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# Effect of Temperature, Pressure and Humidity on Battery Consumption in Unmanned Aerial Vehicles

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**Abstract**

With the advancing technology, unmanned aerial vehicles (UAVs) have shown significant development. However, the battery technology has struggled to keep pace with these advancements, resulting in UAVs needing to efficiently manage their limited energy resources. Therefore, this study aims to examine factors that contribute to battery energy consumption beyond planned usage scenarios.
A quadcopter equipped with Pixhawk Holybro 4 flight controller was used in the study. It was tested under varying atmospheric conditions of air pressure, humidity, and temperature. The quadcopter performed automated flights, hovering at a height of 5 meters for 3 minutes, while the battery consumption was monitored. The study was conducted under real atmospheric conditions to simulate practical scenarios.
The research revealed that the examined factors significantly impact battery depletion. Specifically, temperature and humidity were observed to have a more pronounced effect on battery consumption compared to air pressure.

## 1. Introduction

The demand for unmanned aerial vehicles (UAVs) is increasing day by day due to the advancing technology, the production of lighter and more durable materials as a result of developments in material science, and the availability of electronic components at lower costs. Consequently, UAVs have begun to be used in many fields. Today, fixed-wing, rotary-wing, and VTOL UAVs, which possess the characteristics of both, are in use. Fixed-wing UAVs can fly long distances due to the lift generated by their wings and their high aerodynamic properties, but they cannot perform vertical take-offs and landings and require a runway for such operations. On the other hand, rotary-wing aircraft have the advantage of being able to perform vertical take-offs and landings and maneuver easily, but they have lower aerodynamic properties and shorter ranges. VTOL aircraft, however, incorporate the advantageous features of both models. Considering these advantages and disadvantages, these aircraft are used in various fields today. Especially, the ability of rotary-wing UAVs to perform vertical take-offs and landings and move rapidly has enabled many tasks to be accomplished quickly. They are increasingly used not only in military, reconnaissance, and photography applications but also in agriculture, healthcare, and cargo transportation.

Since UAVs operate in airspaces close to the ground, they are significantly affected by weather events. The primary weather events impacting UAVs include wind and rain, while factors such as air pressure and temperature also affect flight (Demircioglu & Basturk, 2017; Ercan et al., 2022). These effects cause the limited energy of the batteries that power UAVs to deplete more quickly (Ercan et al., 2024). Although it is not possible to completely mitigate the impact of such environmental conditions, efforts are being made to use the battery more efficiently (Bianchi et al., 2024; Yacef et al., 2017). In particular, studies focused on predicting energy consumption in advance have been conducted. For instance, Prasetia et al. (2019) proposed a black-box modeling approach to predict UAV energy consumption, achieving a prediction accuracy of 98.773%. In the studies conducted by Abeywickrama et al. (2018a) and Abeywickrama et al. (2018b), the factors affecting the UAV's battery were individually examined.

UAVs face various environmental challenges during their development and mission execution. There are many obstacles in our world that endanger UAV flights, and UAVs are also significantly affected by atmospheric weather events. One such effect is temperature, which dramatically impacts the flight characteristics, motor RPM, and battery discharge duration of UAVs. UAVs typically use lithium-ion and lithium-polymer batteries, which are known to perform inefficiently under extreme hot and cold conditions. A study by Li et al. (2021) found that at 60°C, the discharge capacity of these batteries significantly decreases, and the battery can even fail due to high temperatures. At temperatures below -25°C, UAVs were observed to malfunction. Furthermore, a literature review by Vidal et al. (2019) examined various issues related to lithium-based batteries in very low temperatures, including capacity loss, power loss, reduced lifespan, safety hazards, uneven capacity, charging difficulties, thermal management system complexity, battery model and state estimation complexity, and increased costs. These studies demonstrate that low temperatures adversely affect batteries in multiple ways.

Temperature, humidity, and air pressure have significant effects on air density, and consequently, on the thrust generated by an aircraft (Calva & Espino C., n.d.; Leal Iga et al., 2008). An increase in air pressure is known to increase air density. Higher air density allows propellers to generate more thrust at the same RPM, thereby reducing battery consumption. On the other hand, an increase in humidity decreases air density. In lower air density, at the same RPM, an UAV will generate lower thrust. As air temperature increases, the kinetic energy of air molecules increases, causing them to move more vigorously. This results in a less dense air and lower thrust generated by the UAV's propellers.

This study investigates the combined effects of humidity, temperature, and pressure on battery consumption under real-world weather conditions. Evaluating these parameters simultaneously in real-world conditions is crucial for making more accurate calculations, and this aspect is where the uniqueness of the study lies. While previous studies in the literature have focused on a single parameter, this study considers three different parameters and performs a correlation analysis between them.

