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Power-over-Tether UAS Leveraged for Nearly-Indefinite Meteorological Data Acquisition

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ABSTRACT. *Use of unmanned aerial systems (UASs) in agriculture has risen in the past decade. These systems are key to modernizing agriculture. UASs collect and elucidate data previously difficult to obtain and used to help increase agricultural efficiency and production. Typical commercial off-the-shelf (COTS) UASs are limited by small payloads and short flight times. Such limits inhibit their ability to provide abundant data at multiple spatiotemporal scales. In this paper, we describe the design and construction of the tethered aircraft unmanned system (TAUS), which is a novel power-over-tether UAS leveraging the physical presence of the tether to launch multiple sensors along the tether at multiple altitudes. With power from a ground station, the TAUS can acquire continuous data for several hours . The system is used to sense atmospheric conditions and temperature gradients across altitude. The development of the prototyped system is presented, along with the results of field experiments. The influence that power losses across the tether have on the sensors' abilities to accurately sense is discussed. We demonstrate a 6-hour continuous flight at an altitude of 50 feet, and a 1-hour flight at sunset to acquire the gradually decreasing atmospheric temperature from an array of 6 sensors. An empirical evaluation of the system's performance found that the prototype successively demonstrated proof of concept by considerably increasing flight times and throughput by simultaneously acquiring data from the sensor array. The TAUS will be improved by integrating performance-monitoring circuitry, elevated levels of algorithm-based autonomy, and multivariable sensors.*

Keywords. *Power-over-tether, temperature sensors, TAUS, UAS, UAV.*

Introduction

Over the years, the agricultural sector has continuously used various sensors and robotic systems in their work (Shekhar et al., 2017, and Lawrence-Dill et al., 2018). Successful and sustained applications have taken the form of automated field machinery (Lei & Yong, 2005, and Katupitiya et al., 2005), weather stations (Hubbard, et al., 1983), and a network of soil moisture sensors for precision irrigation (Dong et al., 2013), among many other applications. These systems have helped increase efficiency and production in the agricultural sector. In recent years, unmanned aerial systems (UASs) have become more ubiquitous and offer the ability to acquire data from various altitudes and resolution that was traditionally hard to access. UASs have found their way into agriculture with applications in environmental and phenotype monitoring via red, green, blue – depth (RGB-D) (Vit & Shani, 2018), normalized difference vegetation index/near infrared (NDVI/NIR) (Gennaro et al., 2018), and hyperspectral (HS) imaging (Saha et al., 2018). Other non-imaging application can take the form of atmospheric sensing (Wivou et al., 2016) and precise applications of pesticide (Mogili & Deepak, 2018), among other proximal sensing capabilities. Typically, UASs are assumed to be a multi-rotor variant, but even fixed wing UASs have shown promise in providing the sector data (Pederi & Cheporniuk, 2015). Data from onboard imaging and environmental sensing are more pertinent, unique, and readily available to farmers, improving our abilities to predict phenotypes.

Despite the advantages UASs provide, they have practical limitations. Current commercial off-the-shelf (COTS) systems are limited in their maximum payload and duration of flight; therefore, travel distance and volume sensed are limited. In addition, COTS systems overall lack autonomous operation, an aid in user friendliness and system integration. A flight duration of only ~30 minutes roundtrip from a higher-end COTS system is limited in representing both space and time, leading to constrained agricultural decisions, predictive evaluations, and applications. Based on a survey of agricultural decision makers (Frisvold & Mu-rugesan, 2012), particularly producers, atmospheric temperature data ranked a close second to soil moisture amongst the most important information. Temperature data aids in decisions about planting, harvesting, defoliating, crop modeling, and preventing diseases and pests, among others. Therefore, there exists an agricultural application for an affordable UAS that can autonomously dispatch itself, self-sustain operation in an isolated agricultural location, and continuously acquire high spatial and temporal resolution atmospheric temperature data. Furthermore, as a basic and easily sensed physical variable, atmospheric temperature can be used to assess the robustness, reliability, and suitability of the platform. This leads us to the question: Can we develop a novel UAS that can increase flight times and throughput of useful data for the agricultural sector? We hypothesize that we will be able to accomplish this if we engineer a novel UAS powered over a tether that leverages the physical presence of the tether for placing meteorological sensors. In doing this, we predict that the system will gain increased flight times and throughput, but we acknowledge it will become spatially bounded by the tether, creating a new system limitation. In this paper, we present our preliminary design of the tethered aircraft unmanned system (TAUS), which includes a direct current (DC) to DC-based power-over-tether and an array of discrete temperature sensors. We also present results of a series of preliminary field tests to acquire data and evaluate the performance of the prototyped system.

