EE 449 Milestone 4 Hardware

Thermal Camera Team

Introduction

The purpose of this milestone was to highlight the hardware and software used in the design of our project. Although many evolutions have been made for our product the current design with collaboration with NASA's Ames Laboratory has allowed us to meet all the specifications of our customer. Materials have been the greatest challenge to obtain however in order not to fall behind we have begun the development of a stainless steel prototype that will be used to test the control system and rotational components before applying them to the final thermal camera enclosure.

Electronics Systems and Design

While there are many components to the electronics system, it can be separated into two main parts: sensing/ control and power/actuation. With exception to the sensors and actuators, where performance was paramount (within reason), the biggest selection considerations for the electronics were price, simplicity and support.

Fire Tracking / Controller Subsystem

Fire Sensors

To track the heat of the wildfire, there exists only one commonly available sensor capable of detecting the appropriate thermal radiation. This sensor, known as a thermopile, is produced for the automobile industry and subsequently is relatively inexpensive. Since this device is an unamplified photo-electric effect driven sensor, a very high gain is needed to perceive its value. To accomplish this, a dual stage differential amplifier was designed using a common low noise op-amp.

[Image of amplifier circuit]

Caption: The dual stage amplifier circuit can deliver roughly a gain of $1:10^6$.

Controller

Along the line of the circuitry for the controller electronics, due to its simplicity, low cost and community support, [Arduino Framework] the Atmega328 was used. Almost all logic is accomplished with the microcontroller. The schematic is included.

[Image of controller circuit]

Caption: The circuit for the controller portion of the system. All logic occurs within the Atmega328.

In addition to running the estimator and control algorithms, the microcontroller will read the quadrature encoder. Using hardware interrupts for accuracy, the signal from the encoder will be run directly into the I/O of the processor where the position can be tracked even with the microcontroller powered off.

Power/Motor Driving Subsystem

Power Supply

Since the infrared camera requires 7.2V, the power supply of the housing robotics was tailored to accommodate that. To simplify this subsystem and remove as many failure modes as possible, Mikron was contacted to determine if a 7.4V supply was permissible. Upon their affirmative, the decision was made to use a 2-cell 7.4V Lithium Polymer (li-poly) battery to directly power the camera as opposed to using a switching supply from a 12V battery. When a fire is detected, the microcontroller asserts a signal to a MOSFET that connects the li-poly battery to the camera's power port.

The power conditioning for the microcontroller is planned as a simple and inexpensive linear regulator, while the final design may use a second, lower voltage battery to minimize quiescent current and improve efficiency. Since the processor only draws 2mA or so in active mode and less than 1mA in sleep mode [Atmel], an improved efficiency may not be necessary with the current battery configuration.

Since the system must be able to wait for as long as a couple weeks before the fire, reducing the power drawn during that time is critical. Along those lines, the fire sensing circuitry is planned to be powered down, when not in use, by disconnecting it from the battery supply. Every minute or so, the sensors will be activated briefly to check for fire and will again be turned off to conserve battery. Since the sensors themselves are un-powered, the start-up transient for the sensor system will be just from the amplifier circuitry and, while needing to be tested, is not expected to cause significant problems.

Motor Driver

The DC motor is powered by an H-Bridge switched by the PWM output on the microcontroller. While snubbing is not needed with the current motor/switching frequency configuration, the final build may require such circuitry.

Motor

The motor for controlling the position of the camera housing was chosen largely upon availability and its integrated quadrature encoder. When acquired, the motor was smaller than expected. Although it is anticipated to perform well enough for controller prototyping purposes, a larger motor might need to be acquired for the final box design.

[Picture: Image of motor from website.]

Caption: The present motor is anticipated to work for prototyping purposes.

Electronics Partslist

- Microcontroller: Atmega328
- Battery: Lightmax 5800 mAH Li-Poly from HobbyKing.com
- Linear Regulator: LM7805
- H-Bridge IC: L298
- Motor: Robotiks Micromouse Motor
- Thermopiles: MLX90247ESF-DSA
- Dual Op-Amp: NE5532
- Camera-Switching MOSFET: MTP10N10E

Mechanical Side

The mechanical side of this project incorporates all of the materials needed to house the thermal camera and shield it from the extreme heat of a wildfire. The main dilemma of this project is that out of all the data collected on wildfires so far there were no exact design criteria that would guarantee perfect performance under all possible conditions. The paradox of the situation is that we are designing a device to essentially collect the data we need to properly design such a data collection device. With this realization we knew we could only improve on the older design. The customer provided the design constraints that would give the best protection of the thermal imaging camera based off of his expertise in this particular field.