## 2. Methodology

In this study, a Pixhawk Holybro 4 flight controller was used on a drone where battery consumption data was obtained. Flight tests were conducted at various altitudes above sea level. To ensure consistent conditions for measuring battery consumption, all tests were conducted in calm weather conditions, excluding factors like wind that could affect battery usage.

Flight tests were conducted at different air pressures, humidity levels, and temperatures, and battery consumption data was directly obtained from the flight controller's log records. The aircraft maintained a steady hover at 5 meters altitude for 3 minutes during automatic flight.

The battery consumption rates of interest in this study are related to the thrust generated by the UAV. As the thrust ratio increases, the battery consumption also increases. Thrust production is influenced by parameters such as temperature, humidity, and air pressure. Therefore, to examine battery consumption, these parameters need to be investigated. Equation (1) shows the formula for the thrust generated by the UAV propeller. Here, $T$(Newton) represents the thrust, $C_T$ denotes the thrust coefficient, $\rho$(kg/m³) stands for air density, $n$ represents the propeller rotational speed, and $D$ (m) signifies the propeller diameter.

$$T = C_T.\rho.n^2.D^4 \tag{1}$$

Air pressure and ambient temperature affect air density. In Equation (2), air density $\rho$ is directly proportional to air pressure $P$(Pascal), which is used to express pressure. As air pressure increases, the number of molecules per unit area increases, thus increasing density. Similarly, as shown for temperature $T$(Kelvin), as temperature increases, the number of molecules per unit area decreases, resulting in decreased density.

$$\rho = \frac{P}{R.T} \tag{2}$$

Another factor that affects air density is humidity. As the amount of water vapor in the air increases, air density decreases. Equation (3) illustrates the effect of humid air on density. $P_d$(Pa) represents the pressure of dry air, and $P_v$(Pa) represents the pressure of water vapor. When these values are calculated, the density of dry air is higher compared to humid air.

$$\rho = \frac{P_d}{R_d T} + \frac{P_v}{R_v T} \tag{3}$$

It is known that air density affects the thrust generated by UAVs. However, the specific effects of temperature, humidity, and air pressure—which influence air density—on UAV thrust and their subsequent impact on battery consumption are not well understood. Therefore, this study aims to investigate how each of these parameters individually affects battery consumption through their influence on thrust.

### 2.1. Components of UAV and Other Tools

In this study, a quadcopter UAV with four rotors was utilized, as depicted in Figure 1. The quadrotor used in this study features an X-configuration.

**Figure 1.** The quadcopter used in the study. (Ercan et al., 2024)

The quadcopter used in this study weighs 1760 grams. It features a F450 type frame with a diameter of 45 cm, equipped with four brushless motors, four 30A ESCs (Electronic Speed Controllers), a flight controller, telemetry system, and a remote-control receiver. The components of the UAV are detailed in Table 1.

**Table 1.** Components of UAV (10p)

| Components | UAV |
|---|---|
| Frame | F450 Frame |
| Flight Controller | Holybro Pixhawk 4 |
| Battery | 6200 mAh Li-Po battery |
| Propeller | 4 1045 propellers |
| Electronic Speed Controller | 4 Emax 30A ESCs |
| Motors | 4 brushless Motors Emax XA2212 980 kv |

The UAV used in the study is equipped with a PID (Proportional-Integral-Derivative) algorithm for the flight controller, GPS (Global Positioning System), and automatic flight systems, enabling it to hover in place during flight.

A BMP180 sensor was used to measure pressure and temperature. An Arduino Uno microcontroller was utilized to read data from this sensor, as shown in Figure 2.

The Pixhawk Holybro 4 flight controller installed on the aircraft provides log data related to the battery. The remaining battery capacities were obtained using these data. The analyses and visualizations were conducted directly in the MATLAB environment, and the graphs were generated within the same application.

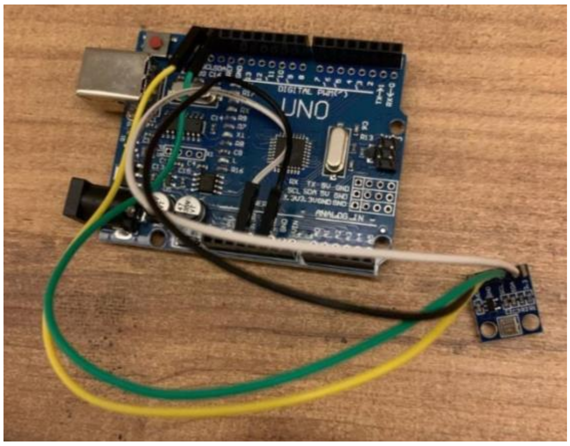


**Figure 2.** The BMP180 sensor for obtaining temperature, humidity, and atmospheric pressure data and the Arduino Uno microcontroller

## 3. Experimental Study

Flight tests were conducted under real atmospheric conditions with different temperatures, humidity levels, and air pressures. The battery consumption and atmospheric parameters for the quadcopter's first flight are shown in Figures 3A and 3B. At the end of 300 seconds, the quadcopter's battery level dropped to 44%, completing the flight. The battery consumption and atmospheric parameters for the quadcopter's second flight are shown in Figures 3C and 3D. At the end of 300 seconds, the quadcopter's battery level dropped to 48%, completing the flight.

