An Investigation of the Relationship Between a Drone's Payload Mass and its Flight Stability

Afton Ryba

ENGAGE Program - Citrus College

Faculty Mentor: Lucia Riderer, Ed.D.

Abstract

Within almost every commercial application, it is important that drones be designed with some consideration for wind resistance so that energy and maintenance costs do not diminish the efficacy of individual drones. This research focuses on the impact of payload mass on the stability of a particular drone. A 2.5-pound radio-controlled quadcopter drone with flight control and self-stabilizing systems that are typical of automated drones was assembled and made to hover while carrying a variety of weights. Orientation data from each flight was graphed, and the sum of all pitch and roll values throughout each flight created “instability scores” which are unique to this study and are measured in degrees. Instability scores were categorized based on the wind and payload mass during their associated flights.

The data collected in this study showed the absence of a measurable relationship between payload mass and drone instability. This suggests a procedural error or limitation. In many trials there was a rapid switching from positive to negative values in either or both pitch and roll columns. Multiple factors could have contributed to these results, including a narrow range of wind speed and a sample too low to meaningfully detect rapid wobbling motion. A thorough future investigation of the relationship between a drone’s payload mass and instability could lead to tangible results.

There is currently a vast variety of uses for aerial drones, most of which have only been around for the last few years. As industries surrounding these applications grow, their drones must become more efficient for their unique purposes. In the process of designing more purpose-built drones, features such as intended payload mass, optimal flight altitude, total mass, and overall shape will need to be adjusted so that drones can perform their work at the highest possible quality for their associated operational costs. The most pertinent application to this research is parcel delivery. Drones built for this purpose must be extremely reliable and energy efficient, while carrying different sized parcels through a wide range of environmental conditions. One of the most important hindrances that these designs need to consider is wind. The goal of this investigation is to identify a relationship between stability and payload mass across a variety of wind speeds for an industry-representative drone.

Literature Review

Because aerial drones are constantly being put to new purposes, improvements to their systems are highly valued. Already, they have proven more effective than conventional aerial data-collection methods within industry, agriculture, emergency management, parcel delivery, and entertainment (Dragomir Bălănică et al., 2021). Although drone-based package delivery is not yet used by major delivery companies in the United States, many expect it to soon become common practice because of one important legal change (Palazetti et al., 2021, p. 109): The Federal Aviation Administration has recently allowed unmanned aerial vehicles (i.e. drones) to carry out “routine operations” over people as well as at night. This new rule is a large step towards the integration of unmanned vehicles into the National Airspace System (FAA, 2021). This, along with other recent changes, motivates much of the research done in drone technology; drones optimized by research are effective for the companies using them.

Despite their strengths, drones will always be susceptible to strong winds. Even if it does not cause them to capsize or fail, wind can significantly decrease the energy efficiency of drones (Simma et al., 2021). To recreational drone owners, this effect might not matter, but to businesses interested in using drones on a large scale, both energy and maintenance costs are significant. The most extreme winds are at high altitudes, but even wind close to the Earth's surface can move quickly if the latitude, time of year, and/or climate make it so (Hedin et al., 1996, p. 1443). Drones must be capable of operating at all times of the year and at a wide range of latitudes to be effective for large companies that already have functional delivery systems.

Existing drones are equipped with stability controlling devices, the higher-end versions of which are extremely effective at maintaining level flights. These devices - usually algorithms within flight control software - are known as Proportional Integral Derivative (PID) controllers. They operate by calculating motor outputs that are proportional to rotational errors accumulated over an interval of flight time (Tang et al., 2001, p. 757). The implementation of PID control would improve the flight-time stability of any drone, but it is not deemed necessary for all drone uses (Sree Ezhil et al., 2022, p. 1314). Still, PIDs can be used for any aspect of a flight that a user might want to stabilize. PIDs are well developed and highly effective, but they cannot always anticipate the speed and direction of the wind (Stamate et al., 2023, p. 6). Even the most effective PID system cannot completely stabilize a drone experiencing a sudden change in wind direction, so there is always some error to measure. Such errors are significant to commercial drone applications because of their effect on energy efficiency (Simma et al., 2021).