Old Design:

- Used recycled space shuttle tiles as an insulation
- Unknown type of stainless steel for outer casing
- Used Ice as a phase change material
- Used a glass window for video capture
- Was small and easily transportable
- Used a normal video camera

Our Design Criteria:

- Withstand 1200 degree Celsius Heat for 2 minutes while exposed to direct flame.
- Withstand 300 degree smoldering temperature for 2 days immediately after being exposed to direct flame.
- Withstand wind speeds of 50MPH.
- Keep the thermal camera under 50 degrees Celsius for the entire duration that it is out in the woods.
- Be able to conserve battery power when a fire is not present.
- Be able to rotate 360 degrees.
- Acquire the target flame in under 20 seconds (re-adjust camera position).
- Capture infrared data during the entire burning process of a wildfire.
- The setup must be light weight such that two men can hike with it. Roughly 50 lbs.
- Setup must be reusable.
- Camera must take data at 4 - 4.5 ft off of the ground

Why the old design will not work:

- Virtually no stainless steels can survive a 1200 degree temperature.
- The box is too small for the thermal imaging camera we were given to work with.
- The glass lens will not pass infrared waves therefore not capturing the data that our customer is interested in.
- It is not able to withstand 50 MPH wind.
- Not able to conserve camera battery power.
- Phase change materials will not last for a month at ambient temperatures.

- Cannot rotate to guarantee data collection if a fire is nearby but not directly in front of it.

Our Design:

Materials:

Optics Development and Selection

In order for the camera to observe the wildfire, a viewing port was needed to breach the insulation. To prevent the massive heat transfer inherent to an open viewport in combustion level conditions, a window was also needed.

Caption: The Mikron 7604 is capable of measuring heat using the 3.9μm wavelength. [Mikron]

In addition to blocking convective heat, the following requirements needed to be considered in order to not inhibit the thermal camera.

Window Selection Requirements:

- Must be transmissive for 3.9μm infrared radiation, in order for the camera to function.
- Heat resilience: must be able to repeatably withstand direct contact with flame (1500^{o}C)

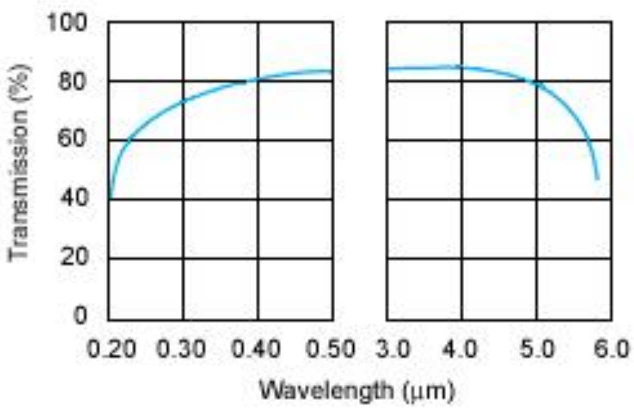
Since silica-based glass is only transparent to visible light, custom optics were required to accomplish these requirements.

Material	Bandwidth	Melting Temperature
CaF_2	0.17 – 7.80μm	Low

Al_2O_3	0.18 – 4.5µm	2030 °C
MgF_2	0.12 – 8.50µm	1255 °C
Ge	2.0 – 14.0µm	Very Low
ZnSe	0.6 – 20 µm	1525 °C

Caption: List of known window materials [RedOptronics, Paper on CaF2 for IR, List of IR Window Materials]

The material chosen was Al_2O_3, also known as Sapphire. With its very high melting temperature and suitable pass-band, it was precisely what was needed. Additionally, being extremely hard, a Sapphire lens was better suited for the chaotic environment of a wildfire than the competing, softer window materials. The lens needed is currently being manufactured at RedOptronics, a custom optics supplier.



Caption: IR Sapphire window response curve.

