Development of Low Cost, Rapid Sampling Atmospheric Data Collection System: Part 2 – Sensor & System Integration

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As unmanned aircraft systems (UAS) evolve into a primary role for remote atmospheric sensing, there exists a need for a sensor system that can match the capabilities of the aircraft. Current commercially-available sensors that are lightweight enough to be installed on a UAS log Temperature, Pressure, and Humidity (TPH) data between 1-10 Hz. Of these systems, none feature a method of directly monitoring wind speed and direction save for 5 Hole Probe (5HP) sensors. To purchase such a probe costs in excess of $5,000. Explored in this paper is a low cost, custom sensor package that logs TPH data at 10 Hz while also featuring a 3D printed 5HP design that records wind speed and direction data at 150 Hz. The higher resolution of data captured allows for aircraft to traverse the target environment quicker while maintaining the same spatial resolution of data, allowing aircraft to either fly faster or gather data in higher wind conditions. The sensor has been flight tested and is currently undergoing calibration.

I. Background

The use of Unmanned Aerial Systems (UAS) for meteorological use has been an area of growing interest dating back to the 1980's. During this time, RC aircraft were first outfitted with radiosondes (same sensors placed on weather balloons) to test the feasibility of targeted observations where both sensor and platform could be recovered and reused, as opposed to weather balloons that are one-time use systems. This has grown to now include specific sensor packages and aerial platform combinations. Existing sensors that are placed on various UAS and used to accomplish similar goals include:

Table 1 Common COTS Sensor Options

Sensor	Log Rate	Measurand
iMet XQ	10 Hz	Temperature, Pressure, Humidity GPS Lat, Long, Alt
Young 3D Ultrasonic Anemometer	32 Hz	Wind Speed and Direction
FT 2D Ultrasonic Anemometer	10 Hz	Temperature, Wind Speed, Direction
Vaisala RS92 Radiosonde	1 Hz	Temperature, Pressure, Humidity GPS Lat, Long, Alt Derived Wind Speed and Direction

As can be noted from the max data log speeds, the general trend is for systems to output data at maximum rate of 10 Hz with one exception: the Young Ultrasonic Anemometer. This system logs much faster as it is gathering high resolution wind speed and direction data, but the system itself is much larger and heavier than aforementioned systems (2.6 lbs), preventing it from being installed on many UAS. Part of the reason for this cap of 10 Hz is due to the response of most temperature probes. Though data can be logged as fast as the board powering the sensor can read data, each

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Table 2 Spatial Sensor Resolution at 50 Knots Groundspeed

Log Rate	Distance Between Points
1 Hz	84 ft
10 Hz	8.4 ft
32 Hz	2.6 ft
120 Hz	0.70 ft
150 Hz	0.56 ft

sensor has an intrinsic delay between when the environment it is subjected to is accurately read by the sensor itself. By capping speeds at 10 Hz, it is generally assumed that TPH sensors are outside of the response times, as can be seen by many calibration and validation (cal-val) techniques executed for the above COTS sensors. The main atmospheric observations that would most benefit from higher logging rates are wind speed and direction. In general, temperature gradients are not as severe as wind gradients. If wind observations can be logged at a fast enough rate, in theory one would be capable of measuring turbulent behavior, a key component that is still largely unpredictable.

Though the aforementioned sensing systems are generally high accuracy, most target only a specific set of variables rather that a wide array with the exception of the Radiosonde. The downside to the Radiosonde that prevents it from being used for UAS observations is its size and the pre-set rate of 1Hz for data acquisition. Having the capability to log not only TPH data but also wind speed and direction at high rates would be an ideal system. The reasoning for this is shown in the table below, which shows spatial resolution of data points at various logging rates assuming an aircraft is flying at a nominal airspeed of 50 knots:

As is expected, the faster logging rates result in a tighter spatial resolution. This means the sensors from Table 1 that topped out at 10 Hz have an average spatial resolution of 8.4 ft. Though this is sufficient for TPH measurements, this is not sufficient for rapid windspeed and direction observations, which is the reason the Young Ultrasonic Anemometer logs at 32 Hz, yielding an average spread of 2.6 ft between points. Much higher rates (>100 Hz) are required to track rapidly changing or dissipating atmospheric conditions such as turbulence or wind shear (reference here). To supplement the shortcomings of COTS systems for differing target environments, various research groups have developed custom sensors to fill these sensing and data gaps. The University of Kentucky has developed a metal 5HP design to measure 3D wind vectors of their fixed wing aircraft. University of Oklahoma designed a quadcopter with an integrated TPH sensor, called the CopterSonde, that directly measures TPH with triple-redundancy, and uses the internal IMU with calibration offsets to track windspeed and direction when stationary. This system has been calibrated and compared against lidar, ultrasonic, and other sensing systems to verify the results gathered are accurate. Oklahoma State University has designed their own 3D printed 5HP to track 3D wind speed at high resolution while keeping the cost of each sensor package low [12]. This system was designed to operate at 200 Hz, allowing for very high data resolution. Oklahoma State has also developed their own TPH sonde that attaches to both fixed and rotary wing UAS and has flown the sensor along the 100m tower at the Department of Energy Atmospheric Radiation Measurement Climate Research Facility (DOE ARM site) in Oklahoma for data comparison between the sensor and the tower over a variety of altitudes. OSU's sensor has also been tested against 10m tall Mesonet towers that track temperature, pressure, humidity, windspeed, and direction, among other variables.

