig. 24: Thermal imaging and night vision camera unit

B. Software

Mission Planner and Octacopter firmware code are downloaded from official ardupilot website https://www.ardupilot.orgArduino mega2560 is connected to the laptop via USB cable and the corresponding COM port is selected. After detecting Arduino, we upload the '.hex' octacopter file to the microcontroller. This finalizes our board and makes it ready for operation.

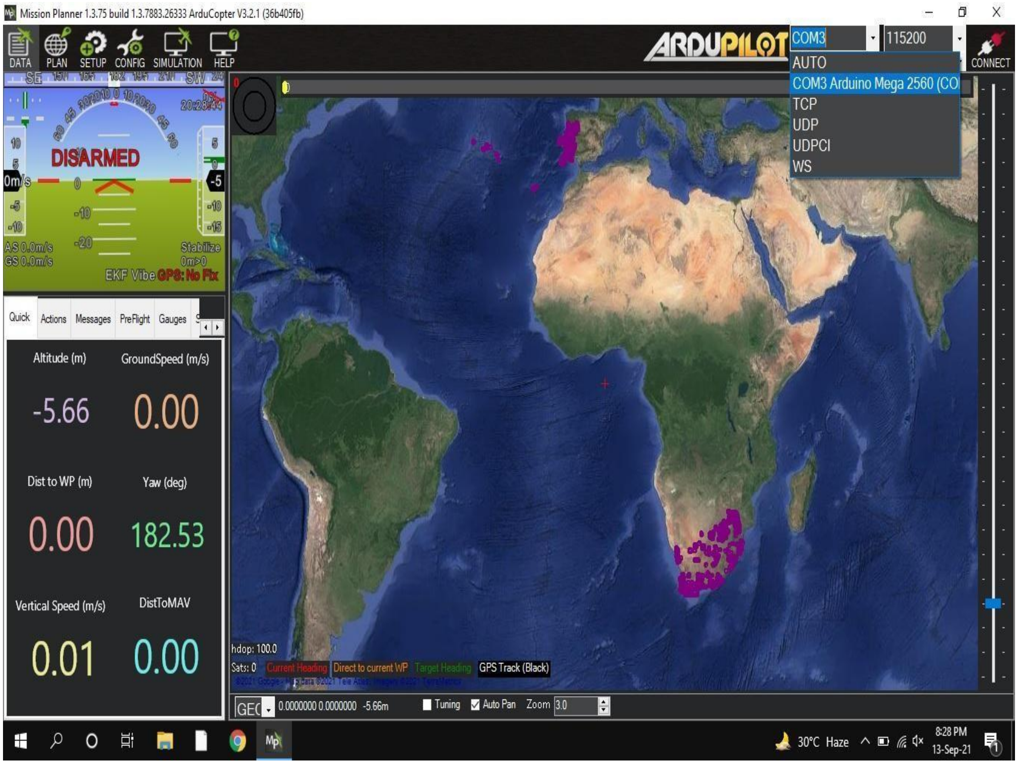

Fig. 25: Mission planner software connection

Next we calibrate the accelerometer, compass and radio. The Accel Calibration menu is to be entered and the UAV is to be placed on each surfaces when indicated in the screen. After that the compass is to be calibrated in open field to avoid interruption by metals as much as possible. At least six 360-degree turns are required to calibrate the compass. Lastly, the radio controller is calibrated by capturing the maximum and minimum values of each channel for correct interpretation of the inputs. Entering the Calibrate Radio menu, each joy stick and buttons are shifted to their maximum and minimum positions. We should also test each motors' rotation direction. Reversing ESCs will change the direction. Four motors should rotate clockwise and four anti-clockwise.

