Developing a Portable Sensor Package for Remote Delivery by an Unmanned, Aerial System

Adam G. Archuleta[1], Devon B. Campbell[1], M. Tess Geiger[1], Thomas H. Jeffries[1], Kevin P. Mulcair[1],
Nick K. Peper[1], Kaley N. Pinover[1], Esteben F. Rodriguez[1], Johnathan P. Thompson[1]
University of Colorado, Boulder, Colorado, 80309

A sensor package was designed in order to remotely collect and transmit temperature data back to an operator. This sensor package needed to be able to be carried beneath a drone, without interfering with the operation of the drone. Additionally, the drone-sensor system must be able to integrate with a future mother rover, forming a larger, multi-purpose system. There were many considerations while designing the sensor package. In addition to the customer specified capabilities, being carried and delivered by a drone introduced a new set of challenges. The sensor package must be light enough to be carried by a drone for the mission specified duration. The sensor package must physically not interfere with the drone operation. Additionally, the sensor package needs to be robust enough to survive deployment from the drone. Furthermore, it must be stable enough to maintain the proper orientation for communications during deployment. The sensor package was designed using polycarbonate to form a stabilizing baseplate and extruded polystyrene to support and protect the electronic components. The flight electronics are housed on custom printed circuit boards. The data is collected with a LM43CA temperature sensor, to within 5°F accuracy. The data is then transmitted back to the operator at the ground station via an Xbee-Pro XSC S3B. A custom interface between the sensor package and the drone was created using 3D printed ABS P430 Plus. Through power testing of the completed sensor package, it was found that the battery could supply our sensor package for up to 12.5 missions. Initial testing of the sensor package communications system demonstrated the ability to successfully transmit data at 200 meters with 95% success rate in data reception.

Nomenclature

$q_{generated}$	=	Power generated by Sensor Package electronics
$q_{conduction}$	=	Heat dissipated by conduction
$q_{convection}$	=	Heat dissipated by convection
A	=	Area
t	=	Thickness
T_s	=	Internal temperature of Sensor Package
T_∞	=	Ambient temperature
k	=	Thermal Conductivity
$\bar{h}$	=	Convective Heat Transfer Coefficient
R	=	Ideal Gas Constant
λ	=	Wavelength
f	=	Frequency
c	=	Speed of Light

[1] Undergraduate Student, Aerospace Engineering Department, University of Colorado Boulder, Boulder, CO, 80309

I. Introduction

THE goal of the INtegrated Flight Enabled Rover for Natural disaster Observation (INFERNO) project is to design and create an aerial sensor package delivery system for future integration with a natural disaster observation system known as FireTracker. A brief concept of operations for the INFERNO system is as follows: under autonomous control, the INFERNO system will take off from a ground station, fly to commanded GPS coordinates, land and deploy the sensor package (SP), take off again to perform visual reconnaissance of the environment, and return to the ground station, where a trained pilot will land the child drone (CD) on a simple landing bay mockup. A diagram of the full FireTracker concept of operations is shown in Fig. (1).

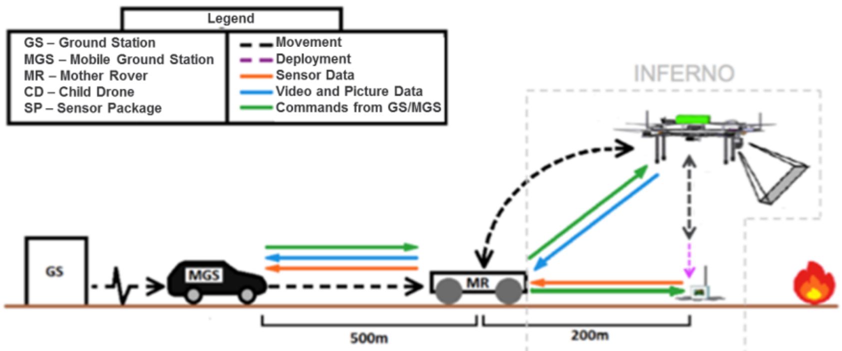

Figure 1. INFERNO Concept of Operations.

A. Field of Application

Mitigating wildfires has been the work of the United States Forest Service since 1905. While the technology for fighting fires has developed to incorporate firetrucks, helicopters, and planes, the technology to survey and assess the condition of a wildfire has proven to be complicated and expensive. This project seeks to improve the field of wildfire surveying by designing and creating an aerial sensor package delivery system for future integration with a natural disaster observation system.

