# Realtime Extreme Atmospheric Conditions Sensing with Fixed-Wing Drones

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**Abstract**

The increasing utilization of drones across various fields necessitates advancements in their safety and control, especially for fixed-wing drones navigating in highly dynamic environments [1]. This research addresses the challenge of navigating through desert tornadoes, called twisters, which pose severe risks to drone stability and functionality. The primary objective is to develop a machine learning-based system that enables drones to detect twisters, path plan around them, and maintain stability within their intense flow fields. Central to this research is the development of a multi-hole pitot tube system, which measures flow direction and magnitude, providing data for understanding and adapting to wind conditions. Once assembled, a robotic arm orients the tube in many positions facing incoming airflow, collecting data on individual pressure sensor readings. To provide a clean flow to calibrate the multi-hole probe, a settling chamber was designed, ensuring minimum turbulence level and flow uniformity, which is then used to provide ground truth for the calibration process. Short-term goals include conducting testing in the wind tunnel and fan array and using this data to improve the pitot tube calibration. In the future, we will integrate our pressure sensing mechanism into more robust drones.

**Background**

In the rapidly evolving landscape of autonomous flight, drones have become integral across various fields, from recreational and commercial applications to use in the military. With this widespread adoption comes an increased concern for safety and precise control, especially as drones navigate diverse and unpredictable environments. Fixed-wing drones, in particular, face significant challenges due to their reliance on aerodynamic stability. The motivation for this project stems from the need to equip these drones with capabilities to handle dynamic situations, such as the harsh terrain and turbulent wind flows created by desert twisters, thereby improving their robustness and safety.

Figure 1: Drone Flying Through Desert [2]

The Gharib Research Group and Dr. Xiaozhou Fan have been focusing on enhancing drone stability through advanced sensor mechanisms and machine learning algorithms. The approach takes inspiration from the remarkable stability seen in many flying animals, specifically birds and bats. Even at high wind speeds and turbulence that would shift current drones dramatically off course, these animals are seemingly unaffected. What looks simple to onlookers is deceivingly complicated. Behind the scenes involves the animals' own receptors and sensors that allow it to seamlessly navigate the world. To replicate the stability of these animals, the research group has developed an experimental setup, led by Dr. Xiaozhou Fan, consisting of a standard commercial fixed wing drone, with an array of sensors on and around the wings. Using machine learning techniques, optimal wing angles and thrust are calculated in real-time to stabilize the drone, given various turbulent wind environments. Through this research endeavor, the Gharib Research Group aims to give drones the ability to fly successfully in harsh conditions.

**Project Goal**

The project goal consists primarily of creating a simple, fixed-wing drone with an advanced pressure sensing mechanism. In this way, we aim to enable drones to understand the environment around them. Unlike most current sensing mechanisms, we will be able to sense vortices and complicated wind flow patterns. Once implemented, we hope to use our drone setup to create a machine learning algorithm that allows drones to detect and path plan around twisters. By using a standard drone, we will be able to implement our general algorithm across a variety of drones. While we aim to make our drone simple, we also must make our sensing mechanism with lightweight material and a low form figure.

**Pitot Tube Mechanics**

A standard two-hole pitot tube is a widely used instrument for measuring fluid flow velocity, particularly in aerospace and fluid mechanics applications. The basic principle behind the pitot tube is rooted in Bernoulli's equation, which relates the pressure and velocity of a moving fluid. In a two-hole pitot tube, one port faces directly into the oncoming fluid flow, known as the total pressure port, while the other port, the static pressure port, is positioned perpendicular to the flow. The total pressure port measures the stagnation pressure, which includes both the dynamic pressure (due to the fluid's motion) and the static pressure (due to the ambient conditions). The static pressure port, on the other hand, measures only the static pressure of the surrounding fluid. By subtracting the static pressure from the stagnation pressure, the dynamic pressure is obtained, which is then used to calculate the velocity of the fluid. This method provides accurate measurements when the fluid is flowing directly toward the pitot tube. However, the accuracy can be compromised when the flow is angled relative to the tube's orientation, as the two-hole design is limited to capturing information only along a single axis. The effectiveness of the two-hole pitot tube depends heavily on proper alignment with the flow, making it less reliable in environments where flow direction changes frequently or is turbulent.