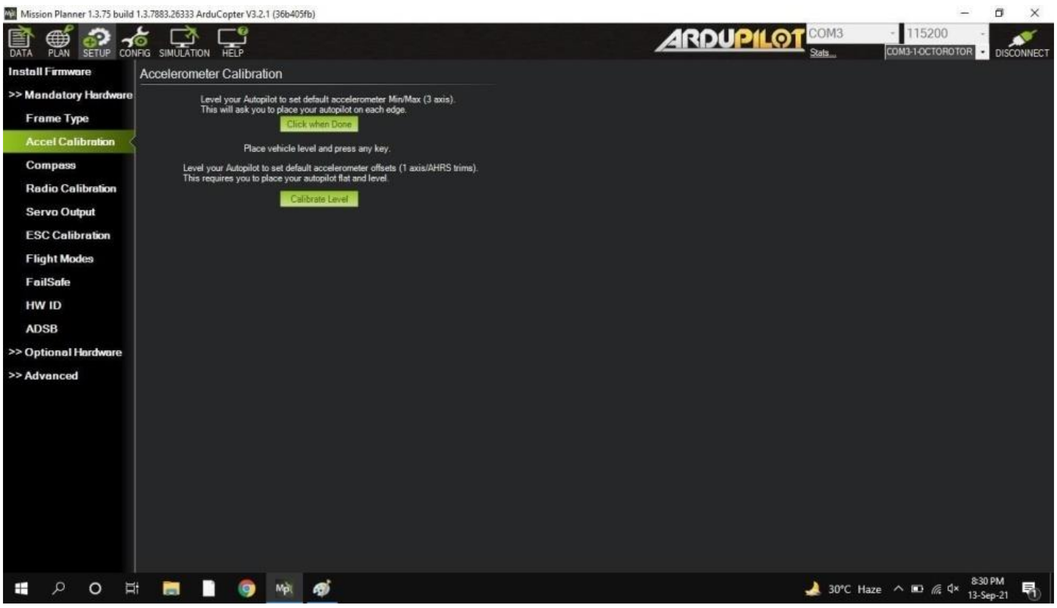

Fig. 26: Accelerometer calibration

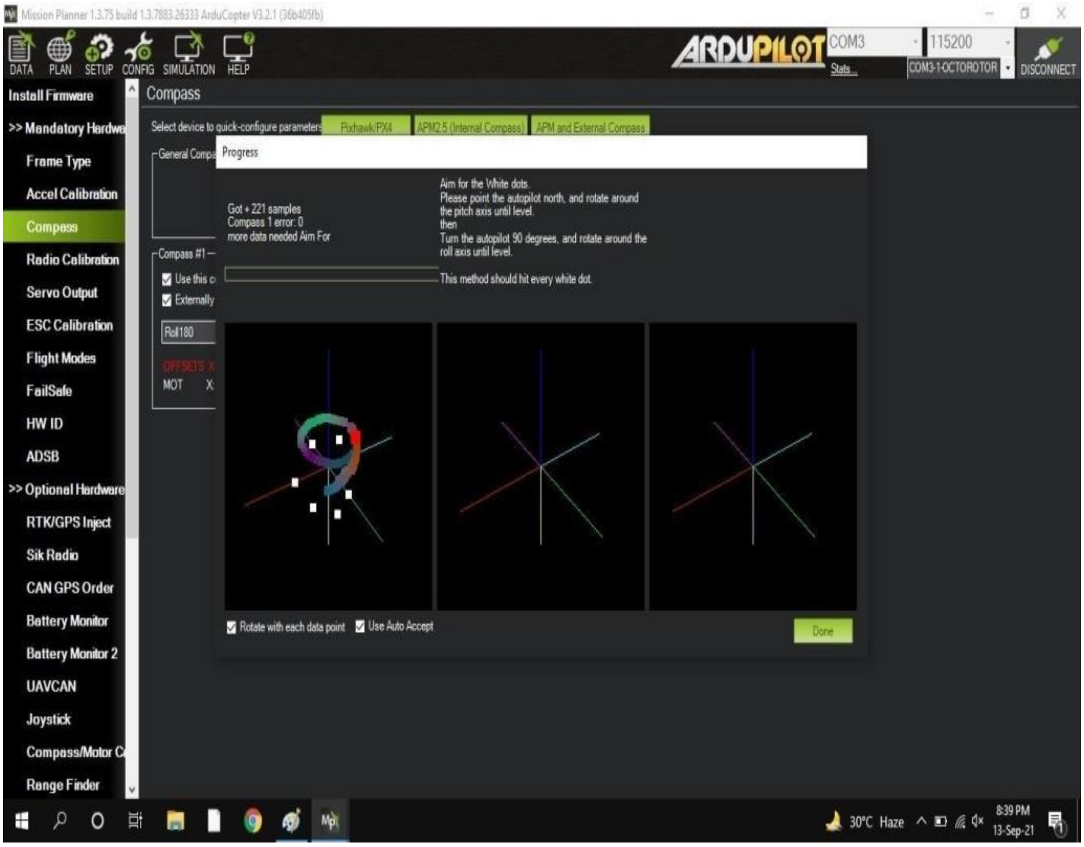

Fig. 27: Compass calibration

Fig. 28: Radio Calibration

C. *Prototype Finalization:*
After the above mentioned steps are properly followed, we will have our prototype ready for evaluation.