B. Needs Being Addressed

Wildfires are a highly prevalent, costly, and dangerous natural disaster in the United States, particularly in the mountains and other difficult to access locations. Substantial resources are needed to monitor forest health, mitigate conditions that promote fire hazards, suppress wildfires, and rehabilitate areas damaged by wildfires. Fire prevention and suppression efforts by the United States Forest Service currently total $320 million and are projected to reach $1.8 billion by 2025[1]. Not only is wildfire mitigation and containment expensive, but it requires personnel to enter hostile conditions to obtain information about the fire, which often results in casualties. In order to reduce the expense and human risk associated with wildfires, the FireTracker project seeks to develop and implement an aerial drone-based data collection system (INFERNO) for use in hazardous environments and areas impassible by ground-based method.

C. Context.

To monitor wildfires, many new surveillance techniques are being used throughout the United States. The United States Forest Service routinely uses air-tankers to monitor fires from above. More recently, aerial drones are being used alongside the air-tankers to provide information to firefighters and scientists alike. The camera footage and GPS data that are collected are used to help improve models of the fire's behavior. Even satellites such as Landsat have been used to track every major fire in the country since 1984[2], mapping severity. Unlike these previous technologies, the INFERNO system allows actual ground temperature reading at any location the operator specifies within a 200 meter radius.

D. Key Issues and Rationale of Design Choice

Development of the sensor package was driven by a few key factors which ultimately derived the design of the system. The overarching goal of the sensor package is to transmit temperature data back to the user at the ground station. To do this, transmitting range, communication method, and physical integration were critical to mission success. Onboard electronics were chosen to be as lightweight as possible while still supplying the required transmitter power. Transportation to the location of interest was also a driving factor in the sensor package design. Many deployment techniques were considered including carrying the sensor package on top of the vehicle and constructing an internal housing for the package. In the end, carrying the sensor package beneath the child drone was favored. This selection put constraints on the size and shape of the sensor package. Since the child drone has limited flight power and endurance, minimizing the weight of the sensor package was critical as well. Extruded polystyrene was selected for the sensor package housing because of its lightweight and protective properties. The combination of minimizing mass and being deployed directly underneath the child drone led to an issue that the package could flip if downwash from the rotors was too extreme after sensor package deployment. If the sensor package were to flip, antenna orientation would be compromised, leading to possible failure of the communications system. To minimize the chances of flipping, a large but lightweight baseplate was developed from polycarbonate.

II. Design Objectives

The primary objective of the INFERNO project is to design and develop an aerial-based remote sensing system for scientific data collection in hazardous and remote areas. Ultimately, INFERNO will be integrated with the FireTracker system, which enables temperature profile characterization along the perimeters of active wildfires. In order to collect this information without jeopardizing human life, INFERNO must create a disposable sensor package to fulfill data measurement at a designated Location of Interest (LOI); this package will be delivered to the LOI using a flying Child Drone (CD).

A. Primary Design Criteria and Functional Requirements

Functionally, the sensor package must be capable of observing ambient temperature at a frequency of 1 Hz for at least one hour, and transmitting data back to the INFERNO user. Since the mother rover is not currently operational, this transmitted information will be received by INFERNO's Ground Station Mother Rover Simulator (GSMRS), which mimics the interfaces between INFERNO, FireTracker, and the system user.

The functional requirements for the entire INFERNO system can be seen in Table (1).

Table 1. INFERNO System Functional Requirements.

Functional Requirement	Requirement Description
FR 1.0	The system shall collect 1 Hz ambient temperature data at ground level for 60 minutes at the Location of Interest.
FR 2.0	The system shall collect 1080P aerial video at 30 fps for 15 minutes.
FR 3.0	The system shall collect 8MP aerial pictures.
FR 4.0	The system shall wirelessly receive commands at a minimum horizontal range of 200 meters.
FR 5.0	The system shall wirelessly transmit data at a minimum horizontal range of 200 meters.
FR 6.0	The system shall be able to land under piloted control in a 1.10 m long by 1.10 m wide landing bay with 80% confidence.

FR 1.0 addresses the INFERNO system's need to collect 1 HZ ambient temperature data for one hour at a designated location, while FRs 2.0 and 3.0 address the quality and resolution of the reconnaissance imagery. These requirements are motivated by the customer's expected system performance. FRs 4.0 and 5.0 require INFERNO to communicate at a maximum horizontal range of 200 meters, which coincides with the maximum separation of the LOI and GSMRS. FR 6.0 limits the size and landing functionality of the fully integrated INFERNO system in order to enable future integration with FireTracker.

