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The Cold Chain and Drone Delivery

The Development of Supplementary Technology for Delivering Cold Chain Medical Supplies via UAV

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by

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Abstract

Abstract— More than a billion people in the world lack access to all weather roads, leading to major difficulties in health services distribution. Many have proposed the use of Unmanned Ariel Systems (UAS) to improve the last leg of the supply chain. These proposals have addressed the distribution but not the cold chain required by critical supplies like vaccines. The development of lightweight, actively cooled chain technology for drones is crucial to the expansion of the supply chain's final leg. The following explains the development of a system to maintain and monitor the package for temperature, location, and supply integrity. Using simple materials and 3-D printed parts to insulate and actively cool the internal chamber the system meets established minimum volumes for medical supply transport via UAS. A simple SMS based communication protocol and modular attachment mechanism allows the device to be used by anyone with any UAS system. Validation of the 2-8 C °target will be verified using WHO prequalified Vaccine Vial Monitors (VVM's) proving the viability and efficacy of the use of UAS in cold chain supply distribution.

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1 Introduction

Some 400 million people around the world lack access to healthcare which is considered as a fundamental human right.[1] A simple statement from the Assistant Director-General, Health Systems and Innovation, at the World Health Organization, Dr. Marie-Paule Kieny, highlights the groups that suffer the most from a healthcare system broken in the last leg care. "The world's most disadvantaged people are missing out on even the most basic services, a commitment to equity is at the heart of universal health coverage. Health policies and programmes should focus on providing quality health services for the poorest people, women and children, people living in rural areas and those from minority groups". While Dr. Kieny refers to the cost prohibitive nature of this issue and large scale policies, she does not propose a solution, simply a focus. Such a focus has guided many initiatives, such as those focused on the most important part of health care, prevention and diagnosis. Access to these critical health measures is often dependent on the inaccessibility of services and care for a variety of reasons.

One of these is infrastructure access and the limits it places on healthcare. The World Bank estimates that "one billion people lack access to an all-weather road." That road for many is a key to prosperity and health that in areas with a limited number of doctors and poor infrastructure, the delivery of medical supplies becomes very difficult using traditional supply chains. Diagnostics also suffer the same constraints, where even when doctors can visit their patients they do not have access to reliable lab facilities that to support their assessments. Prevention, diagnostics, and treatment all suffer from the limited reach of the traditional supply chain. Many organizations have recognized this need and propose to solve it through the use of smaller unmanned aerial systems or vehicles (UAS or UAV). By using small unmanned aerial vehicles, the delivery of medical supplies can be more efficient, cost effective, and reliable.

The use of these systems and vehicles solves the challenge of that last leg in the healthcare process in inaccessible areas. While the transport of supplies is being addressed by a number of organizations such as Zipline Inc., Matternet Inc., and Flirtey Inc. who have all worked to add UAS to the healthcare supply chain. Recognizing that there are a number of barriers to success in this emerging function in the supply chain, this project aims to provide a physically and environmentally stable container for sensitive items in the process such as vaccine and lab samples. While the aforementioned organizations look to solve the issue of traversing the distances between care and patients, this project aims to ensure that those supplies can be used effectively by providing a stable and secure container to protect sensitive critical healthcare supplies.

2 Literature Review

Globally there are dramatic differences in the level of health care available to people. A few key elements in regards to facts and concepts are required to understand the greater context in which an improved cold chain delivery system applies. While some of these statistics are often quoted they carry significant meaning in indicating the scope of the problems left in global health.

- As of 2013, 1 in 10 people in the world live under $1.90 a day. [2]
- Over one billion people live more than two kilometers from an all-weather road. [3]
- Over 400 million people do not have access to essential health services. [1]
- An estimated 19.4 million infants worldwide are still missing out on basic vaccines. [4]

These statistics are just some of the metrics used to understand the unbalanced scales of health throughout the developing world. These are by no means the best metrics in which to understand the entirety of the situation, but provide a window with which to view access to healthcare. They are meant to shock by way of contrast with the typical picture of the developed world. Many researchers, philanthropists and good Samaritans have proposed solutions or volunteered their time to the issues of global health. The proper actors and policies are a lightning rod in certain circles and this project is sure to invite criticism in regards to its technocratic nature. While a deep understanding of patient needs is critical to the development of a successful system, a student team is limited in many regards with their capacity to conduct said analysis. The following literature review offers an overview of technical solutions to complex health problems. Rather than defend the scope of the project, this review is intended to demonstrate the constraints and knowledge in a rapidly developing field that led the team to the project detailed in the report.

Rather than wade into the debate on the applicability of the device outlined in this report, this literature review examines the factors that have led to the investigation of unmanned aerial vehicles (UAV), commonly know as drones as a part of the supply chain system. Reviewing the context in which these drones hope to operate and the current need in the supply chain systems targeted lead to the difficulties in the effective use of drone delivered models of care.

Technological solutions are increasingly offered as solutions to issues of global health and poverty. These "fixes" often have limited long term success for a variety of reasons. Chief among these are considerations of public health vs. health technologies. A new treadle pump and a motorcycle helmet will reduce malnutrition and road accident deaths respectively. These solutions are not what people normally think of[5]. As health technologies are considered their place should be well defined.

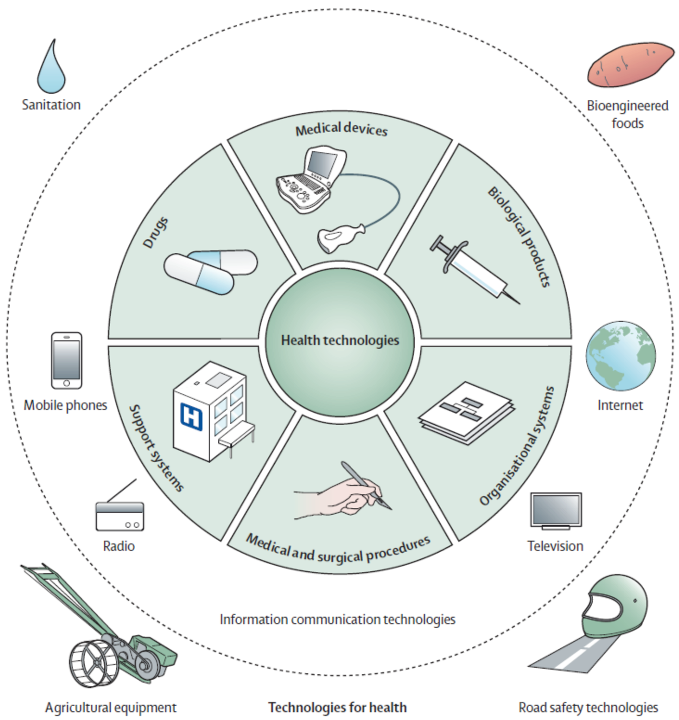


Figure 1: An examination of what constitutes the various section of health technology[5].

Secondly many developed world donors want to see deliverables for their dollars and intentionally or not push health focused organizations to visualize quantifiably simple returns on their efforts. The Bill and Melinda Gates foundation has been criticized frequently for their focus, and their tactics to force others to apply their methodology to global health interests [6]. The considerations are far ranging and often polarizing for how global health dollars should be spent.

To understand the interest in the use of unmanned aerial systems (UAS) and vehicles (UAV) as a part of health technology there are a number of critical pieces that should be examined such as the stakeholders involved, the needs, environment of use, and current solutions. By examining each of these the constraints and assumptions used for design can be accurate and provide for a more informed and therefore productive design solution.

2.1 Access to Care

Working backwards from the current use of drones in healthcare, the team set out to identify the problems actually being solved. The team began understanding drone use by reaching out to a number of researchers and organizations involved in the field. Speaking with representatives from a Matternet, Zipline, and Vayu as well as an Pathologist at Johns Hopkins School of Medicine conducting research in the area, the team began to understand the barriers to care. The barriers to care in the targeted areas seen in Table 2 or similar situations are complex set of issues[7]. Examination of the subject suggests that while the supply side of health services is a portion of access to care the demand exercised by those in poor positions whether financially or geographically have not accelerated need [7]. For example it is estimated that deficient care seeking is a factor in 6-70% of child deaths. In Bolivia 60% of children who died during a study period were not taken for medal treatment during the sickness episode[8]. These incidences highlight that access while two sided has significant issues.

The sad fact is global coverage for most interventions is below 50%. If level 1 or 2 interventions were universally available, 63% of child deaths could be prevented. These findings show that the interventions needed to achieve the millennium development goal of reducing child mortality by two-thirds by 2015 are available, but that they are not being delivered to the mothers and children who need them[9].

2.1.1 Physical Access to Care

Frequently research examining healthcare distribution foucses on physical access to care. The volume of research on the subject is significant and quantified in a number of ways depending on how recently the study was performed. This ranges from driving and walking times to clinics and hospitals relative to census data in China [10] and Nigeria [11] . In these two studies that there was a, "high negative correlation between population aging and healthcare accessibility," in Deqing County China and in Ghana that distance is the most important factor that influences the utilization of health services in the Ahafo-Ano South district. The Ghanaian study recommended locating a clinic or piece of the health system so that 5km was the maximum travel distance. Unfortunately given models this impossible, however expanding the healthcare network to provide more immediate access would be a more effective interpretation of the recommendation.

Some alternative methods relied on the use of GIS mapping to asses distances with a variety of computer models then applied to the data points of homes and villages relative to clinics and hospitals. South Africa for example the median travel time to the nearest clinic was found to be 81 minutes and over 65% of homesteads travel 1 hour or more to attend the nearest clinic, for a hospital this extends to 170 minutes[12]. In regions with more difficult terrain such as Andean Bolivia there is significant variability in physical access to primary healthcare [13], calling existing distributions inadequate in most cases and the imbalance severe calling out minimum travel times over an hour in many areas. The authors acknowledge this does not comprehensive cover midwives and traditional healers. Considered a fundamental part of meeting millennium development goals improved vaccination rates are absolutely crucial to community health. Niger is considered especilaly burdened by physical access where "children living in clusters within 1-hour of a health center 1.88 times higher odds of complete vaccination by age 1-year to compared to children in clusters fruther form health centers"[14]. These are reflected by other daunting statistics and annecodtes:

- "Remote villages were accessed using "25 camels, 45 donkeys, and more than a dozen boats." [15]
- In Nigeria it is not uncommon for women in rural areas to walk 26 miles to seek medical assistance [14]
- 64% of pregnant women spend at least 60 minutes travel to health facility by walking or biking in Ghana [16]
- Hospitalization from malaria is greatly reduced when primary facilities were within a two hour walk [17]

It stands that utilization of healthcare facilities diminishes with and distance [14], [18]–[21] and the quality of transportation and road conditions [22] especially given the impact dry and wet season cycles can have in the worlds equatorial regions. The physical barriers to healthcare are clearly a key part of those 400 million who lack access to basic care. Any improvement there could potentially bring existing life saving technology to millions.

2.1.2 Reduced quality of Facilities

multiple studies point to a variety of factors such as: income, service cost and education [11] Many of these factors are well known and the set stage for a solution that is cheap, reliable, and brings care closer to those who need it. That said no matter how close a supply gets there need to be people there to receive it and use it properly. This is definitely one of the larger issues in the space. Key issues in the global health supply chain focus on system and facility level issues such as poor inventory management and demand forecasting or lack of communication between operators in the system[23]. At an item level however the top identified areas o f need the supply chain are expiration of products and temperature control.

Distance to improved health facilities and the total cost of seeking healthcare needs to be reduced to enhance accessibility to improved health services by various socioeconomic groups[24]. However more recent work conducted n Nigeria suggests that citizens in many cases turn to private solutions. While not presented in [24] data from other surveys indicates private models due to lower waiting times and shorter distances in sub-Saharan Africa [25] or in India [26] in many cases are reduced in quality or more expensive. However while the aforementioned travel times are unimaginable in a country considered by many standards developed. The travel times point to a variety of factors, poverty is often highlighted as one of them and few countries prioritize access to care for the lowest incomes as can be seen in Table 1 where availability can been seen in broad form of global context. An important note is the ratio of nurses and doctors from Low-income countries (LIC) to High-income countries (HIC). There are countries however that have maintained a commitment

Table 1: Availability Of health services around the world.

Country Grouping	Hospitial beds per 10,000 population	Doctors per 10,000 population	Nurses per 10,000 population
Economic Group			
Low-income countries	9	0.49	0.83
Middle-income countries	21	0.97	1.45
High-income countries	57	2.67	8.16
WHO Region			
Africa	<1	.21	.93
Americas	25	1.94	4.88
Eastern Mediterranean	13	0.74	1.11
Europe	64	3.2	7.43
Southeast Asia	9	0.52	0.81
Western Pacific	31	1.1	1.7
World	26	1.23	2.56

Source: Calculations performed by the original author [27] using WHO data as of 2007.

to equitable coverage of not just health but of education as well. These include Costa Rica, Cuba, and Sri Lanka [27].

A critical part of modern healthcare is the laboratory technology that enables effective diagnoses for anything from malaria to HIV. Unfortunately, in many places labs are of low quality or of high cost as can be seen in various parts of Uganda, Namibia, and Botswana[28]. Only 0.3% of the evaluated labs in the Ugandan capital of Kampala met international quality standards[29]. Dr Timothy Amukele an author of both the aforementioned papers corresponded with the team describing the need to evaluate drone transport systems and their possible effects and the potential utilization for healthcare needs. His work in recent months has focused on the subject and he has co-authored a number of papers with founders of healthcare drone companies such as Vayu seen in Table 2. The low qulaity and high variability thorughout many low and middle income countries (LMIC) represents a significant additional barrier that is much more difficult to assess and would likely be better met with native innovations rather than importation of high income countries left over or outdated supplies.

2.2 Current Solutions to Access to Care

There are a number of contemporaneity solutions to improve access to care. Some of them are a better understanding of people needs based on geography and some of them seek to better equip hospitals [30]. In some cases that is improved models for financing care such interest free loans for emergency care [7]. Due to the importance and effectiveness on reducing morbidity and mortality vaccines have made their way to the top of the list in terms of global health needs. In order to get basic vaccinations to those 19.4 million children each year the vaccine supply chain stands to be vastly improved [31] as the primary method of improving large portions of global health. By no means the only solution or the solution to the whole problem recent outbreaks of diseases such as Ebola and Zika viruses stand to detriment human health. In fact some argue it is only a matter of time before a new easily transmissible zoonotic virus affects the lives of everyone on earth, similar to the early 20th century Spanish Flu[32]. As many look to add new vaccines to the supply chain there is concern in the WHO that supply chains will fail and that exposes society to the risk of not just the disease being actively fought but those that in many places are unheard of. These experts argue serious measures need to be taken to improve supply technology and actions for health supplies specifically vaccines if humanity wants to survive. This extends to demand forecasting, improve and increase training, distribution method technology improvements and more.

A number of countries with successful models were mentioned earlier, Costa Rica among them where indicators of care (outpatient clinic within 4km, hospital within 25km) show reform led to a decline from 30% to 22% of inequitable outpatient care from 1994 to 2000 [33]. This improvement is attributed to targeting the least privileged populations first and opening community medical offices. This type of work is an effective solution, policy is often one of the key aspects to improving healthcare. The world of policy is often complicated by multiple organizations who pull on purse strings, are granted differing levels of autonomy by governments and the WHO as well the decision making structure. It is then by extension quite easy to imagine the greater degree of complications when census data is inaccurate, the region is in open conflict, and that regional governments may not cooperate with national governments over political disagreements.

Given the team's background in a variety of engineering disciplines these problems are important considerations, but not the focus of the project. These situations help define the project constraints and goals. Given the direction of expertise the team choose to focus on technical solutions within their capabilities, staying away from information and management systems or supply chain models.

Instead give the understanding that in many places there is a serious set of barriers where physical distance is a key variable, the team examined solutions at technological level that may improve the situation.

Hoping to avoid the fallacy of technocracy where some technology is highlighted as the "magic bullet" to a given problem, the focus was on reducing the barriers to access especially in regards to the accompanying circumstance of large physical distances[34].

2.3 UAS for Healthcare

A cursory examination performed by systems engineers explores the the popularized and well know ventures in the field, detailing: range, supply type, and payload. The table below summarizes their examination and is by no means comprehensive, it serves to highlight critical areas of interest such as operations, method of delivery and various specifications. Various additions of modifications were made as Table 2 was condensed from research [35] . -stands to reduce costs and transportation times moving to a pull system rather a broken push system, those who ask receive. Effective use of drones as the last mile in the supply chain alleviates a number of pressures on the supply chain and it's operators extending out from the system to facility and item level improvements in reliability and access to critical supplies [23], [31]. One of the largest advantages would be the parallel development of improved inventory control with UAS implementation leading to improved results.

UAV's the primary component of a UAS have significant advantages over land transportation models. They are direct to the destination and require minimal operating oversight unlike traditional vehicles such as trucks and motorbikes. They have robust communication networks and present a cost effective way to move supplies for the last leg of the supply chain.

UAS is not fix all solution or magic bullet to many of these issues but is an easily accessible and relatively cheap technology that can be rapidly deployed and with proper expertise developed into effective ways to move supplies faster and or cheaper than before, in many cases to areas that previously did not have access. As the technology improves so will its capabilities and the number of uses will increase.

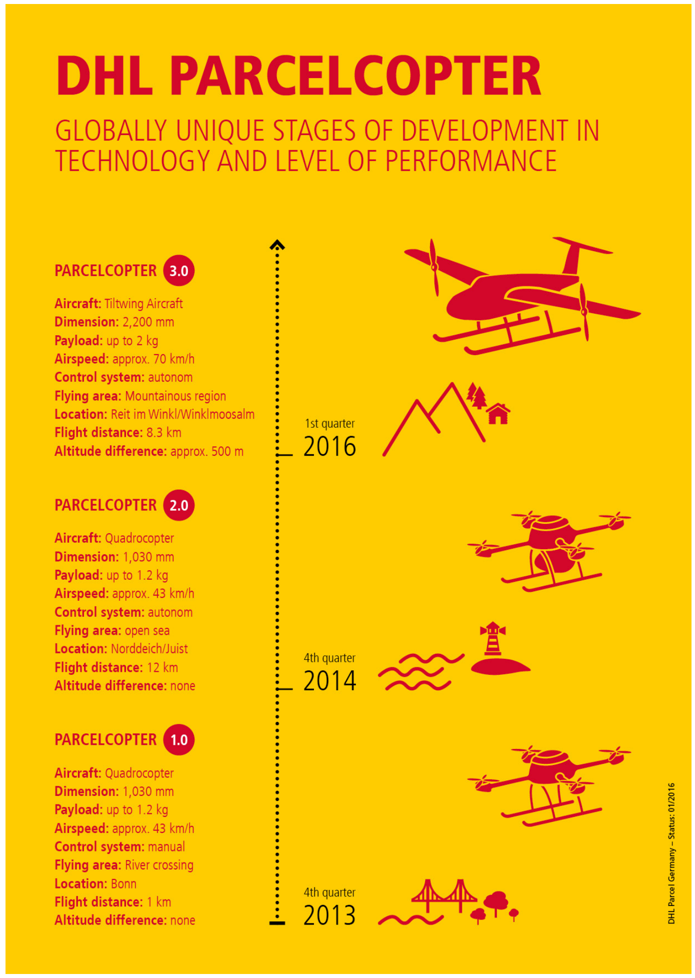


Figure 2: DHL's timeline and evolution of the Parcelcopter

Given the wide ranging capabilities of drones and the variety of supplies being moved over differing ranges it became clear that their was a burgeoning need. Rather than intermediately begin with unmanned aerial vehicles and systems the team began by trying to understand the reason people were using drones to begin with. What necessitated that drones be used to provide care? Once that had been understood the following question was: what needs have these delivery models met, where are the issues that still need to be addressed? Luckily these two categories divided up quite nicely in areas of operation and the type of setting involved as well as the UAS, developed and two separate solution spaces fixed wing and the more familiar quad-copter design.

2.3.1 Developed World UAS

While in the table the balance between low and high income countries seems relatively even the first distinctions should be drawn the differing supplies being moved. A more through examination

Table 2: A review of current drone models for delivering healthcare compiled from[35] and additional research or updates indicated by the off color row and *.

	Operations		Methods		Capabilities		
Drone Company	Health Care Items	Delivery Location	Launching Pad	Delivery Method	Payload	Range	Speed
Matternet	blood, medications, lab samples*	Haiti, Dominican Republic, Papua New Guinea, Switzerland, Bhutan*	Automated Ground Station	Automated Ground Station	2 kg	12 km*	40 kmph
DHL Parcel	blood, medications, lab samples*	Germany	Automated Skyport	Automated Skyport	2 kg	12 km	>64 kmph
Zipline	vaccines blood	Rwanda, rural: Maryland, Nevada, Washington*	Nest	Paper Parachute	1.36 kg	72 km	145 kmph
Flirtey	medications	Virginia, Nevada, New Zealand*	Airport	Lowered by rope*	2 kg	32 km	?
Delft University	defibrillators	Netherlands	Hospital, Clinic?	Ground Landing	4 kg	12 km	96 kmph
Vayu	medicaiton, lab samples	Madagascar	Launching Pad at Clinic	Ground Landing	2.2 kg	60 km	?

reveals that the samples that DHL in Germany is moving is to remote locations in the mountains and islands in the North Sea where no advanced lab is available. [36]–[38]. The DHL project has evolved through multiple iterations but due to the automated Skyport and short flight time and distance (9 minutes, and 8.3 km), supply integrity concerns are small. Both Skyports are also located near villages that just happen to remote, not severely under-resourced. This can be seen in Figure 3.

Figure 3: DHL Parcelcopter 3.0 in use with the Skyport

(a) Servicing of a Skyport. (b) The Parcelcopter 3.0 taking off from a Skyport.