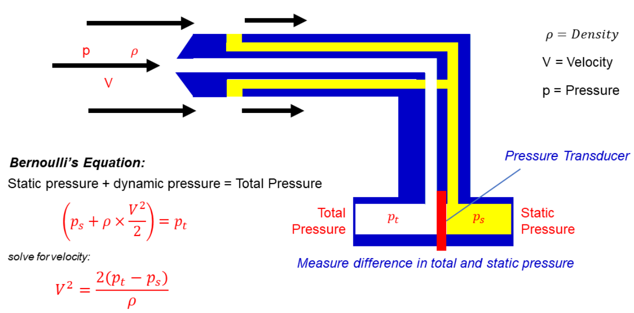


Figure 2: Schematic Drawing of Pitot Tube [3]

In contrast, multi hole pitot tubes offer a significant improvement in measuring fluid velocity, especially in situations where the flow direction is variable or complex. A multi hole pitot tube typically has four or five ports arranged around the circumference of the tube, allowing it to capture pressure data from multiple directions simultaneously. These additional ports enable the multi hole pitot tube to measure both the static pressure and the dynamic pressure from different angles, providing a more comprehensive understanding of the fluid's velocity and direction. The design of the multi hole pitot tube makes it highly sensitive to changes in flow direction, which is critical in applications such as aerodynamics, where airflow over surfaces can be turbulent and multidirectional. By capturing data from multiple angles, a multi hole pitot tube can determine not only the magnitude of the velocity but also the flow's angular components, such as pitch and yaw. This is especially useful in environments with complex flow patterns, such as the wings of an aircraft or within wind tunnels. Moreover, the multi hole design reduces the need for precise alignment with the flow, making it more versatile and reliable in real-world conditions where flow is not perfectly aligned with the instrument. The enhanced accuracy and flexibility of multi hole pitot tubes make them a superior choice for applications that require precise measurements of flow velocity and direction, particularly in fields like aerospace, where understanding the full flow field around a surface is critical for optimizing performance. While two-hole pitot tubes remain useful for straightforward applications with predictable flow, multi hole pitot tubes offer a significant advantage in complex or dynamic flow environments.

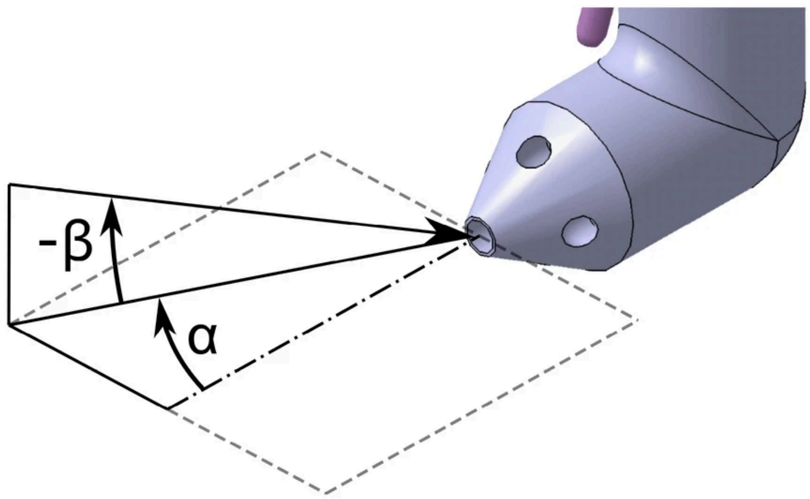

Figure 3: Drawing Showing Flow Angles Obtained Using Multi-hole Pitot Tube [4]

**Pressure Sensor Board**

The first step in building a pitot tube is creating a board fitting with pressure sensors that will ultimately measure the inputs from each of the pitot tube holes. To create the 5-sensor board for measuring real-time air pressure differences on the drone's wing, I first designed the layout, considering the arrangement of components like the resistors, pressure sensors, and multiplexer. Initially, I sketched out the design on paper and then proceeded to physically assemble the board. During assembly, I encountered challenges with the layout, particularly the spacing of the resistors, which extended into a fourth hole rather than fitting into the three holes I had planned. This overlap posed a risk of short circuits, so I shifted the resistors vertically to prevent contact. I also rethought the wiring strategy, opting to wire each pressure sensor individually to the power and ground ports, placing some of these connections on the underside of the board. This decision minimized clutter and helped keep the form factor compact while avoiding overcrowding of the connection points.

