Designing a Hexacopter for the Collection of Atmospheric Flow Data

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Abstract - Vertical profiles of temperature, pressure, relative humidity, wind speed, and wind direction in the atmosphere are typically collected using radiosondes attached to free-flying or tethered balloons. This method is inefficient when data are only required for the first hundred feet above the ground. Free-flying balloons and the attached payload drift away from the launching location and are often not recovered. Tethered balloons require large amounts of helium and become unstable with increased winds, and inflating balloons takes an extended period of time and requires a skilled team.

The scope of this project is to eliminate the impracticalities of balloon-based measurement systems by creating a recoverable, versatile, user-friendly unmanned aerial vehicle (UAV). The project requires development of a flight-control system, a data-collection system, and a communications and user interface. The development of the flight-control system involved researching autonomous flight controllers, followed by the construction, prototyping, and tuning of a hexacopter. Creating the data collection system required researching environmental sensors and determining the effects of the copter motion on sensor performance. The designed communications interface incorporated real-time data flow and local storage on the copter. The final product will be an autonomously flying hexacopter which can collect accurate weather-related data within the lowest 1000 feet of the atmosphere.

Index Terms – Atmospheric data, Autonomous flight, Hexacopter, Real-time data visualization

INTRODUCTION

Low level atmospheric data can be useful in many environmental science applications, but collecting the data can be time-consuming, difficult, and expensive. Current methods of data collection rely almost entirely on the use of radiosondes attached to free-flying or tethered balloons. Radiosondes are small packages with battery-powered electronic equipment that take atmospheric measurements and transmit the data to a ground station. Radiosondes attached to free-flying balloons are typically lost when the balloon drifts too far away and out of the range of the ground-station or when the batteries stop working before the radiosonde has returned to the ground. The expenses can build up for a balloon system, especially if a new balloon and radiosonde need to be used every time. Additionally, the preparation time for these projects can be quite large, requiring a team of people to inflate the balloon and to make sure the electronics are working. Another option for the collection of data in the lower atmosphere is the tethered balloon. However, operating the tethered balloon system, including the tetherline and winch, inflating the balloon, attaching the radiosonde on the tether, and handling the balloon in windy conditions can be labor-intensive. Furthermore, the tethered balloon system and helium can be expensive.

To solve all of the above mentioned problems, we aim to develop a reusable, unmanned aerial vehicle (UAV) system, which allows more efficient and detailed data collection in a variety of environments [1]. Hexacopters are a potential replacement for balloon-based systems because they are cheap, are easy to operate, can fly in a range of atmospheric conditions, and can be used repeatedly while carrying a comparable sensor package. Our client, Professor Stephan de Wekker, mainly conducts research in local and mesoscale atmospheric environments where data collected in the lowest 1000 feet is crucially important. Having a reliable and repeatable method for atmospheric data collection will allow accurate and detailed investigations of the lower atmospheric structure and dynamics.

PROBLEM FORMULATION

The requirements of the system were determined through client interviews. The clients, Professor Stephan de Wekker and his graduate student Stephanie Phelps, were frequently consulted during the problem formulation stage of the project. We also investigated current standards, methods, and applications of weather data collection to better understand the motivations behind the project [2]-[3].

Through client interviews and research, the following customer needs were determined: the system should 1) be easy to use without needing advanced programming skills, 2) collect accurate data, 3) fly autonomously, 4) deliver sensor payload with minimal damage, 5) be safe for field use, 6) be easily retrievable after each flight, 7) be able to conduct multiple flights, and 8) be operable in a variety of environmental conditions (temperatures between -10 and 40 degrees Celsius, humid environments such as clouds and fog, and in differing wind conditions). The clients do not
expect the copter to fly in rainy conditions. These customer needs were then converted into requirements to be used throughout the project as guidelines for project success.