Many aspects of the drone-delivery scenario have been thoroughly researched (Dragomir Bălănică et al., 2021), but the question of total payload mass' effect on stability has yet to be tested physically. Hypothetical logistics are well understood, and the eventual widespread implementation is likely to be one that uses both drones and trucks in tandem (Liu et al., 2024, p. 11). With this or with any other drone-delivery system, the mass of a drone's payload will change frequently. Doing so inadvertently moves the drone's center of mass, affecting the PID. With an altered payload, the same motor output affects the rotation of the drone differently since the torque generated by a requested output is changed. This creates more work for the PID, especially if the mass is altered mid-flight, as it would be if a drone dropped off a package and immediately flew away. PID algorithms can adjust to such changes, but this does not always go smoothly (Pounds et al., 2012, p. 130). As a result, the most stable drones are those that have effective systems such as PIDs, propellers, and accelerometers, for a drone of their specific mass.

It follows that when the total mass of a drone-payload system changes, the design of that system should change too, so that it can be optimally wind-resistant and cost efficient. This study investigates the relationship between the mass of a student assembled drone's payload and the drone stability during flight.

Methodology

A Hawk's Work F450 quadrotor drone was assembled, paired to a radio remote, and calibrated. An Arduino Uno, a 3-axis accelerometer, and a bluetooth antenna were all fixed to the underside of the drone using a combination of custom 3D printed mounts and zip ties. There was also an additional Arduino Uno and bluetooth antenna plugged into a laptop for receiving data as it was collected. Prior to each flight, the drone, the drone-mounted Arduino circuit, the drone's radio remote, and the receiver Arduino were all unpowered. This is also when the appropriate weight was attached via a metal hook to a loop in the Arduino Uno mount. The attachment point for the weights was approximately 8 cm below the underside of the drone, to simulate a hanging package. Weights ranged from 0 to 500 g and most flights had either 0g, 200g, or 500g, which was denoted in each flight's file name. Figure 1 shows a picture of the drone assembled without including additional collection and transmission hardware.

Fig 1. The drone used for data collection without additional hardware

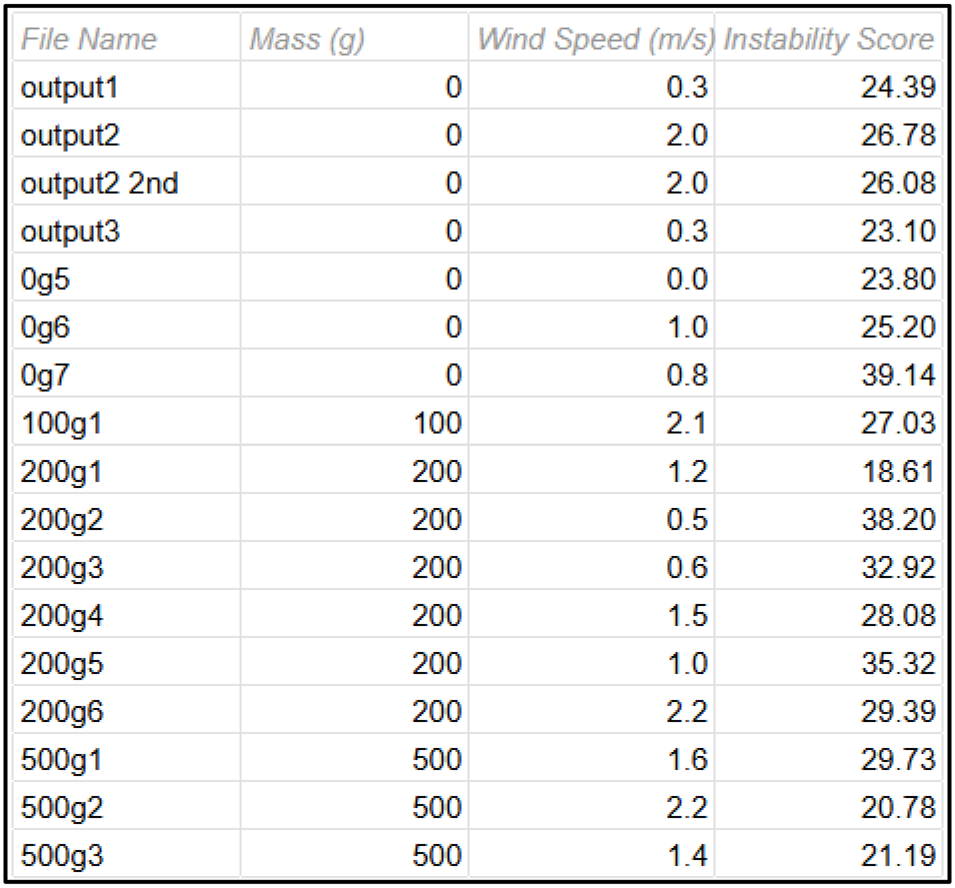
To conduct a data collection flight, all components were powered on and a python script to control data transmission between the two Arduinos was started. The drone was disarmed by pressing a button on its chassis and then sending a disarm input from the remote. After takeoff the drone was piloted to a controlled area slightly over a meter above the ground. Once positioned, a flip was switched on the remote to enable “loiter mode” and send a command to the airborne Arduino to begin data collection. In loiter mode, the drone’s PID and GPS systems worked to keep it stationary while the Arduino and accelerometer were sending pitch, yaw, and roll measurements once per second. Once the drone had loitered for at least 60 seconds, the “loiter mode,” was turned off, the drone was landed, and the components were unpowered in preparation for the next flight.