Meteorological Variables and Accuracies	
Temperature	+/- 0.2 ^{o}C
Relative Humidity	+/- 5.0 %
Pressure	+/- 1.0 hPa
Wind Speed	+/- 0.5 m/
Wind Direction	+/- 5 Degrees Azimuth

Sensor Response Time	
Time	< 5 s (Preferably < 1 s)
Operational Environmental Conditions	
Temperature	-30 – 40 ^{o}C
Relative Humidity	0 – 100 %
Wind Speed	0 – 45 m/s

Fig. 1 Desired meteorological sensor specifications for meteorological observations. [11]

The above table is from an analysis by Jacob et al. on the minimum specs required for atmospheric sensors installed on UAS for the application of Atmospheric Boundary Layer (ABL) research [11]. These values were derived from a collaboration between meteorologists, atmospheric scientists, and engineers on the capabilities required by sensors for accurate measurements of atmospheric characteristics, and as such are the minimum requirements of the custom sensor package. As can be noted in comparing Figure 1 to Table 1, the COTS sensors analyzed previously all exceed these minimum specs for the characteristics each sensor is observing. This means any of the COTS sensor options listed are capable of capturing the changing atmospheric conditions,

II. Sensor Design

Arising from the lack of sensors logging both TPH and 5HP data accurately at high speeds (10 Hz and >100 Hz, respectively), a custom sensor package was developed to achieve each of these metrics. Similar to OU's approach with the CopterSonde, the resulting sensor package is intended to primarily be integrated with the Nimbus VTOL fixed-wing aircraft, though alternate systems can be created on a case-by-case basis for other applications.

A. Component Integration

The system builds on the progress of both the TPH sonde and 5HP from OSU, beginning with the five hole probe design [12]. This system logged data from three Honeywell SSCDRRN001PD2A5 digital pressure transducers to the microSD card of a Teensy 3.6 microcontroller. This system allowed the user to change what data rate the 5HP operated at, from 1 Hz up to the max of 200 Hz. Added to this system were three iMet XF-b thermistors and three HYT-271 humidity sensors, which are the same sensors used in the iMet XQ. In order to integrate these 9 sensors to a single Teensy board, I2C address deconfliction was required. The Honeywell 5HP pressure transducers were all 0x28, which used 3 of the 4 I2C buses on the Teensy 3.6. The iMet XF-b thermistors can be ordered with up to 4 different pre-configured addresses, and the ones used were 0x39, 0x3A, and 0x3B. The HYT-271 humidity sensors are user-changeable and were set to 0x30, 0x31, and 0x32. Both the thermistor and humidity sensors were installed on I2C bus 1 (I2C0) as the repurposed board did not provide access to the fourth I2C bus. Of note is the lack of gauge pressure sensors on this prototype system. This is due to I2C address conflicts between the 5HP transducers and the gauge pressure transducers, as they both have the same basic I2C addresses available. The most readily available of both types is 0x28, which requires access to the fourth I2C bus in order to integrate the gauge pressure transducer. For the final design, each of the 5HP transducers will operate on their own I2C bus with all the TPH sensors operating on the fourth I2C bus (I2C3), including dedicated gauge pressure transducers. The prototype utilized the 5HP board with wire leads to I2C bus 1 (I2C0) soldered on. These leads were soldered to a breadboard to distribute power to each sensor and simplify the data acquisition process. To prevent the need for a separate GPS system to geotag data points, the RX and TX lines in the Telem2 port of the Pixhawk were wired to the TX and RX ports of the Teensy, respectively. The entire package is powered by the 5V and GND lines of the Telem2 port. A microUSB plug was soldered to the end of these lines to power the board while airborne, ensuring the sensor is acquiring data for the duration the aircraft is booted while minimizing the need for additional batteries onboard.