Once I began soldering the first pressure sensor to the board, I encountered issues with inconsistent connections and error readings from the sensor. After troubleshooting with the help of a multiplexer, I found that the stripped wires connecting the sensors to the board were unreliable, causing intermittent connection failures. To resolve this, I opted to solder the wires directly, which improved the reliability of the connections and ensured stable readings from the pressure sensors. I repeated this process for the remaining sensors, carefully adjusting the wiring and placement to ensure all components fit together without causing interference. Ultimately, the final layout allowed for simultaneous readings from all five pressure sensors, providing accurate and consistent data for air pressure differences across the drone's wing.

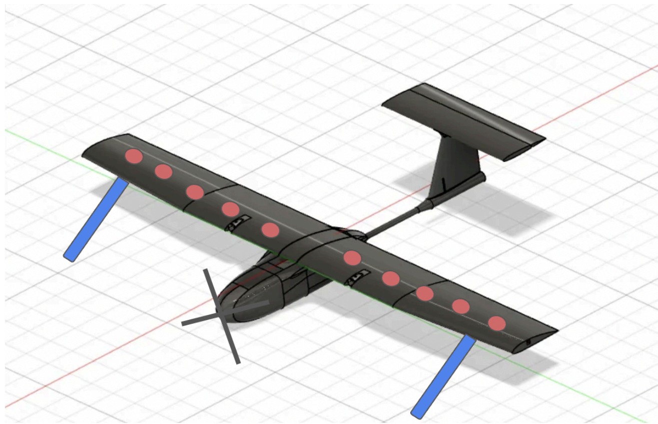

Figure 4: Diagram Illustrating Drone Sensor Mechanism[5]

**Initial Multi-Hole Probe Design**

Next, I designed the physical components of the multi-hole probe. For my initial design, I decided to use 5 carbon microtubes of length roughly 270mm. These would run through a carbon fiber shell and open at the nose. The ends of the tubes would each be connected to their own pressure sensor. One of the primary challenges I encountered was connecting the pressure sensors to the carbon microtubes. The pressure sensors I used had an inner diameter of 2 mm, while the carbon microtubes had an outer diameter of only 1 mm, necessitating a reliable method to bridge this difference in size. I explored a range of potential solutions, including using sealants, clamps, and tape, as well as designing 3D-printed adapters. Ultimately, I opted for a more flexible approach by using silicon tubing as a connector, with a 2 mm outer diameter and 1 mm inner diameter. By cutting sections of the silicon tubing to size and using a soldering pen to gently melt the inside end of the pressure sensor tube, I was able to insert the connector tube securely. To reinforce the connection, I applied a strong sealant around the joint, ensuring a snug fit between the carbon microtube and the sensor. This method worked effectively, creating a solid and airtight connection that allowed for reliable pressure readings.

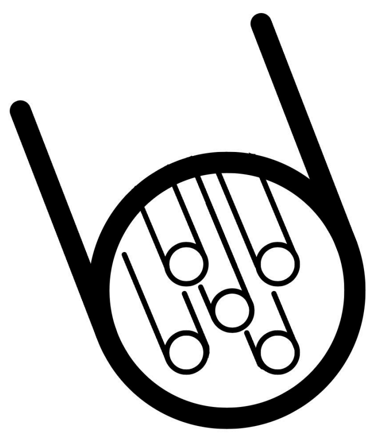

Figure 5: Diagram Showing 5 Carbon Microtubes in Carbon Fiber Casing

Figure 6:  Drawing Showing Side-View of Assembled Pitot Tube

With the sensor connections established, I shifted my focus to optimizing the aerodynamic design of the pitot tube's nose cone to minimize drag. After researching various shapes, I found that parabolic nose cones, rather than sharp conical shapes, are more effective at reducing drag in high-speed fluid environments. Based on this research, I designed a 3D-printed nose cone and end cap for the pitot tube, each featuring five holes for the carbon microtubes. I carefully threaded the carbon microtubes through the holes in the nose cone and end cap, ensuring the layout aligned with the multi hole pressure sensing configuration. To test the system, I blew through the pitot tube's openings to confirm that the pressure sensors responded appropriately, and all the connections remained secure. Using a Dremel, I precisely cut the carbon shell of the pitot tube and then glued the end cap and nose cone in place to complete the assembly. After successfully building the first pitot tube, I replicated the process to construct a second tube with minimal adjustments or issues.