The operations DHL has been participating in are a strong indicator of the rapid growth and the potential applications of our project in the developing world. While the published literature reflects an interest in certain time sensitive medical supplies the larger interest is the cost reduction in small payloads. Rather than pay a driver or for gas costs part of a traditional multi-tiered land transportation system (TMLTS) the drone is a great option for smaller payloads below 2kg. That 2kg figure actually makes up a larger portion of the supply chain. According to Matternet, more than 90% of the goods transported over the last mile weigh less than 2 kilograms (4.4 pounds) [39]. Given this statistic, it is clear that developed world sees the need for drone logistics. The temperature and time sensitive nature of medical supplies makes drone delivered healthcare models particularly interesting for critical and sensitive supplies. Recognizing this need in the developed world Matternet has been heavily involved in the implementing UAS systems in different areas. Most recently these operations have been in Lugano. Where they have developed a collaboration with Swiss Post the Swiss government run postal service and Matternet. The project plans to use, "drones to deliver blood samples and other small parcels between hospitals" [39]. FLirtey has performed a number of licensed tests with FAA approval in the United States ***Flirtey tests*** While the developed world has focused on the incentives of decreasing cost and improving on operations of time sensitive supplies the situation is different in less developed nations.

2.3.2 Developing World UAS

In countries where the access to care is severely limited by infrastructure and lack of medical professionals such as Malawi and large parts of sub-sarahan Africa as highlighted in Section 2.1, the use of a UAS would greatly improve access to care. The addition of a drone transportation system would save women from a marathon of walking for simple blood tests or filling a prescription. Matternet has operations in both the developed and the developing world. While they have clearance to fly in Lugano and other parts of Switzerland, they have been key in clearing the way for research to use drones for critical supplies in other parts of the world. They have operated in Haiti [40], Bhutan [41], and more recently Malawi [42]. While Project Redline, another initiative, explored the use of drones for both types of supplies by creating small drone airports throughout limited access areas, developing mini transportation hubs. The conceptual vision seen in Figure 4 highlights the various states of the logistic systems used in target areas.

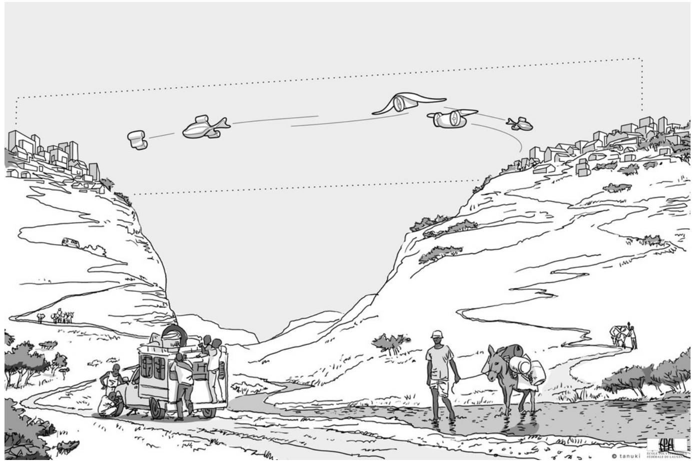


Figure 4: DHL Parcelcopter 3.0 in use with the Skyport

Note the donkey and broken down Land Cruiser on the left side. Project Redline implemented a smaller drone for medical supplies with a 3m wingspan and a payload of 10kg, using a fixed wing system rather than the more popular quad rotor design seen on recreational drones. Project Redline was described by Samburu elder in northern Kenya as, ”putting a donkey in the sky.” [43]. In fact, the fixed wing design is more popular in the developing world as it significantly expands the range of a given UAS which leads to improved access to care. However in the case of Zipline which is currently being used in Rawanda to deliver a number of supplies such as Blood Products, lifesaving medicines, vaccines, other essential medicine, diagnostic supplies and emergency response needs. Most of the needs are not overly difficult to anticipate from a project point of view as they are considered crucial elements of the health system in most countries.

Figure 5: A Zipline ”Zip” delivering supplies via paper box and parachute.

2.3.3 Efficacy of UAS for Healthcare

A critical part of understanding the use of drones for this type of operation is the cost analysis and whether this really decreases cost of transport for current systems. However, in some cases that cost assessment is not possible due to lack of current information for comparison. For a number of cases that might be due to the lack of care provided in anyway let alone a metric. The issues found in the supply chain are tied to a number of concepts. Chief among them are issues with resources, lack of well trained and funded personnel, and a both sensitivities and importance of the supplies in the healthcare supply chain.

Researchers at the Johns Hopkins Bloomberg School of Public Health and the Center for Department of International Health, Public Health Computational and Operations Research (PHICOR), International Vaccine Access Center (IVAC) developed a Highly Extensible Resource for Modeling Event Driven Supply chains (HERMES) software to discretely simulate the WHO Expanded Immunization Program (EPI) in a province of Mozambique[44]. The model indicates that drones with payloads of .15L for regular EPI, .2L after small introductions, and .4L after more introductions could achieve cost savings. In some cases the UAS reduced the logistics cost per dose by 20% in the baseline model for comparison. This model held cost savings were still applicable even under 6 different variables for sensitivity analysis.

The feasibility of moving medical supplies at an item specific level has also been achieved by Dr. Amukele for multiple products from whole blood, to paired blood samples, with routine microbiological and chemistry testing indicating no differences between the samples [45], [46]. This research suggests that drones are provide cost savings and so far for supplies are clinically valid.

William Easterly
Lancet [5]

2.4 Areas of Focus

Vaccines and other critical supplies such as lab samples and organ transplants are considered the primary objects of transport by most of these companies and other efforts. in fact Zipline claims to move supplies in most of the following categories plus some more such as whole blood.

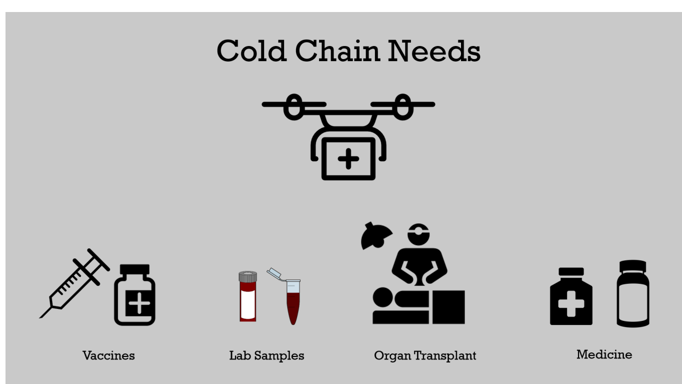


Figure 6: A simple graphic highlighting potential cold chain needs for UAS delivered healthcare.

discussion of global health involves a couple of core facts prior to design using [5], [30] as key drivers

2.4.1 Vaccines

As different supplies within global health needs none are considered as crucial as vaccines which stand to prevent 7.6 million deaths for those under 5 by scaling up vaccine delivery to 90% coverage [47]. Vaccine biological efficacy is incredibly complicated but in an effort to improve the reliability of the supply chain Vaccine Vial Monitors were created in the late 1980's that use cumulative heat exposure to monitor the viability of the vaccine. These indicators have been validated by the World Health Organization. They additionally serve as outside method to validate the supply chain concerns of those involved in global health logistics. This and the need to move vaccines at more cost effective levels reliably makes vaccines an excellent model to explore for UAS healthcare models.

2.4.2 Lab Samples

Laboratory samples are often critical to diagnosing various conditions and easily conspired critical infrastructure in desperate need of improvement as highlighted by [28], [29]. Estimations suggest that diagnostics impact around 70% of healthcare decisions and are key to a modern healthcare system **M** The time sensitive nature and high sensitivity of supplies makes it critical they be a part of a robust supply chain. Unlike vaccines though there are low temperature requirements and the cold chain is less necessary.

2.4.3 Organ Transplants and Similar Biologics

Both time and temperature sensitive organ transplants are a perfect platform for UAS as a reliable supply chain. However the organ is often being moved farther the range of current small scale UAV technology. Despite that, United Therapeutics recently placed an order in the fall of 2016 for a 1000 UAV's for organ transplant [48].

2.4.4 Various Medications

Zipline moves all of the following medications for time sensitivity: rabies PEP, anti-venom and other essential medicine such as antibiotics, anti-infectives, anesthetics, and analgesics. Some of the above medications are temperature such as oxytocin, rabies PEP and anti-venom, while the small amount of heat exposure seen by the supplies during a simple flight is low readers should be reminded that Zipline can only move supplies from a central facility and drop them via parachute, also a potential issue for lab sample transport. Until thermo-stability is achieved for the vast majority of supplies mentioned there will be cold chain needs.

2.5 Cold Chain Needs

Noticing there was a lack of control for the cold chain, the team identified cold chain technology as an area of need. Feeling that the above companies were in a better position to improve on drone design itself, the team chose to focus on the critical payloads being delivered. This concern began with what supplies would be transported and how much? The payloads were determined based on literature analysis of cost effective requirements and what other systems are currently capable of.

Vaccines and other critical supplies such as lab samples and organ transplants are considered the primary objects of transport by most of these companies and other efforts and require constant temperature control and monitoring. For reference the Vayu drone which uses a smartphone system for communicaiton can transport 4 units of whole blood, or 160 lab samples at a weight capacity of roughly 2.2kg.

Examination of the healthcare environment in the developing world made it quite clear that access to effective and reliable healthcare within small travel times, at low travel and overall costs, as well as decreased distances were the largest barriers to basic healthcare services. Out of the supplies evaluated for time sensitive supplies in Section 2.4, vaccines and organ transplant stood out as the critical time and temperature sensitive items. The conversations with those in the field pointed towards regulations as the largest current barrier but it has become clear that on a weekly to monthly basis that governments around the world from Switzerland to Bhutan to Rwanda to Malawi to even the United States are creating space for drones focused on medical needs.

The use case for drones is quite clear. What is also clear and considered a key variable is the temperature of medical supplies specifically vaccines. Multiple studies have found issues at both ends of the narrow temperature window of 2°C to 8°C where vaccines are lost due to freezing or heating such as in Bolivia and Thailand [49], [50]. These and other results such as those found in a survey of a district wide survey of Polio vaccine cold chain in India and a similar study in Papua New Guinea highlighted the need for a technology that could maintain the cold chain and reduce human error leading to vaccine losses[51], [52]. The supply chain needs and clearly demonstrated cold chain needs led the team to a sufficient level of understanding an open ended problem. That there is a need to use drone effectively to move supplies like vaccines but that these supplies need to be moved reliably within the cold chain, and no device or technology currently exists to meet that need.

3 Project Strategy

3.1 Initial Client Statement

Given the self directed nature of the project and no outside client, the team developed the following early stage client statement. This was based on preliminary research and a few interviews with professionals aligned in the field from two companies and a practicing pathologist interested in the field.

The goal of this project is to deliver usable vaccines and other medical supplies to a medical professional in the field via drone. The team will accomplish this by actively controlling the temperature of a container system to actively maintain a set temperature for each type of medical supply. The supplies will fill an internal cavity and will be continuously monitored with sensors that are part of the control loop and report to an external monitoring system. This container is also then fastened to a given drone with minor modifications and the mechanism of attachment is a part of the system for transporting the medical supplies in a physically and environmentally stable container.

3.2 Mission Statement

Using the initial client statement and a review of the project and a more comprehensive review of relevant literature seen in section 2 the statement was revised to a simple mission statement: *Provide a controlled and monitored environment for the movement of medical supplies via drone.* This revised client statement guided the overall development of the project and helped define the workspace for the problem at hand.

3.3 Objectives and Constraints

A number of constraints limited our project in terms of scope and design restrictions. These as well as corresponding enablers, outputs, and inputs of the system to be designed as seen in outline the project. By applying principles from systems engineering and the established mission statement the team developed the following system level view.

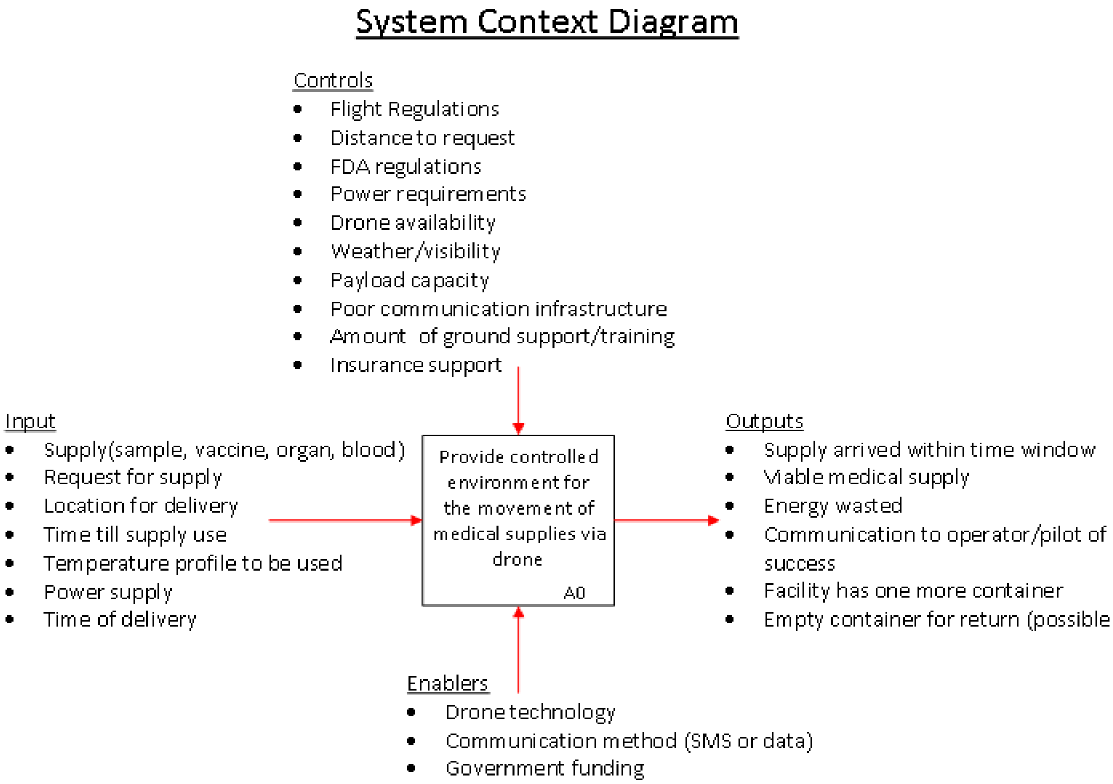


Figure 7: System Context Diagram

To develop these objectives, the team defined a number of assumptions and constraints.

Assumptions and Working Constraints:

1. Conditions will be such that the drone will be able to fly with the attached payload
2. The distance of the flight will be within a predetermined range set by the team
3. The drone will be monitored by someone with adequate knowledge
4. The attached device including payload will be less than five kilograms
5. The operators at either end of the delivery will know how to use/access the device
6. There will be no shortage of power for duration of flight to ensure delivery
7. The sensors will relay data as desired by the team back to the control hub

3.3.1 Stakeholders and Desirable Functions

There are a number of stakeholders involved in the device whose voices are important to the development of the system in consideration. Literature analysis for similar situations and the medical environment (a consideration in the environment of use) the team is primarily considering rural China and sub-Saharan Africa as areas with large enough population densities and with large enough gaps in medical infrastructure to merit the system's need. These users make up a number of different categories and while this likely does not consider all of the possible stakeholders, the team's limited access to voice of customer led to the team selecting the following groups and their characterization. These stakeholders can be seen in Figure 8.

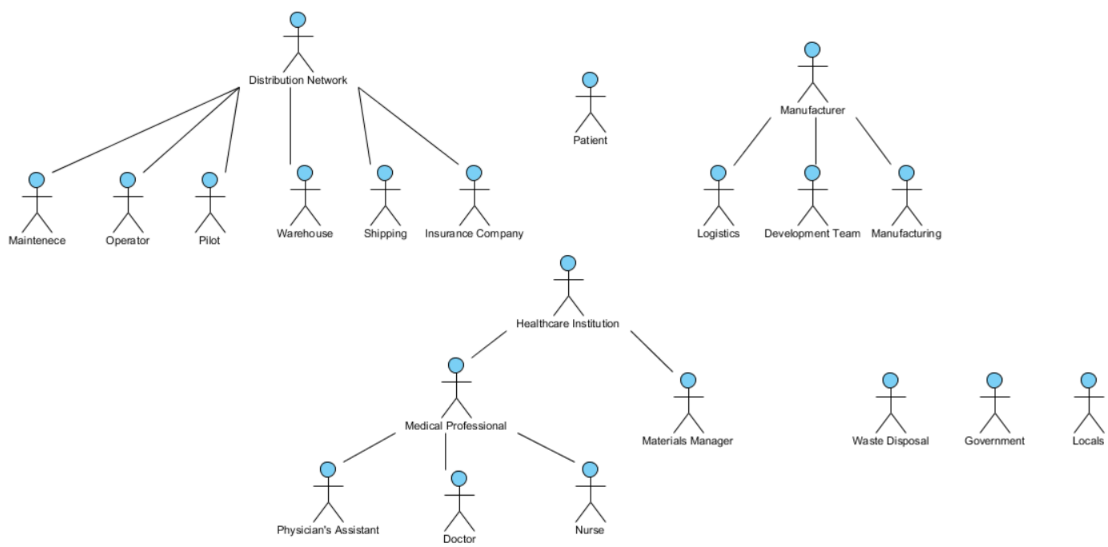


Figure 8: System Context Diagram

Each category of stakeholder was defined as best as possible and team sought out input from parties as close to the defined categories as they could represent. The stakeholders listed below are all categories of users who interact with device or have a stake in the results of the system. In many cases it was difficult to get a full picture of all possible stakeholders given the scope of the project. To account for this, certain stakeholders have been used as representatives for larger groups as their interests seemed highly similar at a cursory view.

Healthcare Institution:

The healthcare institution serves as a place holder for the wide range of healthcare environments the system might interact with, from first world highly industrialized resource rich areas with full competently trained staff to the clinics and traveling practices indicative of resource limited areas. As seen in the stakeholder map this encompasses a number of roles. These roles are all considered but for the purposes of the project certain stakeholders serve as representatives of larger groups.

Medical Professionals: While the medical professionals might interact with packaging and will interact with the final supply before or after delivery (depending on the supply) they rarely will interact with the system itself. These stakeholders (Doctors, Nurses, Physicians' Assistants and others) in a high resource environment likely have little interaction with the system itself, however in a low resource environment will likely also be the materials manger or simply due to the more multidisciplinary nature of their task be more likely to have a greater degree of interaction with the system.

Materials Manager: A stakeholder within the healthcare institution who is responsible for the materials used by the facility and the medical professionals inside it. They will be the most frequent user at that end of the delivery system, caring for the container, ensuring it made the flight safely and responsible for efforts to return it to the supplier. A materials manager will be responsible for the supplies in the container once the container lands and responsible for the container itself. These materials managers in low resource settings are likely to also be medical professionals but with less training in handling the materials and less resources to support the system.

Distribution Network

The distribution network would have a larger team behind it the majority of stakeholders affecting the system are the pilot and operator who load the supplies into the drone. These roles would likely overlap with each other and other roles of a logistical nature. Such roles include an initializing supply handler, a maintenance team, warehouse, shipping and likely the initial payer, or the insurance company. The pilot and operator are discussed more in depth below as the primary users and representatives.

Pilot: The pilot is responsible for the drone and its flight, pre-planning the path, assessing weather conditions and understanding the payload attached to the drone to ensure that the payload does not adversely affect flight.

Operator: The operator might have the largest role to play as they have the most interaction with the system. The operator would be responsible for moving supplies from stock to the system, priming the system for flight, ensuring the validity of the supplies and assisting the pilot with any pre-flight checks. Upon return of the drone the pilot is then responsible for a post use check of the system and returning any supplies to their correct location, disposing of consumables, and moving any incoming supplies from a return trip (such as blood samples) to the correct location. This is different than the warehouse staff but in some environments it may be the same person or have significant overlap.

Manufacturer

A stakeholder involved with the design, development, or production of the container. These stakeholders have a direct impact on the function of the system as they take into consideration the requirements and output the best method of creating and producing the container.

Government

This stakeholder is involved in the regulatory process regarding drone flight and safety of those in the area. They are also interested in the expedited delivery of medical supplies to help increase healthcare infrastructure.

This project serves the greater purpose of improving the final leg of healthcare and why the stakeholders seen in the stakeholder map serve in a number of roles. Many of these fall under the conditions covered by the WHO and China's Country Cooperation Strategy's strategic priorities of:

1. Strengthen health systems towards universal health coverage.
2. Reduce morbidity and mortality from major diseases of public health importance and from risks to health and health security.
3. Reduce inequities in health in the western region of China through subnational public health action (source)

Each of the stakeholder categories was mapped to various parts of the overall process that the above stakeholders would interact with it as seen in Figure 9.

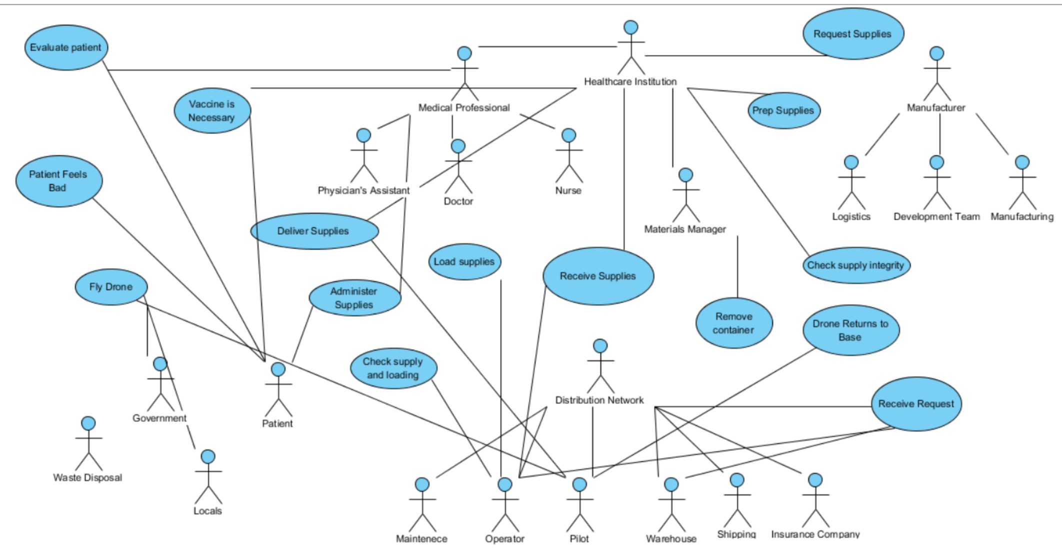


Figure 9: The critical system functions desired by various stakeholders

Desired Functions

Through the analysis of the stakeholders, the team outlined principles of operation for the system. First and foremost, the team decided the package must be designed for drone flight. This included the overall weight of the package, while also considering its aerodynamics. The point of the project was to design a package to be transported by drone, so the package would need to be optimized for this use. Another desired function of the system was active temperature control. This could be used to ensure the internal temperature was between 2 °C and 8 °C. If the canister would be able to maintain this temperature for the duration of the flight, it could be used for a majority of cold chain vaccines. In terms of package volume, a minimum of 0.2 liters of vaccine was chosen due to the supply chain and logistics review at the Bloomberg School of Health [44]. Because of the package's likely use in low-resource areas the team decided to try to make the system as easy to use as possible. The final major desired function of the system was remote communication, including package status and location. This was primarily a security measure for the Healthcare Institutions or the Governments who would invest-in and use the device.