B. Code for Data Acquisition

The Teensy was programmed to compile data from the 9 sensors on the prototype and receive data from the Pixhawk simultaneously, logging all data to the SD card. It did this by having a MavLink data parsing code interpret Pixhawk data, namely time since boot (microseconds) and time since Unix Epoch (milliseconds, synchronized UNIX clock from GPS timestamps). Any data acquired by the Pixhawk (IMU, attitude, states, etc.) can be gathered, but the goal was to reduce the total amount of parsing by sending only the aforementioned time stamps to the Teensy. With this in mind, a static offset between the Pixhawk board time and GPS-adjusted UNIX times can be established. A second static offset between the Pixhawk board time and the Teensy board time can be established and a similar (but not identical) offset applied to effectively tag each individual TPH and 5HP data point with a unique date and time stamp from the GPS system. This MavLink parser recorded values every time a unique time value was provided by the Pixhawk, which for testing purposes was set to 1 Hz but will be increased to 10 Hz for the final design for greater temporal resolution.

The thermistor and humidity values were recorded at a user-defined speed, which was set to 10 Hz to match the current COTS limitations. The humidity values were simple I2C read requests from the Teensy where each byte was recorded and bit shifted until all expected values are present for a given read, then converted to their respective temperature and humidity values. The thermistor values were recorded by reading ADC values from the thermistor boards and converting the scalars to their respective variables (temperature and voltage). The speed at which these sensors can operate is dependent on the read speed of the ADCs. By default, the library for the thermistor ADC (Adafruit_ADS1X15, using ADS1115 ADC) has a delay of 9 milliseconds per read. With a total of 4 ADC reads per thermistor across 3 thermistors, this led to the max operating rate for the temperature and humidity sensors to be 13 Hz with an average of 10 Hz. However, by increasing the internal sampling speed in the library to its max, the delay could be safely reduced to 2 ms, increasing the max speed of the temperature and humidity sensors to 41 Hz. Of note, the sensors themselves may not be capable of acquiring data at this high of a speed due to the sensor's response time. Much testing of each sensor's response time must be conducted before a given logging rate can be fielded. However, increasing the overall efficiency of the sensors to achieve this max operation speed allows for the the overall acquisition rate to be scaled back to lower values, allowing for additional CPU time to be used for integration with the 5HP sensors without sacrificing performance.