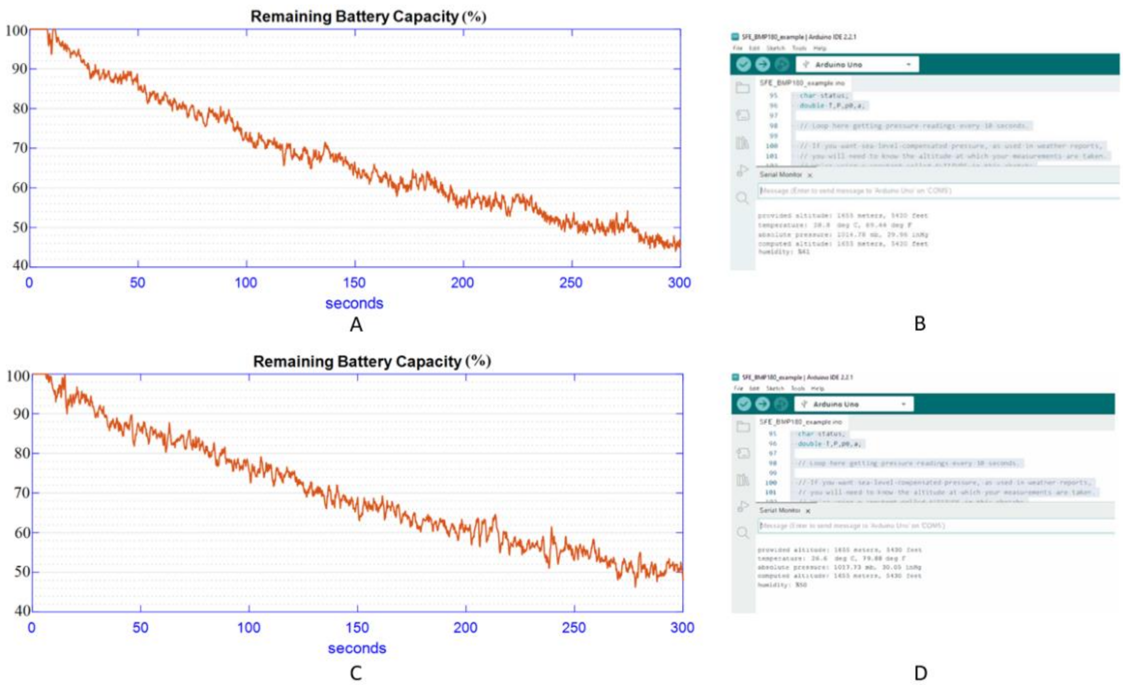



**Figure 3.** (A) Quadcopter's Battery Consumption During Flight At 20.8°C Temperature, 1014.78 Millibar Pressure, And 41% Humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 26.6°C temperature, 1017.73 millibar pressure, and 50% humidity, (D) atmospheric parameters of (C).

The battery consumption and atmospheric parameters for the quadcopter's third flight are shown in Figures 4A and 4B. At the end of 300 seconds, the quadcopter's battery level dropped to 58%, completing the flight. The battery consumption and atmospheric parameters for the quadcopter's fourth flight are shown in Figure 4C and 4D. At the end of 300 seconds, the quadcopter's battery level dropped to 55%, completing the flight.