The main contributions of this work are:

- Development of a novel power-over-tether UAS prototype that includes temperature sensors placed along the tether.
- Preliminary field experiments and results demonstrating the viability of this platform to sense temperature fluctuations within a 50-ft range.

Related Work

UASs have been previously engineered to be powered over a tether (Zikou & Papachristos, 2015), and there are multiple companies founded in recent years that leverage this technology to accomplish various tasks such as surveillance (Hoverfly, 2020, Elistair, 2020, and Powerline, 2020), and cleaning off high and hard-to-reach structures with pumped water and solution (Ibekwe, 2018). *To our knowledge, our project is the first one attempting to leverage the physical presence of a power-over-tether UAS to acquisition a gradient of environmental data--in particular, surface atmospheric temperature.* Current technology that attempts to sample the troposphere is lighter-than-air (LTA) radiosonde, (better known as weather balloons). Twice a day every day in the conterminous United States, 69 weather balloons are simultaneously released to acquire temperature, pressure, and relative humidity as the balloons ascend to approximately 35 km, relaying sensed data every 1-2 seconds for approximately 2 hours. This low-resolution spatial and temporal data is then used to drive weather models to help make weather predictions even locally despite major generalization due to the spatial and temporal resolution. This form of technology is often deployed without a physical tether and, therefore, not recovered due to a lack of system position control and significant physical drift up to 300 km caused by wind (NOAA, 2020). This drift has shown to have a negative effect on high-resolution data accuracy (Laroche & Sarrazin, 2013). An attempt to use a typical battery-powered hexacopter UAS to sample the troposphere to address the drift limitations of weather balloons (deBoisblanc et al., 2014) and improve on-board sensor performance (Islam et al., 2019) was carried out with success. Another current technology that samples the atmosphere at constrained spatial extents are Eddy-covariance (EC) towers. This technology samples the troposphere's vertical profile at a high frequency from ground level to fixed heights typically ranging anywhere between 8m and 75m. The sampled data is typically used to derive air quality via concentrations of gases and their flux (NSF-NEON, 2020), as well as gas and water exchanges between the atmosphere and the land surface. Tower installation is relatively expensive, and there are only about 800 active and registered towers with the FLUXNET global network database (FLUXNET, 2020), and 300 active and registered towers with the AmeriFlux network database (AmeriFlux, 2020). This means there is low spatial resolution, and since these are physical towers intended for long-term sensing, this technology is not readily deployable.

Materials and Methods

The proposed TAUS prototype is shown in Figure 1. In this section, we will discuss the system's electrical, mechanical, and computational components. The TAUS is composed of three major subsystems: ground, tether, and aerial. The subsystems are physically linked via the tether subsystem. The composition of each subsystem is presented in Table 1.

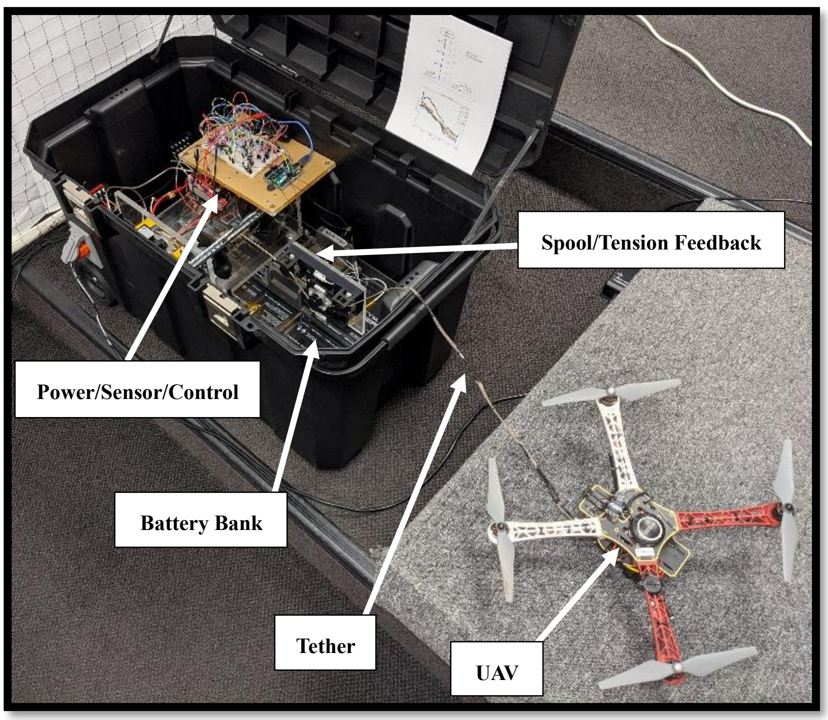


Figure 1 – TAUS prototype.