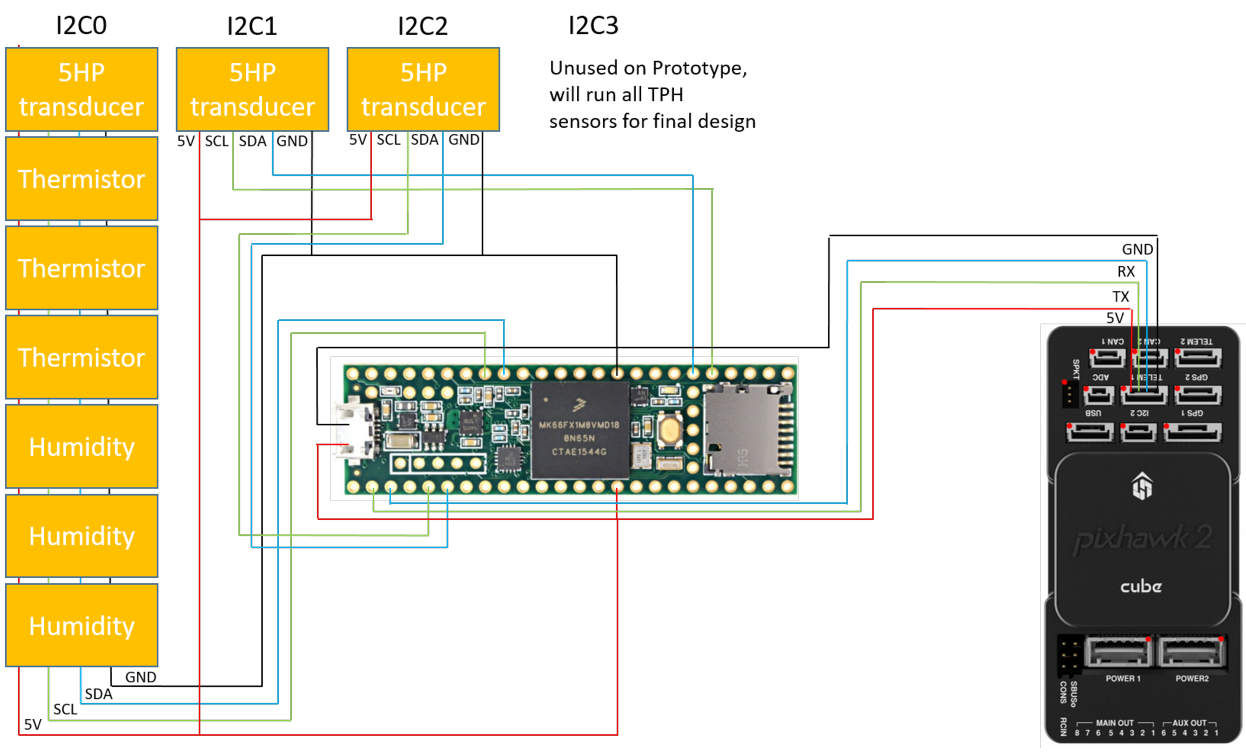

Fig. 2 Wiring diagram of prototype sensor package

The pressure transducer values for the 5HP were recorded with every cycle of the Teensy's main loop. With no other code on the Teensy except for what is necessary for 3 pressure transducers, the data will output at a maximum stable speed of 200 Hz due to a 5 ms delay required to read all three 5HP transducers. When the Pixhawk parsing code is added to the system, there is no change, a full 200 Hz output can be achieved with Pixhawk timestamps logged. When adding in the temperature and humidity sensors, the data rate of all sensors become directly related to the data rate of the temperature and humidity sensors, as can be seen in Table 3. This is due to the much longer read times associated with the total of 12 ADC's per TPH measurement.

Table 3 Dependency on Temperature Data Rate

Temp Log Rate	5HP Rate Before	5HP Rate After
10 Hz	50 Hz	160 Hz
5 Hz	119 Hz	167 Hz
2 Hz	155 Hz	174 Hz

The goal of this sensor was to, at minimum, match the capabilities of the COTS sensors, and by altering the default thermistor library within the manufacturer's specifications, the package is capable of acquiring data at the same rate as COTS options while having the versatility to feature a custom 5HP. Though gauge pressure transducers have not yet been added, they have been tested and verified to operate at the same speed as the differential pressure transducers used for the 5HP. Integrating the gauge pressure transducers is expected to reduce the overall speed, but not dramatically as it will only be polled at the rate of the temperature and humidity sensors, which is 15 times slower at the chosen default speed than the 5HP sensors are polled at. Of note with this sensor setup: the TPH and 5HP speeds can be tuned independent of each other, Table 3 just shows the current max operational speeds at given TPH speeds. This means, should high rate windspeed and direction not be needed, it can be reduced or even turned off in favor of the TPH data. Likewise, the TPH rates can be reduced or even turned off entirely to capture the full 200 Hz data rate seen from standalone testing. This is a unique feature that is not seen in COTS systems, as it allows the user to program the sensor package as a standalone TPH system, standalone 5HP system, or a combined sensor, whichever the user requires for the situation.

C. Data Handling

One of the major issues with fielded flight campaigns utilizing multiple sensing systems spanning many days in series is the proper tracking of data files, storage locations, and data parsing techniques of each sensor for future use. One such case is for the iMet XQ, which can take anywhere from 5 minutes to an hour to offload data depending on how full the memory is and it requires (free) specific software in order to convert the data to usable CSV files. OSU's TPH sonde required loading the .CSV data into Microsoft Excel and parsing all the data by hand, which for a large number of data sets could be overbearing. To overcome this, a Matlab GUI was created to allow a user to set what data parameters are gathered, navigate to the file, and the program parses all data files of the set (including Pixhawk autopilot log, sensor package data, iMet data, etc.) based on user-chosen start and end points, outputting parsed data files in .csv format, and providing plots comparing different data sets to the actual flight characteristics. The program keeps the user's chosen settings for the next set of analysis, allowing for a rapid parsing of similar data sets.

III. Flight Testing

A. Initial Flight

As part of the initial testing of the sensor, the package was installed in the nose of a VTOL Nimbus, a fixed wing aircraft with tilt motors and a single rear propeller. The prototype package, featuring 3 Temperature and 3 Humidity sensors with a 3D-printed 5HP and 3 corresponding differential pressure transducers, a was flight tested alongside an iMet XQ for data comparison. The payload was installed in the nose of the aircraft to ease installation of the package while ensuring the sensors would have clean airflow while the aircraft was in fixed-wing flight.

Fig. 3 Installation of prototype sensor package in Nimbus nose.

Fig. 4 Nimbus with sensors installed prior to flight test

The following figures depict flight values recorded from the first data collection flight: Figure 5 shows 5HP and Figure 6 shows TPH data.