3.4 Project Approach

The overall problem to solve for the project was keeping medical supplies in a thermally stable environment. To solve this problem multiple systems were considered:

1. Measuring the internal temperature
2. Controlling the internal temperature
3. Monitoring the vaccines and displaying validity
4. Package security

These systems are explained in more depth in Section 4.

4 Design Process

4.1 Needs Analysis

Table 3 lists the stakeholders determined at the beginning of the project that will either feel an affect or be involved in the design process.

Table 3: Stakeholders Analysis

ID	Title	Description	Role	Priority
SH.01	MQP team	Evan Bosnia, Michael Beinor, Scott Cazier, Keegan Train	Direct, positive	1
SH.02	MQP Advisors	Professors Jianyu Liang and Greg Fischer of WPI	Direct, positive	1
SH.03	Community health experts	People with knowledge of rural or small village health knowledge	Indirect, possibly positive	2
SH.04	Aid organizations	Those potentially able to use the system	Indirect, possibly positive	3
SH.05	Patients	Those receiving medical supplies via drone	Neutral	3
SH.06	Drone operators	Those who will be monitoring drones to deliver supplies	Indirect, neutral	1
SH.07	Medical suppliers	Companies who currently make drugs, vaccines, etc.	Indirect, possibly positive	2
SH.08	Gov't flight agencies	China's equivalent to the FAA: Civil Aviation Authority of China	Neutral, compliance	1
SH.09	Gov't. drug agencies	China's equivalent to the FDA: The China Food and Drug Administration	Neutral, compliance	1

From the Stakeholders Analysis Table 4 was developed to reflect what was most crucial to study in order to achieve the requirements set out by the team.

Table 4: Needs Analysis

ID	Title	Description	Traceability	Priority
N.01	Drop in a controlled manner	Likely to have fragile materials inside, control descent to ground	SH.02SH.01	1
N.02	Carry determined amount of volume/weight	Drones can only handle so much weight before becoming inefficient or unable to fly	SH.02SH.01	1
N.03	Execute drop in reliable manner	Making sure the goods leave the dropping mechanism every time	SH.02SH.01	1
N.04	Climate controlled pods	Potential to have temperature sensitive materials on board	SH.02SH.01	2
N.05	Able to withstand high impact	Incase method of controlled falling fails	SH.02SH.01	1
N.06	Easy to load/unload materials	For ease of operators and receivers of supplies	SH.02SH.01	1
N.07	Disposable/recyclable	Recovery of containers could be either difficult or out of the question if dropped while flying by	SH.02SH.01	2
N.08	Communicate with Operator	Package can send data and location to hub	SH.02SH.01	1
N.09	Simple User Interface	Minimal instructions/training required if any	SH.02SH.01	1

4.2 Design Requirements, Functions (Specifications)

The team determined the design requirements by examining the needs of the system, as well as the specifications of the supplied drone. These requirements were used as a baseline to develop the system against and influenced all of the design decisions made. A list of the design requirements as well as explanations of each is shown below.

Package must maintain temperature stability in supplies

In order for the package to successfully carry cold-chain medical supplies, the temperature of the package must be kept stable. Having a variable temperature could cause thermal degradation or freezing, both of which could spoil the package contents.

Package must weigh less than five kilograms

This requirement was based around the flight characteristics of the drone supplied to our team. The max payload of the drone is 5.1 kilograms (11.2 lbs), so this was set as the maximum weight of the package, including all electronics and the payload.

Package must mount securely on the drone

Maintaining package security requires that the package is secured to the drone. The package must not be able to translate or rotate around any axis. However, the package must still be able to be taken off the drone for loading and maintenance.

Package must remained powered for at least an hour on battery power

The flight time of the drone under maximum payload is roughly twenty minutes. The powered time of one hour was set to account for setup and takedown time, as well as the potential use of different drones with longer ranges as the transportation method.

Package must allow for easy access to battery

The battery of the canister must be easily interchangeable or accessible to charge while still attached to the drone. Otherwise charging the battery, which would happen after each trip, would be difficult for the user, which could cause damage to the package.

Package must be able to be directly powered

The need for direct power comes with the need for power efficiency. Lower the temperature from room temperature to the desired temperature takes power. In order to not waste battery power, the package needs to have some method of direct power.

Package must allow for easy access to supplies

This requirement is fairly straightforward. In order to have an effective system, the user should be easily able to access the medical supplies within the package without damaging the supplies or the package.

Package must be designed to limit drag

In order to improve the flight distance of the drone, the package must be designed in a way to limit drag. Reducing the drag also decreases the effect that the package has on the flight path of the drone. If the drag coefficient is high, the drone would get pushed by the wind more than if the drag coefficient is low.

Package must hold its contents securely

Vaccines and other medical supplies often come in glass vials. In order to avoid the supplies becoming damaged during transportation, they need to be held in place. The mechanism restraining the vials must also not cause any damage to them.

Package must allow for transport of different supplies

Because the package needs to transport different supplies, it needs to be design in a way that allows for the user to easily configure the package for these different supplies.

Package must be durable enough for repeat use

The package will be returned after each use, so it should be durable for multiple uses.

Package must communicate data to the user

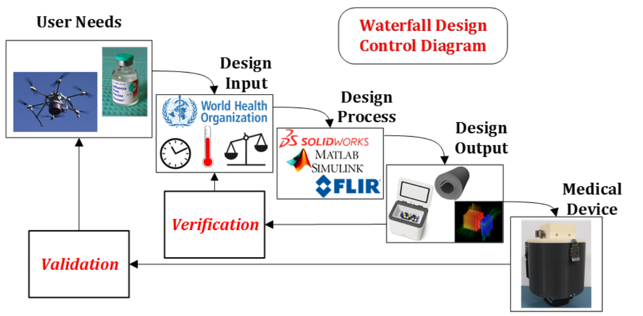
Package security is important for transporting sensitive materials such as vaccines. The user should be able to know where the package is and its status remotely.

4.3 Important Industry Standards

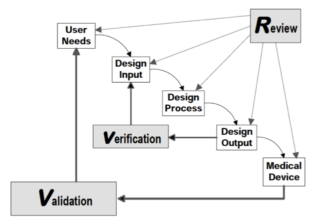
For the project the team looked different industry standards. These include ISO 13485, 62366, 61025, as well as FDA Part 11, 21 Code of Regulations 820, the WHO PQS Guidelines, and the WHO vaccine handling guidelines. Each of these is a different component within the larger medical device industry.

In order to familiarize the team with the context of medical device development ISO 13485 and FDA CFR 21 Code of Regulations Part 11 820 most specifically 820.30 led the process for designing the device as can be seen where the FDA design controls diagram was used to inform the process the team followed which can be visualized in Figure 10.

Figure 10: Comparison of waterfall diagrams as visualized in the process used by the tam and that of the FDA guidance.



(a) Visualization of the team's use of the design controls diagram.



(b) The original diagram provided by FDA guidance.

In addition to the FDA guidance the team did it's best to simulate the process most organizations use by adopting the principles of ISO 13485 and maintaining an internal QMS with design reviews at the prescribed stage gates as possible in a small scale research environment and lack of expertise.

Larger standards considered in design decisions were WHO guidelines for prequalification, usability of medical devices called out in ISO 62366 and the use of cursory fault tree analysis in solving design issues with regards to ISP 61025.

4.4 Initial Conceptual Designs

4.4.1 System Architecture

The team decided to control the electrical system using an Arduino Uno microcontroller (MCU). This MCU has enough versatility to handle a variety of different external components, ranging from running serial modules to handling digital inputs and outputs, for a reasonable cost. All package control would flow through the microcontroller.

4.4.2 Refrigeration Method

There are many different methods of moving heat out of a container and into the environment. These include thermoelectric coolers (TEC), passive ice, and vapor compression. Each method has its benefits and detriments that taken into the context of the project selected the best method. A visual representation of the analysis of the three choices is shown in Table 5.

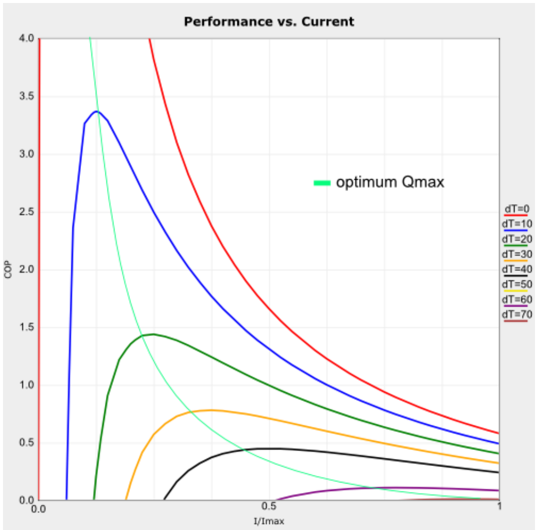
	Weight (2)	Control (2)	Efficiency (1)	Cost (1)	Weighted Total
TEC	1	1	3	2	9
Passive	2	3	1	1	12
Compression	3	2	2	3	15

Table 5: Weighted Factor Comparison

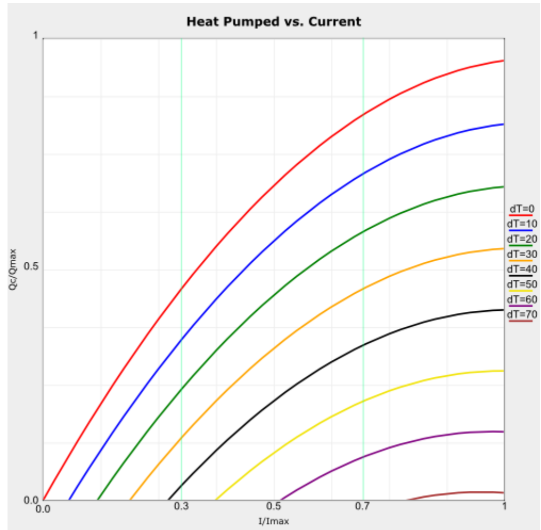
The two main categories considered were heat system weight and controllability. Weight is a critical consideration for any form of airborne transportation, so it was weighted more heavily than other factors. Controllability was weighted more heavily as well because of the limited temperature range that vaccines stay viable in. Without accurate control of the refrigeration element, the viability bounds could easily be broken. Efficiency and cost were considered less important because of the short lifespan of the system and ability to be reused. With these factors in mind, the team decided the best choice for refrigeration method would be using a thermoelectric cooler.

Thermoelectric Cooler

Thermoelectric coolers (TEC) take advantage of the Peltier effect to move heat from one face to the other. TECs are driven by a voltage differential between the two leads. Because energy is wasted as heat to move heat from one face to the other, these modules are relatively inefficient. The performance of TECs is highly dependent on the current applied to the plate and the temperature differential between the hot side and the cold side. A graph of the efficiency is shown in Figure 11a. Note that $\dot{Q}_c$ in this figure is the ideal situation. A complete explanation of the math behind TECs is shown in Appendix E.



(a) Efficiency of TEC



(b) Heat Transfer of TEC

Figure 11: Graphs taken from [53]

As shown in Figure 11a, the performance of TECs drop as the temperature differential increases. Moving heat away from the hot side of the TEC is important to improve the efficiency of heat transfer. An unfortunate side effect of this is in higher external temperatures with the same internal temperature, the TEC will perform worse than in cooler temperatures [53].

The temperature differential across the TEC also has an effect on the heat transfer rate provided. As with the efficiency, higher temperature differentials hurt performance. This is shown in Figure 11b. An effective method of improving the performance of the heatsink would be to improve the heatsink on the hot side of the TEC. The better the heatsink, the lower the temperature will be on the hot side, which will improve the temperature differential.

4.4.3 Temperature Measurement

To generate a control signal to the TEC, there needs to be some form of input signal obtained from the temperature of the package. The signal, in the form of an analog voltage, is read by the MCU and interpreted into an output to the TEC. There are a few methods of electronic temperature measurement, including thermocouples, NTC thermistors, and RTD thermistors. These measurement methods all react to temperature by changing resistance, but the actual reaction is different for each type.

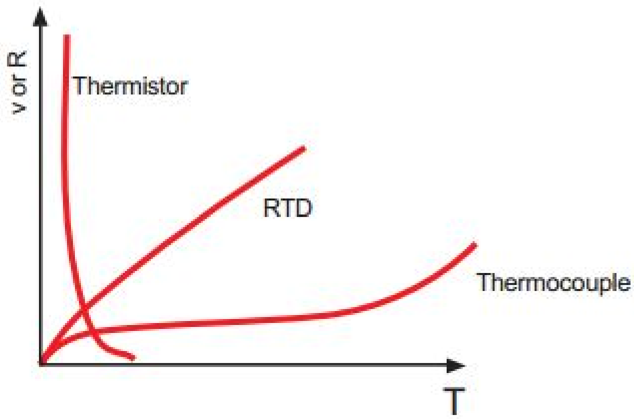


Figure 12: Generic graph of thermistor resistance changes

Figure 12 shows a general representation of the changes between each thermistor type. Thermocouples experience the lowest rate of change, but can reach the highest temperatures. RTD thermistors experience an almost linear temperature change, but have average sensitivity and temperature range. NTC thermistors (shown as "Thermistor" in Figure 12) can only effectively measure a small temperature range and follow a curved resistance function, but have the highest sensitivity of the three [54]. Because of the high sensitivity, the team chose to use NTC thermistors for temperature measurement.

The MF52-103 NTC thermistor was chosen for its lightweight, cost, and accuracy. To calculate a function of thermistor resistance per temperature, the resistance values of certain temperatures were plotted. An exponential trendline was fit to the resulting scatter plot, shown in Figure 13. Note the trendline equation is shown on the right side of the graph. Thermistor specs were taken from [55].

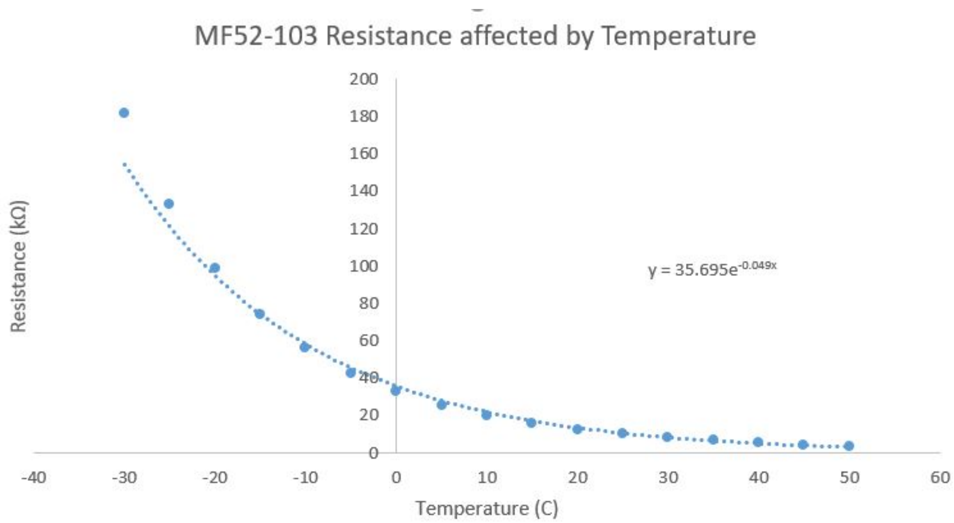


Figure 13: Determination of intermediate resistor values

To determine a more accurate model of the system focused on the viability range of vaccines, a straight line approximation was used only on data within that range. Because the temperature range is relatively small, it was assumed that generating a linear equation relating temperature and resistance would be an adequate approximation of the measurements.

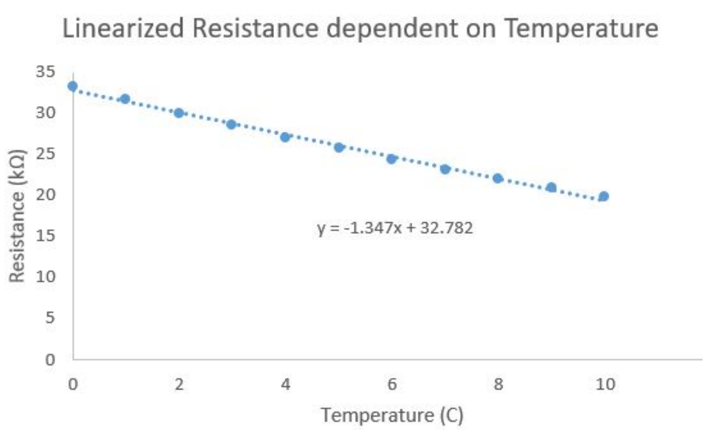


Figure 14: Determination of intermediate resistor values

Measurement of the MF52-103 NTC thermistor only works with something to compare the resistance to. A simple voltage divider circuit was used to generate a variable output voltage readable by the Arduino. The voltage output using a 10 kΩ reference resistor is shown in Figure 15.

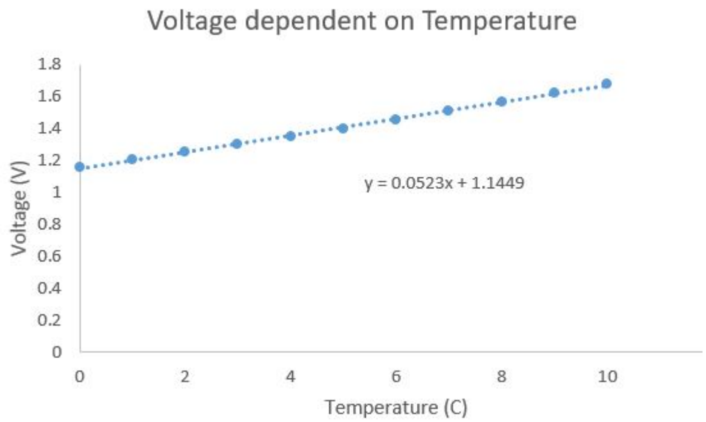


Figure 15: Voltage divider output dependent on temperature

The the analog inputs on the Arduino Uno are 10 bit analog to digital converters with a reference voltage of 5 volts. With the given voltage linearization, the minimum change in temperature that can be measured by the Arduino in the given setup is 0.093 °C, shown in Equation 1.

$$Sensitivity = \frac{Vref}{2^n} * \frac{temperature(C)}{voltage(V)} = \frac{5}{2^{10}} * \frac{1}{0.0523} = 0.093 \tag{1}$$

The precision of the thermistor is far under the functional requirement of 0.25 °C.

4.4.4 Vaccine Validity

To determine a rough estimate of the validity of the vaccines, the team decided to add a second thermistor to the container placed within one of the vaccines. Using this temperature, the validity of the vaccines would be roughly measured by running a constant sum of any temperatures above the set maximum temperature of the vaccine.

4.4.5 User Interface

Physical Interface

The user interface was determined from the functional requirements of the system. After moving through the functional requirements, it was also decided to make the user interface as simple as possible. Figure 16 shows a basic representation of the system interface. There were three status LEDS's: one showing the system is powered, one showing the system is armed, and one showing the validity of the vaccines. The two switches controlled power to the system and locking the temperature settings (arming the system). The two knobs set the max temperature and the temperature range for the vaccines. The team decided that this setup would provide the user enough functionality while remaining simplistic.

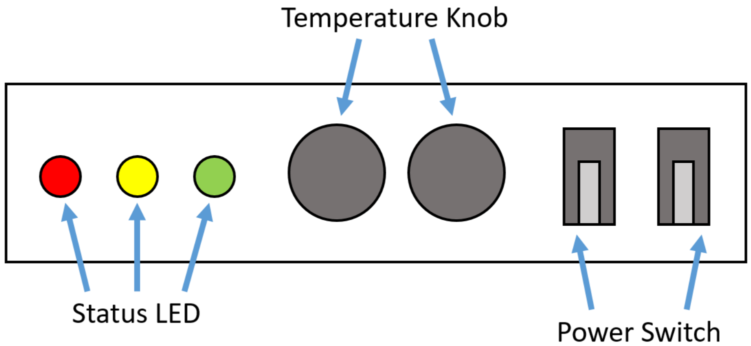


Figure 16: Basic representation of proposed user interface

Remote Interface

To receive mobile updates from the package in flight, a GPS-GSM system was added to the package. This would allow for package tracking and current status to be sent remotely. The team decided to implement GSM and GPS in order to improve package security, fulfilling the respective functional requirement.

4.4.6 Power Management

Battery

The challenge of powering the system came down to power density and the ability to be reused. Because the TEC element is electrically controlled, a battery needed to be used. The are many types of rechargeable batteries, but the type that best fits the application is Lithium Polymer (LiPo) batteries. Lithium Polymer batteries have a high energy density. Because the TEC takes a lot of power to operate, this is important to improve the duration of refrigeration while lowering the battery weight needed to power the TEC. The basic structure of a LiPo battery is a series of 3.7 volt cells. The "s" value of LiPo batteries gives the voltage of the battery; a 6s LiPo battery has a voltage of $3.7*6 = 22.2V$. To measure the voltage of each cell, LiPo batteries have a balance-charge connection.