Inconel

Initially the ideal material for a forest fire application was Haynes 214. This metal was a nickel based super alloy whose operating temperatures were in the ranges that fit our particular design requirements of 1200 degrees Celsius. Unfortunately the metal was unavailable unless purchased in large quantities and only a single company sells this alloy. It was ideal in the sense that not only did it meet all of our design requirements but also would have eased the manufacturing process. At this point we have chosen Inconel 601 since its material properties are relatively similar to that of Haynes 214 the trade off is that it is almost impossible to fabricate anything by hand especially if it involves welding. The material properties found in the data sheets referenced show that it has excellent oxidation, carburization and corrosion resistance at the theoretical temperatures that we will be using it at. The forest will have oxygen and thus oxidation must be prevented such that the device retains its protective material properties at high temperatures. This is a problem with many metals that have high melting points. Through the research done so far oxidation at high temperatures reaches an extreme where the outer layer of many metals becomes embrittled causing it to be useless after a single run at high temperatures even though it won't melt at those temperatures. Our device must be reusable. It also resists carbon absorption at high temperatures. Since we will be putting the device in an open flame carbon dioxide will surround the box while it is at high temperatures. The inconel is like stainless steel in the sense that it resists corrosion and oxidation by having an amount of chromium and nickel.

Aerogel

The use of Aerogel was a last resort due to the cost of the material. It is about 99 percent air and has a very low coefficient of thermal conductivity meaning that heat will take a long time to penetrate into it. Although it is an ideal solid insulator for our design, it allows for heat transfer by radiation to pass right through just like air. This poses a problem since the temperature of the inconel box will equalize with the outside environment rather fast. That means that on the inside surface of the box the temperature will be 1200 degrees Celsius leading to massive heat transfer by radiation to the camera if the radiation is not reflected. A design change was made to create an inside box of stainless steel such that the heat transfer due to radiation would be reflected back for the most part. This would be because the surface of the metal wouldn't behave as a black body and reflect the majority of the radiation. Due to the extreme low coefficient of thermal conductivity the rate at which heat energy will be transferred to the finite thermal load (specifically the air and phase change material) will be minimized. After testing the material properties in our simulation created in Matlab we found a thickness that would theoretically work such that the camera could be protected for all time at steady state conditions. That thickness was 2 inches of Aerogel separating the outside box and the inside box. This steady state condition is basically the smoldering temperature acting on the outside of the box for a very long time. The problem is the time period where the inside temperature will theoretically reach 95 degrees Celsius. This occurs during the time when the box is exposed to a direct flame at 1200 degrees for 6 minutes. Figure 1 below shows the simulation of internal box temperature at the inner Aerogel surface without phase change material present.