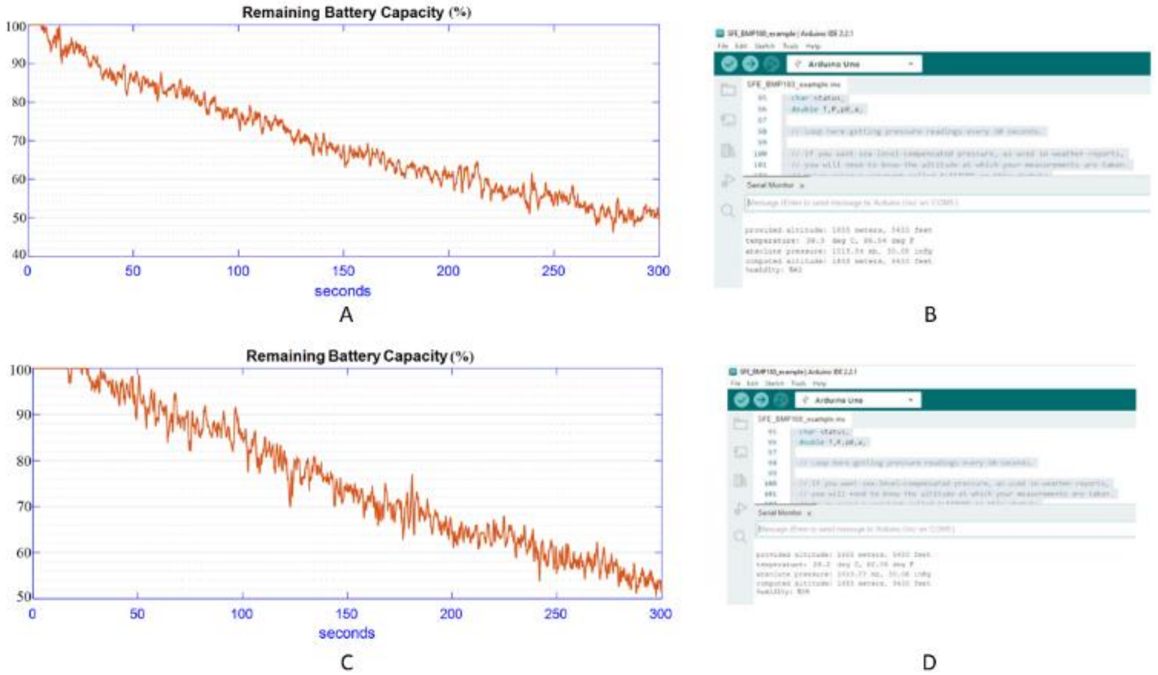



**Figure 4.** (A) Quadcopter's Battery Consumption During Flight At 30.3°C Temperature, 1018.84 Millibar Pressure, And 42% Humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 28.2°C temperature, 1018.77 millibar pressure, and 39% humidity, (D) atmospheric parameters of (C).

The battery consumption and atmospheric parameters for the quadcopter's fifth flight are shown in Figures 5A and 5B. At the end of 300 seconds, the quadcopter's battery level dropped to 40%, completing the flight. The battery consumption and atmospheric parameters for the quadcopter's sixth flight are shown in Figures 5C and 5D. At the end of 300 seconds, the quadcopter's battery level dropped to 56%, completing the flight.

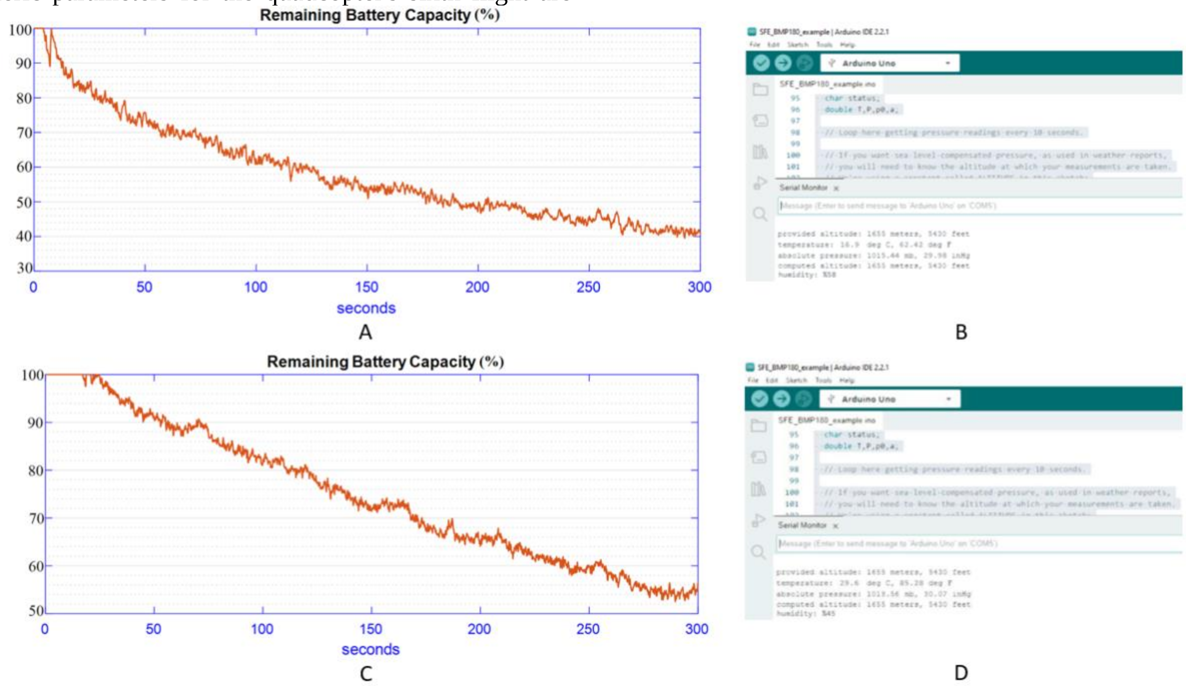



**Figure 5.** (A) Quadcopter's battery consumption during flight at 16.9°C temperature, 1015.44 millibar pressure, and 58% humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 29.6°C temperature, 1018.66 millibar pressure, and 45% humidity, (D) atmospheric parameters of (C).