I. Requirements

- Must collect data at least once every second
- Must measure standard meteorological variables with following accuracies:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>± 0.3°C</td>
</tr>
<tr>
<td>Specific Humidity</td>
<td>± 0.25 g/kg H₂O</td>
</tr>
<tr>
<td>Wind Direction</td>
<td>± 20°</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>± 0.25 m/s</td>
</tr>
<tr>
<td>Pressure</td>
<td>± 0.5 kPa</td>
</tr>
</tbody>
</table>

- 5 seconds for temperature time constant (a measure at how quickly the temperature sensor reacts to the change in ambient temperature)
- Must land autonomously without crashing a minimum of 80% of the time
- Must be able to autonomously take off and land with no critical damage occurring to the weather sensors
- Must be able to fly to an altitude of at least 1000 feet while collecting data
- Must be able to deliver a complete data set at the completion of each test that can be accessed by the user
- Must be able to present a real-time visualization of data to the user during flights
- Must be stable in all anticipated flight conditions
- Must have automatic landing fail-safes in the event of low battery or lost GPS signal
- Must be able to have ascent and descent rate controlled by the user
- Must return (descend) to landing base quickly
- Must be able to take data during flight ascent
- Must utilize an open-source type of software to allow for portability
- Copter must be able to carry the entire payload of system

CONCEPTUAL DESIGN

I. Overview

As the initial requirements were rather open-ended at the beginning of the project, we were able to make numerous design decisions at every phase of the project’s development. We began by selecting a platform on which to base our entire system. For each subsystem we researched and identified viable options, evaluated their performance, and made a selection for the prototype based on the results. Ultimately, we chose a suitable platform and flight pattern, sufficient sensors, and a simple user interface.

II. System Platform

We decided early on to build a multirotor copter since it would be smaller, easier to deploy, and offer more versatility than a balloon-based system. At the same time, a multirotor is constrained by limited battery life.

Multirotors come in various shapes and designs; the most common are the four-rotor quadcopter, the six-rotor hexacopter, and the eight-rotor octocopter. These are the three primary configurations, although there are several more exotic ones as well. All three formats behave similarly, but as more rotors are added, greater stability and lift are gained at the price of increased battery usage and cost. Additionally, hexacopters and octocopters are able to remain airborne even if a motor fails by allocating more power to the surviving motors. The hexacopter configuration was selected as it provided sufficient lift to carry the expected payload and offered security against motor failure. From preliminary flight testing, we found the battery life to be roughly 25 minutes in low-wind conditions, allowing enough time for data collection. However, the battery life is subject to change based upon wind condition and flight plan.

Currently, the copter is controlled by an ArduFlyer flight controller board using the open-source flight software Arducopter 3.0; it is capable of autonomously flying simple, pre-programmed flight patterns as well as maintaining position via GPS lock within a cubic meter (established in the tuning process).

III. Temperature Sensors

A number of sensors were evaluated in order to determine which would optimally serve our purpose. Important criteria were accuracy and speed of measurement. To make accurate (within ±0.3°C) temperature profiles during fast ascents, it is necessary to find a temperature sensor that can reach equilibrium quickly. As few manufacturers post information regarding the time constant values (the time required to reach 63.2% of a step change in temperature), several sensors were tested for response time and accuracy. In order to measure the time constant, the sensors were introduced to a step-change in temperature from a refrigerated environment to room temperature. Accuracy of the temperature sensors was confirmed by comparison to a calibrated SHT15 temperature sensor.

The most promising candidates were the SHT75, the TMP102, and the Omega 44203 linear thermistor. The TMP102 had an insufficient time constant of about 97s with an accuracy of ±0.5°C over the applicable temperature range. The SHT75 showed marked improvements with a high degree of accuracy (±0.3°C), and a time constant of 41s. Most importantly, it is capable of measuring relative humidity. The Omega 44203 had the shortest time constant of all—7.2s—and the highest degree of accuracy at ±0.15°C. The downside of the Omega 44203, however, is that it requires relatively frequent recalibration based on comparison against another temperature sensor. Therefore, the accuracy can only be guaranteed up to the standard of the comparison sensor.
THE TEMPERATURE SENSOR RESPONSE TO STEP-CHANGE IN TEMPERATURE. THIS CHART ILLUSTRATES THE TIME IT TAKES FOR EACH SENSOR TO RESPOND TO AN INSTANTANEOUS 20°C INCREASE IN TEMPERATURE. THE TIME CONSTANT IS THE TIME REQUIRED TO REACH 63.2% OF THE DIFFERENCE.

The SHT75 and Omega 44203 both meet the minimum requirements for accuracy. However, none of the sensors meet the minimum requirement for time constant. Though imperfect, the Omega 44203 is the fastest of the tested sensors and was therefore included in the final design. The SHT75 is the only sensor that measures relative humidity and was also included in the final design as it met the required accuracy we needed, while maintaining the lowest sampling rate for humidity that we could find through research.