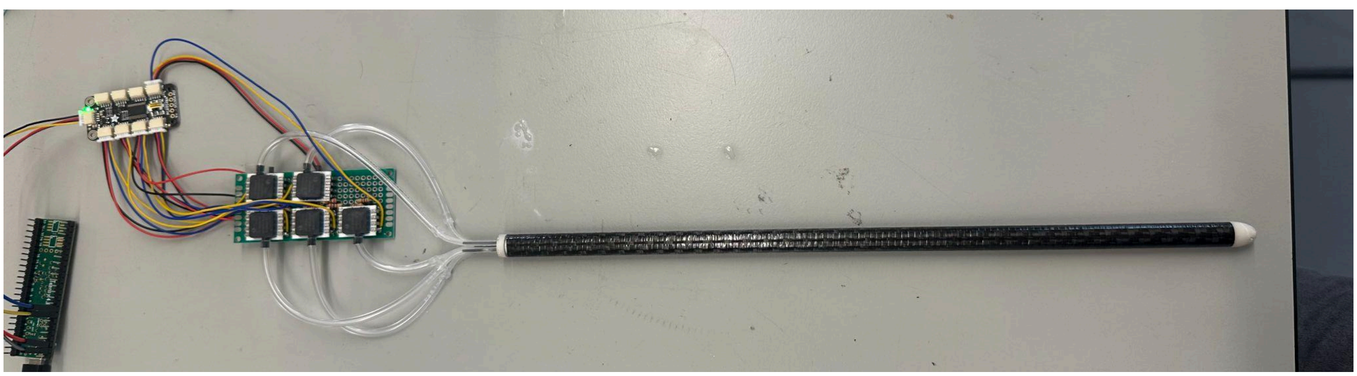

Figure 7: Image of Pitot Tube Connected to Pressure Sensors and Teensy

**Redesign of Multi-Hole Probe**

Upon testing the initial pitot tube design, which relied on carbon microtubes for airflow measurement, one of the microtubes snapped during handling, revealing the need for a more robust solution. To address this issue, we redesigned the pitot tube using a more durable metal-based structure. The new design incorporated a 10.5-inch steel tube with a 5 mm outer diameter (OD) and 4 mm inner diameter (ID) as the main casing to provide structural support and withstand mechanical stresses. For the airflow channels, we used Albion aluminum microtubes with a 0.5 mm OD and 0.3 mm ID, cutting them into six sections of approximately 32 cm each. These aluminum microtubes were threaded through the steel casing and carefully aligned through a resin-printed nose cone and two resin-printed end caps. The alignment of the tubes in the nose cone and end caps was crucial to prevent crossing within the casing and to ensure accurate airflow measurements through each tube. To secure the aluminum tubes in place, we glued them to the second end cap, making sure the first end cap remained free to allow for final adjustments. The aluminum tubes were then connected to silicon tubing, each fitted with 3D-printed connectors to ensure a snug fit. After assembling the pitot tube, we used Loctite super glue to secure all connections, paying careful attention to prevent any glue from flowing into the openings of the aluminum tubes, which could block airflow. This revised metal-based pitot tube design not only significantly improved the durability of the probe but also enhanced the reliability of the airflow measurements, as the aluminum microtubes are more resistant to mechanical failure than the original carbon microtubes. The use of steel for the casing further reinforced the structure, making the pitot tube better suited for the harsh conditions it would encounter during testing and operation on the drone's wing.

**Calibration**

Calibrating the pitot tubes is a crucial step to ensure that they provide accurate airflow measurements across a range of conditions. Pitot tubes are sensitive to both the angle of the incoming flow and the wind speed, so calibration is necessary to account for any discrepancies that may arise due to variations in orientation or airspeed and manufacturing flaws. The calibration process involves using a robotic arm to precisely orient the pitot tube at various angles relative to the airflow, simulating different flight conditions. It is critical that the position of the pitot tube tip stays in constant position, so only the angle of wind changes, while all other aspects remain constant. This allows us to gather data on how the probe responds to changes in pitch, yaw, and flow speed. By moving the pitot tube through a controlled range of angles and wind speeds, we can map out how the pressure readings vary across different conditions.

The first step in calibration is creating a successful calibration environment. The key to this is providing evenly distributed, horizontal airflow. If there is noise in the air, this will have detrimental effects to the accuracy of the calibration, as pressure values will not be stable. The past experimental setup failed in creating even flow. It utilized a double layer of 9 computer fans. One good aspect of this mechanism is that it is very easily controllable. We can cycle through a variety of wind speeds very quickly and easily. However, the problem is that computer fans create wind in a swirl pattern. This is far from easily distributed and can make calibration ineffective. The first improvement I made was attaching a honeycomb array across the fans. This helped to direct the flow into a more even pattern. I then 3D printed a settling chamber to help ease any turbulence caused by the honeycomb. Next, I strung a metal mesh across the chamber. I used springs bolted on the outside of the chamber to hold it taught. This screen acted as an even smaller filter to create even flow. The last component was a 3D printed funnel that directed the airflow to the tip of the pitot tube. This setup proved effective for calibration.