After each flight, that flight’s data was run through a second python script that saved it as a .csv file so that it could be analyzed later in google sheets. In google sheets, yaw data was discarded while pitch and roll were normalized by subtracting their averages. For drones, stability is typically expressed with plots of horizontal deviation over time. This defect is called attitude and it is the measure of the angle between a horizontal plane, and a plane that contains all drone’s rotors. Considering that pitch and roll data was measured in degrees, the average of the summed absolute values of pitch and roll became the instability score, leaving just three values associated with each flight: instability score, payload mass, and wind speed. Using wind speed to organize the data points into two similarly sized groups, instability was plotted against payload mass. Also, a plot was created of wind speed and instability.

Results

Table 1 below provides an overview of all the flight data collected: payload mass, wind speed and instability score. The instability score was calculated as shown in the previous section.

Table 1. Collection of Flight Data: Payload Mass, Wind Speed and Drone Instability Score



File Name	Mass (g)	Wind Speed (m/s)	Instability Score
output1	0	0.3	24.39
output2	0	2.0	26.78
output2 2nd	0	2.0	26.08
output3	0	0.3	23.10
0g5	0	0.0	23.80
0g6	0	1.0	25.20
0g7	0	0.8	39.14
100g1	100	2.1	27.03
200g1	200	1.2	18.61
200g2	200	0.5	38.20
200g3	200	0.6	32.92
200g4	200	1.5	28.08
200g5	200	1.0	35.32
200g6	200	2.2	29.39
500g1	500	1.6	29.73
500g2	500	2.2	20.78
500g3	500	1.4	21.19

Figures 2a and 2b show graphs representing the data generated for every flight conducted. Pitch, Roll, and a sum of the two are represented as degrees changing over time. The farther away from zero the total deviation value tends to be, the greater the instability score.

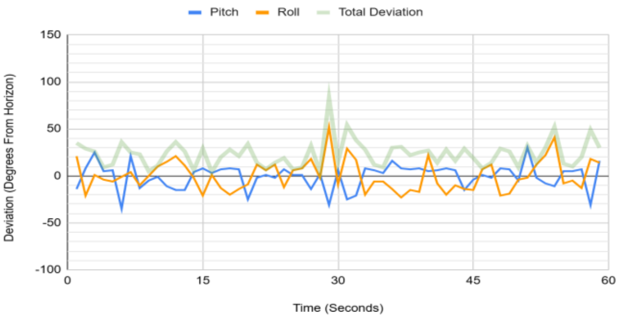


Fig 2a. Flight graph from "output3" (example) showing deviation over the course of the flight

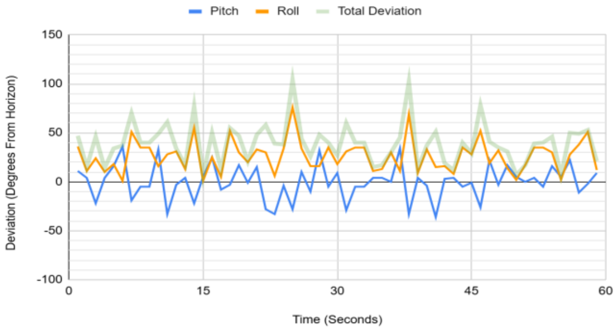


Fig 2b. Flight graph from "0g7" (example)

Figure 3 below organizes the instability scores of every flight conducted by their masses. It indicates a lack of a significant relationship between instability and payload mass.