To further reduce the time constant of the temperature sensors, the sensor payload can be positioned just below a rotor to maximize airflow over the sensor. The downside, however, is that this air is mixed with surrounding air and therefore may not be representative of the actual air temperature at the copter’s altitude. Further exploration into this issue is needed.

IV. Anemometer

Attempting to measure wind data above rapidly spinning rotors is complicated. The blades create a downwash that could possibly affect the airflow around the anemometer, and rotor effects while the copter is moving are largely unresearched so we had no reference to go on. To begin this process, we first needed to identify the appropriate sensor type. We considered various options, including using a hot-wire anemometer, a traditional cup anemometer and wind vane, and a sonic anemometer.

The hot-wire anemometer, which works by heating a small wire and measuring the convective heat loss as a result of ambient airflow, is traditionally used in more delicate settings to measure highly turbulent flows. It requires frequent recalibration due to dust accumulation, but has a rapid response time. It does not capture wind direction, however, and a separate wind vane would be required, if not multiple anemometers.

A cup anemometer and wind vane were used on our initial prototype design due to simplicity of use and low cost. However, since they have moving parts, cup anemometers suffer from slow start-up speeds, poor response to strong gusts, and maintenance issues resulting from vibration, icing, and general wear [4]. Errors resulting from overspeeding in turbulent winds can be greater than 10% of the true value [5]. Additionally, a wind vane can only a reference wind direction relative to the front of the copter (which is not necessarily north facing), therefore a separate compass would be needed.

The Airmar 200WX sonic anemometer, which was designed for usage on boats, works by sending high frequency pulses between two transducers and calculating the latency due to airflow. Though more complicated and expensive, the Airmar contains instrumentation that allows for corrections due to angle of attack and lateral movement, and requires less maintenance since there are no moving parts.

The accuracy of the Airmar was determined by comparing the Airmar next to a Kestrel 4500 anemometer which uses a small impeller to measure wind speed. Both anemometers collected data simultaneously for over an hour at an outdoor location. The Kestrel 4500 was mounted to a wind vane to measure wind direction as well. The test results indicate that the Airmar is less responsive to changes in wind speed than the Kestrel, showing a mean wind speed for the Airmar that is 0.81 m/s lower than the Kestrel with less variability. These initial results may indicate that the Airmar may not be the optimal anemometer for use on the hexacopter in weak wind conditions. However, the Kestrel is advertised as a “pocket weather meter” and may not be accurate enough to provide meaningful data to compare for accuracy. Because of this, the results from the Kestrel test may not be the best comparison for our Airmar anemometer. Further testing is required to determine whether the deviation from this initial test is due to inaccuracy of the Airmar in low wind speed or the Kestrel.
in our airflow or false readings. Although we expect cleaner data as the anemometer is further from the propellers, the increased moment arm of a larger support shaft also decreases the stability of the copter.

In order to test for the appropriate anemometer distance, we brought the copter to a large room with no ventilation (a decommissioned nuclear reactor) to ensure the test would not be affected by unsteady wind. The copter was mounted on a shaft roughly 10 feet off the ground in the center of the room to minimize ground effects from the props. The anemometer was attached on three differently sized mounts (8.25", 16.5", and 24.75") and collect wind data while alternating between props on and props off once every minute.

When tested on the 8.25” shaft, the anemometer recorded a mean difference of 0.13m/s between the wind measured with propellers on and propellers off, although with increased fluctuations possibly due to strong vibrations induced by the test rig. The difference is less than the tolerable error in wind speed of 0.25m/s so is considered acceptable, but more testing is required to confirm this result for the Airmar. Unfortunately, when the longer two support shafts were tested, the induced vibrations were so violent that we feared the hexacopter body might break. As a result, we were unable to collect usable data without risking the hardware. Since the Airmar may not provide accurate results at low wind speeds, we will repeat our tests with a more sensitive anemometer using shafts that range in heights from 5 to 10 inches (in intervals of 1 inch) to measure the effect of the rotors more accurately in the near future.