Table 1 – TAUS Composition (major components of subsystems)

Ground	Tether	Aerial
Containment Structure	4C 22 AWG (50ft)	DJI F450 Flame Wheel
Battery Bank (2S3P)	DS18B20 Temp. Sensor (6)	Pixhawk Flight Controller
DC-DC Boost Circuit		Pixhawk Peripherals
Sensor/Control Circuit		Futaba RC Rec. (2.4 GHz)
Spooling Mechanism		DC-DC Buck Circuit
Tension Feedback Mech.		

The *ground subsystem* is composed of a battery bank, power/sensor/control circuitry, and a mechanical spooling and tension feedback mechanism all packaged in a containment structure. The battery bank is 6 Mighty Max deep cycle 12 Volt (V) DC 22 Amp-hour (Ah) batteries compartmentalized and configured as 2-series 3-parallel (2S3P), as shown in Figure 2. This configuration allows for an overall nominal battery bank supply voltage of 24 V at 66 Ah of capacity. Since the primary electrical load of the battery bank is an unmanned aerial vehicle (UAV) that is inherently weight limited and requires a DC supply, we decided to maintain DC throughout the entirety of the system. Advancements in power electronics allow us to easily and efficiently modulate DC voltage, providing us the opportunity to avoid heavy power transformers, and rectifier circuits. Therefore, an adequate DC-DC step up (Boost) circuit was integrated that could increase the voltage and source enough DC current to the load across the tether. These electrical parameters were derived by first measuring maximum power demands of the load and working power calculations backward to the source, which can be seen in Figure 3. At maximum throttle, the UAV demands a steady 12V and 30A or 360 Watts (W) of power. Therefore, it was determined that a Boost circuit that could raise the voltage to ~55V and source a current of 8A was adequate for 50ft of tether. A custom spool was coupled with a slip ring and mountable bearing to allow for seamless electrical contact while rotating. The spool was designed in OpenSCAD and 3D printed on a Markforged-Mark Two printer with Onyx filament. The bidirectional nature of spooling was achieved with a high torque DC motor controlled by a high-power H-bridge circuit. The decision to either release or retract tether from the spool is determined by a custom-designed tension feedback mechanism shown in Figure 4. The center section of the mechanism can actuate vertically and, in doing so, magnetically couple to one of two reed switches mounted on the device. The spool controller can exist in only 1 of 3 clearly defined states at any moment in time; therefore, control of the spool can be described as a rudimentary finite state automaton. The 3 states from the tension feedback system are designated high-tension, low-tension, or explicitly neither state, a steady state. To interpret sensor data and control the various aspects of the ground subsystem, we integrated a microprocessor into the system. Specifically, we used a standard AVR architecture 8-bit 16-Mhz ATmega328P. The processor was programmed in C via the Arduino integrated development environment (IDE).