B. Sensor Package Derived Requirements

Since FR 1.0 and FR 5.0 directly influence the design and functionality of the sensor package, the FR 1.0 derived requirements that are pertinent to the sensor package are shown in Table (2).

Table 2. FR 1.0 Derived Requirement Flow Down.

FR 1.0	The system shall collect 1 Hz ambient temperature data at ground level for 60 minutes at the LOI.

DR 1.1	The system shall contain a disposable sensor package capable of collecting 1 Hz ambient temperature data for 60 minutes.
DR 1.1.1	The sensor package shall contain a sensor capable of measuring temperature between 10˚C and 47.8˚C with a minimum accuracy of ±2.78˚C.
DR 1.1.2	The sensor package shall be capable of operating continuously for a minimum of 60 minutes.
DR 1.1.2.1	The sensor package shall contain a power system capable of sustaining operations for 60 minutes.
DR 1.1.2.2	The sensor package shall have a minimum storage capacity of 10.8 kilobytes.
DR 1.1.3	The sensor package shall contain a CDH system capable sampling the temperature sensor at a minimum frequency of 1 Hz.

These derived requirements highlight the baseline functionalities of the sensor package at a system level. In order to measure temperature data for one hour, the package must contain a temperature sensor with an accuracy of ±2.78˚C that is functional within the designated system operation window. Additionally, the sensor package must utilize a power system that can function for one hour, must store all collected data, and must be deployable from the INFERNO child drone.

Table 3. FR 5.0 Derived Requirement Flow Down.

FR 5.0	The system shall wirelessly transmit data at a minimum horizontal range of 200 meters.
DR 5.3	The sensor package shall possess a communication system capable of transmitting data at a minimum horizontal range of 200 meters.
DR 5.3.1	The sensor package shall possess a communication system capable of transmitting 90% of measured data a minimum horizontal range of 200 meters.

FR 5.0 indicates range requirements for the INFERNO system's operations; since the Location of Interest must be located within 200 meters of the INFERNO user, the sensor package must be capable of transmitting collected data across that distance. In order to ensure accuracy of the measured temperature profile, the transmission must deliver 90% of all temperature data.

C. Levels of Success

The sensor package's associated levels of success are shown in Table (4).

Table 4. Sensor Package Levels of Success.

Level of Success	Sensor Package Requirements
1	• Wired communication with GSMRS • Collection of 1Hz time-stamped temperature data with 8 bit resolution
2	• Established wireless communication with GSMRS at 200 m • Store 1 hour of data
3	• >50% wireless transmission of temperature data to GSMRS at 200 m
4	• >90% wireless transmission of temperature data to GSMRS at 200 m • Retransmission of data possible upon data inspection

In order to reach level four success, the sensor package must successful implement full functionality of its measurement, storage, and transmission capabilities.

D. Sensor Package Critical Project Elements

The sensor package has four primary critical project elements: mass, power, communications, and ease of integration. Since the sensor package must be delivered by an aerial-based child drone, mass is a system-limiting design driver which will influence the endurance capabilities of the child drone and thus the entire INFERNO system. This is critically linked to ease of integration; the child drone and sensor package must integrate seamlessly through a deployment mechanism, which is vital to the INFERNO system's ability to achieve mission success. Since the sensor package will be operating remotely, it must complete its nominal operations on a limited power supply, and must transmit back all data to the user; these functions are crucial, and are therefore both critical project elements.

III. Design Methodology

The following section describes the methodology used to develop a design for the Sensor Package using the mission objectives and requirements that were discussed in the previous section. The information is presented chronologically up to where a final design was chosen. The final design and any small changes made to address issues after the start of manufacturing are presented in the Design Results section.

A. Structural Design: Iteration 1

The first step in developing a design for the sensor package was to determine the baseline design for the mission. The two components of the baseline design that were the primary drivers in the design of the sensor package were the method in which it would be deployed and secured to the child drone. In both cases, a solution space was developed and trade studies were performed to narrow the design choices. The primary requirements that needed to be considered for the trade studies were that the child drone shall be capable of releasing the SP during flight, and that the SP shall remain within five meters of a defined GPS location. Other concerns that had to be addressed included the weight and power requirements of the deployment mechanism and attachment mechanism, since they relate directly to child drone performance.