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V. Flight Control

To collect atmospheric data with the hexacopter in the lowest few hundred feet of the atmosphere, we identified three potential flight patterns. The first is a steady vertical ascent logging data continuously. This pattern allows for high-resolution data; however, the sensors may not have sufficient time to reach equilibrium. The second method is to ascend in discrete increments—roughly 1 meter at a time—and take measurements at each stopping point. In this method, the sensors have time to reach equilibrium at each altitude, but the resolution is reduced. Between these two designs, an optimization must be made as to whether resolution or data accuracy is more important, and which is more affected by each profile. A third design would be for the copter to process the weather data in-flight and adjust the ascent rate based on the magnitude of the change in the variables. That is, if the copter flies through an intense temperature gradient, it could slow down to collect higher resolution data. This flight pattern would maximize resolution over critical regions in the atmosphere while reducing total flight time. On the other hand, interfacing the data collection board with the flight control board is nontrivial and is not an available feature in Mission Planner—our current ground-station software. This design decision requires further research.

VI. Software

Xbees (Pro Series 1) were chosen for transmitting data because they are easy to use, they allow for quick and simple communication and data transfer, and can be integrated into the Arduino microcontroller boards and the BeagleBone Black. Other options were considered, but after originally testing the Xbees they were determined to be sufficient for the project’s needs (ranges up to 1 mile).

Establishing a uniform software platform was important to maintain simplicity of the full project. Excel macros were initially considered to process the data, but were replaced by java programming as it provided more versatility and easier editing and debugging. After the original Java program was written to process the stored raw data, other methods of data processing such as python code and JavaScript were considered to handle the serial data delivered by the Xbees. Using JavaScript through Chrome Apps was explored as the best potential platform for our project as it allowed for easy customization and cross-platform use. Given our familiarity with java and its capability to perform all the required data processing, a chrome app was the most feasible option.

FINAL DESIGN

I. Hardware Platform

The hexacopter platform chosen is an off-the-shelf 23” diameter frame. We chose this size because it provided sufficient space to place an electronics payload, while replacement parts are inexpensive. The 23” copter size also is paired with standard motors and 10” blades that provide the necessary lift and stability for our payload.

The Beaglebone Black was chosen as the control board that handled outgoing sensor data from the copter. This board runs a Linux platform which can be easily modified and programmed so that the system is customizable for the user. Real-time data will be sent to the ground station using XBee’s and is also stored on a micro SD card mounted on
the board. Furthermore, the individual sensors will be easily connected to the Beaglebone through individual pins or a serial connection.

II. Software Platform

The software portion of this project can be separated into two sections: the part that handles the real-time data from the copter and the part that handles the stored data on the copter. The purpose of this two-part design is to prevent potential data loss from wireless communications malfunction. The real-time data are sent through an Xbee on the copter, which wirelessly pushes data from the Beaglebone to the second Xbee connected to the ground-based computer through USB. A Chrome App, which utilizes JavaScript to process and visualize the data, immediately graphs the serial real-time data. The real-time data is graphically presented to the user via the Chrome App in 8 charts: four that show temperature, humidity, wind speed, and wind direction in terms of altitude (derived from air pressure, as air pressure can be directly correlated with altitude) and four that express that data as time series data. The raw data are also stored on an SD card located on the Beaglebone. This data can then be uploaded to a computer and run through the same Chrome App to be parsed and stored as a comma separated file for later use. Figure 4 shows the complete data flow diagram for the system.

III. Sensor package

We included several temperature sensors—a Sensirion SHT75 digital thermometer and two Omega 44203 linear thermistors. The SHT75 provides sufficient accuracy and also measures relative humidity, while the Omega has the shortest response time and is also highly accurate. We placed one linear thermistor above the rotors to measure the temperature of the undisturbed air during ascent, and one thermistor was placed below a rotor to maximize airflow over the sensor to further reduce the time constant.

The chosen anemometer was the Airmar 200WX sonic anemometer. The Airmar simplifies wind direction calculations by correcting for the copter’s heading angle using gyroscopic measurements, GPS, and compass data. Unfortunately, we have not been able to thoroughly test its accuracy in both wind speed and direction. Preliminary results show a possible insensitivity to weak wind speeds, which would make the Airmar not an ideal anemometer for use on the hexacopter. It is incorporated into our final design as more testing is being conducted to confirm or reject this hypothesis.

The anemometer serves as a cantilevered weight, and so the higher it is placed, the less stable the copter becomes. On the other hand, a location well above the rotors is desired to minimize the effect of rotor downwash on the wind data. The anemometer was placed 8.25” above the copter due to constraints in copter stability. At this length, the rotor has little effect on the recorded wind speed.

DESIGN EVALUATION

I. Requirements Met

The hexacopter platform was able to retrieve data at every second.

The required accuracies for the temperature sensors were met. The temperature sensors chosen were the SHT75 and the Omega 44203. They were both within the ±0.3 degree required threshold (±0.3 and ±0.15 degrees respectively).