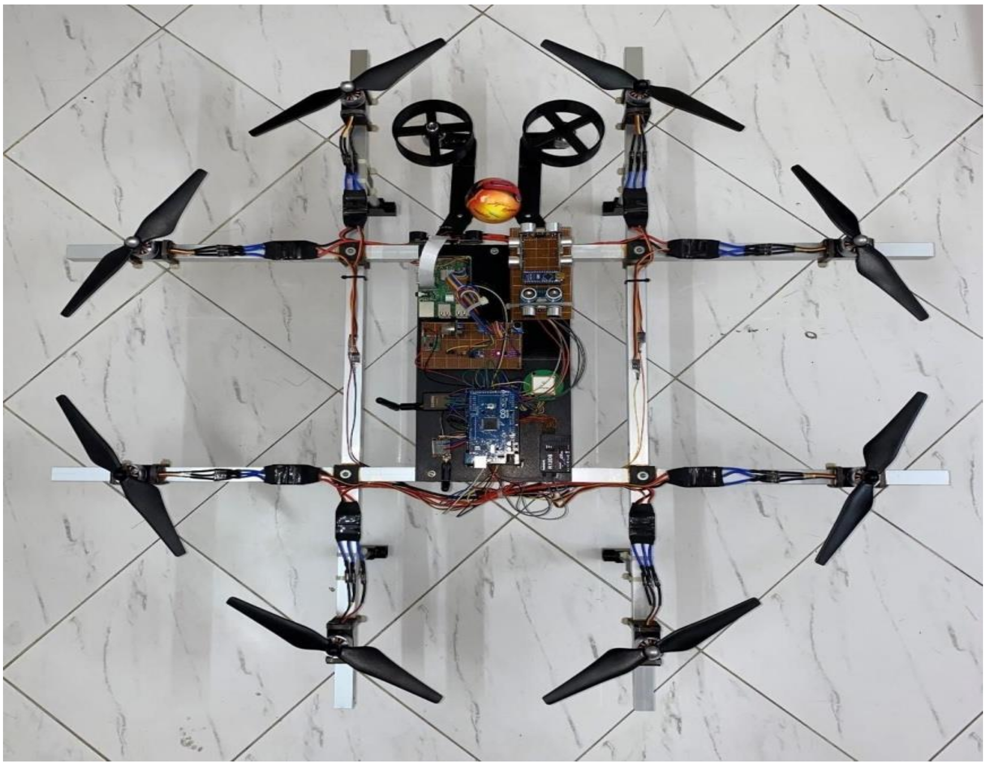

Fig. 29: Final design of the flying unit

Fig. 30: Prototype of the ground station

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V. RESULTS AND DISCUSSIONS

We evaluated our refined design on the basis of specific performance:

A. Stability:

The drone was locked for 15-minute during hover by 13-14 satellites. Horizontal and vertical drift reached a maximum of 0.7 meters and 1 meter respectively. The drone has matched expectations of stability. The desired vs real roll and pitch are presented below.