Based on the trade studies and feasibility analysis, it was decided that the sensor package would be attached to the child drone with a linear actuator and the deployment method would be either to drop the sensor package at altitude or land the drone for deployment. The development of the structure of the SP was then started with focus on developing a design that was lightweight, would land in a known orientation when dropped, and could protect the electronics upon impact with the ground. The three engineering principals that were considered for reducing the impact force experienced by the electronics are as follows: a slower moving object will have a smaller impact force, increasing area perpendicular to the velocity direction while decreasing weight lowers an objects terminal velocity, and increasing the time an object takes to come to rest decreases impact force. Basic tests were performed with various structures containing an egg that were dropped to compare their effectiveness in protecting the egg. The structures included crumple zones or foam to reduce the impulse upon impact and oblate objects to slow the speed of the falling object upon impact. Based on the results of the testing, four basic structural models were compared: a spherical structure, a structure with a crumple zone, a self-righting structure, and an oblate structure. The self-righting structure and oblate structure were determined to be the best two options. However, in the end, the oblate design was chosen. The reasoning behind this decision was that although the self-righting structure would have given a single possible landing orientation versus the two possible orientations of the oblate structure, the tolerances needed to get the structure to self-right would be difficult to machine, especially if foam were to be used to keep the structure light. In addition, the effectiveness of the self-righting ability could greatly diminish with uneven, rocky, or grassy terrain. With the oblate structure chosen, it was also decided to use foam as the primary material for the sensor package, since it will allow the structure to be light and allow for a softer impact for the electronics.

B. Electrical Design

The electrical design of the sensor package was reliant on a few requirements: specifically, that the SP is capable of collecting temperature data for 1 hour at 1 Hz with a minimum accuracy of ±2.78˚C, and that it is able to both store and transmit that temperature data at a range of 200 meters. A couple of design constraints originate from the first requirement of data collection. First, since the sensor package will be collecting data for one hour, the electronics would have to be capable of operating for at least an hour. As discussed previously, the SP needed to be designed with low mass, meaning extra batteries could not be added to prolong life. Secondly, the accuracy of the chosen temperature sensor needed to fulfill the ±2.78˚C requirement. The second requirement of data storage required that the electronics needed to include enough memory to hold an hour of data. Since a transmitter is necessary to transmit data to the GSMRS, the third requirement of data transmission translated into the necessity to design an interface between the electronics and the transmitter.

After picking well-known, reliable temperature sensors that met our basic requirements, a trade study was performed, looking at sensor accuracy, temperature range, current draw, and experience within the department. The results of the trade study were fairly close and the final choice was made based on the team's judgment that it would be wise to select a sensor with a proven heritage in the Aerospace Department at the University of Colorado, Boulder. Due to the number of connections needed to communicate between the microcontroller, temperature sensor, transmitter, and battery, a printed circuit board was needed to handle these connections. In order to simplify the design and reduce manufacturing effort, the INFERNO team decided to modify a pre-existing design from the Aerospace Faculty. This design already included the chosen microcontroller attached to a baseboard that needed no alterations. The only change required of the team was to change the breakout board to allow for interfacing with the sensor package's XBee radio transmission board. The microcontroller on the baseboard included 128kB of flash, which is more than enough room to store the temperature data, thus satisfying the data storage requirement. All of the chosen components added little mass to the system and were able to run off of a single cell LiPo battery. The final design is discussed in the Design Results section of this paper.

C. Communications Design

Selecting the appropriate communications system for the Sensor Package was driven by the requirement that temperature data collected by the sensor package must be transmitted up to 200 meters to the GSMRS. As with the structure of the SP, minimizing weight was also critical. With these given requirements, there were only a few usable communication systems on the market. Ultimately the choice became an XBee module to transmit the data from the Sensor Package to the Ground Station. XBee modules have seen significant use in remote sensing application and have a large knowledge base at the University of Colorado, Boulder.

D. Communications Model/Testing

In order to determine the feasibility of an XBee, a link budget was developed for the communication architecture. This link budget predicted a link margin of approximately 50 dB. To verify this link budget with a preliminary system, testing was done in an open field using XCTU software developed by Digi International (the developers of the XBee), which demonstrated that the link budget was very accurate. This can be seen more clearly in Fig. (2); on the left, we see a snapshot during testing of the percent of data sent that was received accurately by the receiver and on the right we see the Received Signal Strength Indicator (RSSI) value which is a measure of the strength of the received data. When the difference of the RSSI and the minimum power required by the receiver to differentiate the signal from noise (-106 dBm) is computed, the same dB margin in obtained as that computed in the link budget.