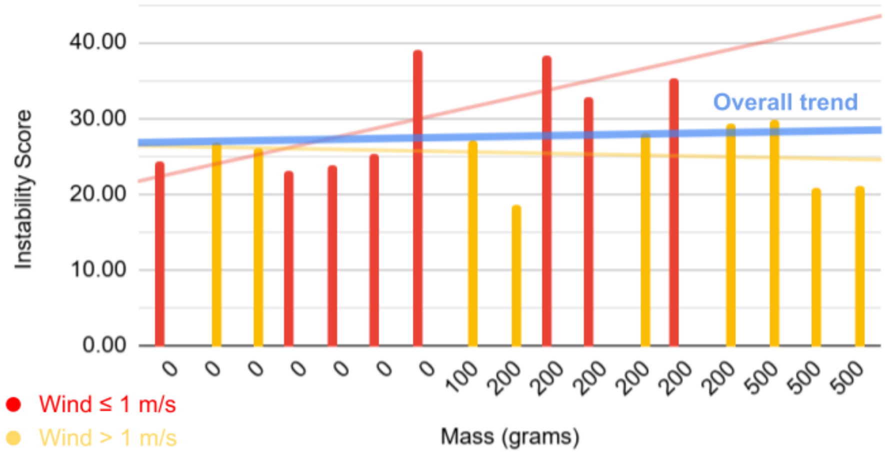


Fig 3. Instability score versus payload mass. All scores are ordered by mass and colored based on wind speed groups. Low wind speed shows a positive trend while trends for all trials taken together and for high wind speed are zero

Figure 4 compares two measures, instability score and wind speed. These are expected to be correlated but the data collected indicates no significant relationship.

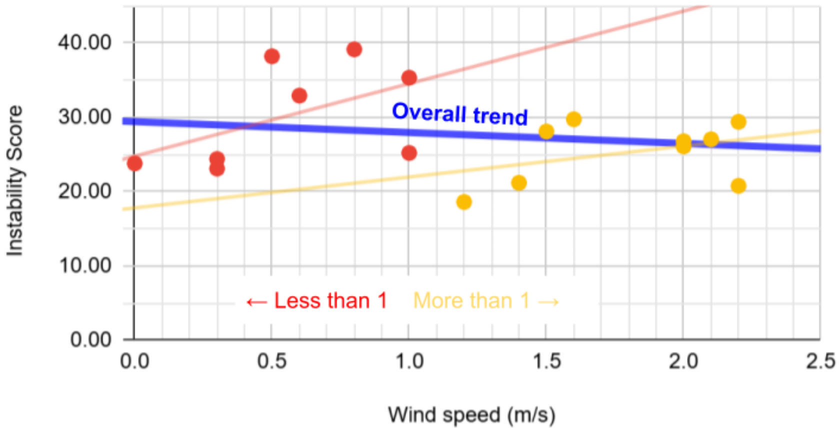


Fig 4. Instability score versus wind speed. Points are grouped as indicated in Figure 3 with positive trendlines for each group and a zero trendline overall

The data collected in this study indicates a lack of a significant relationship between the drone's instability and payload mass. The noise in Figures 2a and 2b is representative of all the data that contributed to the relationships illustrated in Figures 3 and 4, which could have contributed to a decrease in the accuracy of the data outlined in those figures.

Discussion

Contrary to what was expected before collecting the data, there was no significant relationship shown between a drone's payload mass and the drone stability in flight. Additionally, an analysis of the data collected indicates the absence of a significant relationship between wind speed and drone instability, suggesting that the study has limitations. There are three possible factors to account for this: there is truly no trend, the data was not collected from a broad enough range of wind speeds, or the data was not collected at a high enough sample rate.