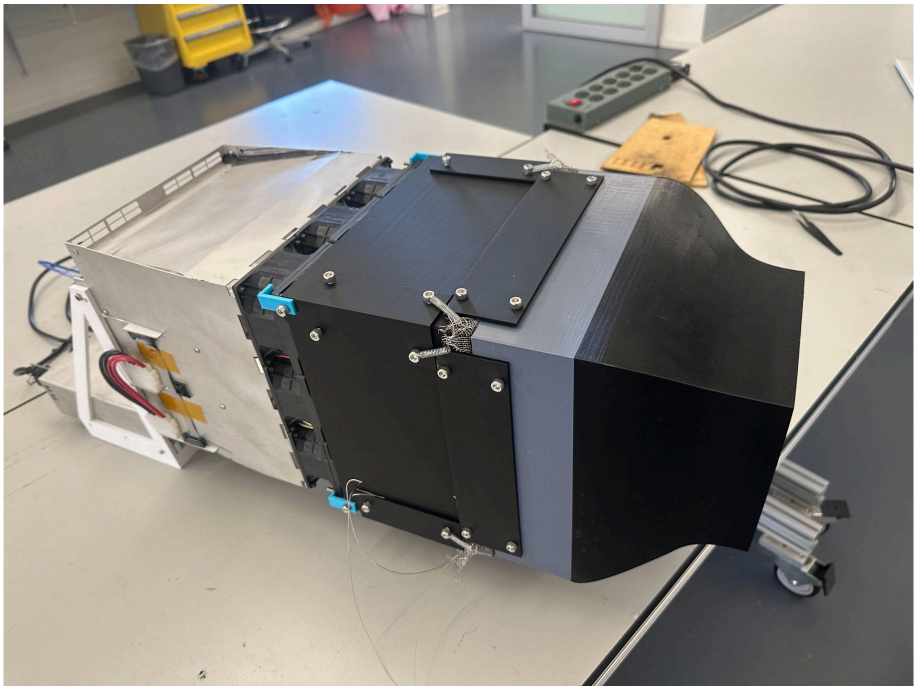

Figure 8: Fully Assembled Calibration Environment

For calibration, the pitot tube was mounted to a robotic arm using a 3D-printed converter to ensure precise alignment and stability. It was critical to maintain the exact orientation of the pitot tube relative to the airflow throughout the calibration process to ensure consistent results. The calibration began with the robotic arm positioning the pitot tube directly facing the horizontal wind flow. From this starting point, the arm rotated the pitot tube 360 degrees, simulating wind blowing from all possible angles. During each full rotation, five snapshots of pressure sensor readings were recorded for each angular position. After completing the first 360-degree rotation, the arm was incrementally tilted downward by 3 degrees, after which another full 360-degree rotation and data collection sequence were performed. This process was repeated for tilt angles up to approximately 50 degrees. The calibration was conducted at two wind speeds, 10 m/s and 25 m/s, to capture the pitot tube's response under varying conditions. All data points from the calibration process were stored in a CSV file for further analysis, providing a comprehensive dataset for correcting the raw sensor readings and ensuring accurate measurements during flight.

The final step involved developing a machine learning model to predict airflow velocity and angle based on the five pressure sensor readings from the pitot tube. To begin, I preprocessed the data by normalizing the pressure readings, as well as the alpha and beta angles, using their respective standard deviations to ensure consistency across different scales. The input vector was constructed by dividing the normalized pressure values by the difference between the minimum and maximum pressure readings at each time step, which helped capture the relative pressure variations. To further enhance the model's ability to differentiate between different wind speeds, I included this pressure difference as a sixth feature in the input vector, as higher wind speeds result in greater pressure differences. The output vector consisted of the dynamic pressure, normalized by the true pressure, followed by the alpha and beta angles. The model architecture included a series of linear and Tanh activation layers, which I trained over 1000 epochs to minimize validation loss. After training, I visualized the predicted versus actual angles to assess model performance, achieving a mean squared error (MSE) of less than 2 degrees for wind speeds of 10 m/s and less than 1 degree for 25 m/s, demonstrating the model's accuracy in predicting the flow characteristics.