To determine which XBee model was best suited for the project, various models were tested to determine their transmitting capabilities. During testing of the XBee 802.15.4, it was found that the transmitter struggled to successfully transmit data at 200 meters when sitting close to the ground. Next, two XBees in the 900 MHz series were tested. From the results of the test, discussed in the Design Results section, the XBee-Pro XSC S3B was chosen.

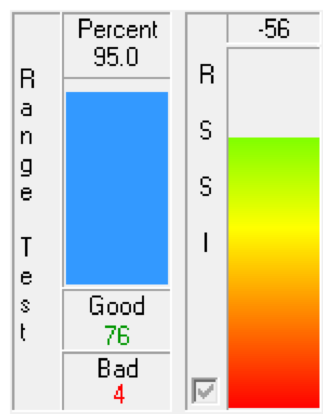

Figure 2. XBee Testing.

E. Design: Iteration 2

The results of the communications testing ended up having major implications on the structure of the Sensor Package. The use of a 900 MHz Xbee required the use of a six inch antenna for optimal radiative signal power. While a six inch antenna could fit vertically underneath our chosen QAV500 V2 airframe, an oblate structure able to properly protect the antenna upon impact with the ground would be much too large to carry underneath the chosen multi-rotor aircraft. This meant that a mechanism would be required on the SP to move the antenna from a horizontal position during flight to a vertical position after deployment. All investigated solutions to this problem proved to be either too heavy, electrically intensive, or too risky to be considered feasible. Due to these constraints, it was decided by the team to abandon the method of dropping the sensor package as the means of deployment and rather, to change the concept of operations to include landing the system before deployment. However, it was decided to retain the use of foam for the majority of the structure due to its low density and consequently its small impact on system mass. To further develop the structural design of the sensor package, models were developed and tests were performed to account for critical design considerations, as described in the following sections.

F. Thermal Model

A thermal model to predict the temperature of the electronics in the sensor package was originally developed during the first iteration of the structure when there was some concern that the original design could lead to high temperatures of the electronics due to being almost fully enclosed in an oblate foam structure. Although the final Sensor Package design was later changed, initial analysis did show that conduction through foam would likely lead to temperatures in the electronics that were above their operating temperatures. This issue was addressed in the second iteration of the sensor package by not fully enclosing the electronics. The thermal model was thus updated to reflect this change.

The model developed uses 1D heat transfer under steady state conditions. The model takes into account both convection through the openings in the sensor package and conduction through the foam structure, as shown in Fig. (3). Under steady state conditions, the power generated by the electronics should be equal to the heat dissipated by conduction and convection, as shown in Eq. (1). The internal temperature of the sensor package was assumed to be at a constant temperature, which is a reasonable assumption since the internal volume is small and primarily taken up by the electronic components. With this assumption, a vertical plate model for free convection air was assumed at the two openings of the sensor package. This model allowed for the calculation of the convective heat transfer coefficient ($\bar{h}$) given tabulated thermodynamic properties of air at various temperatures and expressions involving both the Nusselt number and Reynold's number[3]. The thermal conductivity (k) was computed from the R value of the foam insulation used for the Sensor Package using the simple relationship shown in Eq. (2).

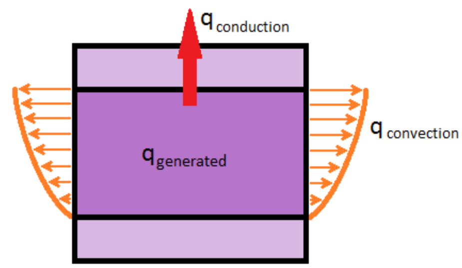

Figure 3. Thermal Model Diagram.

$$\begin{aligned} q_{generated} &= q_{conduction} + q_{convection} \\ q_{conduction} &= \frac{k}{t} A (T_s - T_\infty) \\ q_{convection} &= \bar{h} A (T_s - T_\infty) \end{aligned} \tag{1}$$

$$R = \frac{t}{k} \tag{2}$$

With an electronic power generation of 106 mW, corresponding to the average power during operation, the model was run over an ambient temperature range of 10-47.8 ºC, which is the operational temperature range for the project. The modeled temperature difference between ambient and inside the sensor package is shown in Fig. (4). Note the addition of the upper and lower bounds included in the plot. The lower and upper bounds were calculated by using a typical range of convective heat transfer coefficients (2-25 W/(m^{2}K)) for free convection air. The model predicted the sensor package internal temperature to be 3.3 ºC above ambient for the entire operational temperature range with a possible range of 1.1-4.4 ºC. This range is well within the operable temperatures of the sensor package electronics.