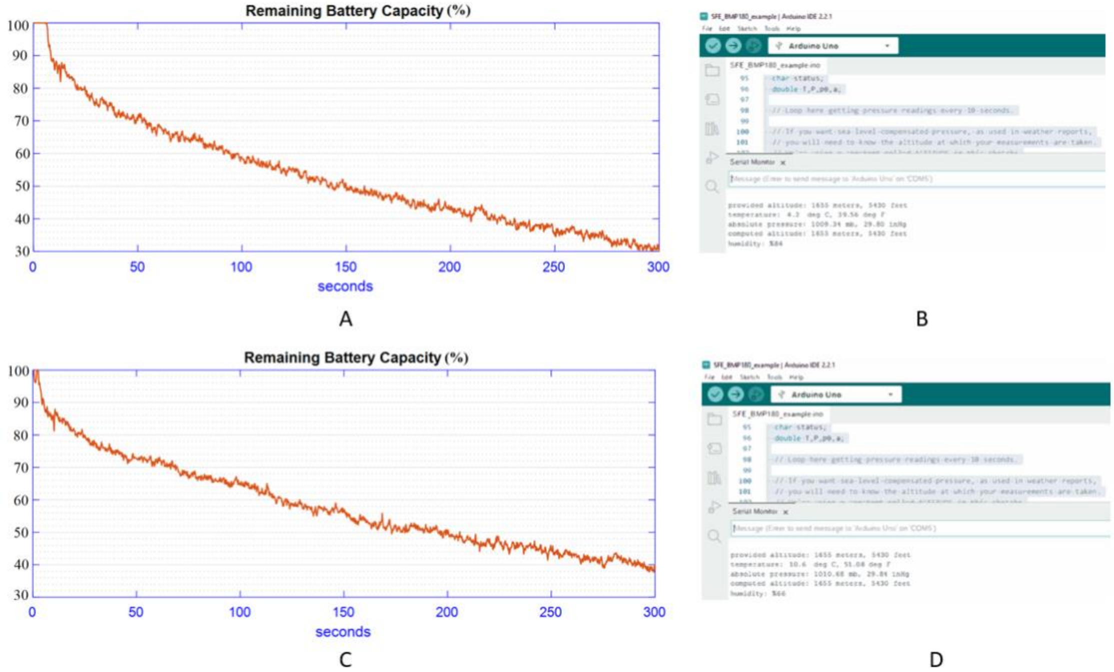



**Figure 6.** (A) Quadcopter's Battery Consumption During Flight At 4.2°C Temperature, 1009.34 Millibar Pressure, And 84% Humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 10.6°C temperature, 1010.68 millibar pressure, and 66% humidity, (D) atmospheric parameters of (C).

The battery consumption and atmospheric parameters for the quadcopter's ninth flight are shown in Figures 7A and 7B. At the end of 300 seconds, the quadcopter's battery level dropped to 46%, completing the flight. The battery consumption and atmospheric parameters for the quadcopter's tenth flight are shown in Figures 7C and 7D. At the end of 300 seconds, the quadcopter's battery level dropped to 50%, completing the flight.