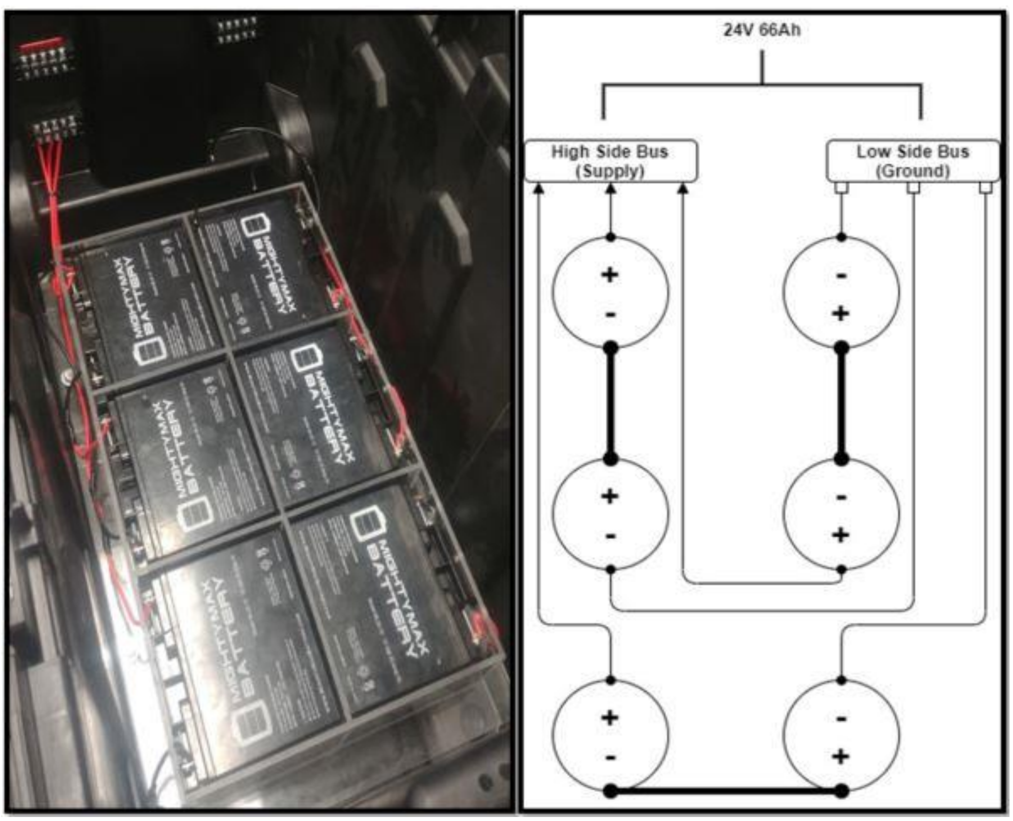


Figure 2 – Battery bank (2S3P) at 24V and 66 Ah of capacity.

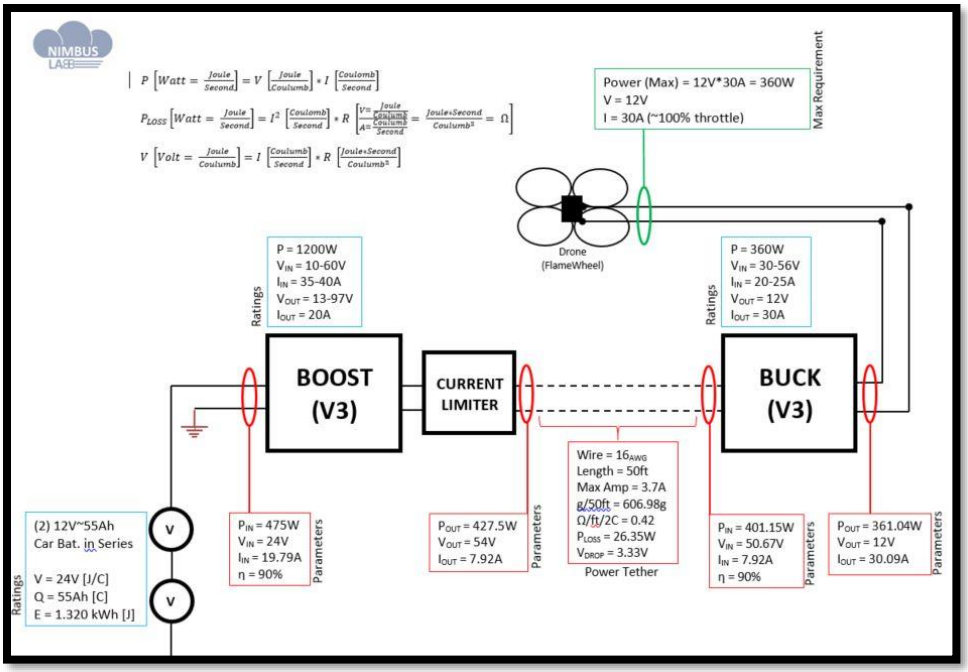


Figure 3 – Example of power calculation results.