Control

To control the TEC, two methods were discussed: using a relay to do an "on-off" method of control, or using an operational amplifier (op-amp) to amplify output voltage and isolate the current from the MCU to the TEC. Pulse width modulation (PWM) control does not work with TECs as it damages the TEC's semiconductor elements. The team decided to test each method of control to determine the better method.

4.4.7 Mounting Mechanism

An important consideration of the package was its ability to mount onto the drone. The team determined that the best option was to create a rail that the canister would slide onto to align itself to the mounting piece on the drone. Using a rail would limit the vertical translation in two directions. Motion in the third direction is restrained by the use of a latch that compresses the two mounting brackets together. In order to remove any rotation of the system, a dual rail system would be used.

4.4.8 Container Shape

The team decided to use a cylinder for the container shape because of the multiple advantages cylinders have over other solids. Cylinders have the lowest surface area for the highest volume among prismatic shapes. Having a low surface area limits the heat transfer into the package which is critical for maintaining low temperatures. The cylindrical volume also fits to the vials as the vials are cylindrical. Another advantage for a cylinder is that it is more aerodynamic than other prismatic shapes such as a rectangular prism. The curved face of the cylinder allows air to pass more easily around the drone reducing the drag. The lower the drag, the less energy the drone uses and the longer it can fly. The cylindrical shape also limits the amount of cuts needed to shape the foam.

4.4.9 Internal Structure

The contents of the package need to be held securely. The team decided to hold the contents using cutouts in the foam. This method would hold the vaccines while insulating them. By using different inserts, the package could be configured for different supplies, fulfilling one of the design requirements.

4.4.10 Insulating Material

The insulating material was determined by cross checking various materials for thermal resistance, weight, cost, durability and ease of application. The most important factor being thermal resistance. Through initial research different foams were found, including urethane, neoprene, and polyethylene. Initially, the team looked at using urethane, as it had the highest thermal resistivity of the three. However, after initial prototyping it was clear that urethane, a liquid foam, would be too difficult to form into the correct tubular shape. The team decided to use polyethylene for initial testing because of its thermal properties, flexibility, and convenience.

4.5 Design Progression

4.5.1 Design 1.0

Design Features

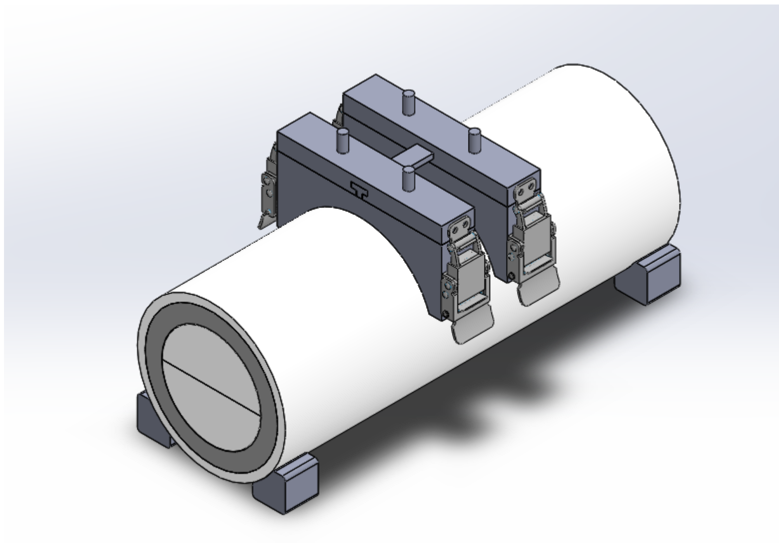


Figure 17: Design 1.0 Assembly

The initial design for the canister was an elongated cylinder that encased the vials completely in foam. The outer shell was constructed out of 4 inch diameter polyvinyl chloride (PVC). PVC is a decent thermal insulator with a low k value of 0.19 W/m*K and comes in various diameters. For this design, a four inch internal diameter was selected.

On the inner wall of the PVC pipe there was sheet of foam lined around the entire circumference. The foam used was a closed cell polyethylene foam with a density of 2lb/ft^3 and was 0.5" thick. Polyethylene foam has good insulating properties for a low density material, with a thermal conductivity of 0.33 W/m*K. As mentioned in Section 4.4.10, the team chose polyethylene as it was readily available in large sheets and easy to work with.

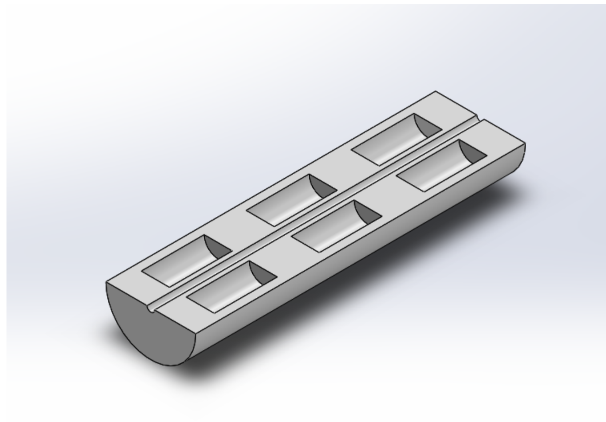
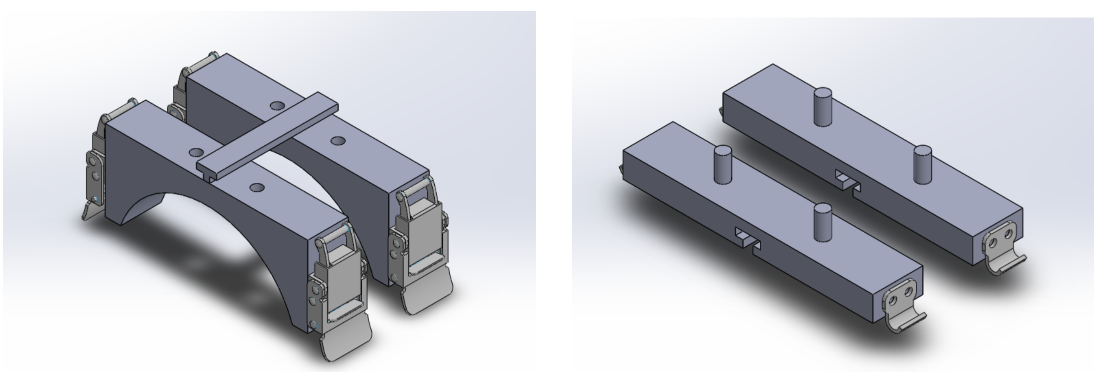


Figure 18: Design 1 Foam Core

Within the foam-inlaid PVC tube, a foam core carried the vials. Figure 18 is one side of the foam core that protects and insulates the vaccine vials from the outside. The core can house 6 10ml vials down the center of the core. The core was in two parts to allow central loading of the vaccines. The core held the vials securely, while improving the insulating properties of the package.

Down the center of the core was a hole to fit a copper rod. The rod in turn acted as a large coolsink for the thermoelectric cooler, which would ideally provide an adequate cooling surface. The core came completely out during the vaccine loading process and the copper rod could be used as an aligning tool during insertion.



(a) Tube Mounting Brackets

(b) Drone Mounting Brackets

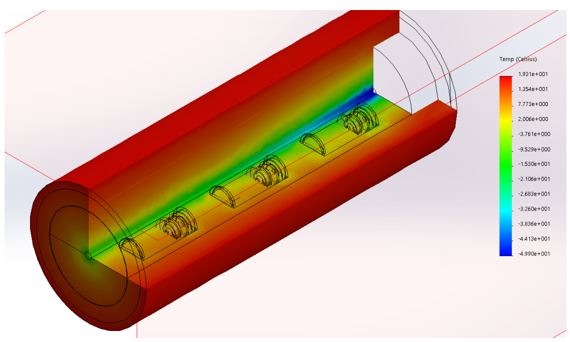
Figure 19: Two Part Mounting System for Design 1.0

The mounting mechanism on the canister consisted of two fixtures mounted onto the top of the canister and two fixed to the drone. Each fixture had two compression latches with a safety catch on either side of it. The safety catch ensured that the latch would not accidentally open during operation. Between the two brackets attached to the canister (Figure 19a) there was a rail that slid through both sections. The rail acted as a guiding system, ensuring that the canister was properly aligned to the clips that were attached to the bottom of the drone. The canister could hang freely from the rail during attachment allowing the operator to use both hands when engaging the latches.

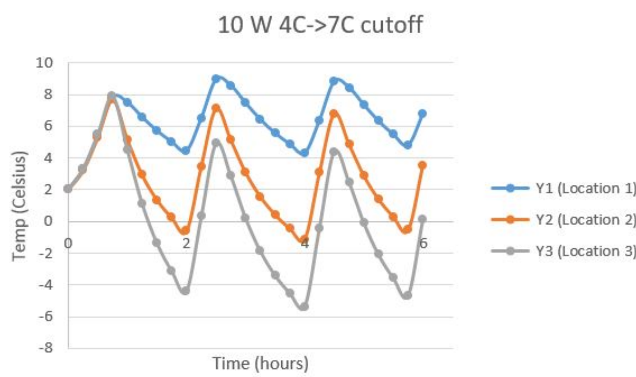
The drone mount (Figure 19b) was designed similar to the canister mount. The drone mount had two fixtures that align with the ones mounted on the canister. The bottom of each drone fixture had a cut that was the same shape as the rail. Once the canister was fully inserted into the drone fixture, the clips that were on the ends lined up with the compression latches on the canister mount. The compressive force generated by the four latches kept the canister from sliding as well as moving up and down. The rail that guided the canister onto the mount also prevented any twisting motion during operation.

Analysis

A thermal analysis was conducted using SolidWorks thermal modeling. Using the transient thermal modeling feature, the cooling of the rod was dependent on the temperature of the vaccine the farthest away from the thermoelectric cooler. Once the vaccine reached 7 °C the cooling was turned on and turned off once the temperature decreased to 4 °C. Figure 20a shows a color scale of the results and Figure 20b is a graph of the vaccine temperatures in the three different locations. "Location 1" are the vaccines the farthest away from the thermoelectric cooler and "Location 3" is the closest.



(a) Design 1 Thermal Simulation



(b) Design 1 Graph of Simulation

Figure 20: SolidWorks thermal model and resulting temperature plots for each vial location

The temperature of the vaccines in this model varied greatly. The vaccines at location 1 that got too warm and did not stay in the desired range. The vaccines at locations 2 and 3 both went below the desired temperature range. At location 3, the temperature of the vaccines went far below freezing, maxing out at -5 °C. A graph of these temperatures is shown in Figure 20b.

The reason for the large variance in temperature of the vials was due to their positioning within the canister. Because of the temperature gradient caused by conduction, the temperature of the copper pipe was not uniform. This can be seen in Figure 20a, where the area around the copper pipe is colder at the end with the TEC. The vials that were closer to the TEC cooled faster than the ones farther away. For this reason, this design did not fulfill the temperature stability requirements of out project, prompting the team to move to convection methods for Design 2.0.

4.5.2 System Modeling

In order to improve the performance of Design 2.0 over Design 1.0, a more in depth analysis of the thermodynamics in the system was conducted. The first step was the development of a theoretical model determining the thermodynamic properties of the system. This model used the proposed geometry of Design 2.0 which was a shorter and wider cylinder than Design 1.0. This model was used to optimize certain system design parameters prior to prototyping, including the thickness of insulation.

Thermodynamics

$$\dot{Q} = \frac{T_o - T_i}{R_t} \tag{2}$$

$$R_{conv} = \frac{1}{k * A} \tag{3}$$

$$R_{cap} = \frac{L}{k\pi r^2} \tag{4}$$

$$R_{cyl} = \frac{\ln(r_2/r_1)}{2\pi Lk} \tag{5}$$

To create the thermodynamic model of the system, Equation 2 was used. R_t is the total thermal resistance of the system, including the internal and external convection resistance (Equation 3), the cap conduction resistance (Equation 4), and the cylinder conduction resistance (Equation 5). To find the R_t of the entire package, the resistance of the tube was found separate from the package. These resistances were used to find $\dot{Q}$ for the cylinder and the caps, which were then summed to find the heat loss of the system at different internal temperatures. The lower bound of 2 °C for vaccine cold chain was used for optimization of design parameters.

Modeling Method

There were two models created: one to show the rate of ambient heat transfer into the system, and another to determine the final temperature of the system running at different TEC power ratings. These models were created using MATLAB and run iteratively with different design constants to optimize certain values. Complete documentation of the code is shown in Appendix D.

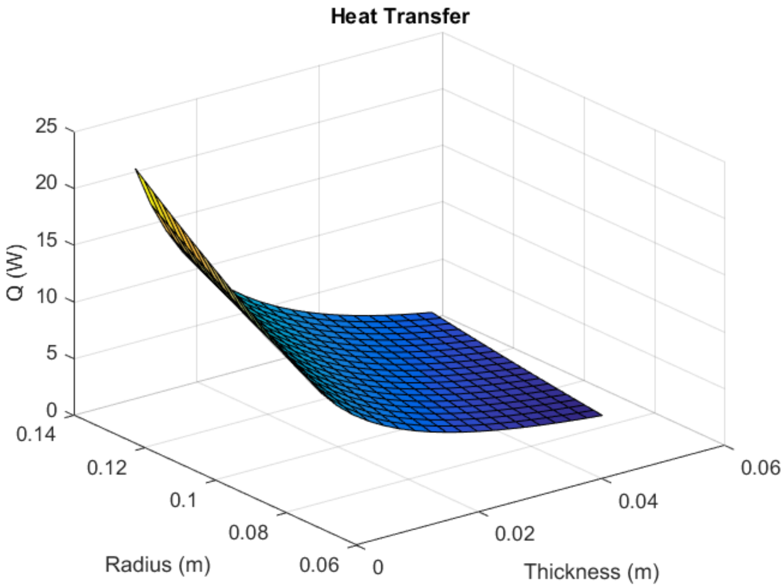
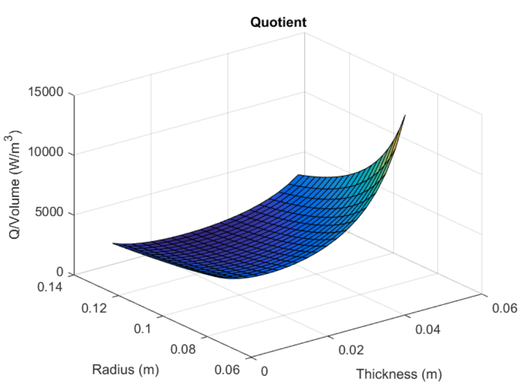
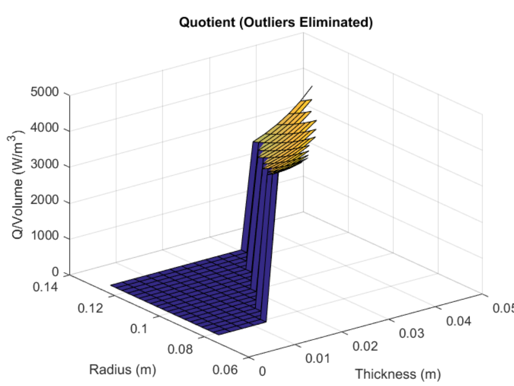


Figure 21: $\dot{Q}$ entering the package

The first value calculated was the heat entering the system. This assumed the TEC was unconnected and the package was cylindrical. Figure 21 shows a three dimensional graph of the heat transfer into the package dependent on the radius of the package and the insulation thickness. $\dot{Q}$ also varies on the temperature differential (shown in Equation 2), so the values 275 Kelvin and 300 Kelvin were used for the internal and external temperatures respectively.



(a) Full graph



(b) Outliers removed

Figure 22: $\dot{Q}$ per volume against radius and insulation thickness

Using the data calculated for part one, a quotient between the heat transfer rate and the was created. This value was used to get a general idea of what cylinder radius and insulation thickness values would get the most volume for the least amount of heat transfer. From Figure 22a the data suggested that having a maximum radius and minimal insulation was optimal. Unfortunately, the graph did not take into account the approximate wattage the TEC could remove at those temperatures. To improve the analysis, any data points with a too high heat transfer (> 6 Watts) were removed, and any data points with a too low volume (< 1.0 L) were also removed. Figure 22b shows the new graph with the outliers removed. Using this graph, the design specifications of four inch tube radius and one inch insulation thickness were selected.

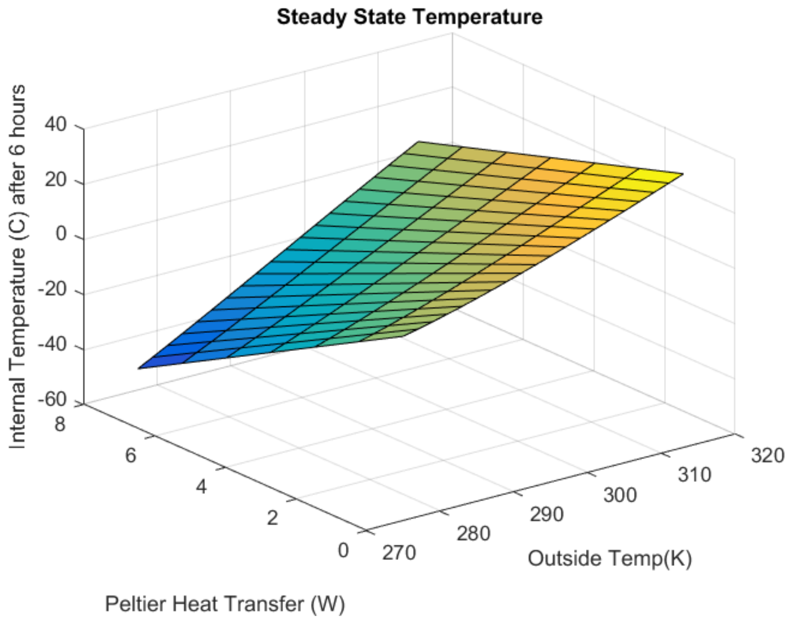


Figure 23: Steady state internal temperature at different TEC wattages and external temperatures

The next step was to find the expected steady state temperature of the package at different TEC wattages and external temperatures. While TEC do not move heat at a constant rate as it is heavily dependent on the ΔT across the element, they do reach a steady state condition which was modeled. To find the steady state temperature of the system, Equations 6 and 7 were used.

$$\dot{Q} = m * C_p * (T_o - T_i) \tag{6}$$

$$Q_n = Q_{n-1} + \dot{Q} * \Delta t \tag{7}$$

To start the iteration, first the Q value of the container was determined. A three-dimensional graph showing the steady state temperature of the package related to the TEC heat transfer and the external is shown in Figure 23. For example, at five watts the TEC could lower the temperature to 2.92 degrees Celsius if the outside temperature was 301 Kelvin. 2.92 degrees Celsius was on the lower end of the target temperature range of two to eight degrees Celsius, so the decision was to move forward with a tube radius of four inches and an one inch insulation thickness.

4.5.3 Design 2.0

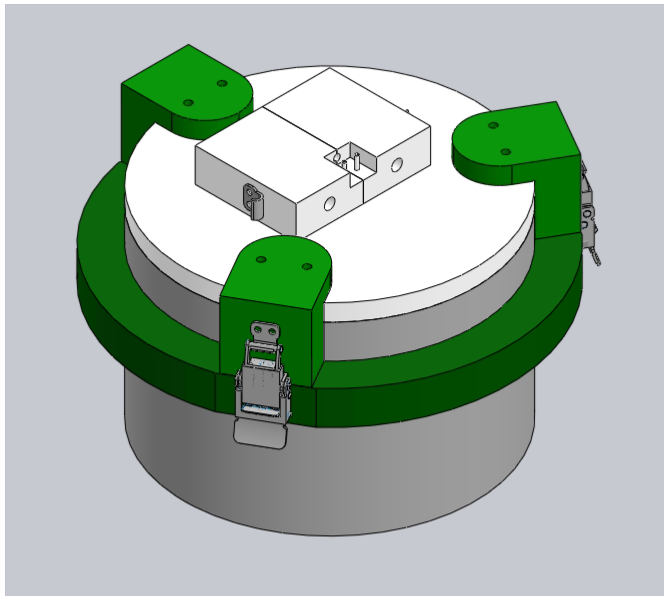


Figure 24: Design 2.0 Assembly

Design Features

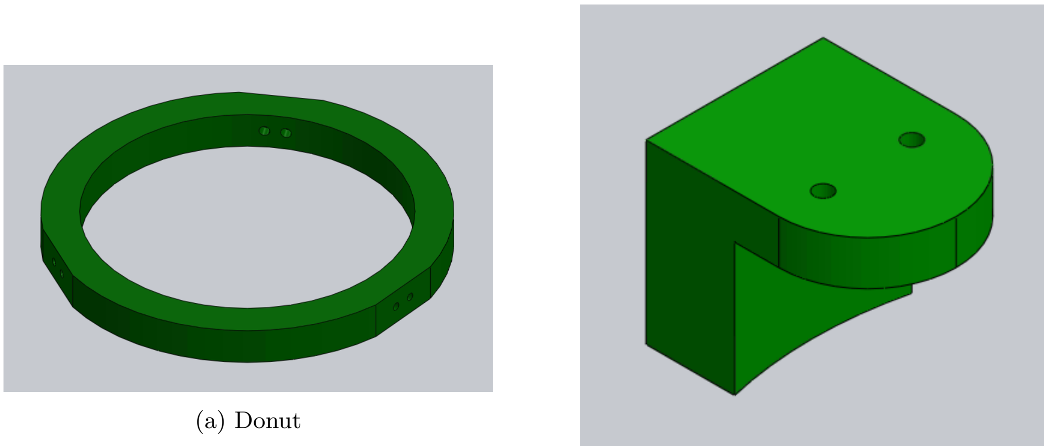
The major design change from Design 1.0 to Design 2.0 was the switch from conduction based cooling to convection based cooling. Conduction cooling amplified the issue of temperature gradients, so the thought with moving to convection cooling was that the air circulation would level the temperature of the package. This switch resulted in a variety of design changes, both inside the package and external.