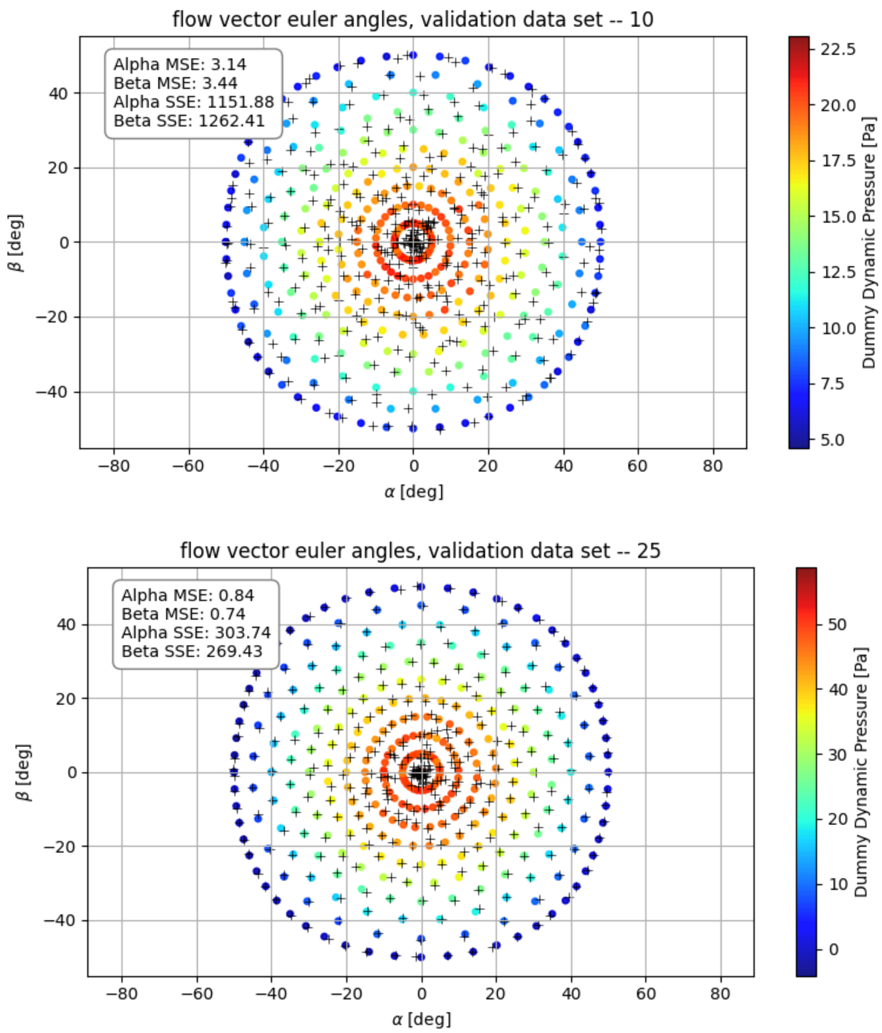


Figure 9: Neural Network Flow Angle Predictions (+) Compared with Actual

**Future Work**

Our next phase involves extensive testing of the pitot tubes to collect additional data and refine their performance under real-world conditions. We will first integrate a force transducer into the drone test bed in the wind tunnel to measure how the drone responds to varying wind speeds and flap movements. This will allow us to capture detailed information on the interaction between the drone's aerodynamic surfaces and airflow. In parallel, the pitot tubes will be attached to the drone wings, and their data will be used to verify and improve the calibration process. This testing will serve as the foundation for developing a machine learning model capable of detecting twisters by analyzing the complex wind patterns they generate.


Figure 10: Purchased Opterra 2m Wing Drone [6]

In addition to wind tunnel testing, we plan to optimize our fan array to simulate more realistic twisters. By refining the fan configuration, we aim to create a more accurate representation of twister wind patterns, which we will then measure using the pitot tubes. To further simulate real-world conditions, we will construct a zipline system to fly the drone over the twisters, allowing us to study how it handles these turbulent wind fields. Furthermore, we have recently acquired a more robust drone, which will serve as the new platform for our sensor mechanism. Testing with this more advanced drone will provide crucial insights as we continue to develop and improve the system, ultimately enabling the drone to navigate extreme atmospheric conditions, such as those created by desert twisters.

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