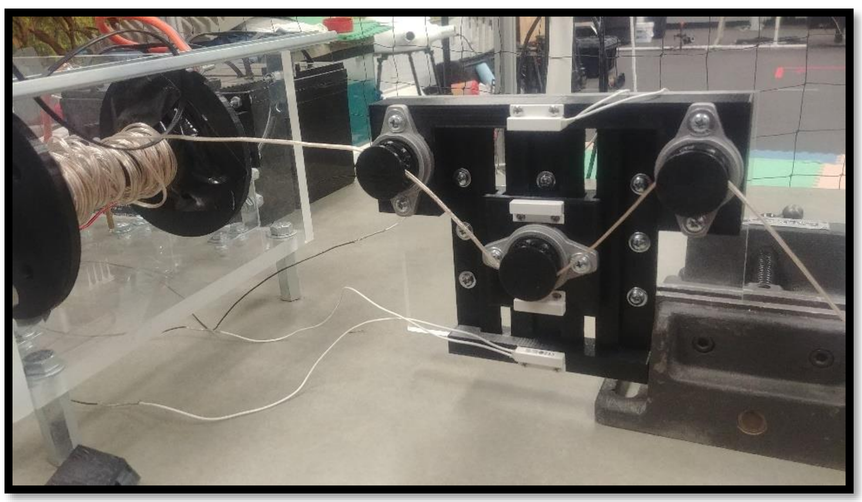
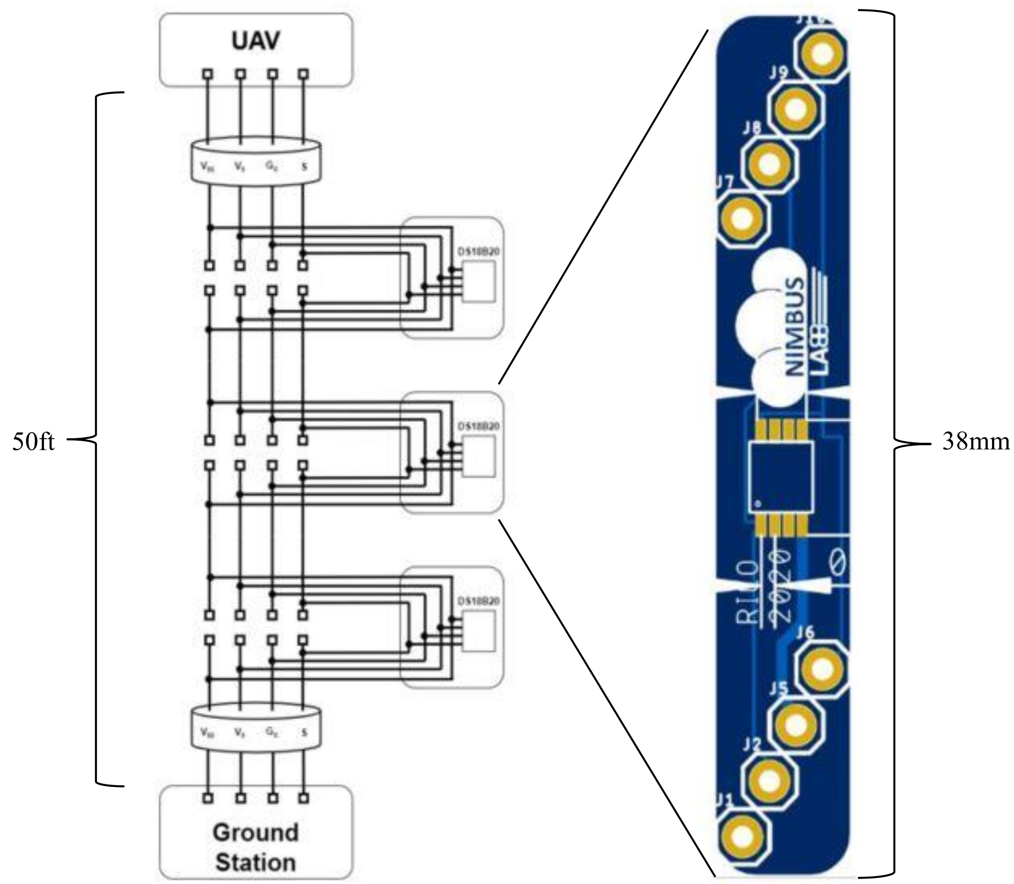


Figure 4 – Spooling and tension feedback mechanism.

The *tether subsystem* is composed of the physical power tether and the temperature sensor array along the tether. Since the amount of released tether from the spool contributes to the overall weight the UAV experiences, it benefits the overall system if the tether is minimum gauge and, therefore, weight. The gauge and composition of the tether has implications on the power calculations previously discussed. In general, power transmission is proportional to an inverse relationship between tether wire gauge and the transmitted voltage across it. If you want to decrease the tether, you need to increase the voltage. The reason this is so is that the wire is rated for a particular continuous current, which if exceeded for a time, can result in the wire becoming thermally compromised and resembling the behavior of a fuse, creating an open circuit. With this in mind, we initially engineered the prototype to work with a 22-gauge tether. As discussed, limiting the weight of the tether is ideal; therefore, adding temperature sensors along the tether will increase the overall weight, particularly because of an additional communication line. If the sensors used require an independent communication line, implementation becomes impractical. Thus, we decided to integrate the DS18B20 temperature sensor. This integrated circuit (IC) has a reprogrammable resolution up to 12 bits, and can communicate via 1-Wire protocol at a nominal sampling rate of ~0.750 Hertz (Hz). This is a unique form of open drain communication similar to inter-integrated circuit (I^2C), but instead of a designated clock and data line, these sensors rely on a single communication line.

We integrated sensors along the 4C tether in tapped-off parallel fashion on PCBs (see Figure 5). The field test configuration, with sensors integrated every 13ft, is shown in Figure 6. This placement scheme was determined based on high-sensor sampling resolution and the minimum possible natural atmospheric temperature gradient. A high-quality iMet temperature sensor was present on the ground alongside another DS18B20 sensor (Sensor 7). These ground sensors allow for a static undisturbed temperature reference to match the physically dynamic array's data against.