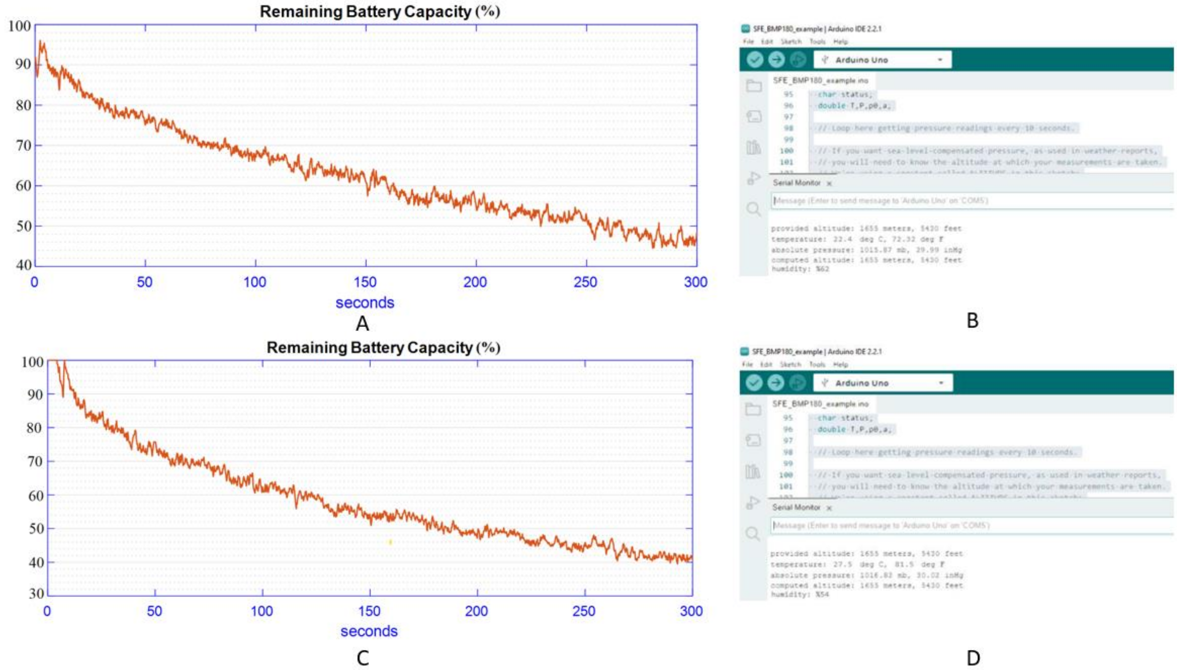



**Figure 7.** (A) Quadcopter's Battery Consumption During Flight At 22.4°C Temperature, 1015.87 Millibar Pressure, And 62% Humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 27.5°C temperature, 1016.82 millibar pressure, and 54% humidity, (D) atmospheric parameters of (C).

The battery consumption and atmospheric parameters for the quadcopter's eleventh flight are shown in Figures 8A and 8B. At the end of 300 seconds, the quadcopter's battery level dropped to 35%, completing the flight. The battery consumption and atmospheric parameters for the quadcopter's twelfth flight are shown in Figures 8C and 8D. At the end of 300 seconds, the quadcopter's battery level dropped to 42%, completing the flight.

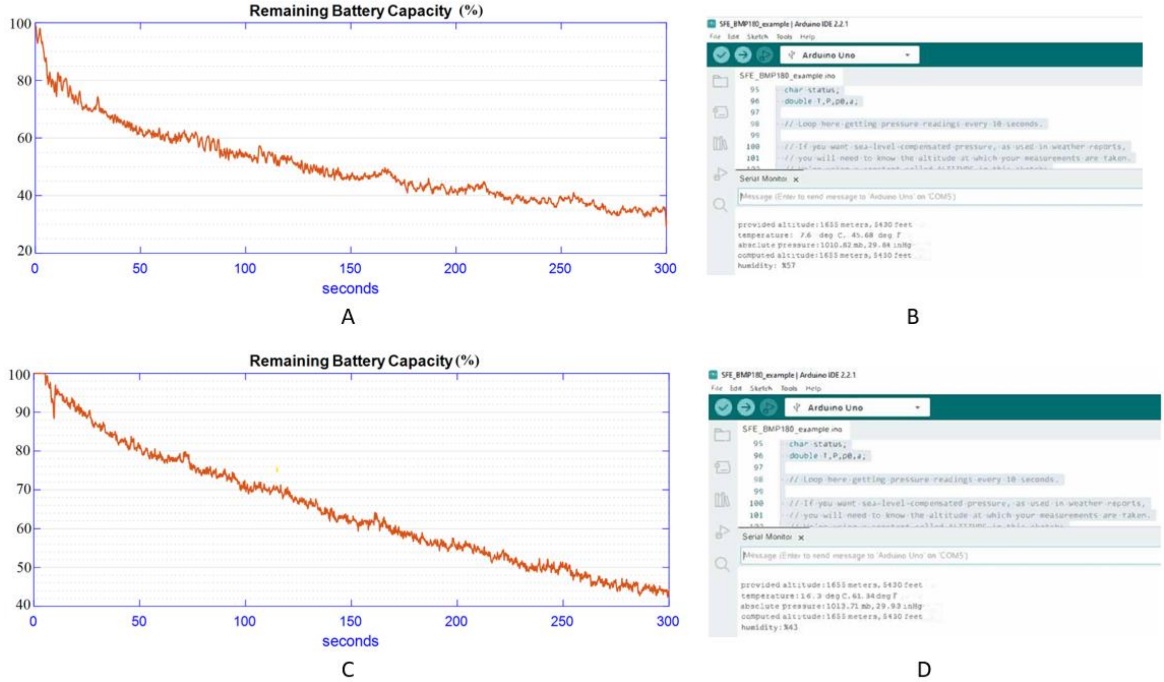



**Figure 8.** (A) Quadcopter's Battery Consumption During Flight At 7.6°C Temperature, 1010.82 Millibar Pressure, And 57% Humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 16.3°C temperature, 1013.71 millibar pressure, and 43% humidity, (D) atmospheric parameters of (C).