Two non-flying trials were conducted for the sole purpose of verifying that the accelerometer-Arduino system was functional and reasonably precise. In one of those, data was collected as the drone rested on flat ground for one minute while in the other, the same was collected but with an extra 30 seconds at the end. During that time, the drone was picked up, set down, and then left alone on a 9-degree inclined surface. Fully processed data from both are shown in Figure 5 below.

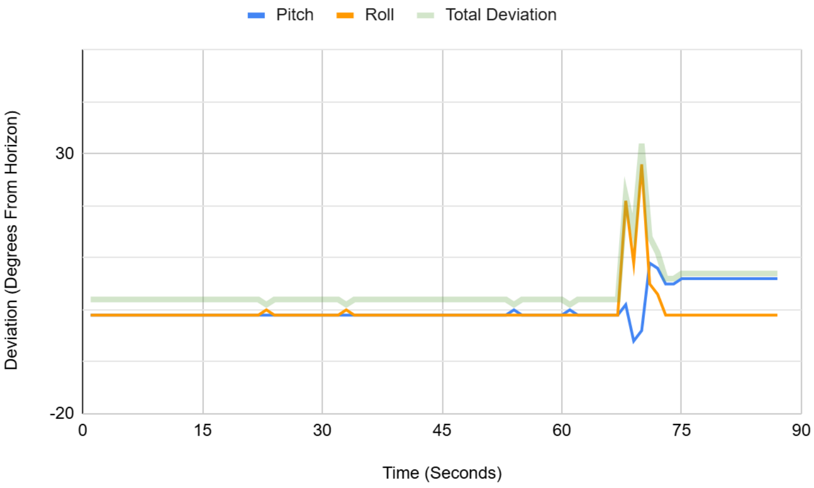


Fig 5. Non-flying test data in which the drone was picked up and moved to an inclined surface. Shows very little noise besides the interval when it was being moved

The data provided in Figure 5 and Figure 3 suggest that the payload mass does not predict instability in wind conditions like those seen in this study.

Assuming the noisy accelerometer data creates an accurate measure of stability, another potential fault could be the variety of wind speeds. The trials featured wind speeds that only ranged from zero to two meters per second and, while two meters per second wind is noticeable, it would likely not qualify a day as “windy” to most people. If the maximum wind speed was insignificant, the arm/imbalance created by the experimental weight might not have been affected enough to create instability. Therefore, the rage of wind speeds could account for the lack of a positive result.

The most significant factor that could have disrupted this data is the sample rate. To simplify the data collection process, orientation data was only updated once per second. In the event of a strong, seconds-long gust of wind, the disturbance would have contributed to that trial’s instability score. Other types of instability, such as a wobbling or vibrating, however, would probably not have been meaningfully detected since those typically occur at higher rates. Having relatively few data points in each trial means it cannot be determined whether the noise seen in Figures 2a and 2b, which is like that seen in every other trial, is a fast oscillation or a random spray of values. If that distinction were known, future experimenters would know what parts of the experiment to change: the sample resolution or the sensor hardware.

Conclusion

While this experiment was initially intended to lay groundwork for research that would contribute to drone design, it may, ultimately, only inform future experiments. The data, examined altogether, points to there being no relationship between a drone's stability in flight and the mass of its payload, but there are enough reasons for that result to be inaccurate that the core focus of this research remains undecided.

In order for a more concrete result to be found, more data from a larger span of wind speeds would need to be collected. Ideally, each trial would have a plot of wind speed over time to accompany the orientation data. The present narrow range of wind speeds caused a chart of wind speed and instability to yield no relationship, which is inconsistent with the literature in this field. That failure was important enough to the analysis of this experiment that a future experiment should seek it as well, to ensure reliable methods.

Another valuable improvement would be to increase the sample rate of the data from 1 Hz to 100 Hz, so long as there is access to hardware that is capable of that rate. This would most likely require storing flight data on the drone and offloading it in between flights, as opposed to sending the data to a laptop in real time, as was done in this experiment. More data would allow the experimenter to analyze their equipment as well as make better guesses as to the source of any potential noise. Until an experiment is conducted with significant methodological changes, including the ones mentioned, a relationship between instability and payload mass is unlikely to be found.

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