When dealing with power transmission, power losses are inevitable due to quantum collisions as electrons flow along the conductors. These losses can be expressed as $P_{loss} = I^2R$, where 'I' is current (charge/time) in Amperes and R is the resistance in Ohms across the conductor. These collisions release energy in the form of heat, which increases the temperature of the conductor. To determine the effect this generated heat has on the sensor ability to accurately sense the atmosphere, two sensors were placed at each position. One sensor is physically touching the tether influenced by conduction, and the other sensor is 4 inches off structure influenced by convection. Results derived from this sensor configuration will dictate future sensor placement.



(a) (b)

Figure 5 – Sensor in-line integration diagram (a), and the PCB for surface-mount sensors (b).

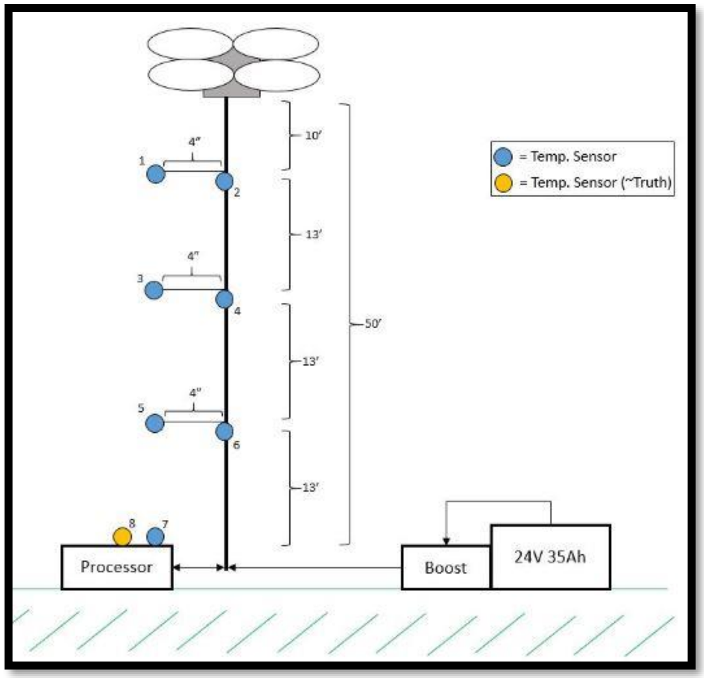


Figure 6 – Field experiment high-level diagram.

The *aerial subsystem* is composed of power circuitry, and a COTS quadrotor UAV with flight controller and associated peripherals. Specifically, the UAV is a DJI Flame Wheel F450 (DJI, 2020), and the coupled flight controller and remote control (RC) is a Pixhawk PX4 (Pixhawk, 2020), and Futaba T6J, respectively. As discussed, the UAV is expecting a steady 12V DC supply, but at various low electrical load conditions, low throttle, the UAV will experience nearly all of the 55V stepped-up voltage from the Boost circuit. The UAV and flight controller onboard power electronics are not rated for such a high sustained supply voltage. Therefore, we integrated a DC-DC step down (Buck) converter circuit onboard the UAV that is rated for such input conditions but can still source up to 30A for max throttle.

Upon complete physical construction of the TAUS prototype, we conducted outdoor experiments to assess the effectiveness of our system in the field. We looked to first test the system's ability to fly for significantly longer times than typical COTS systems and, second, to simultaneously sense the atmospheric temperature from the array of sensors integrated along the tether. Taking into account the capacity of the battery bank, average demand of the load, and a COTS system average flight time of 30min, we decided a field test of 6 continuous hours or a 12-fold increase at an above-ground level (AGL) of 50 feet would be a satisfactory demonstration and benchmark. When carrying out the test, we used an autonomous flight mode on the flight controller that attempted to hold a particular GPS position. We also used an onboard barometer to attempt to hold a particular altitude. In regard to a field test to determine the sensor array's ability, we decided to run an hour-long AGL of 50 feet test at sunset. We chose sunset because it is a predictable period of time each day where a natural and deliberate decreasing transition of atmospheric temperature can be observed. The experiments were conducted at North 84th Street and Havelock Avenue in Lincoln, Nebraska, USA.