The move from conduction based cooling to convection based cooling changed the form factor of the package from a long thin tube to a shorter wide cylinder. The outer cylinder of this canister was made out of an 8" piece of PVC piping. As in Design 1.0, PVC provides good thermal insulation of the system and does not shatter when dropped. To improve the insulation of the canister, the foam on the inside was switched from polyethylene to neoprene. The thermal conductivity of neoprene is 0.05 W/m*K compared to polyethylene which is 0.33 W/m*K. As mentioned in the Section 4.5.2, this design will implement a 1" thick foam lining of the canister.

Unlike with Design 1.0 there was no foam insert to hold the vials in place, as the center cavity had to be kept open for air circulation. In order to secure the vials inside the canister, a lightweight frame was designed to stop the vials from moving side to side within the canister. To prevent the movement of the vials up and down within the system, the top of vials were pressed against foam that was attached to the top of the canister. The foam compressed the vials firmly into the base of the canister. The frame was 3D printed out of PLA in multiple parts.

The loading and unloading of the vials from the canister would be from the top of the system. To secure the top cover to the shell, a ring was made to fit securely around the outer diameter of the

PVC pipe. On the ring, there were three locations where the ring was flattened and compression latches were mounted. There were three corresponding L-brackets that mounted to the top cover that the three latches attached to.



(a) Donut

(b) L-Bracket

Figure 25: Latching Mechanism for Design 2.0 Top Cover

Design 2.0 implemented the use of the thermoelectric cooler, which Design 1.0 examined but never completely used. The cooler was inlaid into the bottom cover, sandwiched between two heatsinks. For naming purposes, the heatsink on the cold side of the TEC (package internals) is known throughout the paper as the coolsink. The coolsink was fixed on the inside using four brackets that were part of the bottom cover. There was also a hole in the center of the wireframe for the coolsink to pass through. The heat sink was attached to the bottom cover using four screws.

A new attachment system for the canister to drone was created that built off the initial rail design. The assembly that is always attached to the drone is a L-shaped piece that has two aluminum rods that run parallel to the long side of the L (Figure 26). These two rods slide into a mounting piece that is attached to the top cover with screws. The two pieces are then latched together using the same type of compression latches as the ring has.

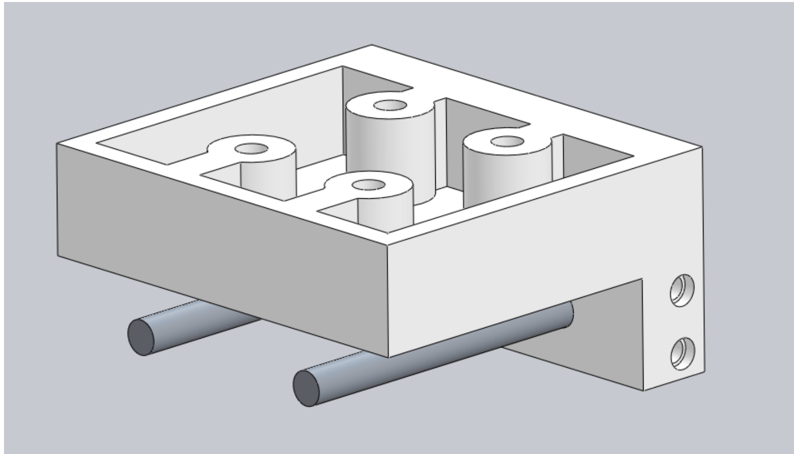


Figure 26: Revised Drone Mount Model

To ensure that this new mounting design would be robust enough to carry the weight of the entire system, a Finite Element Analysis was conducted on the mount that simulated the Von Mises Stress on the system. In the simulation, 25N of force was applied to each of the aluminum rods to simulate 2.5kg of weight on each rod. After running the simultation, the stress in critical sections of the assembly were determined. The stress at the mounting holes of the plastic L-shape was calculated to be 3.6 kPA. The average yield strength of 3D printed PLA is 51MPa so in our application this material will be able to withstand the load. The stress on the aluminum rod was calculated by the software to be 6.5kPa which is well below the yield strength of aluminum. Figure 27 is a picture of the SolidWorks simulation.

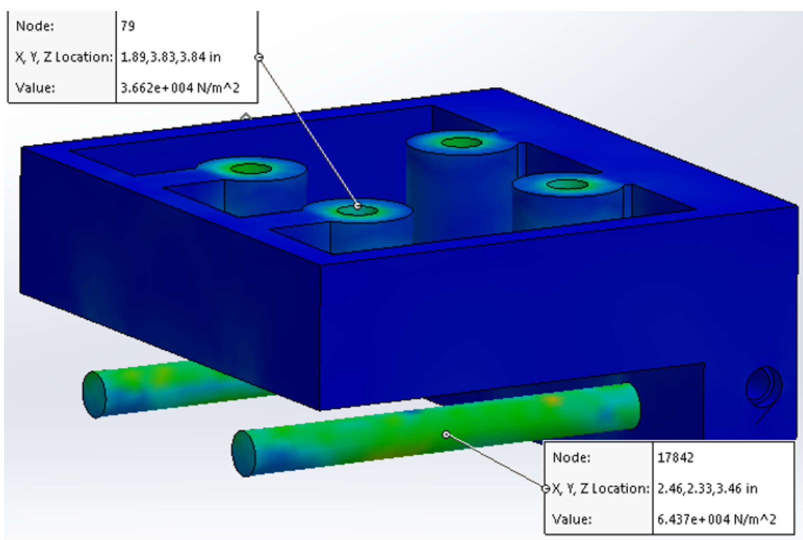


Figure 27: Solidworks Simulation of Von Mises Stress on the Drone Mount

Analysis

The first thing that the team realized while assembling Design 2.0 is that the PVC pipe outside adds a lot of weight to the system. The total weight of the PVC used was 1.36kg (3lbs). Reducing the weight of the outer shell would increase the flight time of the drone and would allow that ”extra” weight to be used in other components of the canister. Examples of this included the addition of more vials to reach the desired transport for new vaccine introduction of 400ml, and any desired electronics for improved monitoring/security. Material could be also added to sections of the canister that experience more loading to reduce the chance of fracture. The next design iteration also has to take into account the weight of the electronics and any necessary mounting equipment which was not part of this design.

Initial thermal testing of this model showed that the 0.5” neoprene foam was not enough insulation to allow the system to reach the desired temperature, verifying the MATLAB modeling. In Figure 28, the lowest temperature that was achieved running at 11 volts and 4 amps was roughly 12 degrees Celsius.

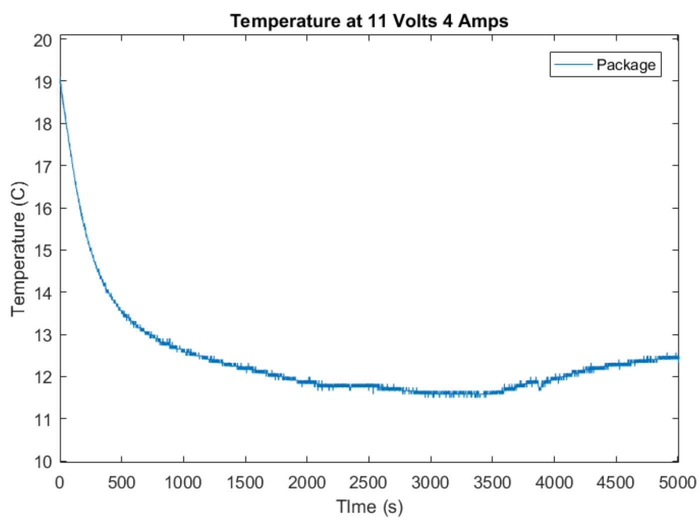


Figure 28: Measured temperature of package with 0.5in insulation thickness

However, doubling the thickness of the neoprene and testing with the same electrical input allowed the internal temperature of the canister to reach below 5 degrees Celsius. The result of the one inch insulation test can be seen in Figure 29. The thicker insulation layer also helped create a better seal protecting from any outside ambient air leaking into the system. Having a lower achievable temperature for the same amount of powered applied to the system would mean less power is used overall during the active cooling of the vials.

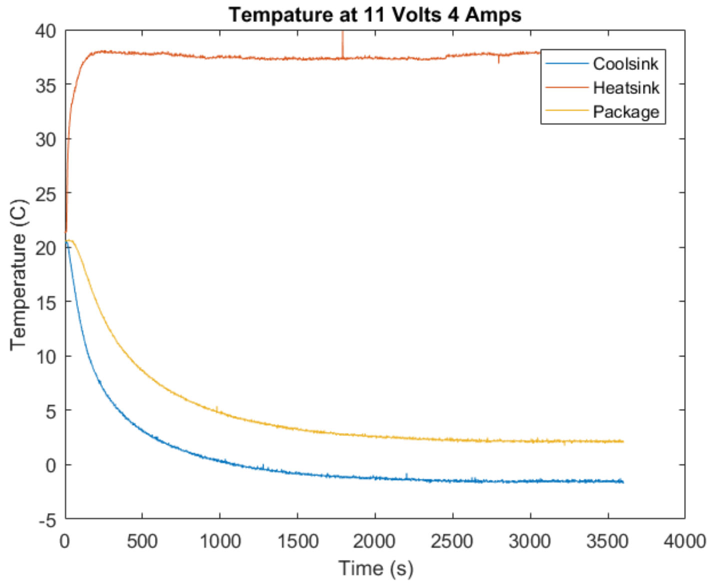
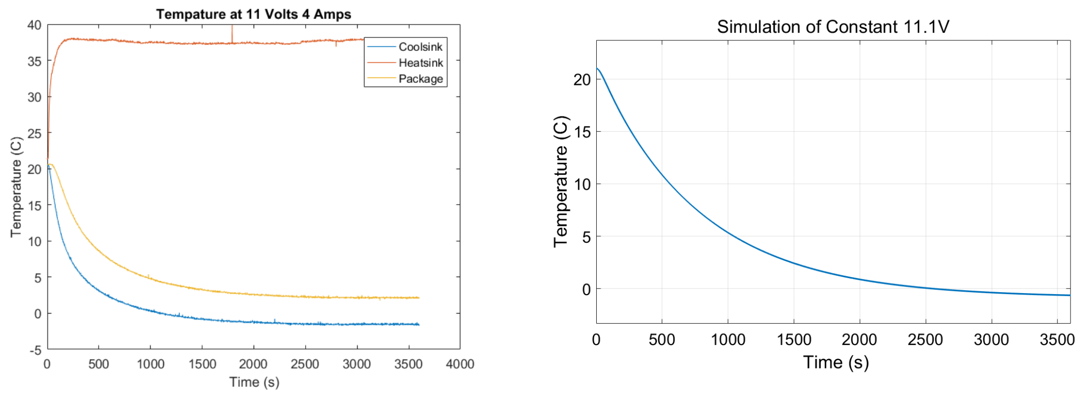


Figure 29: Measured temperature of package with 1.0in insulation thickness

4.5.4 Thermoelectric Cooler Modeling

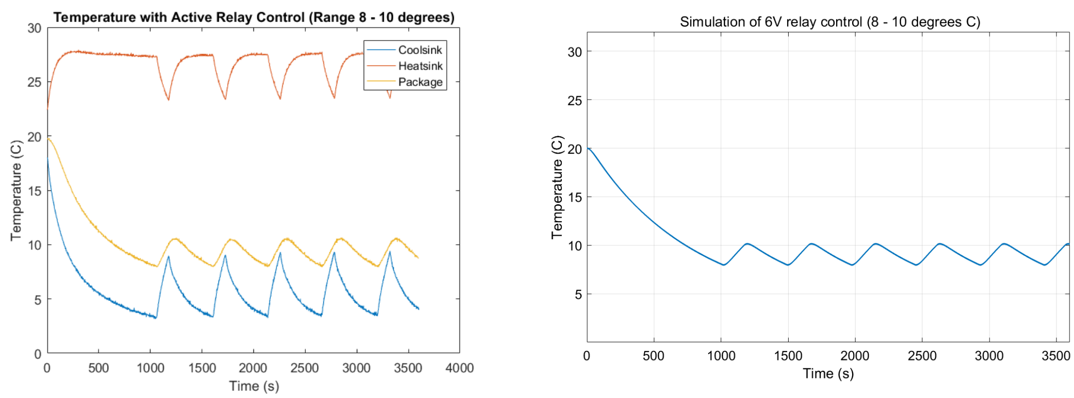
In between Design 2.0 and the Final Design, a complete system model was developed using MATLAB and Simulink. The model took into account TEC math instead of constant wattages, making it more accurate than the MATLAB model in terms of system response. This model could be used to show accurate system response running either relay control or PID control. Complete documentation of the model is shown in Appendix E. To get some of the constants the test data from design 2.0 was used. The main output of the system was package temperature, but the system took into account heatsink and coolsink average temperatures, as well as temperatures at the TEC. Figures 30 and 31 show the comparison between the measured data and the model.



(a) Testing result

(b) Modeled result

Figure 30: Comparison of actual test results and model at constant 11V



(a) Testing result

(b) Modeled result

Figure 31: Comparison of actual test results and model at 6V relay control

A large advantage of the model is calculating the total current used of the system. This value was found by integrating the current applied to the TEC at different voltages. Along with battery capacity, this value was used to determine the expected battery life at different control methods and temperatures. To determine the estimated lifespan of the system, the value was taken over a time period of one hour, so the final result would be an amp hours per hour value. Dividing the battery capacity by this value would give the expected lifespan of the battery. Table 6 shows some different control methods and amps used.

While PID seemed like the most efficient option, there were two factors limiting its actual usefulness. For one thing, op-amps need a heatsink to avoid thermal shutdown. This heatsink would likely need a fan to keep cool, adding another source of current draw. Op-amps are also not as efficient as relays. The model measures the current into the system which does not take into account the efficiency of each controlling component. With these factors considered, the decision

Control Method	Temperature Target (K)	Current (A)
PID (op-amp)	280	1.24
PID (op-amp)	277	1.64
PID (op-amp)	275	2.66
Relay 7.4V	280	1.54
Relay 7.4V	277	1.83
Relay 7.4V	275	Target not reached
Relay 11.1V	280	2.12
Relay 11.1V	277	2.51
Relay 11.1V	275	2.76

Table 6: Expected currents using different control methods (Ambient = 294K)

came down to selecting a relay at 7.4 volts or at 11.1 volts, two common lithium-polymer battery voltages. Because the system should be able to function in higher temperatures, the 11.1 volt battery was chosen.

4.6 Conceptual Design Changes

There were a few major changes from the initial conceptual design that were determined through the different intermediate design iterations and simulation methods.

Vertical Cylinder

The initial conceptual design consisted of a horizontal cylinder. This design was changed to a vertical cylinder to better accommodate the new cooling method as well as better fit the vaccine vials. A shorter cylinder will allow all the vaccines to be closer to the cooling device. The closer and more compact the vaccines are to the coolsink, the less of a temperature difference the vaccines will be smaller.

Convection Cooling

The switch from conduction cooling to convection cooling happened because conduction cooling has a significant temperature gradient. Convection cooling has the advantage of almost equally distributing temperature through circulating air. From the initial thermal simulation, the conduction based cooling method would cause some of the vaccines to freeze and others to be too hot.

Wireframe

The initial idea for holding the vaccines was to inset them into a foam core. This would not work with convection cooling, as it would require there to be passages for air flow. The wireframe allows for some airflow by not completely enclosing the vials.

Relay Control

To start, there was no real idea of how to control the system. During the design iteration process, two methods were examined: PID control using am operational amplifier, and a binary on-off control using a relay. Relay control was ultimately decided on simply because of the heat limitations of the op-amp, despite the op-amp having a slightly better efficiency.

Electronics Box

Another missing element of the conceptual design was a method of holding the electronics. The decision was to fully enclose the electronics and the battery within a 3D printed casing. The casing would allow for easy access to the battery as well as an area to add the user interface.

4.7 Final Design

Figure 32: Final design mounted on drone

4.7.1 Design Changes

Outer Shell

In order to reduce the weight of the shell, the material was changed from PVC to 3D printed ABS. By 3D printing the shell with a 30 percent infill, the weight of the shell was reduced by close to two pounds. Although PVC has better a lower thermal conductivity than ABS, the neoprene insulation on the inside of the canister provides enough insulation that the change in material of the shell is negligible. Because the shell is 3D printed, we were able to create complex geometry in a single piece that would not be possible using conventional material and with the tools at hand.

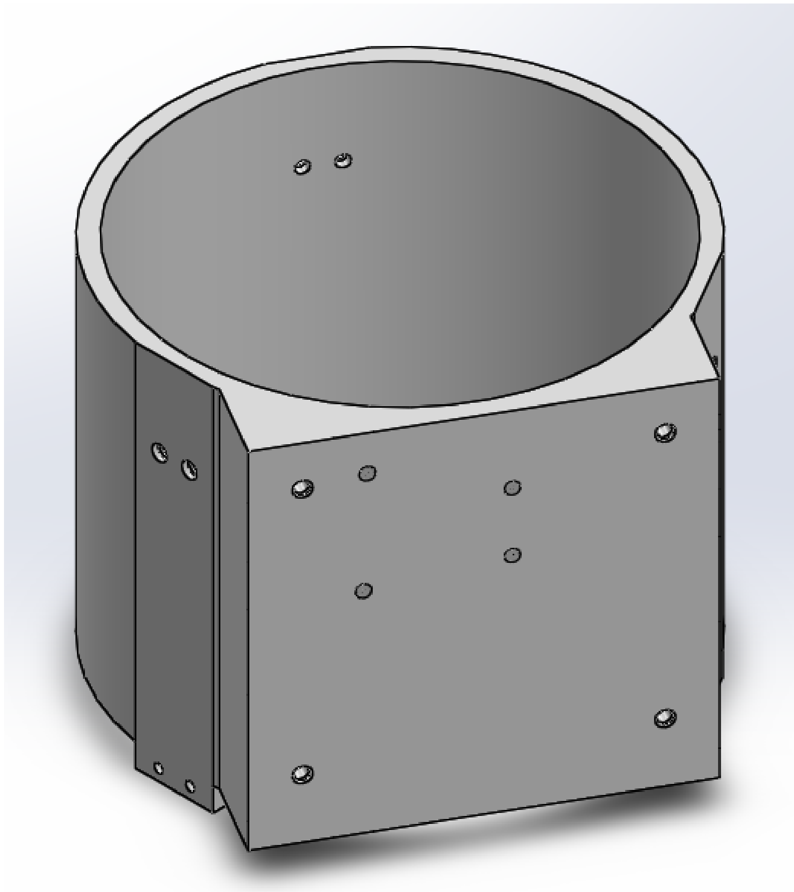


Figure 33: Outer Shell

On the outer shell there was a flat surface that had been made tangent to the outer diameter of the shell. On this surface there were mounting holes for a electronics box to be attached which contained the controlling electronics. To attach the bottom cover to the shell, three flanges protruded from the bottom of the shell. These flanges aligned with cuts on the bottom cover. The attachment of the bottom cover was done on the side of the shell instead of the bottom because the shell is not thick enough for a press fit to be inserted. The thickness could have been increased but that would have added more volume to the shell than the three flange design.

Similar to Design 2.0, three tension latches with safety catches were used to attach the top cover to the shell. To account for these latches, the team designed the outer shell to have three flat surfaces on the outer surface at equal 120° increments around the shell. Press fits were used to mount the safety latches to these surfaces.

Top Cover and Mounting Bracket

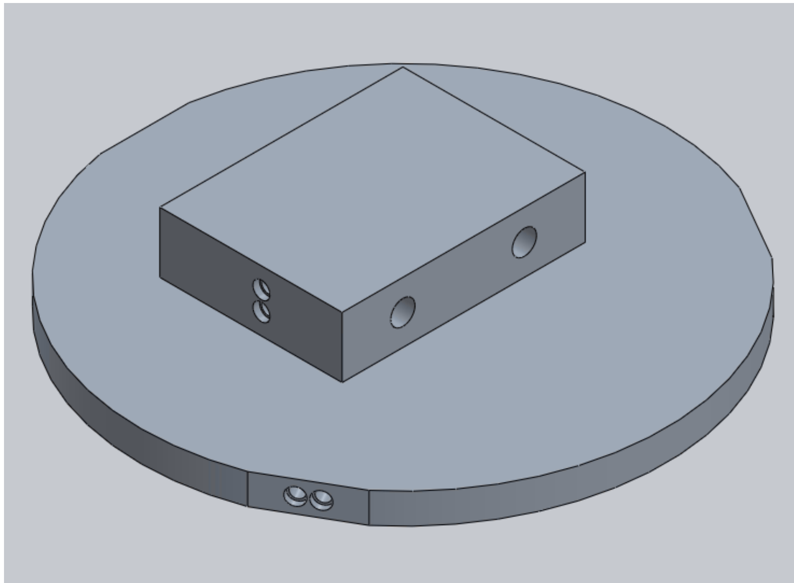


Figure 34: Top Cover and Mounting Bracket

In the previous design the top cover and mounting bracket to the drone were two separate pieces connected by screws. In 3.0 these two parts were combined into a single part. The team also made revisions to the top cover so that there is no need for L-brackets to attach the top cover to the outer shell. Instead, on the top cover there were three flat surfaces that align with the flat surfaces on the outer shell. The flat surfaces had mounting holes for the hook of the compression latch.

Bottom Cover

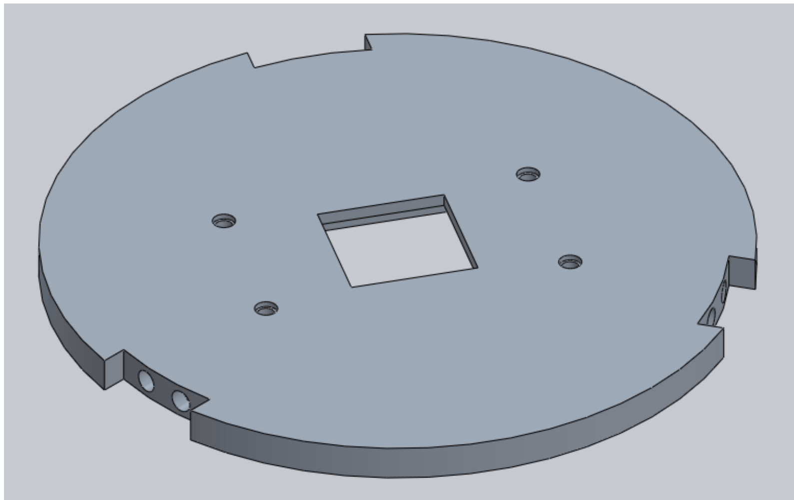


Figure 35: Bottom Cover

The bottom cover was redesigned to make the attachment to the outer shell stronger while still able to be removed for maintenance. The bottom cover had three cutouts along the outer edge that aligned with the three flanges on the outer shell. Two press fits were installed on the inside of each cutout and a screw is used to fix the base to the outer shell. Along with the attachment modifications, the bottom cover was modified for the new heatsink. The team designed an indent in the center of the cover to mount the heatsink, making the thermal system more compact.