The battery consumption and atmospheric parameters for the quadcopter's thirteenth flight are shown in Figure 9B. At the end of 300 seconds, the quadcopter's battery level dropped to 43%, completing the flight. The battery consumption and atmospheric parameters for the quadcopter's fourteenth flight are shown in Figures 9C and 9D. At the end of 300 seconds, the quadcopter's battery level dropped to 52%, completing the flight.

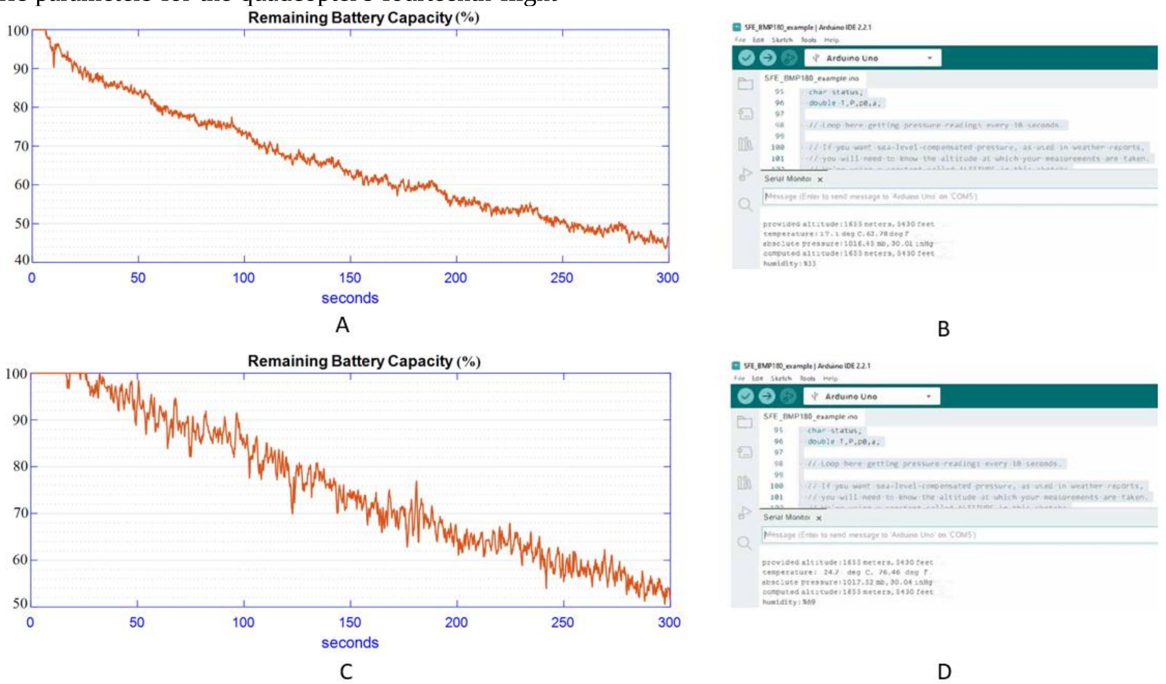



**Figure 9.** (A) Quadcopter's Battery Consumption During Flight At 17.1°C Temperature, 1016.45 Millibar Pressure, And 33% Humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 24.7°C temperature, 1017.52 millibar pressure, and 69% humidity, (D) atmospheric parameters of (C).

The battery consumption and atmospheric parameters for the quadcopter's fifteenth flight are shown in Figures 10A and 10B. At the end of 300 seconds, the quadcopter's battery level dropped to 49%, completing the flight. The battery consumption and atmospheric parameters for the quadcopter's sixteenth flight are shown in Figure 15. At the end of 300 seconds, the quadcopter's battery level dropped to 36%, completing the flight.