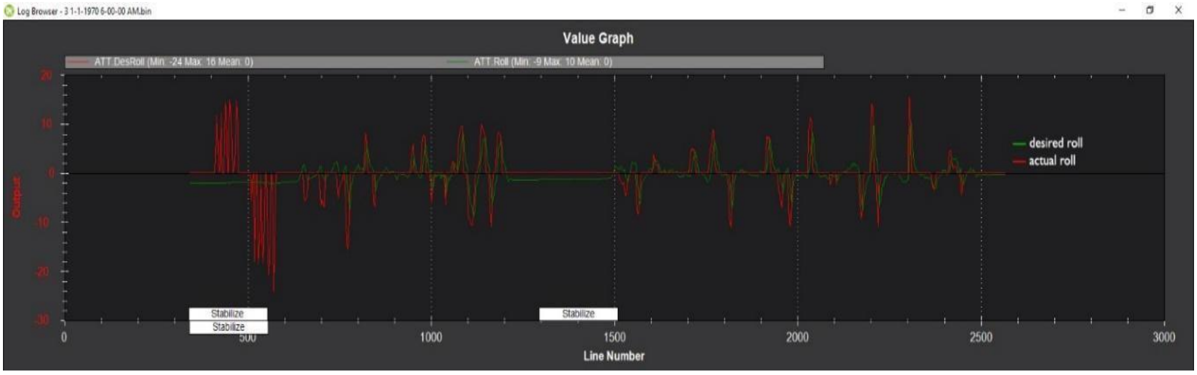

Fig. 31: Desired roll vs actual roll during flight test

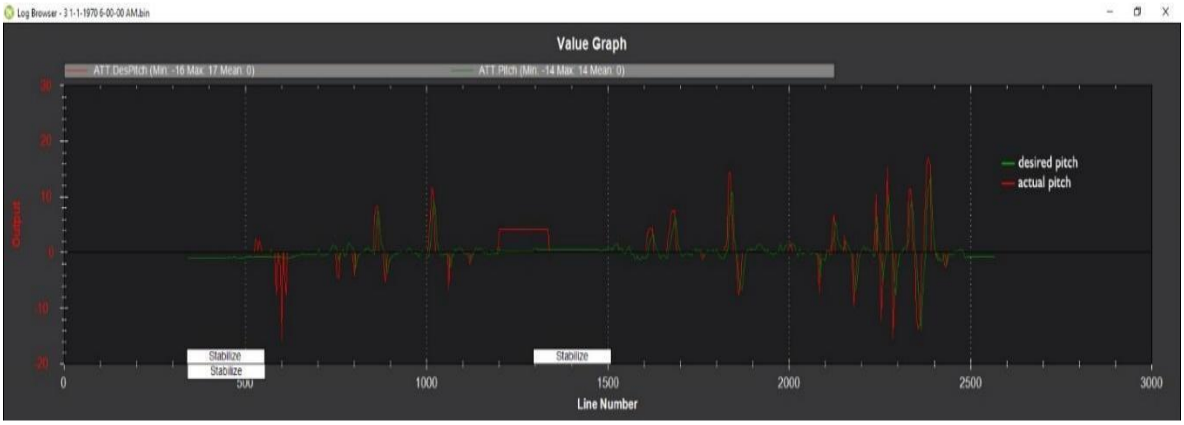

Fig. 32: Desired pitch vs actual roll during flight test

We used a 1500-watt blower to evaluate wind resistance. The drone remained stable up to 44km/h velocity wind as read by the anemometer. This makes the drone Level-6 wind resistant [17].

B. Motor heating

An infrared thermometer was used to measure motor temperature throughout a 34-minutes long flight.

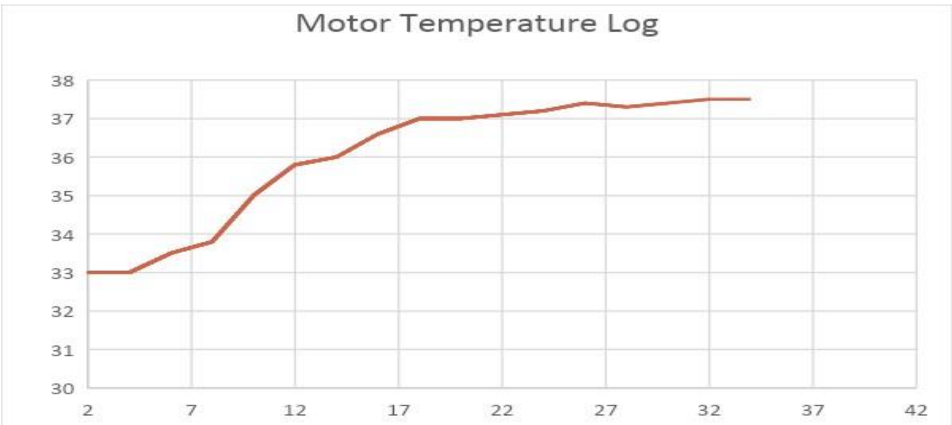

Fig. 33: Motor heat reading

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C. Obstacle Avoiding:

Utilizing cork sheets, we were able to ensure decent functionality of all five sensors, except the top sensor, which was not possible to test with an obstacle atop the drone.

D. Weather Sensing:

We have received accurate metrics across all 16 weather conditions we have tested our station on.