Wireframe

The wireframe used to hold the vials in place was altered slightly from Design 2.0. Because of the change to a inset coolsink instead of a column, there was more lateral area for the vials to be placed. This prompted a different hole pattern, shown in Figure 36. Another goal of the wireframe was to be able to carry the most vials possible with the internal circle size. Using a software tool from Engineering Toolbox, the maximum amount of 30ml vials that could fit is 14 for a total of 420ml, 20ml more than the 400ml minimum generated by Johns Hopkins Bloomberg School of Public Health's HERMES model[44].

Figure 36: Balto 3.0 Wireframe

4.7.2 Design Additions

Electronics Box

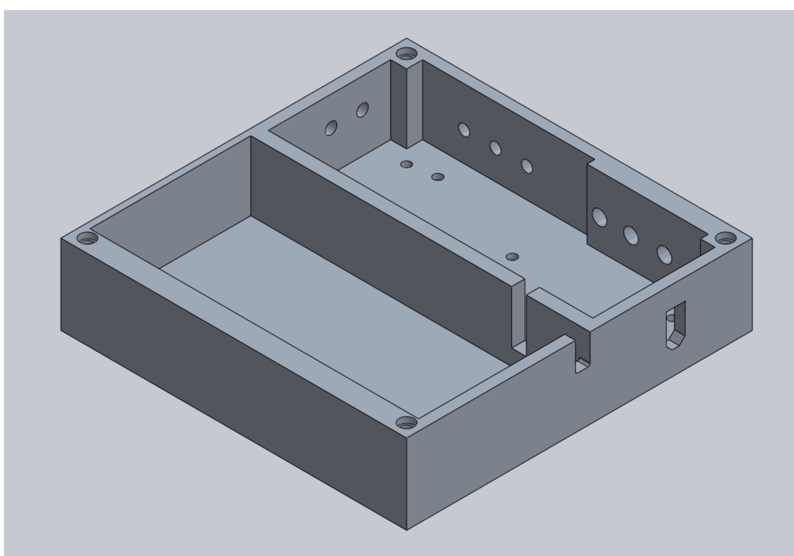


Figure 37: Electronics Box

The electronics box attached to the side of the outer shell. As mentioned in the previous section, there was a flat surface on the shell that included mounting holes for the electronics box to attach to. The electronics box contained two compartments, one for the electronics (top) and the other for the battery that powered the canister (bottom).

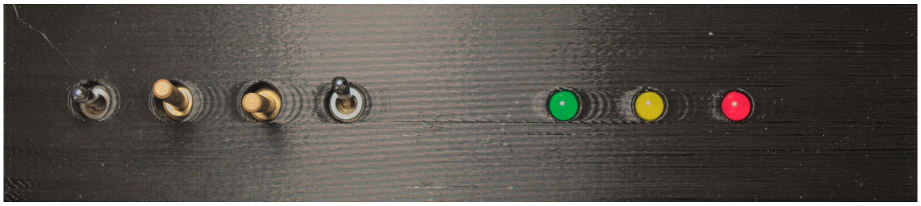


Figure 38: User Interface External

In the top portion of the box there were mounting holes for the Arduino to be fixed to the base of the box. On the box side closest to the Arduino there were two holes for the GPS and communication antennas to come out of. On the top of the box there were three holes for LEDs and four holes for switches and potentiometers (POTs). To make the base of the switches and POTs flush to the top of the box, a feature was extruded off the inside wall of the top equal to the height of the neck on the switches and POTs. This meant that the only visible portion from the outside was the toggle switch and knobs.

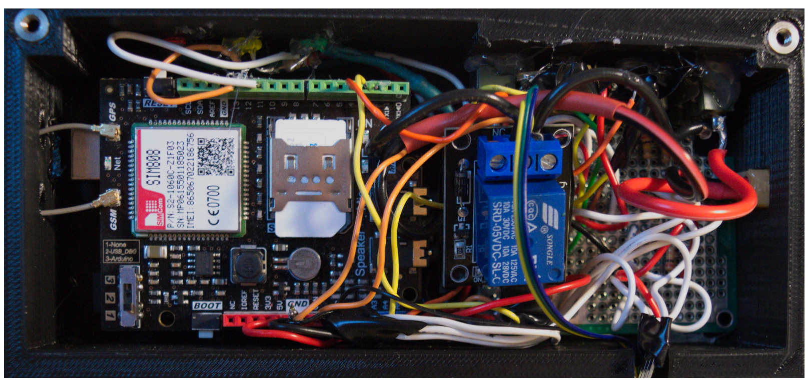


Figure 39: Electronics Box Internals

The bottom portion of the electronics box was space dedicated for the battery that powers the system. To reduce the size of the box and due to the constraint of the flexibility of the battery wires, the power wires for the battery left the box through a hole on the side and re-enter the box on the top portion of the box. The balance leads were flexible enough to bend and pass through to the top section of the box without exiting the box through a slot in the barrier wall. To minimize the chance of the battery not fitting properly and vibrating during flight, the bottom section was created slightly larger than the battery and the excess space could be filled with a compressive foam.

In terms of internal electronics, the system used a relay for on-off temperature control. There is a system of voltage dividers that are used to measure the voltage of the battery. Discharging lithium polymer cells below three volts will damage them, so these dividers were used to let the microcontroller know to shut off the TEC. The temperature sensor passed through the box into the main container along with the power wires for the coolsink and the TEC. The thermistor use a simple voltage divider to create a measurable voltage. A complete schematic of the electronics used is shown in Appendix B.

4.8 Alternative Designs

4.8.1 Box

A possible design change examined was using a box shape instead of a cylinder. Creating a box would be a lot simpler to manufacture than a cylinder. Despite the logical conclusion that because a box has more surface area per volume than a cylinder at constant heights, the team wanted to be sure that this method was indeed worse thermodynamically than the cylinder. To verify this claim, a model of the box was created in MATLAB to compare theoretical values. As expected the thermal values were worse.

4.8.2 Vacuum Insulation

A potential insulation the team initially looked into was to create the package as a similar design to a thermos. Using vacuum insulation reduces the amount of heat entering the system by minimizing the three methods of heat transfer: conduction, convection, and radiation. Conduction is limited by separating the inner container from the outer shell. The lack of contact between the two walls means that no conduction can happen. Convection is limited by creating a vacuum in between the walls; convection is impossible within a vacuum. Radiation is limited by the reflectivity of the materials used. We decided not to use vacuum insulation because it is difficult to manufacture. The cost of developing and creating a vacuum insulation container also was beyond our available budget in terms of cost and time.

4.8.3 Operational Amplifier Control

The team examined operational amplifier (op-amp) control as a more refined method of temperature regulation. The benefit of using an op-amp instead of a relay was that op-amps can directly control output voltage dependent on input voltage, whereas relays simply act as on-off switches. Using an op-amp would allow for a more advanced control method, such as a PID controller.

To examine the controllability of the operational amplifier, the team ran a number of bench top tests examining the effects of different PID constants. An example of one of the tests are shown in Figure 40. In this test, kp was 5, ki was 0.1, and kd was 50. A limit was place on ki in order to prevent it from over accumulating and causing overshoot. Appendix H contains more information on the tests and the values examined.

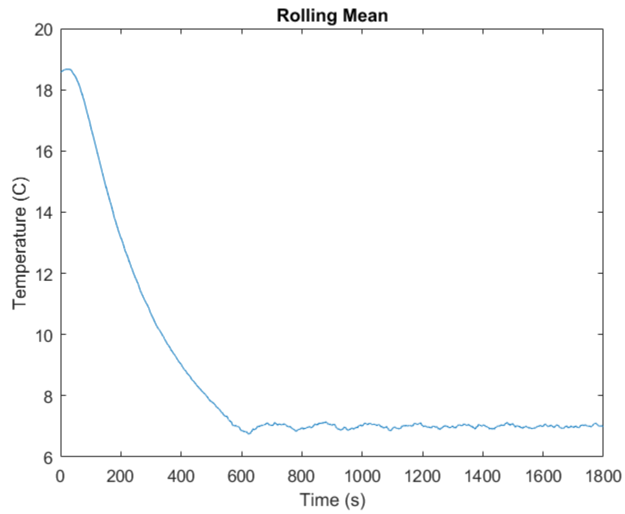


Figure 40: PID control of temperature with a target of 7 degrees Celsius

Despite the op-amp offering better control that the relay, the team decided against its use. The reason was the issue of heat dissipation. Op-amps generate heat during operation, whereas relays do not. Adding another heat sink to the weight restricted package would have been illogical. Using an op-amp could be a future area of interest, but a relay fulfilled the functionality needed without the additional heat and weight concerns.

4.9 Feasibility Study/Experiments

The method of feasibility experiment was to look at the temperature characteristics of the package. Whether it was through physical modeling or simulation, the temperature values were the ultimate determination of the success of the design. Other factors, such as weight or viability could be found simply through research. Hitting the 2 °C to 8 °C range would make the design feasible, so long as the other design requirements were achieved.

Despite only looking at temperature for initial feasibility, the team ran a human factors test to evaluate the ease of use. The test consisted of detaching and removing the package from the drone, removing the top cover and the alotted vials inside, then replacing everything and returning it to its original state. All test subjects were able to complete the task with basic instruction in a relatively quick response time.

5 Final Design Verification

5.1 Thermal Testing

The ultimate goal of the system was to hold a temperature between 2 °C and 8 °C. The effectiveness of the package in this respect was verified through bench top testing. The package was precooled for roughly 10 minutes prior to loading the chilled vaccines. Time zero is when the package is opened to load the vaccines and the reason why the intital temperature is between the chilled temperature and ambient. The package was then turned on and left until an amporixmate steady state was reached for the internal air sensor.

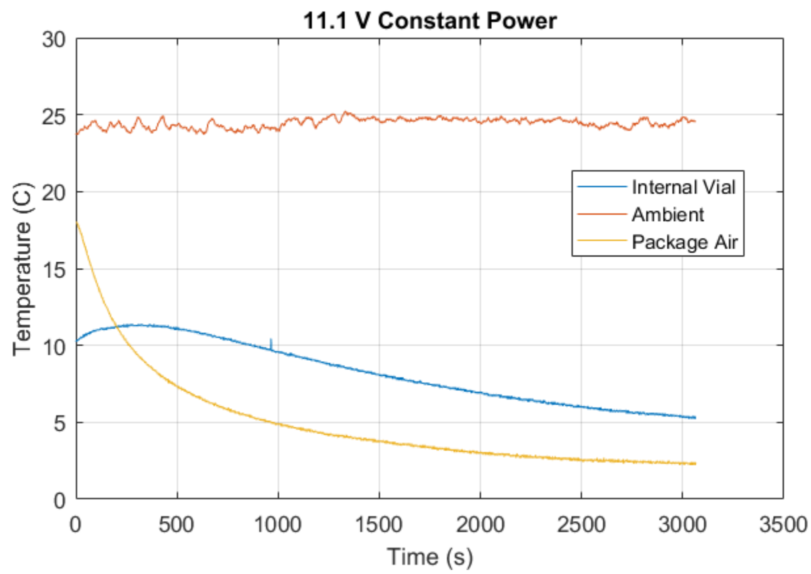


Figure 41: Constant power (11.1V)

At constant power, the temperature of the package reached 1.9 °C, shown in Figure 41. This final temperature is dependent on the ambient temperature. In this case, the ambient temperature was 25 °C. The final settling temperature in this case will shift with the ambient temperature, as both the heat moved by the thermoelectric cooler and the the heat entering into the package are related to this. Expected maximum ambient temperature the package could operate within the two to eight degree Celsius range would be around 33 °C. Any higher and the package would likely not reach eight degrees at max power.

5.2 Battery Life Test

To determine the time that the battery lasts, the team conducted a bench-top test to calculate the amperage that the system drew. Using an input voltage source of 11 volts from a DC power supply, the system used 4 amps. This measurement was obtained from the analog dial on the power supply, shown in Figure 42. The casing in the electronics box for the battery was designed for a

5.2 amp hour battery. This means in a worst case scenario, the battery would last 1.3 hours, which exceeded the one hour functional requirement.

Figure 42: Power supply amperage measurement

6 Final Design Validation

6.1 Transport Load

The first method of validation was the easiest to determine. The package, in order to be cost effective, needed to carry at least 200 ml of EPI vaccines or 400ml of non-EPI vaccines [44]. The final iteration of the design could carry fourteen 30ml vials, giving a final capacity of 420ml. In terms of weight, the package fully loaded was measured at 8.3 lbs, which was beneath the 5.1 kg (11.2 lbs) cutoff. Despite not being able to test on the drone because of technical difficulties. The team feels given more time that there is no reason the drone would not be able to transport the package. Because the final design was able to hit the cost-effective and weight requirements, the transport load was validated. The entire system could not be fully validated due to that range. The internal number of vials possible is *** quite similar to the transport capabilities of the Vayu VTOL drone. Having satisfied the load capabilities the team felt comfortable with the completion of the objectives despite how close they came.

6.2 Vaccine Temperature Stability

The testing of the vaccine temperature stability was a two part test. The first part was directly measuring the temperature of the vaccine inside the vial. For out testing we used water in a 30ml vial. The other part of the test is using Vaccine Vial Monitors (VVM) to check to verify that the vaccines are viable for use. A VVM uses a temperature sensitive pigment to give a visual cue for the user if the vaccine remained within the desired temperature range. The color of the VVM pigment is initially white. Once the temperature that the VVM is exposed to goes out of the range that it is created for, the pigment starts to turn a light red. Depending on how dark the pigment becomes, the user can determine how long the vaccine was out of the temperature range. The an example of VVM results after testing are shown in Figure 43.

Figure 44 below shows the various recorded temperatures during the benchtop test. The internal air package temperature and control vial vaccine temperature were also recorded. The container was pre-chilled to 5 °Celsius before it was opened and the vials were inserted to simulate a real life situation. Both the internal vial and control vial were cooled to 4 °Celsius. The control vial was left outside of the container to compare its temperature to the one inside the canister. The cooling system was turned on and off to achieve the temperatures in accordance with the Simulink model.

From Figure 44 it can be seen that the internal vial remained within the desired temperature range while the control vial warmed up past 20 °Celsius. After opening the canister and removing the vials, it was observed that all the VVM pigments remained white. The temperature data as well as the VVMs confirm that the final revision of the project successfully kept the vials inside the canister between the temperatures to keep the vaccines viable.

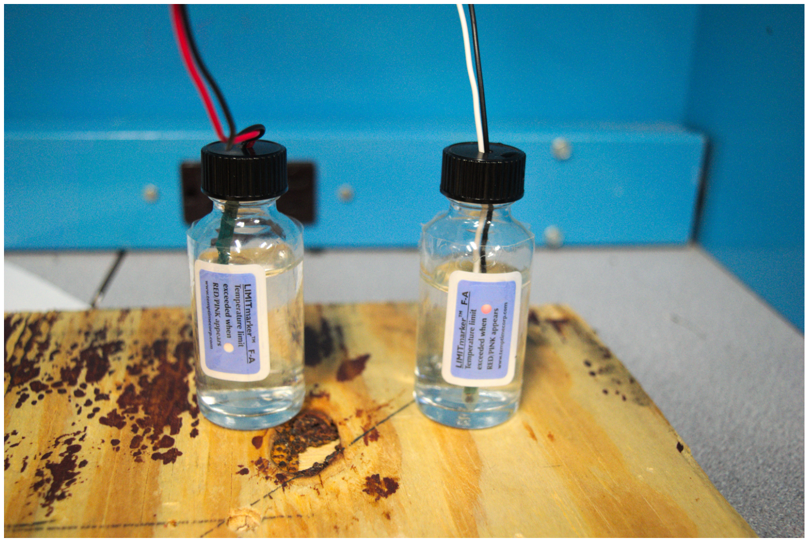


Figure 43: VVM results: test vial (left) and control vial (right)

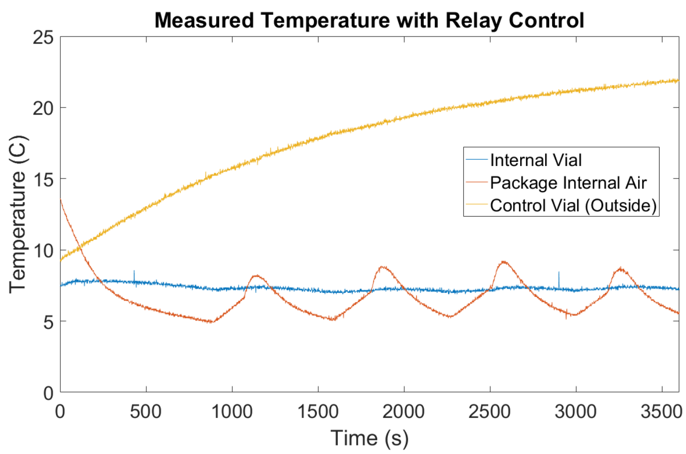


Figure 44: VVM testing temperature results

6.3 Communication

The method of communication was tougher to validate simply because the area tested was in Worcester Massachusetts, a highly developed area of the world. Despite this, GSM and GPS technology covers most of human civilization with long range coverage. Even if the GPS data is incomplete, the package should always be able to send its temperature status. That being said, in order to ensure this signal is reached, a more powerful GPS module would need to be used, as there were issues reading the GPS underneath the drone frame.

7 Discussion

7.1 Analysis of Results

The testing results of the final design were promising. While there was definite area for improvement, the package covered a majority of the functional requirements created by the team in the initial stages of the project. An overview of these results is shown in Table 7. Double checkmark is a complete fulfillment, checkmark minus is a partial fulfillment, and minus minus is a system failure.

Functional Requirement	**Achieved?**
Temperature stability in vials	✓✓
Weight less than 5 kg	✓✓
Secure mounting	✓✓
At least one hour battery life	✓✓
Ability to be directly powered	✓✓
Easy access to supplies	✓✓
Designed to limit drag	✓-
Hold contents securely	✓✓
Ability to transport different supplies	✓✓
Durable for repeat use	✓-
Communication to user	- -

Table 7: Functional requirement analysis

The temperature stability of the vials was demonstrated with the relay control of the package. Weight and mounting security was shown by the physical model of the package, as well as basic stress analysis simulation. The battery life was demonstrated to be at worst 1.3 hours using a 5.2 amp hour lithium polymer battery, which the system is designed for, through TEC simulation and bench top testing. Bench top testing verified the ability to be directly powered by a DC power supply.

The supplies were easy to access by simply opening the top lid of the container. The cylindrical shape lowered the drag relative to other prisms, but the large height and diameter of the package gives it more cross sectional surface area than desired. Contents were held securely within the package between the frame and the foam caps. Different supplies could be transported through swapping out the frames, something that was easy and fully customizable within the confines of the container. In terms of package durability, the system was built to be reusable. Occasionally the press fits for the lid latches would pop out, but this would only occur with excessive force and with different manufacturing methods this problem could be easily solved.

Communications worked to a slight extent, as the GPS sensor was weak and required optimal conditions to function. Carbon fiber inhibits GPS signals, so the drone body limited the effectiveness of the GPS to the point where no data was read. GSM worked to some extent, but without GPS the value of the data received is far less valuable. A potential future fix for this system would be to link the package to the drone and take advantage of the better positioned and more powerful GPS sensor on the drone. This would require some interface between the drone and the package, which would need either a physical connection or a wireless connection to the flight controller. These connections would add complexity to the system and might not be worth it, depending on the expressed needs of the user.

7.2 Future Work

7.2.1 Design Modifications

Supplies

The modularity of the system allows for different supplies to be used. Potential temperature sensitive supplies include organs or blood. Because TECs are polar elements, they can act to move heat into the system by reversing the power to the leads. The insulation of the package should allow for the internals to be thermally stable. The only slight design modification made would be to add an additional thermistor to the internals to measure the higher temperatures. Because the NTC thermistors are do not change linearly with temperature, the thermistor optimized for cold temperatures (linear fit between 0 and 10 degrees Celsius) would not be accurate at 30 and 40 degrees Celsius. The program would have to determine the expected use of the package and accordingly choose the right thermistor to measure.

Size Changes

The thermodynamic model created for package simulation, along with the design validation requirement of carrying 0.4 liters of vaccines, led to the decision of using a four inch radius cylinder for transportation. This could be enlarged, however, for large payloads. The big challenge here would be to adequately cool the package to the correct temperature. This could be done by increasing the wattage of the TEC, improving the heatsink and coolsink, or adding more insulation. The MATLAB model is editable for different design measurements and TEC wattages, so these values could be simulated before implementation.

Control Changes

The major control change, mentioned in the alternative design Section 4.8.3, would be to switch from a simple relay control to using an op-amp to run a PID control feedback loop. The team ran tests using this configuration, and the results were more promising in terms of holding a constant temperature than using the relay. In order to get the op-amp to function correctly, a method of moving heat generated by the op-amp would need to be examined in more depth.

Compression Refrigeration

Compression refrigeration offers better efficiency then a TEC element at the expense of cost, weight, and simplicity. The reasons the team chose not to use compression refrigeration are shown in Section 4.4.2. Despite this, the refrigeration method could still improve the package for large drones. Improving efficiency directly improves battery life, which could enable the package to maintain temperature for longer durations. The team chose to not to pursue this method, but future projects could examine the use of compression refrigeration as a method of improving package efficiency.