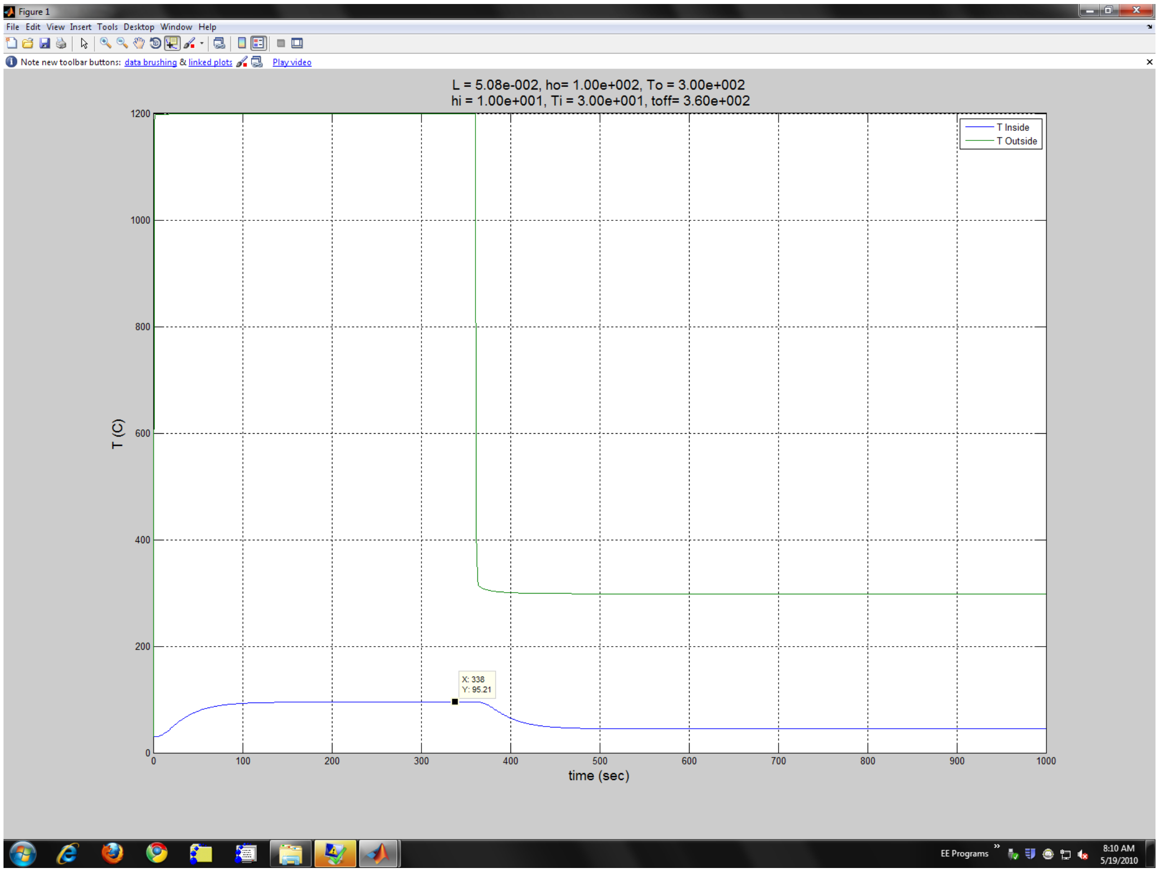


Figure 1: Simulation of 2 inch thick Aerogel exposed to 1200C for 6 minutes steady state internal temperature = 44.97C, peak internal temperature 95.19C

It may be difficult to see but the period where the internal temperature reaches 95.19 degrees Celsius is the one we need to worry about. This simulation shows that once the heat source is removed the internal steady state temperature will reach about 45 degrees Celsius. This means that the camera can survive at smoldering temperatures without the need of phase change material. The phase change will be talked about next. The primary reason for using Aerogel is because other insulations that claim to be nearly as good cause us to go over our weight requirement. The ideal weight given was 50 lbs.

PlusIce

The questions about thermal load keep coming up where as there is a specific amount of air inside the box and the fact that energy can't escape the box once it is inside. The only means of cooling is the phase change material. At this stage of development a controlled cooling system sounds interesting but is not feasible without huge set backs. The specific type of phase change material we are using is called plus ice X40. The name is linked to the fact that its phase change temperature is 40 degrees Celsius. This is good because unless ambient temperatures where this device will be used are above 40 degrees Celsius the plus ice will retain its energy absorbing abilities without melting like ice would in the same conditions. Plus ice x40 can be frozen and refrozen for reuse. The phase change occurs in the form of a change in crystalline structure at well defined temperatures. Figure 2 below shows the material properties relevant to our project.

PlusICE SOLID-SOLID PCM SOLUTIONS

PlusICE Model	Phase Change Temp. (°C)	Phase Change Temp. (°F)	Latent Heat (kJ/kg)	Latent Heat (Btu/lb)	Density (g/cm3) below PCT	Density (lb/ft3) below PCT	Density (g/cm3) above PCT	Density (lb/ft3) above PCT	Thermal Conductivity (W/m K) below PCT	Thermal Conductivity (Btu / ft2 h F) below PCT	Thermal Conductivity (W/m K) above PCT	Thermal Conductivity (Btu / ft2 h F) above PCT
PlusICE X40	40	104	131	56	1046	65	986	62	0.253	0.146	0.209	0.121
PlusICE X80	80	176	192	83	1193	74	1120	70	0.361	0.209	0.335	0.194
PlusICE X180	180	356	301	129	1330	83	1220	76	0.993	0.574	0.508	0.294

Figure 2: Relevant properties for calculating how much energy the plus ice can absorb

Figure 2 is what we will use to calculate the amount of mass that we will need given the amount of energy coming into the box during the times where the internal temperature will reach over 40 degrees Celsius. This calculation will be completed shortly inside of an FEA program called Comsol Multiphysics. Comsol will help us to determine just how much energy is going in for a certain amount of time and allow us to calculate a temperature distribution for the duration of time we need the camera to be protected. A model of our system has been created and is in the process of finalizing the simulation such that the amount of phase change material needed for this application can be calculated and our rudimentary FEA can be validated.

Stainless Steel

Stainless steel will be used for the camera holder and inner box. The reason for using stainless steel is because it is cheap and easy to work with as well as its material properties to reflect the majority of radiation heat transfer coming into the box. Since the Aerogel will decrease the amount of heat energy coming into the box stainless steel will work for handling a couple hundred degree temperatures not that it will need it. The stainless steel also has good corrosion and oxidation resistance. Depending on how the hikers will divide the load the stainless steel will not corrode or oxidize under normal conditions due to its chromium oxide layer. This protective layer will regenerate if scratched off depending on the amount of damage since chromium makes up more than 10.5 % of any type of stainless steel. The chromium bonds with the oxygen in the air and reforms the layer automatically if damaged.