Results and Discussion

The long-term 6-hour continuous flight field test ran to completion and was therefore determined a success. Since the test was carried out in an autonomous fashion, it should be noted that a human had to periodically intervene to reestablish an appropriate AGL. This drift is to be expected due to the significant duration of the test and the inherent limitations of a single, onboard reference barometer. The second test previously described also ran to completion and successfully acquired atmospheric temperature data from the sensor array along the tether shown in Figure 6. It was expected that when the temperature data acquired from the sensor array was plotted, we would see a decreasing trend due to the setting sun, and that is exactly what we see in Figure 7. We conducted the experiment for approximately 1 hour at sunset. The array of sensors were able to collect 2,389 raw samples where 60 (2.5%) were erroneous. Thus, the total net number of samples acquired from the array was the difference of the raw and erroneous samples, which is 2,329. Taking the raw number of samples into consideration, the array sampled at a rate of 0.664 samples per second (0.664 Hz), or 39.82 samples per minute. As previously stated, the anticipated sampling rate for each sensor and, therefore, the array is ~0.750 Hz. This is a difference of 0.086 Hz meaning the array sampled 11.47% slower than expected. This divergence may be explained by the unique sensor configuration and nature of open drain digital communication. The communication line is pulled up to 5V through an external 3.9 Ohm resistor. When the data line is dynamically returning to a high steady state, it must first load the parasitic capacitance of the line through the resistor. The time it takes to do this is expressed as: tau = RC, where R is the pull up resistor in Ohms and C is the load capacitance of the communication line in Farads. Since our configuration places sensors along a relatively long communication line, the parasitic capacitance effect and multiplicative term becomes more influential. This delay may have propagated throughout the duration of the field experiment, resulting in the reduced sampling rate we observe.

The immediate differences observed between Sensor 1-6 and Sensor 7 from the data can be largely explained by sensor physical distance to the ground. The surface of Earth absorbs the sun's shortwave ultraviolet (UV) electromagnetic radiation heating and radiating away via longwave IR radiation after a latency period. This clear differentiation we observe is presumably due to this effect. It should be noted that at ~1500 samples into the experiment, a human had to intervene and correct the TAUS's AGL. The sharp disturbance that can be observed in the data is a result of this adjustment taking place. When looking closer at Figure 7 (a), (b), and (c) we can clearly see points of intersection where two sensors (excluding Sensor 7) exchange profiles. In all three graphs, the sensor that was on-tether initially sensed lower atmospheric temperatures relative to its off-tether counterpart. This is more clearly represented in Figure 7 (e) and (f) and Table 2 where all three off-tether and on-tether sensors are presented together, respectively. Early on through the experiment, we see the behavior flips and the on-tether sensors report higher atmospheric temperatures through the duration of the experiment. This behavior may be explained by the influence of the power-tether. Specifically, before the intersection happens, the tether may behave as a heat-sink through conduction to the sensor, and after the intersection as the experiment progresses through time, the tether behaves more like a heat-source. The power losses across the tether would heat the conductors in the tether over time until potentially reaching an equilibrium. Even at equilibrium, the tether would still steadily radiate heat so we should expect the sensors reported temperature data to level off. If we look at 2000 samples onward in Figure 7 (a), (b), (c) and (f), we can see the on-tether sensors head toward a consensus like horizontal asymptote around 24.75 degrees C. If we extrapolate the data further in time, we would expect to see a clear intersection point between all on-tether sensors and Sensor 7, indicating the influence of the power-tether, specifically the power losses have saturated the sensors' ability to accurately sense the atmospheric temperature. To prevent this negative effect, the efficiency of the power transmission across the tether throughout the duration of the experiment must be relatively high.

Table 2 –Fundamental analysis on data for Figure 7 (e) and (f)

Statistic	Off-Tether (°C)	On-Tether (°C)
Maximum	29.56	29.75
Minimum	23.25	24.56
Range	6.31	5.19
Mean	26.08	26.52
Median	26.25	26.44
Mode	24.00	25.06

The prototyped TAUS has been successfully field tested for base functionality, and therefore, we have demonstrated the proof of concept. We uploaded to YouTube a set of videos that track TAUS developments and field experiments through time (Video, 2019) and provide a high-level overview (Video, 2020). The system performance through these two field tests has been evaluated from an empirical perspective. After the tests were complete, we conducted a thermal inspection on the system hardware with an infrared (IR) thermometer. Moderate elevated component temperatures were measured, invoking little concern. The system was immediately re-deployable, showing system reliability. With the successful demonstration and evaluation of increased flight times, coupled with an ability to acquire data from the sensor array along the tether, the hypothesis presented has been tested and verified as a viable solution to our research question.