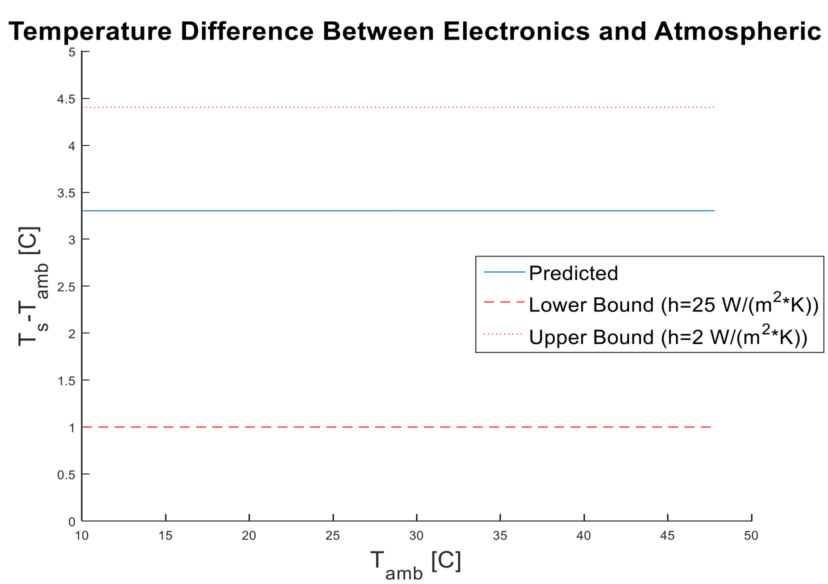

Figure 4. Thermal Model Results.

G. Child Drone Mass Model

One of the projects critical elements is the required endurance of 15 minutes for the child drone, which is directly related to the power draw of the propulsion system, which is in turn affected by the total mass of the child drone. Using mass and power models and budgets developed for the CD, it was determined that the mass of the Sensor Package must not exceed 200 grams. Thus a large part of the design work for the final sensor package structure was keeping the mass below the specified 200 grams.

H. Baseplate Testing

In addition to the primary foam structure of the sensor package, the final design also includes a baseplate, which is discussed in more detail in the Design Results section, but is primarily designed to prevent the sensor package from flipping over. The baseplate was originally designed out of acrylic with a radius of 100 mm. However, testing was performed with a prototype of the structure that revealed that acrylic easily snapped and caused the SP to flip, even when only dropped from a few inches above the ground, which is a situation that could be experienced during operations. Thus the material was changed to polycarbonate, which is less susceptible to breaking. Additionally, it was determined that there was concerns that downwash from the propellers on the child drone could potentially flip the sensor package when taking off after deployment. To decrease the chance of this happening, the baseplate radius was increased to 125 mm. This increased lever arm increased the restoring moment created by the weight of the SP if it were to start to flip.

IV. Design Results

A. Final Structural Design

The finalized sensor package structural and electronics design is shown in Fig. (5) below. The main structure is composed of a 3D-printed ABS attachment piece located at the top of the sensor package, a foam housing to encase and protect the electronics, and a polycarbonate baseplate mounted to the bottom face of the foam. All components of the sensor package structure were designed and manufactured by the INFERNO team with the exception of the male-female mounting standoffs used to attach the electronics assembly to the foam housing.