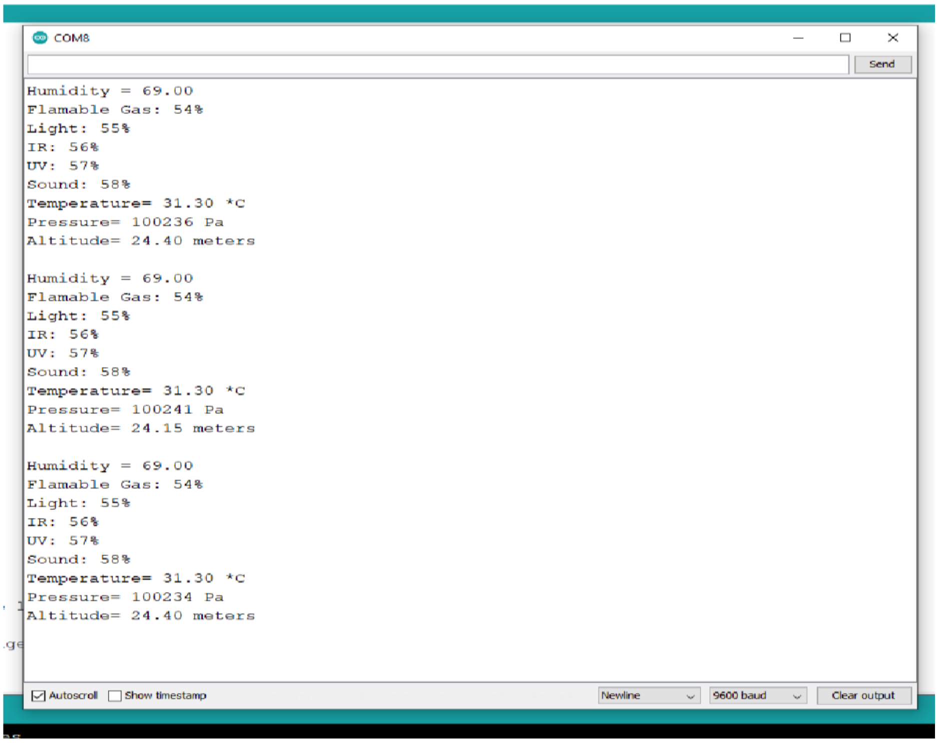

Fig. 34: Reading from weather sensing unit

E. Tethering:

Tethering has been successful through a 12 V 60 A power supply. A 14AWG, 15-feet wire for both positive and negative have been used. The hal-inch water hose was able to achieve a spraying force of 3L/min.

F. Thermal Imaging:

The results have been quite decent with the object being between 5 meters.

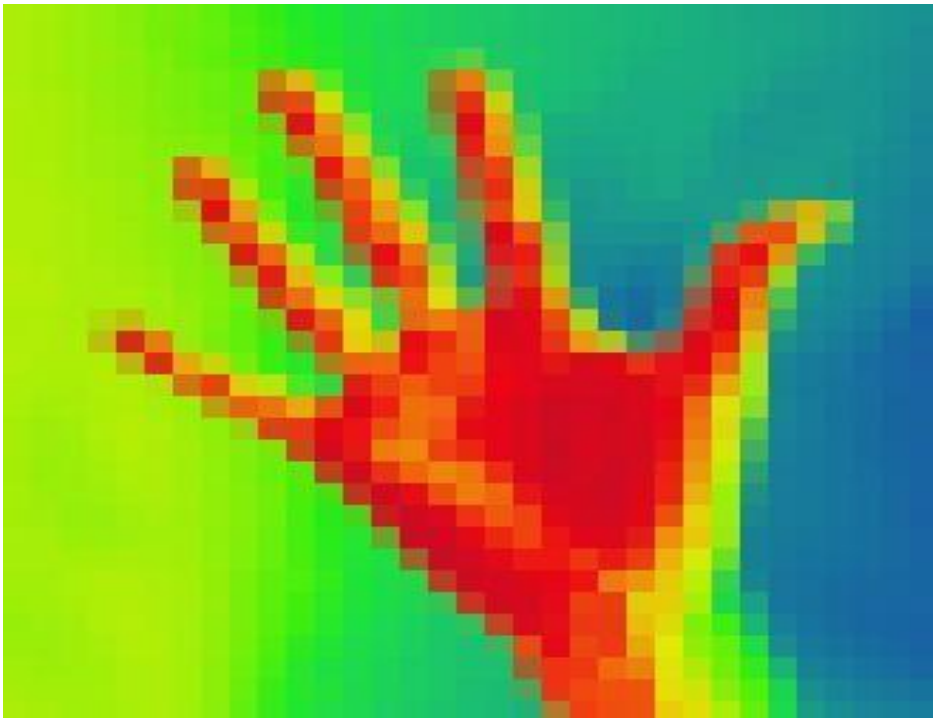

Fig. 35: Thermal image reading from thermal imaging unit

VI. CONCLUSION

In this paper, we designed, built, and evaluated an urban firefighting UAV prototype of a certain configuration. The introduction of tethering and throwing mechanisms is a distinct characteristic of our approach. The performance evaluations have been very fulfilling as the finalized version adopted changes based on experiments.

For further implementation, we are working on an accurately simulated environment to analyze further challenges. We look forward to creating an optimal ball size to validate the throwing mechanism. We are replicating environmental and architectural conditions to ensure the second iteration of the prototype to be radically better.

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