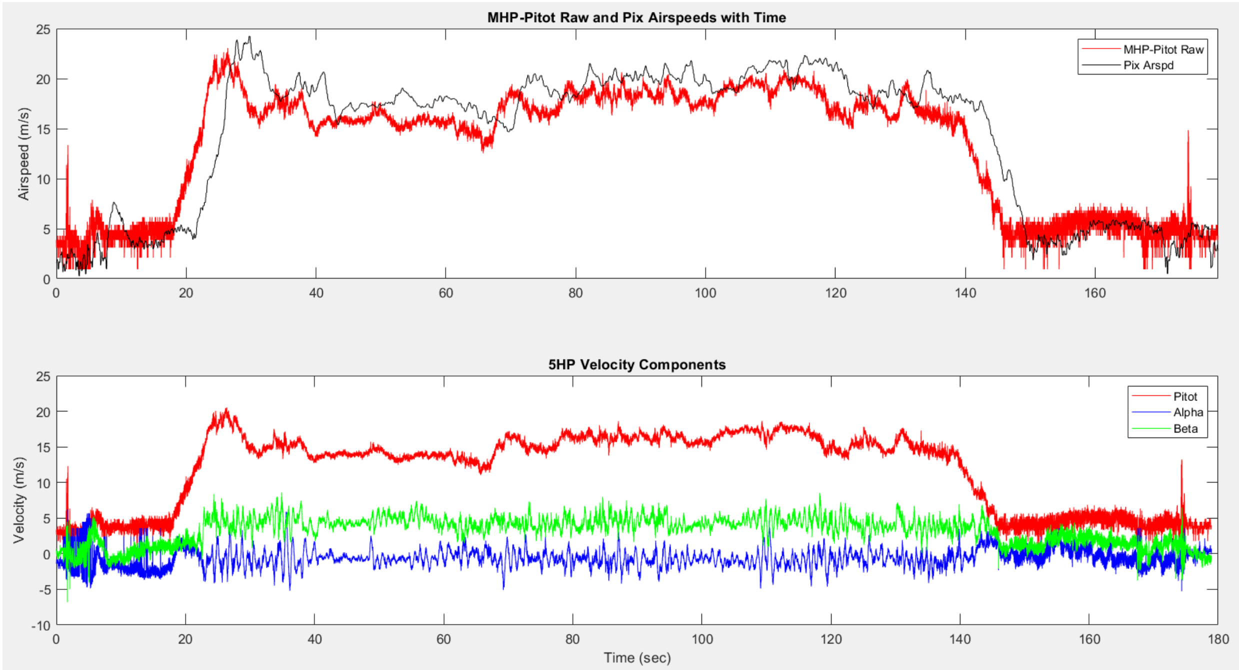

Fig. 5 Initial flight test of uncalibrated 5HP vs Pixhawk Airspeed.

The top plot of Figure 5 shows the Pitot portion of the uncalibrated 5HP tracked the Pixhawk airspeed sensor very well in fixed-wing flight. Though the exact values do not agree for a given time stamp, the general trends appear to agree with future calibrations helping the values more closely align. In fact, it would seem the 5HP pitot leads the Pixhawk-recorded airspeed, suggesting that the 5HP receives, processes, and records the data at a much faster rate than the Pixhawk itself can. This makes sense, as the Pixhawk is merely using airspeed as a method to "speed scale" the PID outputs with the secondary task of showing that data to a user on a ground station. This implies the Pixhawk airspeed logs recorded may not necessarily fully correlate with the given time value, but that airspeed value is "close enough" for the internal loops to run with minimal issue. This could be one area to focus on in future work, as it could pave the way for an external airspeed sensor (like the pitot of the 5HP) to be logged in unison with the Pixhawk, allowing for a clearer view of aircraft response to wind gusts.

In the bottom plot of Figure 5, each individual velocity component of the 5HP can be seen. Though each reading is showing the actual velocity recorded by the differential pressure sensors, these values will be converted into angular values and compared against aircraft angles to derive approximate wind magnitude and direction in conjunction with effective airspeed values. Though the Nimbus VTOL features tilt rotors, which would normally highly disturb the 5HP data being recorded on the nose, the data being represented here has already undergone a single layer of filtering, using a 1D interpolation from data gathered in a wind tunnel. Further analysis into the operation and calibration process of the 5HP can be seen in [12].