Manual flight testing over the lifetime of the sensor payload has demonstrated the hexacopter’s ability to take off and land without damage to the sensor payload.

The copter is able to deliver a complete data set that can be accessed by the user at the end of a flight. Data is sent to a home base wirelessly, through means of the Xbees, in real-time as well as stored locally on the copter itself.

Through use of Chrome Apps and Highcharts specifically, atmospheric data can be visualized in various scenarios in real-time during flights.

The hexacopter platform has demonstrated its stability in flight through an intricate tuning process. Hexacopter tuning accounts for the addition of the sensor payload, allowing the platform to remain stable during flight.

In case of complications during flight, fail-safes have been enabled on the hexacopter platform. These problems include loss of battery power or GPS signal, and if they occur, the copter can return to the takeoff location.

The rate during takeoff and landing has been set to be controllable by the user.

Through use of the Xbees, data are transmitted wirelessly over a sufficient range. As the copter is ascending, the data can be transmitted to the user to be viewed and stored.

The hexacopter utilizes Arducopter, an open-source software. This allows for feasibility and portability of the copter.

Through flight testing with the sensor payload, the hexacopter is able to support the entire payload of the system, weighing about half a kilogram. Payload includes the temperature and humidity sensors along with the Beaglebone and sonic anemometer.

II. Requirements Not Met

The values for the preliminary wind sensor test show that our anemometer is not within the accuracy range we need (see Figure 2). However, the results of this test are
Conclusions

The new system can take atmospheric measurements autonomously and repeatedly, with minimum setup and knowhow required. The hexacopter is a one-time purchase with the only costs coming from the replacement of cheap and off-the-shelf parts. The flight control software is open source and community supported, capable of autonomous flight, controlled flight, and midflight correction in addition to many other features. The sensors are interfaced using a Linux-based chip, the Beaglebone. The Beaglebone supports serial interfacing, allowing for easy collection and collation of data. The data is then transmitted to the ground station using an Xbee wireless transmitter, while also being stored on the copter itself. The system splits the task of data collection and flying, and makes the programming of the flight path independent from the programming of the data collection. The final product is an autonomous, turn-key, modular data collection system that can be easily modified to add more sensors and to execute advanced flight paths.

References


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Inconclusive until we can test against under a wide range of atmospheric conditions.

Our time constant goal was 5 seconds until the temperature reached 63.2% of its final value. In our testing the lowest time constant we were able to achieve was 7.2 seconds (see Figure 1), which does not meet our established goal. However, this time constant is low enough while being accurate, meaning the project can still be completed with accurate data.

The current copter configuration has just been tuned, meaning it has not completed an autonomous flight yet, only manual. As a result, we do not know if the copter can land autonomously. However, other autonomous functions such as altitude and position hold work as they should, and the copter is capable of being landed under manual flight. As a result, we expect that further testing of the copter will complete this goal.

We were not able to meet the goal altitude of 1000 feet as we were restricted by FAA regulations to fly under 400 feet.

So far we have not tested whether or not there is a fastest way down from altitude. In past test flights, the copter was returned to its launch location at a comfortable rate so as not to damage the sensors. All landings so far in the current configuration have been manual. Further testing is required to determine the fastest method of descent.

Recommendations/Future Work

While we continue to test the final hexacopter product, we continue to look for more modern and high-tech solutions to increase the efficiency and efficacy of the design. One of the primary design constraints is the wind sensor accuracy. We will continue to look for a lightweight wind sensor with comparable or better accuracy. In conjunction, we would like to more extensively test the effects of the rotor air circulation on the collected data during flight. We will continue to research and test temperature and humidity sensors to find a faster-responding sensor. For improving the actual performance of the copter itself, we are looking into two main methods: using an optical flow camera and programming more efficient flight patterns. The optical flow camera is pointed downward and tracks movement over terrain, ideally increasing the accuracy of the copter’s position. An upcoming version of Arducopter will incorporate this function, but it is not currently supported. The flight profile itself should ideally react dynamically to the data collected during flight, but we have not had the resources or time to look into this as a preliminary option. In the future, after delivering the final product, we will look into programming this function. We hope that by using simple and effective methods we can future proof our design and extend its shelf life. Although new sensors or control boards may be developed, the platform is developed to be modular, and adding in new parts will be quite simple to anyone with a basic knowledge of electronics.