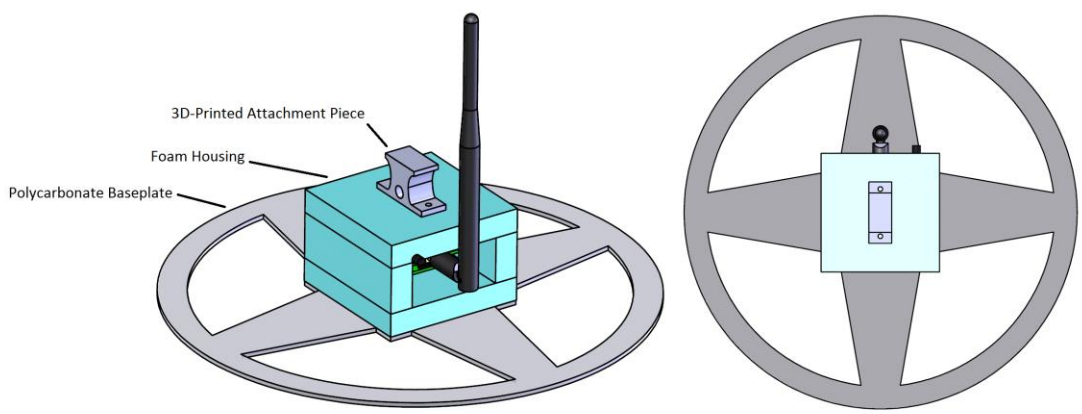

Figure 5. Finalized Sensor Package Design.

The polycarbonate baseplate design was introduced as a response to initial prototype testing which showed that a smaller-radius acrylic design was not sufficient to eliminate risk of landing incorrectly during deployment. This new design increased the radius of the baseplate by 25% from 100mm to 125mm which decreased the likelihood of flipping the sensor package post-deployment by increasing the moment required to induce a flip. In addition, the switch to polycarbonate material from acrylic increased the fracture resistance of the baseplate by approximately 100%, significantly reducing the likelihood of baseplate damage during deployment. This material change did require an increase in man-hours to manufacture the structure however, since the original acrylic material could be laser-cut while the polycarbonate required more time-intensive CNC methods to produce.

Initial flight testing conducted with the sensor package attached to the vehicle also revealed a deficiency in the original 3D-printed attachment piece design. This original design was fixed to the foam housing using epoxy with a tensile strength of 20.5 MPa, which was deemed sufficient to support a 2g-acceleration tensile load of 9.2 kPa due to the mass of the total sensor package assembly. However, the initial flight test revealed that the attachment piece to foam housing linkage failed in another mode, resulting from a delamination of a single layer of foam from underneath the epoxy connection. Analysis based on these results revealed that despite the epoxy itself being strong enough to support the load, an epoxy linkage with the foam would be insufficient to mount the attachment piece to the housing. In response, the design shown in Fig. (5) above was developed to mount the piece using steel screws driven through the foam housing, distributing the force from the attachment through the foam rather than concentrating it at a small layer at the surface of the housing.

After manufacturing and assembly was completed, the full sensor package structure and electronics was weighed in order to assess the accuracy of the mass estimations. The theoretical estimate for the sensor package weight including the updated baseplate design and full electronics assembly was 147g. This compared quite well with our final measured sensor package mass of 140g, leaving only a 4.8% error. Both of these values fall below the 200g maximum mass determined during the design methodology phase. Thus the finalized design not only matches the previously determined model, it also matches the full system mass requirement.

B. Final Electronics Design

As discussed in the design methodology section, the electronics of the sensor package include: the LM34CA temperature sensor, the PIC18F67K22 microcontroller and baseboard provided by the ASEN faculty, the breakout board designed by the team, the XBee Pro, and the battery. The signals needing to be wired on the breakout board to

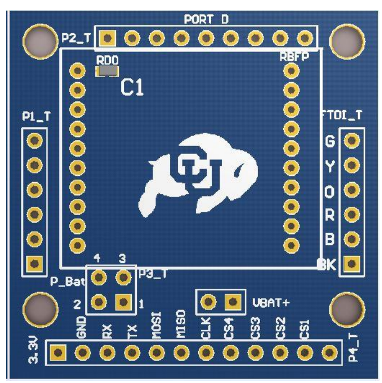

Figure 6. Breakout Board Designed by INFERNO Team.

interface with the XBee were 3.7V power, ground, data in, data out, a line to send the XBee to sleep, and an output from the XBee alerting the microcontroller when the XBee was asleep. Additionally, a decoupling capacitor was added to reduce voltage supply noise. The sleep lines were added to save power when the XBee was not in use for the first 15 minutes of the mission. A board layout diagram showing the design of this breakout board is provided in Fig. (6). After checking the board to ensure that the signals were correctly wired, the five components were integrated together and simple tests were performed to verify communication between the microcontroller and the various interfaces. These tests and the finalized communications system design will be discussed in the following section.