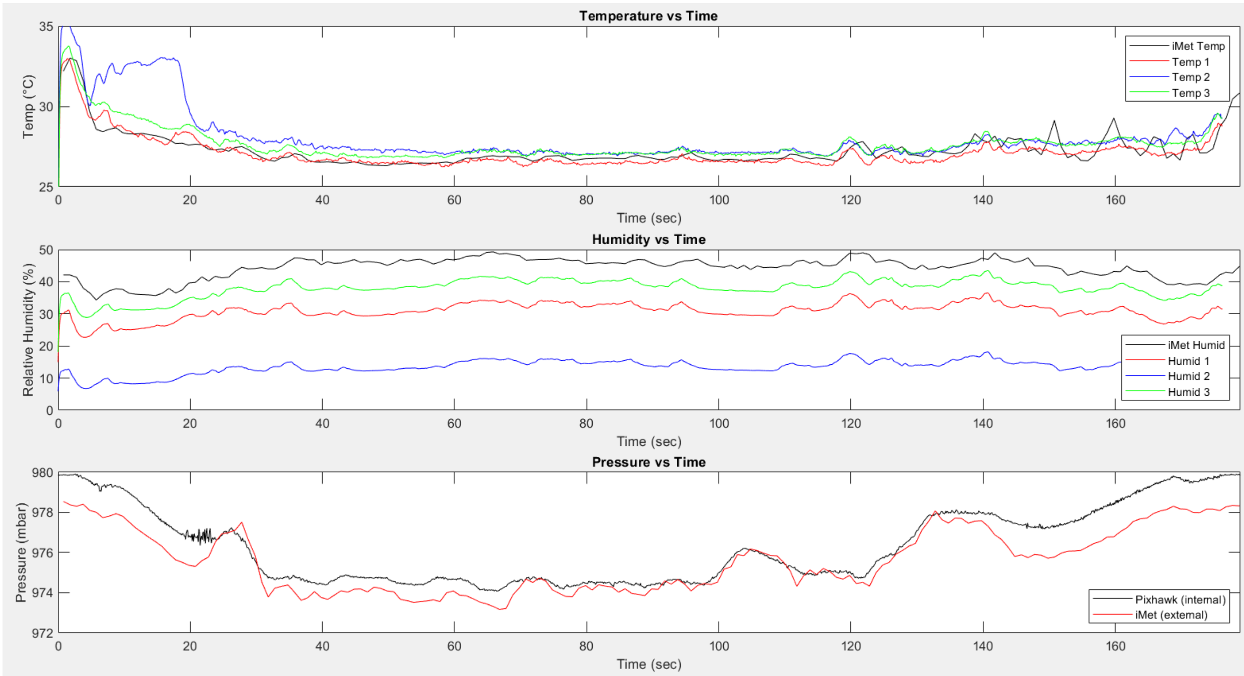

Fig. 6 Initial flight test of uncalibrated Sensor Suite vs iMet XQ and Pixhawk data.

From the above data, it can be seen that the uncalibrated sensor package seems to agree with the iMet XQ in temperature during the flight. In humidity, however, the suite only matched the general trend of the iMet XQ, not the actual relative humidity values. A positive takeaway is it seems a static offset is all that is required to align all three humidity values to match the iMet value, as there is little to no drift in the offset required based on the above plot. The final plot shows the sensitivity of the gauge pressure reading to the aircraft in flight. From the plot, takeoff and landing seems to effect the iMet XQ reading (as the aircraft is a tilt-rotor VTOL platform), but mid-flight the two agree very well. This implies that while takeoff and landing data can be rejected, all in-flight data should be assumed to be valid, including any gauge pressure transducers that may or may not be externally mounted.

B. Data Comparison Flight

For a full system data comparison test, joint flights were conducted with the University of Oklahoma's Center for Autonomous Sensing and Sampling team on August 6th, 2020 at OU's Kessler flight field. The CASS team has developed a CopterSonde, a quadcopter outfitted with 3 temperature and 3 humidity probes that relies on Pixhawk internal barometric pressure readings for the atmospheric pressure. This aircraft has been finely tuned to allow for recovery of wind speed and direction data directly from the Pixhawk. The goal was for two Coptersondes to fly a vertical profile up to 1500 meters AGL while the Nimbus ascends in an orbital pattern centered around the Coptersondes, allowing for all three aircraft to sample what is assumed to be the same simultaneous environment. Though both aircraft collected data, access to the data logged from the CopterSonde is not yet finished. As such, only Nimbus data can be shown until that data is fully processed, which is shown below.

The above plots show how the 5HP performed as the Nimbus flew the ascending orbits around the CopterSondes. The 5HP does not lead the Pixhawk airspeed data like was seen in the first flight, and the 5HP airspeed is now significantly offset from the Pixhawk airspeed values. The key takeaway is that the value still seems to follow a static offset, so once calibration is undergone, these errors should be effectively removed from the system. Though the 5HP velocity components are again plotted, the conversion to angular degree components have not been completed due to progress still needing made into deconstructing the aircraft body dynamics.