Life Extenders

Potential life extenders would be any uncontrolled material with a high heat capacity added to improve the duration of the package. While the vaccines already do this to some extent, something like ice could dramatically increase the duration of temperature stability. These materials would add weight and take up space internally, but could be worth investigating for longevity improvements. The cooling object could even be custom fit for the package to ensure it fits internally without taking up too much package space. A potential spot for this ice pack would be surrounding the coolsink on the bottom of the package. Because the supplies sit above the coolsink, the area around the coolsink is effectively wasted space. This area is shown in Figure 45.

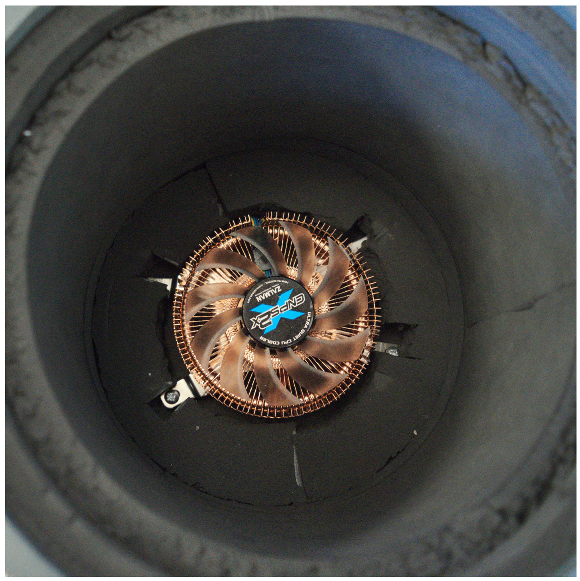


Figure 45: Area around coolsink

Manufacturing Methods

For our project we decided to use rapid prototyping out of PLA and ABS for all of our plastic parts. We decided to use 3D printing because of the short manufacturing time and ability to create multiple revisions with ease. However, the strength of a 3D printed part is much less than if the part was made out of solid plastic in another manufacturing process. One possibility for manufacturing of these parts is injection molding of ABS. Some parts would need modifications to be optimized for injection molding

Vacuum Insulation

By utilizing vacuum insulation along with good insulating materials, a lower temperature is achievable and less energy is needed to keep the vaccines at the desired temperature. The lack on convection and conduction means that the ambient temperature that the container is operating in has little to no effect on the cooling of the internal canister (hotter external temperature means that the Peltier can't get as cool).

7.2.2 Communication Formatting

The main method of communication for the package is SMS messaging. While this gets the data to the user, it is unformatted and to fully understand, the coordinates must be typed into a mapping software. If this data could be converted for the user, potentially via a web application, the usability of the system would improve. GSM does have 2G internet connectivity, so the data could be transmitted directly to the web wirelessly. In combination with a program such as google maps, the GPS data could then be visualized.

7.2.3 Vaccine Modeling

The vaccine validity indicator provided on the package is a rough estimate of the validity of the vaccines in the package. Using heat transfer equations, along with the vaccine validity equations, a more accurate method of validity could be implemented. Similarly to how the package simulation was set up, the temperature of the supplies could be estimated based upon internal air temperature. This method would require greater control over the package, including setting the values directly into the program. Thermal resistance values for each supply transported would have to be determined, as well as the heat capacities. These values would also need to be set prior to transportation. Wireless interfacing with the package could allow for the greater control required. Another potential method would be to have preset values in combination with some method of p

7.2.4 Transportation Methods

VTOL Drone

Using a vertical takeoff and landing (VTOL) drone would require minimal design changes of the package, and could be a great area of improvement for delivery range. VTOL aircraft operate similar to multirotors when taking off and landing, but can take advantage of horizontal flight once in the air. Horizontal flight is much more efficient than vertical flight, meaning the package could be delivered to farther away areas. The company Vayu uses VTOL drones to solve the medical supply challenge, so the use of VTOL drones is feasible.

Fixed-wing Drone

Fixed wing drones have much greater range than multirotors and to some extent VTOL drones. There would need to be changes to the package design and logistics of transportation in order to take advantage of a fixed-wing drone however. Unlike multirotors and VTOL drones, fixed-wing drones require either a runway or a launching mechanism to get airborne and to land. This would require both the supply center and the delivery site to have a runway for the drone to takeoff and land. A possible alternative solution would be for only the supply center to have a runway and the package to be dropped at the delivery site. This would bring up mechanical complications such as ensuring structural stability and effective airspeed reducing dropping mechanisms, but would dramatically increase the potential range of delivery.

Conventional Transportation

Conventional transportation, such as moving supplies via truck or pack-animal, has some potential as a potential area of interest, albeit a different area than the idea behind the project. Instead of focusing on the cost and speed of delivering these vaccines, the focus would be on fitting the most volume of supplies into the container and keeping them thermally stable for as long as possible. The design would likely have to shift from using a small controllable TEC element for refrigeration to using a compression system, simply to get better efficiency when weight is not as much of a concern. The container itself would likely have more insulation, and the internal structure would be more complex. Despite the high-level similarity to the project, the individual design choices made and methods of temperature control would be completely different. Designing a system for conventional transportation would be almost like creating a brand new project, and is not a likely progression from the drone focused project.

7.2.5 Drone Controls

An interesting opportunity for project improvement that was completely ignored by the team would be to implement an autonomous method of controlling the flight of the drone. The target areas being mostly rural would likely not have a built up infrastructure for landing the drone to deliver the package. Figuring out what methods the drone could use to control flight, determine where and how to land, and return to base would be a very interesting drone controls project that could be pursued by future project teams.

8 Conclusion

With the culmination of the project the team was able to design a package that hit these design criteria:

- Achieved cost effective transport
- Developed controlled temperature stability
- Obtained a battery life of 1+ hours
- Secured data communication with the container, separate of the drone
- Designed a simple attachment mechanism
- Modularized interior for various medical supplies

The package was able to keep the vaccine samples withing the desired temperature range of 2 °C to 8 °C Celsius. Multiple tests have confirmed that the internal vaccine temperature was held at a relatively constant temperature of 7 °C. Testing with vaccine vial monitors validated the system's ability to maintain vaccine potency over the desired package operational duration. The modular internal design allowed for different medical supplies and samples to be transported in the canister. The canister fully loaded weighed 2.9 pounds below the drone's max capacity of 5.1 kilograms (roughly 11.2 pounds). Further improvements in the mode of insulation and materials could allow the package to reach a lower temperature with the same amount of power. Ultimately, the team was happy with a successful prototype, even with potential areas of improvement.

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Appendices

A Code Documentation

This appendix includes complete documentation of the code used for to control the package. The code is written in C for use on the Arduino microcontroller.

```
//*********************************************************************************************
// Package Microcontroller Code

// Evan Bosia

// This program runs the high level logic of the package. Functions include reading temperature,
// battery voltage, UI inputs and outputs, controlling the TEC, determining basic validity, and
// sending GPS data.

//*********************************************************************************************
//LIBRARIES

#include <DFRobot_sim808.h>

//*********************************************************************************************
//CONSTANTS
#define LED_ARM 13        //LED arming the temperature settings
#define LED_VALID 11    //LED validity of vaccines output pin

#define ON_SWITCH 2    //arming switch input pin

#define TEC_CTR 3    //relay digital output pin

#define CELL_0 A0    //voltage of cell 0 analog input
#define CELL_1 A1    //voltage of cell 1 analog input
#define CELL_2 A2    //voltage of cell 2 analog input
#define TEMP_PROBE A3        //analog input for temperature probe
#define TEMP_KNOB_RNG A4    //analog input for temperature range POT
#define TEMP_KNOB_MAX A5    //analog input for temperature max POT

#define SET_TEMP 0    //state of setting temperature
#define RUN_PROG 1    //state of running the program

#define PHONE_NUMBER "9784967220" //Mobile phone number, need to change

//*********************************************************************************************
//GLOBAL VARIABLES

int global_time;        //global time variable
int temperature_time;    //temperature measurement time

int temperatures[10];    //rolling array of temperatures

int max;    //maximum allowable temperature
int min;    //minimum allowable temperature

int state;    //state determined by arming switch

boolean power;    //true if relay is powered

int index;

int validity; //Running sum of temp seconds above max

String position;

DFRobot_SIM808 sim808(&Serial); //SIM Card


//*********************************************************************************************
//SETUP

void setup()
{
    pinMode(LED_ARM, OUTPUT);
    pinMode(LED_VALID, OUTPUT);
    pinMode(TEC_CTR, OUTPUT);

    pinMode(ON_SWITCH, INPUT_PULLUP);

```

```
    global_time = 0;
    temperature_time = 0;
    index = 0;

    Serial.begin(9600);
      state = digitalRead(ON_SWITCH);
    attachInterrupt(digitalPinToInterrupt(ON_SWITCH), arm_switch, CHANGE);

    //initialize program to have previously set temperature constants
    max = get_temp(TEMP_KNOB_MAX);
    min = max - (get_temp(TEMP_KNOB_RNG) + 5);

    power = false;

    digitalWrite(LED_ARM, 0);

    setup_GSM();

    setup_timers();
}

void setup_GSM(){
  //*******Initialize sim808 module*************
  while(!sim808.init()) {
    delay(1000);
  }
}

void setup_timers(){
    // initialize timer1
    noInterrupts();           // disable all interrupts
    TCCR1A = 0;
    TCCR1B = 0;
    TCNT1  = 0;

    OCR1A = 1562;            // compare match register 16MHz/1024/~10Hz (slightly faster)
    TCCR1B |= (1 << WGM12);   // CTC mode
    TCCR1B |= (1 << CS12)|(1 << CS10);    // 1024 prescaler
    TIMSK1 |= (1 << OCIE1A);  // enable timer compare interrupt
    interrupts();
}

//**********************************************************************************************
//LOOP
void loop(){
    if(state == SET_TEMP){
        digitalWrite(LED_ARM, 0);
        initialize();
        digitalWrite(TEC_CTR, 0);
    }
    else if(state == RUN_PROG){
        if(temperature_time == 0 && voltage_check()){
            digitalWrite(LED_ARM, 1);
            temp_control();
        }
        //Voltage of battery is too low to operate
        else if(!voltage_check()){
            digitalWrite(TEC_CTR, 0);
            if(global_time % 2 == 0){
                digitalWrite(LED_ARM, 1);
            }else{
                digitalWrite(LED_ARM, 0);
            }
            //FLASH LED
        }

        //Check validity of vaccines while running
        if(validity > 100){
            digitalWrite(LED_VALID, 1);
        }

```

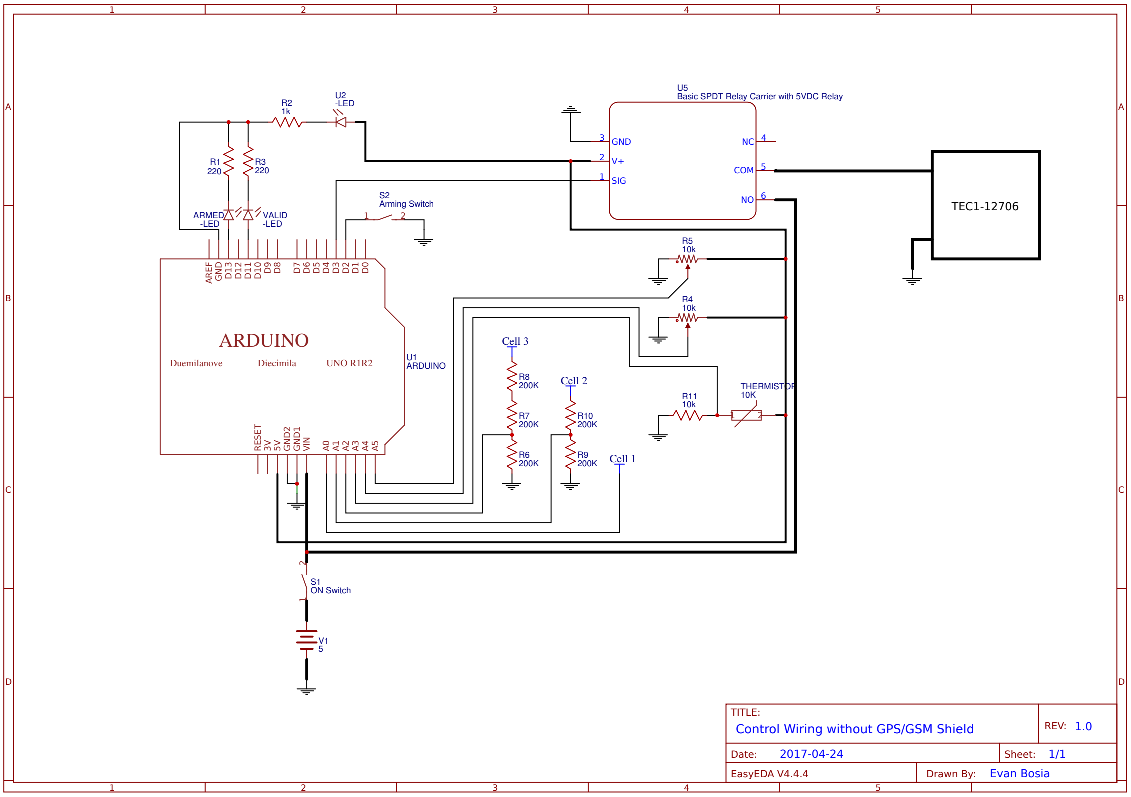
```
        //Send data every 5 minutes
        if(global_time % 3000 == 0){
            sim808.sendSMS(PHONE_NUMBER, position);
        }
    }
}

void arm_switch(){
    state = 1-digitalRead(ON_SWITCH);
}

//Runs initialization steps of the program
//  - waits for attachment to drone
//  - waits for temperature input and arming
void initialize(){
    max = get_temp(TEMP_KNOB_MAX);
    min = max - 10;//(get_temp(TEMP_KNOB_RNG)+5);

    Serial.print("MAX: ");
    Serial.print(get_temp(TEMP_KNOB_MAX));
    Serial.print(" RANGE: ");
    Serial.println(get_temp(TEMP_KNOB_RNG)+5);
    delay(10);
}


//temperature control
void temp_control(){
    int avg = median();    //average of temperature sensor reading array
    int temperature = (avg - 234)/ 1.07;    //convert averaged sensor value to tenth degree Celsius temperature\
    Serial.print("TEMP = ");
    Serial.println(temperature);
    delay(2000);
    //if the temp is higher than max bound and the power is off
    if(temperature > max && !power){
        power = true;
    }
    //if the temp is higher than max bound and the power is off
    else if(temperature < min && power){
        power = false;
    }
    digitalWrite(TEC_CTR, power);
}


//checks battery voltage to avoid damage - true = good, false = bad
boolean voltage_check(){
    int v0 = analogRead(CELL_0);
    int v1 = analogRead(CELL_1);
    int v2 = analogRead(CELL_2);
    int check = 650;


//  Serial.print("V0 ");
//  Serial.print(v0);
//
//  Serial.print(", V1 ");
//  Serial.print(v1);
//
//  Serial.print(", V2 ");
//  Serial.println(v2);

    if(v1 < 100){
        v0 = 1000;
        v1 = 1000;
        v2 = 1000;
    }

    if(v0 < check || v1 < check || v2 < check){
        return false;
    }
```

```
    return true;
}

//changes POT value to temperature setting (~0 to 100 in tenths of C)
int get_temp(int pin){
    return (1023 - analogRead(pin)) / 10;
}

//takes average of temperatures
int average(){
    int sum = 0;
    for(int i = 0; i < 10; i++){
        sum += temperatures[i];
    }
    return sum/10;
}

//takes median of temperatures
int median(){
    int temp = 0;
    int index = 0;
    int high = 0;

    //swap sort
    for(int i = 0; i < 10; i++){
    high = 0;
    index = i;
        for(int j = i; j < 10; j++){
            if(high < temperatures[j]){
                index = j;
            }
        }
        temp = temperatures[index];
        temperatures[index] = temperatures[i];
        temperatures[i] = temp;

    }

    //return average to sorted middle values
    return (temperatures[4] + temperatures[5])/2;
}


//TIMER 1 INTERRUPT
ISR(TIMER1_COMPA_vect)
{
    global_time++;

    if(temperature_time < 10){
        temperatures[temperature_time] = analogRead(TEMP_PROBE);
        temperature_time++;
    }
    else{
        temperature_time = 0;
        validity += max - median();
    }
}

//Timer for transmitting data
void timer_transmit(){

}

/* Arduino 101: timer and interrupts
1: Timer1 compare match interrupt example
more infos: http://www.letmakerobots.com/node/28278
created by RobotFreak
*/

//Updates GPS value - global. If GPS broken / disconnected, do not update to store last know position
void read_GPS(){
```

```
    position = "latitude: " + sim808.GPSdata.lat +
               "\nlongitude: " + sim808.GPSdata.lon +
               "\ntemperature: " + median();
}
```

B Wiring Diagram

This appendix contains complete documentation of the wiring of the system.



C Test Results

This appendix includes the temperature results of different bench-top tests run on the package.

2.0 Testing

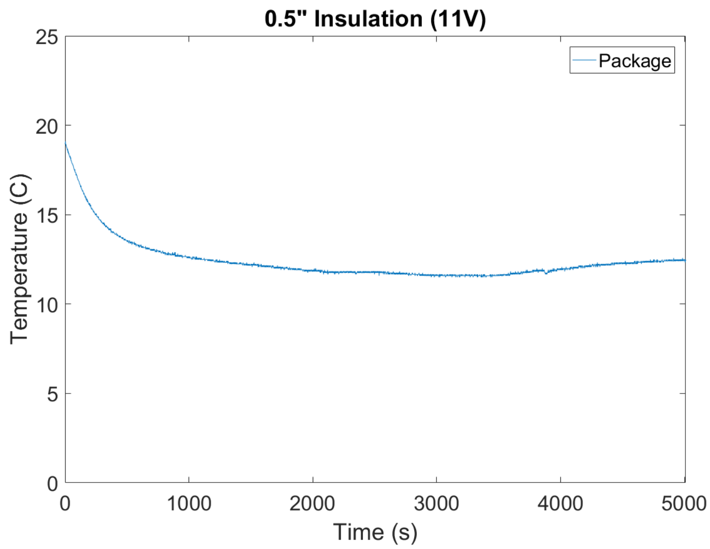


Figure 46: Initial test 0.5" insulation (11V)

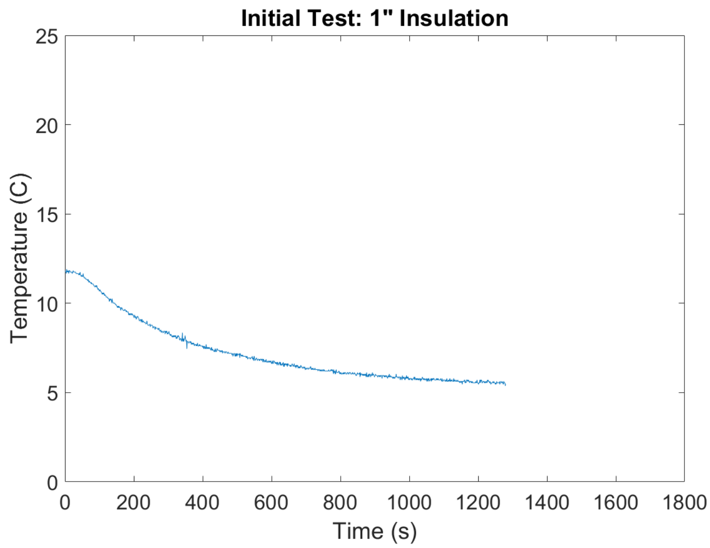


Figure 47: Initial test 1” insulation (11V)

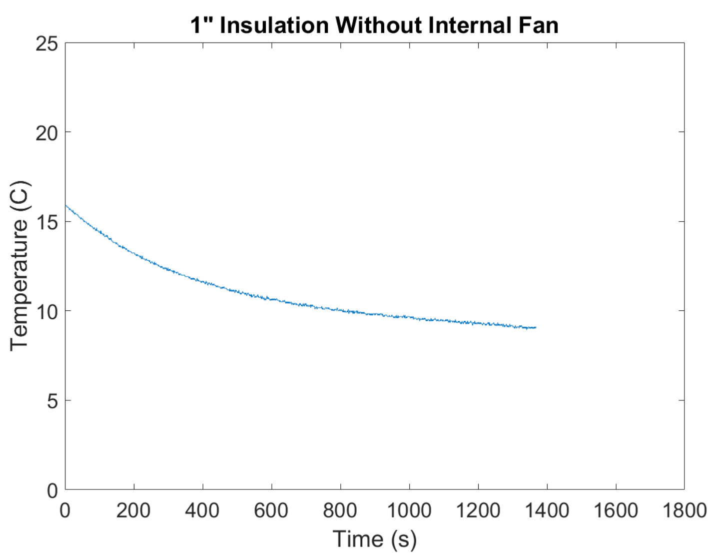


Figure 48: Initial test 1” insulation w/o fan (11V)

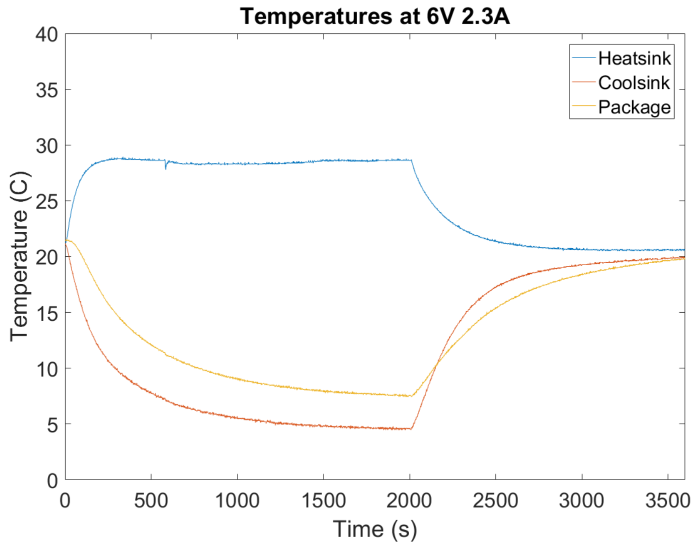


Figure 49: Test 1" insulation with shutoff (6V)