Design:

Rotational System

The rotational system was unavoidable in meeting the design requirements and class requirements of incorporating a control system in the project. This rotational system needed some kind of gearing and an actuator attached to the controller with sensors such that the camera view could be altered to improve the consistency of data collection. This rotational system meant that the box would need to be sealed off to the outside since it would be directly exposed to flame. The initial idea was to run a peg up into the box fixed to the stand and connect the peg to the gear system allowing for motion. The problem with that idea was the sealing of the box. The insulation would need to be able to seal against the peg and thus friction would cause wear in the insulation and eventually fail quickly due to the abrasion of the insulation against the peg. The replacement was a hexagonal or other shaped billet with a wide bottom such that any holes in the bearing could be covered up on both the inside and the outside of the box. The inside would be covered by the insulation and the outside part of the exposed bearing would be covered by the extended base of the hexagonal piece. Figure 3 below shows the resulting seal.

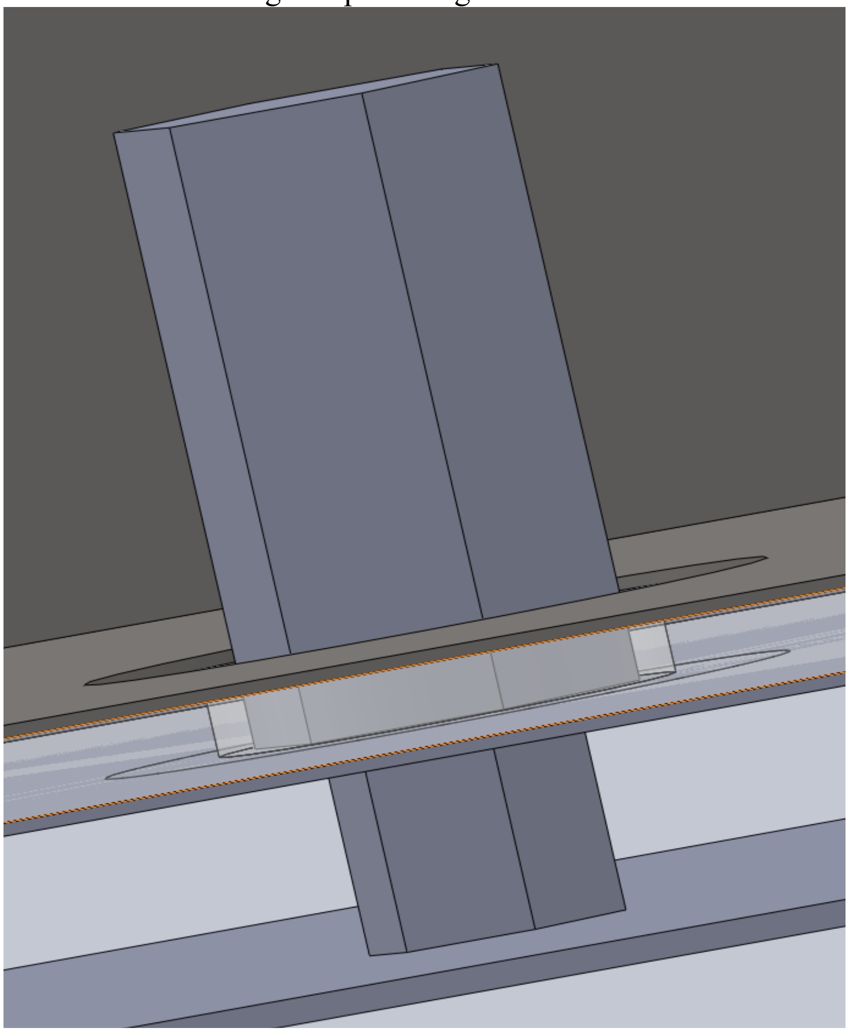


Figure 3: The Aerogel insulation is the transparent material between the inner stainless steel box(top) and the outer Inconel box(bottom) it is staggered with the gap between the Inconel and the bearing to seal off the inside from the fire.