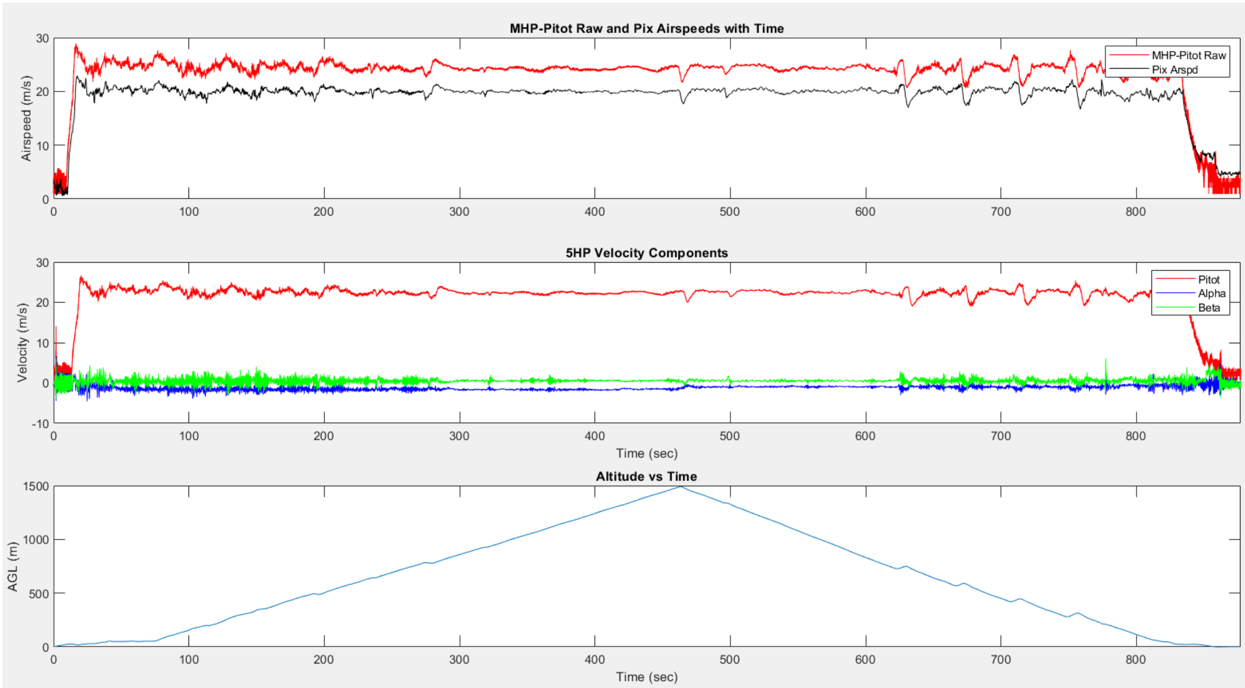

Fig. 7 Uncalibrated 5HP data from Kessler flight on 8-4-2020.