A power model was developed to predict the lifetime of the system; examining the currents and voltages of all of the components and the necessary time to transmit all of our data, the team found that the battery could supply the sensor package with power about 15 hours, and a total energy dissipation of 332 J. The main factor in the power model for the system was the percentage of time the XBee was in which mode. For the first 15 minutes of the mission while the XBee was in sleep mode, the power draw of the Sensor Package electronics was only 30mW. However, once switched into idle mode, the power draw increased by a factor of 3, to 106mW, and while transmitting this number greatly rose to 657mW. However, since the time transmitting was relatively small (0.32%), the 45 minutes after the XBee awoke and began transmitting, the electronics only took about 108mW. Analysis of the power test showed that not only can the electronics survive for well over an hour, but that our power model was verified. Our measured power draw came out to be 356 J, a 7% error from our model.

C. Final Communications Design

The final XBee model was determined based on testing. The team narrowed the final XBee model down to two models, namely the XBee-Pro 900 MHz and the XBee-Pro XSC S3B. Testing both systems in an open field again using the XCTU software yielded the following.

Figure 7. XBee-Pro XSC S3B (left) and XBee-Pro 900 MHz (right) Testing Results.

Figure (7) shows the resulting data reception rate (in percent) at the receiver, and the representative RSSI values for the XBee-Pro XSC S3B and the XBee-Pro 900 MHz. Figure (7) also shows the total number of "packets" sent as well as the number of packets actually received, which is where the percent receive rate comes from. Clearly, the XSC outperformed the 900 MHz in both categories, seeing higher RSSI values (-58 dBm) and significantly higher packet reception rate (94.4%) compared to the 900 MHz receiver which had a packet reception rate of 60% and an RSSI of -87 dBm. Note that the RSSI is measured in dBm, and thus a smaller negative number corresponds to a stronger signal. This result lead the team to select the XBee-Pro XSC S3B for the sensor package communications system. Procuring the XBees was rather simple as the only thing required by the team was placing an order with Digi International.

Finally, antennas had to be purchased for the XBees, which do not come with antennas by default. Selecting the appropriate antenna required some additional research due to the wide variety of antennas available on the commercial market. Ultimately a dipole antenna was chosen due to the fact that its signal pattern is equally broadcasted in all horizontal directions thus removing the risk of improper orientation of the antenna upon deployment of the sensor package. The size of the dipole antenna was selected to be ½ of the wavelength of the transmitted signal which is found using Eq. (3) below.

$$\lambda = \frac{c}{f} \tag{3}$$

Where c is the speed of light and f is the frequency of the transmitter (900 MHz for the XSC).

V. Conclusion

While the initial concept of creating a sensor package to record and transmit temperature data is simplistic in itself, the task becomes far more challenging when the constraints from the delivery method are applied. Not only must the SP not interfere with the basic functionality of the drone, it also must directly interface with the drone for transport and deployment. Furthermore, because the drone limits the maximum mass of the sensor package, many stronger, more robust components were not viable options for use on the SP. This introduced additional complications to the package, such as deployment orientation, deployment stability, radio interference, etc. Success of this overall INFERNO project will pave the way for completion of the FireTracker mission. In future applications of the FireTracker mission, additional, separate sensor packages can be designed to collect, record, and transmit any desired data to the user at the ground station. This technology has the possibility to significantly reduce the risk of life and assets when investigating hazardous environments, including, but not limited to, wildfires.

Acknowledgments

The INFERNO team would like to thank NASA's Jet Propulsion Laboratory for sponsoring the project for the 2015-16 fiscal year, as well as their continued support throughout the program.

References

[1]United States Forest Service, "The Rising Cost of Wildfire Operations: Effects on the Forest Service's Non-Fire Work," United States Department of Agriculture Report, URL: http://www.fs.fed.us/sites/default/files/2015-Rising-Cost-Wildfire-Operations.pdf [cited Aug 29, 2015].

[2]Laura E. P. R., "Burning Wildlands and a Burning Need for Landsat," Goddard Space Flight Center, URL: http://landsat.gsfc.nasa.gov/wp-content/uploads/2013/08/LIL-2-Fire-4.pdf [cited Mar 23, 2016].

[3]Moran, M. J., Shapiro, H. N., Munson, B. R., and DeWitt, D. P., *Introduction to Thermal Systems Engineering: Thermodynamics, Fluid Mechanics, and Heat Transfer*, John Wiley & Sons, Inc., 2003, Chaps. 16-17.