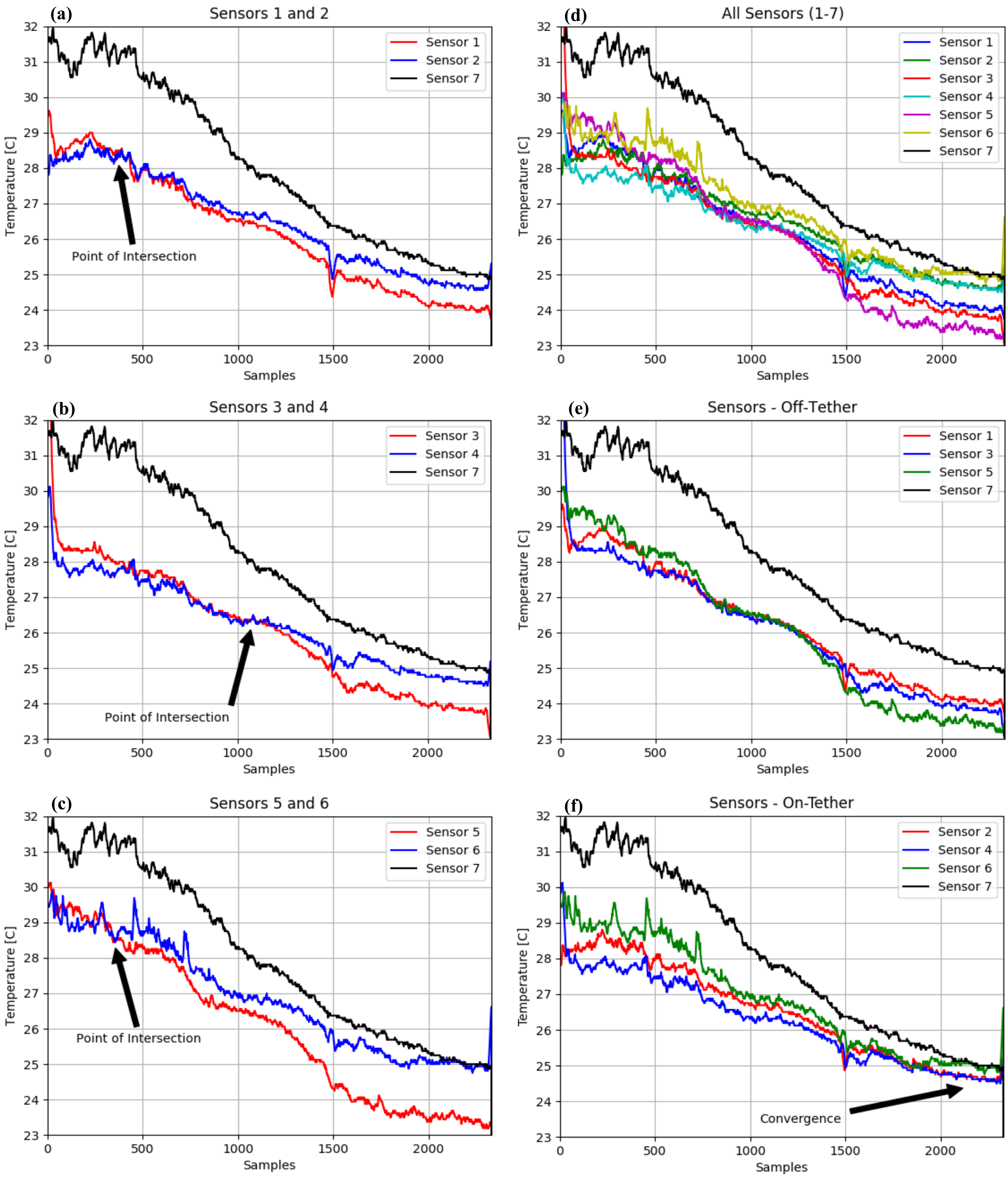


Figure 7 – Field experiment temperature data acquired at sunset. (a) represents sensors 1 and 2 against 7 where the intersection of 1 and 2 is highlighted. (b) represents sensors 3 and 4 against 7 where the intersection of 3 and 4 is highlighted. (c) represents sensors 5 and 6 against 7 where the intersection of 5 and 6 is highlighted. (d) represents sensors 1 through 7. (e) represents the off-tether sensors 1, 3, and 5 against 7. (f) represents on-tether sensors 2, 4, and 6 against 7.

Conclusion and Future Work

A novel UAS was proposed for applications in the agricultural sector. The TAUS was successfully prototyped and field-tested, showing promise as a viable field instrument to help agricultural decision makers make more efficient and optimal choices. Field tests consisted of 6 consecutive hours of flight at 50 ft. AGL, and again at sunset for 1 hour to acquire temperature data. The empirical evaluation shows system robustness and an ability for the system to be redeployed. Our experiments have shown some of the limitations of the system and indicated directions for improvement. There is a significant lack of system performance monitoring, and autonomous abilities preventing this device from being an isolated field instrument prepared for self-deployment. There needs to be more of a quantitative and statistical analysis of the sensor data against high-quality and trusted AGL temperature sensors, perhaps those integrated along an EC tower. Integrating other IC's to sample data such as pressure, relative humidity, and volatile organic compounds (VOCs) will enhance the usefulness of the system to agricultural decision makers. Lastly, creating a network of these systems would increase their overall spatial resolution.

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