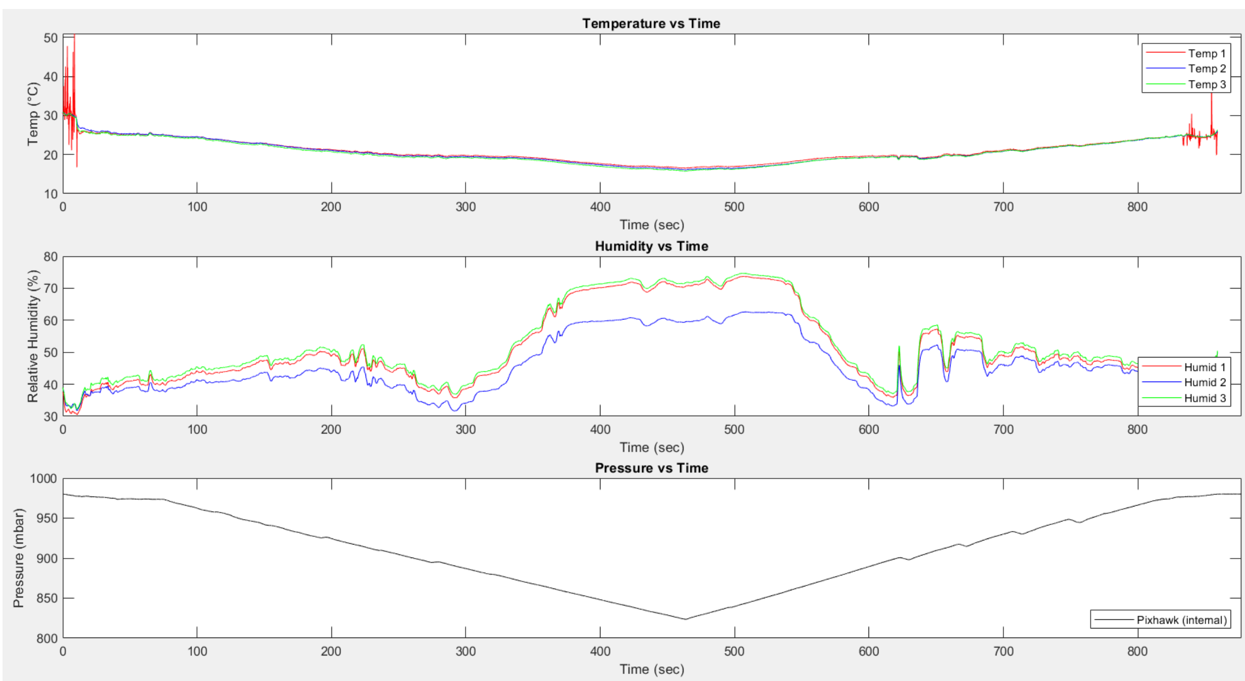

Fig. 8 Uncalibrated TPH sensor suite from Kessler flight on 8-4-2020.

As for TPH values during the flight, a noticeable disturbance exists at the beginning and end of the flight regimes. These disturbances correlate with the takeoff and landing of the Nimbus, so the data can be fully rejected. The rest of the flight shows the temperature probes not only tracking trends together, but also having the same temperature value.

The Humidity probes, however, still are only showing the same trends, the true value still needs calibrated before all three probes agree. This flight test bodes well for the future of the system, as each successive flight test points to a single offset from calibration of each sensor is all that appears to be needed to get all sensors operating to the level expected.

IV. Final Design

The final board design will feature the same temperature and humidity sensors, though the Honeywell SSC series 1 psi differential pressure transducers will be replaced with HSC series 0.5 psi differential pressure transducers. Switching to these sensors reduces the max velocity from 207 knots to 104 knots. Though the max wind speed capable of being measured will be reduced, the resolution of the measured data is greatly increased. The sensor limits for both sensors are between 5% and 95% of the full data range, meaning no data is logged below 10 knots for the 1 psi sensor. This correlates to inaccurate data at low speeds (<20 knots), which is not ideal for an aircraft with a cruise speed of 40 knots. At the Nimbus' cruise speed, the sensor would only be utilizing 20% of the total sensor range. Similar datasets on the 0.5 psi sensor allows for low-value cutoffs of 5 knots with a low range accurate values beginning at 10 knots while using 41% of the total sensor range at the cruise speed. This allows for headwind gusts of up to 60 knots in cruise flight before the sensor maxes out, utilizing a greater portion of the total sensor data range.

Due to the continuing impact of Covid-19, the final sensor board was not able to be produced as anticipated, as the same pressure transducers targeted for the 5HP were highly sought after for rapidly assembled, emergency ventilators to combat low ventilator counts across the country.

V. Future Work

The biggest item to focus on going forward is the final board design. The exact dimensions are currently unknown as sensor availability directly impacts the overall footprint of the package. Ideally, Honeywell HSC series differential and gauge pressure transducers are used for the 5HP and atmospheric pressure readings (respectively), while the existing harness for the TPH sensors can be minimized with direct connections to the master board. This would allow for additional flexibility in mounting the board on an aircraft, a luxury not currently available.

The next step would be to calibrate and validate the sensors to ensure the values they register are reliable. The 5HP pressure transducers can be calibrated in a wind tunnel (as is currently being done in [12]), while the TPH sensors will need to undergo testing down at the University of Oklahoma's research lab, Center for Autonomous Sensing and Sampling, who has a chamber specifically designed to calibrate and validate TPH sensors.

A future goal is to integrate the differential pressure transducers into the 5HP itself (as it is a custom 3D-printed design) and use a harness to attach to the Teensy. This would allow for both the 5HP and TPH sensor sets to be interchangeable on the logging board. If each of these items are serialized and calibrations well documented, this would allow for different combinations of each, allowing for rapid sampling of parts should one or more sensors become defective during use.

Currently under development is a user-friendly GUI that rapidly processes and pushes all data to a server for storage of parsed data sets. This would allow for data to be sampled, the aircraft land, and be uploaded to a remote server in a matter of minutes. This is a precursor to live data upload directly to meteorologist's weather models, allowing for improved forecasting.

VI. Acknowledgements

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