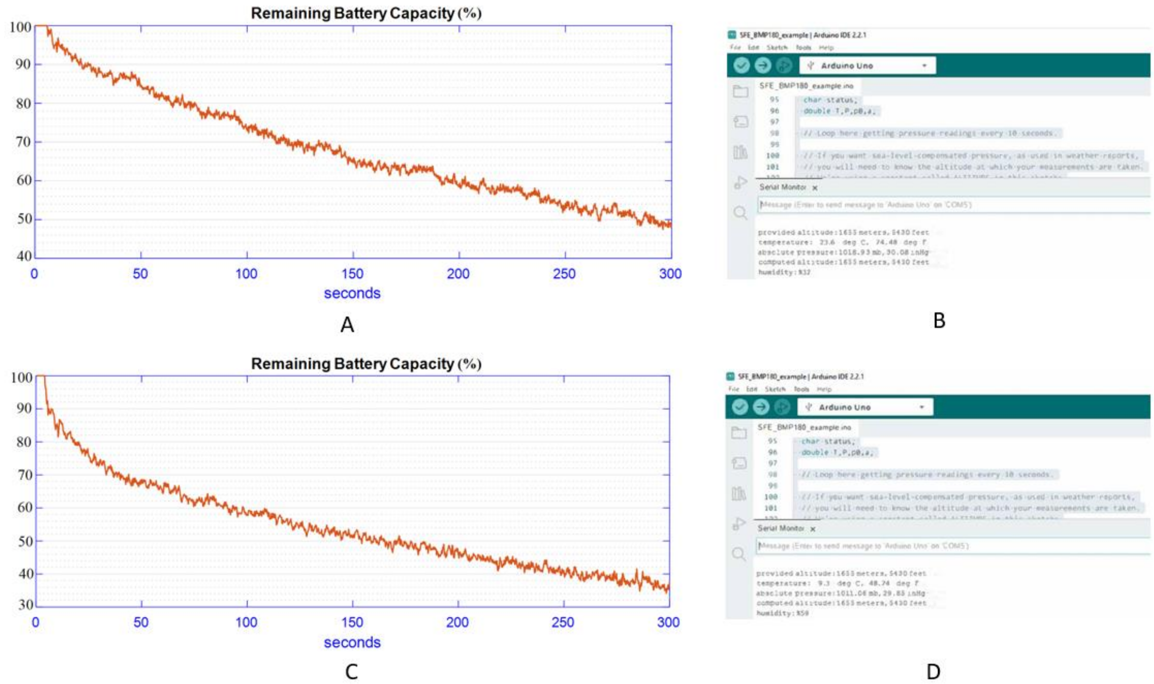
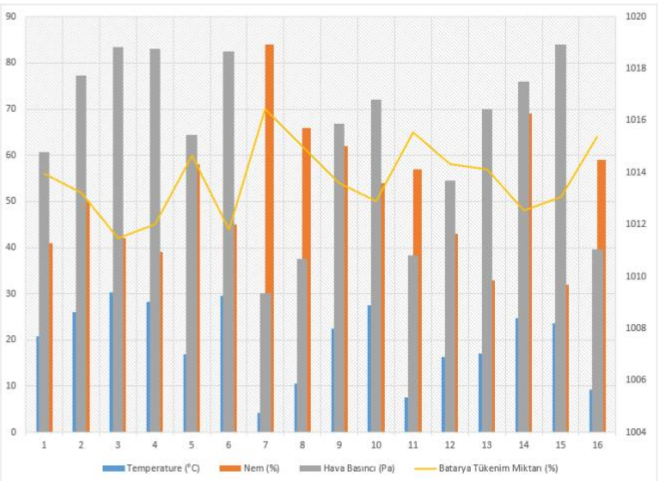



**Figure 10.** (A) Quadcopter's Battery Consumption During Flight At 23.6°C Temperature, 1018.93 Millibar Pressure, And 32% Humidity, (B) atmospheric parameters of (A), (C) Quadcopter's battery consumption during flight at 9.3°C temperature, 1011.06 millibar pressure, and 59% humidity, (D) atmospheric parameters of (C).

Figure 11 shows all battery consumption amounts.




***Units for temperature, humidity, and battery depletion are presented on the left axis, while units for air pressure are displayed on the right axis.**

**Figure 11.** All battery consumption amounts according to temperature, humidity, and air pressure.

## 4. Conclusion

The known effects of air pressure, humidity, and temperature on air density directly impact motor thrust, thereby affecting battery consumption. In this study, conducted to quantify these effects under real conditions, battery consumption varied by 42% to 64% across different weather conditions. Particularly, it was observed that battery consumption significantly increased in conditions of low temperature, low air pressure, and high humidity. Upon examining Figure 11, it was observed that humidity levels had a significantly greater impact on battery consumption. Additionally, when separate correlation analyses were conducted for these three data sets, the correlation coefficients were determined as follows:

-Temperature and Battery Depletion Rate: $r_{SB} \approx -0.876$ (strong negative correlation).
-Air Pressure and Battery Depletion Rate: $r_{HB} \approx -0.482$ (weak negative correlation).
-Temperature and Air Pressure: $r_{SH} \approx -0.204$ (weak negative correlation).

There is a strong negative relationship between temperature and battery depletion rate, indicating that as the temperature increases, the rate of battery depletion decreases. There is a weak negative relationship between air pressure and battery depletion rate, suggesting that air pressure does not significantly affect the battery's depletion rate. A weak negative relationship is also observed between temperature and air pressure, indicating that these two variables do not significantly influence each other.

The 22% variance in battery energy represents a substantial amount for UAV missions previously planned, potentially leading to mission failure.

Given the increasing integration of UAVs into everyday life in the coming years, it is crucial to consider temperature, humidity, and air pressure when planning battery usage. This study serves as a valuable resource for future research on how these environmental factors impact UAV operations.

## Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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