Camera Holder

The purpose of the camera holder is to isolate the camera position in the box to a level that allows the lens of the camera to align with the sapphire window to see outside. It also holds the circuitry and battery and surrounds the camera with a secondary stage of phase change material. The camera holder also has an open area as viewed from the left that allows the gear system to go underneath and connect to the female hexagonal piece to complete the rotational system. The camera holder is made of stainless steel just like the inner box that pins the Aerogel in place along the walls of the outer box. The main purpose is the isolation of the camera, the circuitry and especially the battery. The sensitive components are kept as far from the heat source as possible. It is held in place by blocks of phase change material between the inner box and the camera holder. Figure 4 below shows a picture of the camera holder concept.

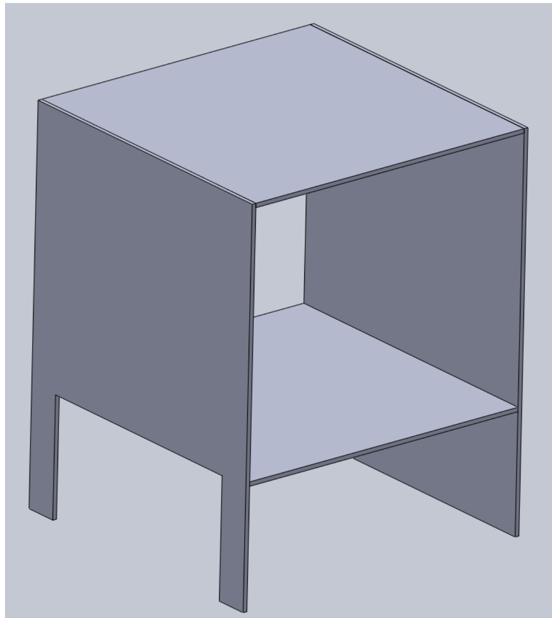


Figure 4: Camera holder

Box size

The size of the outer Inconel box depended solely on the size of the contents inside. Since our component dimensions are fixed the deciding factors for the final dimensions were the insulation and the phase change material. Unfortunately the size was an estimate and has not been finalized at this stage. The balance between phase change material and the insulation is the reason for this. The final amount of phase change material has not been found and thus the dimensions are at this point an educated guess. Within the next week the final FEA simulation is scheduled to be completed such that validation of our simple one dimensional simulation as well as phase change material amounts can be calculated.

Leg placement

The leg placement is dictated by the size of the box that the stand supports. With the size estimated at being 16 inches per side of the cube, the amount of drag force on the box had to be determined. The Design criteria that we were given stated that the heat shield would have to withstand 50 MPH wind speeds. The drag force on simple objects can be calculated using the drag equation shown below which is valid for Reynolds numbers greater than 1000.

<u>Drag Force</u>

□□=*12*□□□□□*2*

where

□□= drag force (N)

□ = mass density of the fluid (kg/m^3)

□ = velocity of the object relative to the fluid (m/s)
A = reference area perpendicular to fluid flow (m^2)
□□= drag coefficient dependent on the geometry of the object (dimensionless)

<u>Reynolds Number</u>

□□= □□□□
where
□□ = Reynolds Number (dimensionless)
□ = density of the fluid (kg/m^3)
V = mean fluid velocity (m/s)
L = characteristic linear dimension (travelled length of fluid) (m)

We looked at different situations and found that the properties of air change at different temperatures. The drag forces at three different conditions were tested. The conditions were the normal conditions at 27 degrees Celsius, the smoldering conditions at 300 degrees and the peak temperatures at 1200 degrees Celsius. As the temperature increased the density of air decreased and thus the drag forces also decreased. Also the orientation of the box in the fluid flow directly affects the drag forces. The assumption made was that the wind was blowing parallel to the ground. The orientation of the box that generated the highest amount of drag was when a side of the box was perpendicular to the fluid flow. This produced a drag coefficient of 1.05. The more dense the fluid the higher the drag force. This is the worst case scenario unless working with 50 MPH wind at freezing temperatures. The maximum drag force on the box at normal conditions was

L = 16" =0.4064m
50MPH = 22.352 m/s
□□□□=*1.1614□□□3 @ 300□ @ 1□□□*

□□=*1.1614□□□3×22.352 □/□2×0.8×0.165161□22=38.3338□*

After calculating the maximum drag on the box the rest is just a simple statics problem. The weight of the box was assumed to be 30 pounds and the height of the camera lens was taken to be 4 ft. so the leg height was then 39". From this the leg positioning was calculated such that if the box were 30lbs or greater then the box will resist 50 mile per hours winds.

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