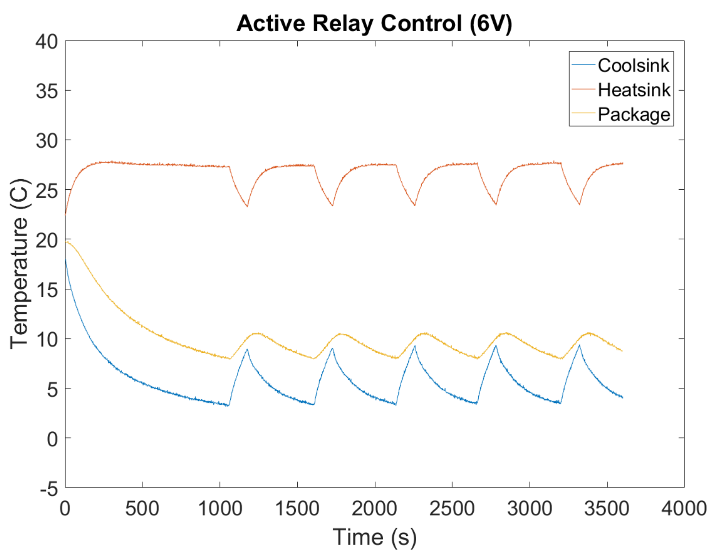


Figure 50: Test active relay control

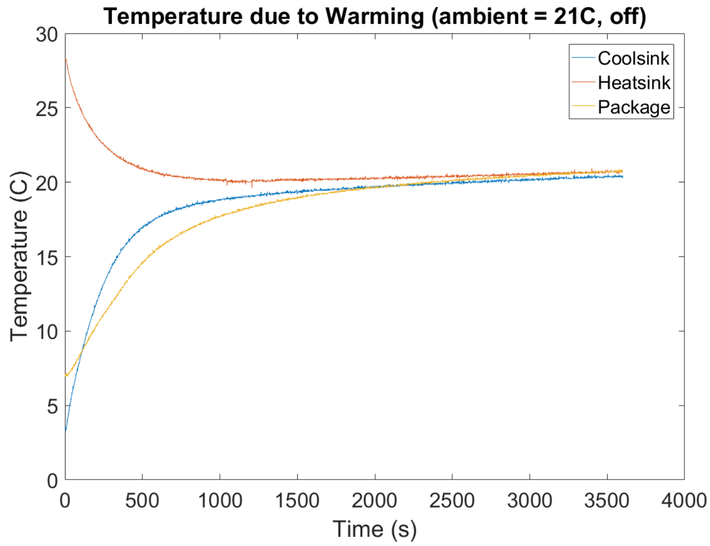


Figure 51: Test warming with no power

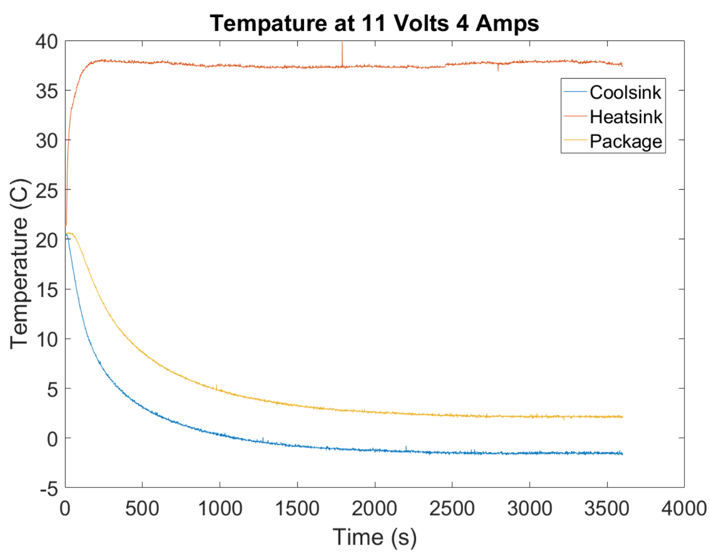


Figure 52: Test full power (11V)

3.0 Testing

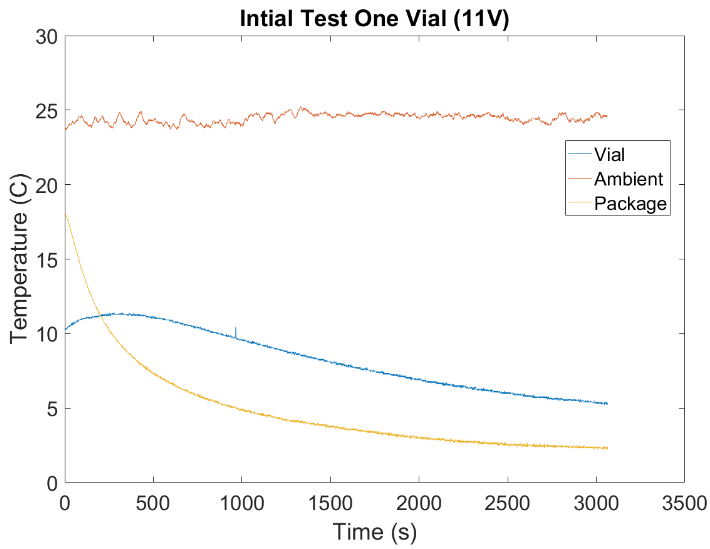


Figure 53: 3.0 Test one vial (11V)

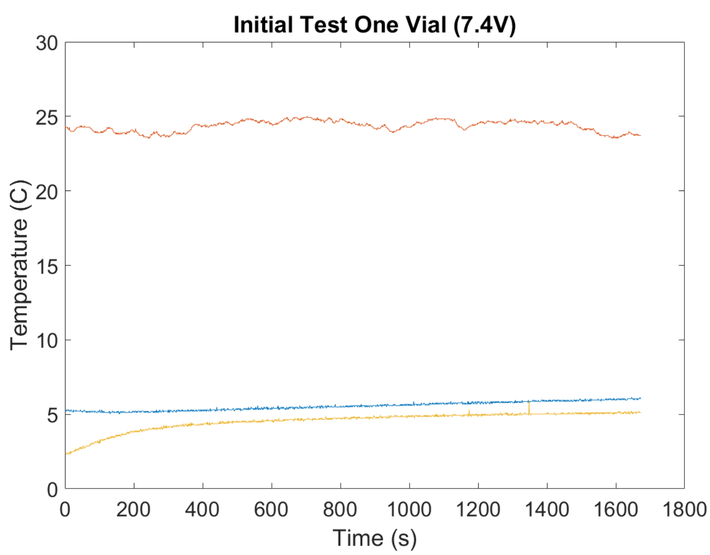


Figure 54: 3.0 Test one vial (7.4V)

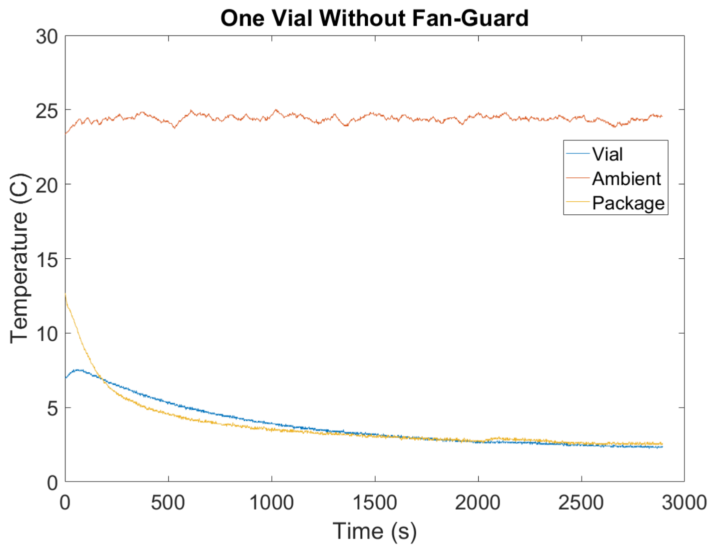


Figure 55: 3.0 Test one vial without fan guard

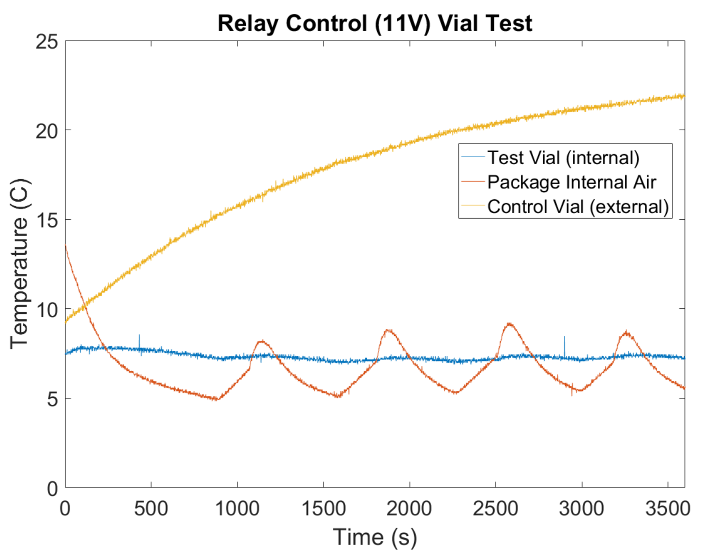


Figure 56: 3.0 Test full load relay control

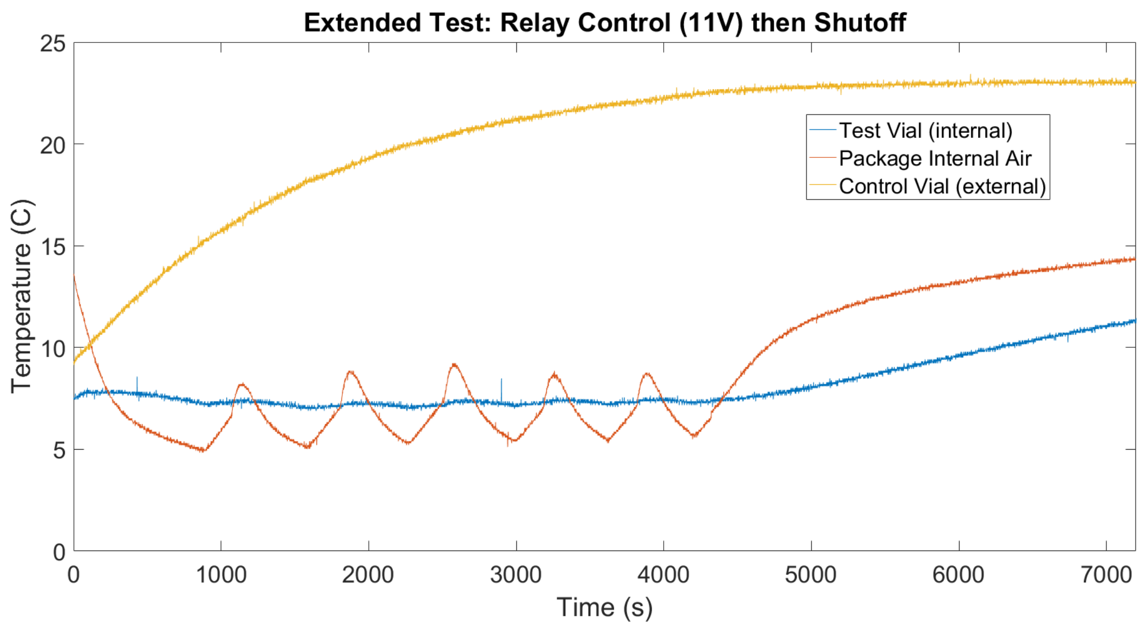


Figure 57: 3.0 Test full load relay control with extended off period

D MATLAB Simulation Code

This appendix includes complete documentation of the MATLAB code used for heat transfer simulation. Some of the constants were changed to examine different values in the system. Each separate function is started by a commented header file explaining...

- the title of the code segment
- what the code segment does
- input parameters if a function
- output returns if a function

```
%{
Heat Transfer Program
Runs heat transfer analysis on a cylindrical package with internal
insulation.

Evan Bosia
%}

clear all; close all;
%Material Thickness
ti = 1 * 0.0254;
ts = 0.625/2 * 0.0254;

rs = 4 * 0.0254; %inner radius of structural pipe

h = 5.5 * 0.0254; % height of the structural container

v_air = 0;

%Material conduction coeff
ki = 0.05; %insulating material ~ Neoprene 0.05
ks = 0.10; %structural material ~ ABS = 0.10
           %PVC = 0.19

To = 310; %outside temp
Ti = 275; %inside temp

Qw = []; %heat transfer through cylindrical shell
Qc = []; %heat transfer through caps
x = []; %stores x axis for 3D graph
y = []; %stores y axis for 3D graph
volume = []; %stores volume for different configurations


%******** ITERATE THROUGH TWO VARIABLES
for j = 1:20

    %Change radius
    rs = (3 + 0.1 * j)*0.0254;
    %To = 290 + 2 * j;
    y(j) = rs;

    for i = 1:20

        %Change insultation thickness
        ti = 0.1* i * 0.0254;
        x(i) = ti;

        %Heat transfer analysis
```

```
        Qw(j,i) = heat_cylinder(rs, ti, ts, v_air, ki, ks, To, Ti, h);
        Qc(j,i) = heat_caps(rs, ti, ts, v_air, ki, ks, To, Ti);

        volume(j,i) = (rs-ti)^2 * (h-2*ti) * pi;
    end;
end;


%3D surface plot of heat transfer
Q = Qc + Qw;
surf(x,y,Q);
xlabel('Thickness (m)');
ylabel('Radius (m)');
zlabel('Q (W)');
figure;

%Set limits for volume to determine valid dimensions
      [r,c]=find(volume<1 * 10^(-3));
      volume(sub2ind(size(volume),r,c)) = 0;

%3D surface plot of volume
surf(x,y,volume);
xlabel('Thickness (m)');
ylabel('Radius (m)');
zlabel('Volume (m^3)');
figure;

%Set limits for Q values to determine most efficient Volume sizes
      [r,c]=find(Q>6);
      Q(sub2ind(size(Q),r,c)) = 0;

%3D surface plot of ratio between heat transfer and volume
Z = Q./volume;
surf(x,y,Z);
xlabel('Thickness (m)');
ylabel('Radius (m)');
zlabel('Q/Volume (W/m^3)');
```

```matlab
%{
Heat Transfer Through Cylinder Function
Determines the conduction heat transfer through a cylindrical body.

Params: radius, thickness of insulation, thickness of structure, external
air velocity, conduction coeff of insulation, conduction coeff of
structure, external temperature, internal temperature, height.

Returns: Heat transfer into the system (watts)

Evan Bosia
%}

function Qw = heat_cylinder(rs, ti, ts, v_air, ki, ks, To, Ti, L)
%Inner Edge
r1 = (rs-ti);
h1 = 10.5;

%Radius to insulation-structure boundary
rm = rs;

%Outer edge
r2 = (ts+rs);
h2 = 10.5 - v_air + 10 *sqrt(v_air);

%Cylinder heat resistance insulation
Rcdi = log(rm/r1)/(2*pi*L*ki);

%Cylinder heat resistance tube structure
Rcds = log(r2/rm)/(2*pi*L*ks);

%Convection heat resistance internal
Rcv1 = 1/(2*pi*r1*L*h1);

%Convection heat resistance external
Rcv2 = 1/(2*pi*r2*L*h2);

%Total thermal resistance
Rt = Rcv1 + Rcdi + Rcds + Rcv2;

%Heat transfer
Qw = (To-Ti)/Rt;
end
```

```
%{
Heat Transfer Through Caps Function
Determines the conduction heat transfer through the circular ends of a cylindrical
body.

Params: radius, thickness of insulation, thickness of structure, external
air velocity, conduction coeff of insulation, conduction coeff of
structure, external temperature, internal temperature.

Returns: Heat transfer into the system (watts)

Evan Bosia
%}

function Qc = heat_caps(rs, ti, ts, v_air, ki, ks, To, Ti)
%Inner edge
h1 = 10.5;

%Outer edge
h2 = 10.5 - v_air + 10 *sqrt(v_air);

%Cap heat resistance insulation
Rcdi = ti/(pi*(rs-ti)^2*ki);

%Cap heat resistance tube structure
Rcds = ts/(pi*(rs)^2*ks);

%Convection heat resistance internal
Rcv1 = 1/(pi*(rs-ti)^2*h1);

%Convection heat resistance external
Rcv2 = 1/(pi*rs^2*h2);

%Total thermal resistance
Rt = Rcv1 + Rcdi + Rcds + Rcv2;

%Heat transfer through 2 caps
Qc = 2*(To-Ti)/Rt;
end
```

```
%{
Steady State Temperature
Determines the steady state temperature of the package with variable power input.

Evan Bosia
%}

clear all; close all;

%Material Thickness
ti = 1 * 0.0254; % meters
ts = 0.625/2 * 0.0254; % meters

rs = 4 * 0.0254; %inner radius of structural pipe

h = 5.5 * 0.0254; % height of the structural container

v_air = 0; %air velocity

%Material conduction coeff
ki = 0.05; %insulating material
ks = 0.19; %structural material

To = 300; %outside temp
Ti = 275; %inside temp

n = 0.125; %TEC efficiency

T = [];
Tf = [];

V = ((rs-ti)^2 * (h-2*ti)) * pi; %Package volume

x = [];
y = [];

%******** CONTROL 1-2 variables
for a = 1:20

    %Vary external temperature
    Ti = 273 + 2 * a;
    To = Ti;
    for b = 1:7
        %Find starting Qair at Ti
        Qair = (Ti)*(1003*V*1275.4);

        %Vary TEC wattage and run iteration over 480 minutes (6 hours)
        T(b,:) = temp_time(rs, ti, ts, v_air, ki, ks, To, Ti, h, Qair, b, n, V, 480);
        Tf(b,a)= T(b,end);
```

```
        y(b) = (b-1)*10 * n;
    end
    x(a) = To;
end

%3D graph of final temperature vs outside temperature and TEC wattage
surf(x,y,Tf);
xlabel('Outside Temp(K)');
ylabel('Peltier Heat Transfer (W)');
zlabel('Internal Temperature (C) after 6 hours');
```

```
%{
Final Temperature Iteration Function
Determines the final temperature of the package by iterating the heat
transfer in and out.

Params: radius, thickness of insulation, thickness of structure, external
air velocity, conduction coeff of insulation, conduction coeff of
structure, external temperature, internal temperature, height, Q of air,
TEC counter, TEC efficiency, volume, iteration time.

Returns: List of temperatures taken every minute.

Evan Bosia
%}



function T = temp_time(rs, ti, ts, v_air, ki, ks, To, Ti, h, Qair, b,n, V, time)
    T = [];
    for t = 1:time
        %Heat through cylinder walls
        Qw = heat_cylinder(rs, ti, ts, v_air, ki, ks, To, Ti, h);

        %Heat through caps
        Qc = heat_caps(rs, ti, ts, v_air, ki, ks, To, Ti);

        %Heat moved by TEC
        Qp = (b-1)*10*n;

        %Total heat rate
        Qt = Qw + Qc - Qp;
        Q(t) = Qt;

        %Iteration of air temperature
        Qair = Qair + Q(t) * 60;

        %Find internal temperature from new Qair value
        Ti = Qair/(1003*V*1275.4);

        %Convert to Celsius
        T(t) = Ti-273;
    end
end
```

E Thermoelectric Cooler Modeling

This appendix contains documentation of the math used to model the TEC. These equations were used to generate the theoretical model in Appendix F. All equations were taken from [56].

Constants

These constants are measured for a TEC with 71 couples and an I_{max} of 6.
$s_1 = 1.33450 * 10^{-2}$
$s_2 = -5.37574 * 10^{-5}$
$s_3 = 7.42731 * 10^{-7}$
$s_4 = -1.27141 * 10^{-9}$

$r_1 = 2.08317$
$r_2 = -1.98763 * 10^{-2}$
$r_3 = 8.53832 * 10{-}5$
$r_4 = -9.03143 * 10^{-8}$

$k_1 = 4.76218 * 10^{-1}$
$k_2 = -3.89821 * 10^{-6}$
$k_3 = -8.64864 * 10^{-6}$
$k_4 = 2.20869 * 10^{-8}$

When DT is equal to 0

$$S_m = s_1 + s_2 * T + s_3 * T^2 + s_4 * T^3 \tag{8}$$

$$R_m = r_1 + r_2 * T + r_3 * T^2 + r_4 * T^3; \tag{9}$$

$$K_m = k_1 + k_2 * T + k_3 * T^2 + k_4 * T^3; \tag{10}$$

When DT is not equal to 0

$$S_{mh} = s_1 * T_h + (s_2 * T_h^2)/2 + (s_3 * T_h^3)/3 + (s_4 * T_h^4)/4 \tag{11}$$

$$S_{mc} = s_1 * T_c + (s_2 * T_c^2)/2 + (s_3 * T_c^3)/3 + (s_4 * T_c^4)/4 \tag{12}$$

$$S_m = (S_{mh} - S_{mc})/DT; \tag{13}$$

$$R_{mh} = r_1 * T_h + (r_2 * T_h^2)/2 + (r_3 * T_h^3)/3 + (r_4 * T_h^4)/4 \tag{14}$$

$$R_{mc} = r_1 * T_c + (r_2 * T_c^2)/2 + (r_3 * T_c^3)/3 + (r_4 * T_c^4)/4 \tag{15}$$

$$R_m = (R_{mh} - R_{mc})/DT; \tag{16}$$

$$K_{mh} = k_1 * T_h + (k_2 * T_h^2)/2 + (k_3 * T_h^3)/3 + (k_4 * T_h^4)/4 \tag{17}$$

$$K_{mc} = k_1 * T_c + (k_2 * T_c^2)/2 + (k_3 * T_c^3)/3 + (k_4 * T_c^4)/4 \tag{18}$$

$$K_m = (R_{mh} - R_{mc})/DT; \tag{19}$$

TEC Conversion Equations

To convert from the predefined TEC to any TEC, the following equations were used. In these equations, I_{new} is the max current of the new TEC, and n_{new} is the number of couples in the new TEC.

$$K_m = (R_{mh} - R_{mc})/DT; \tag{20}$$

$$R_m = R_m * \frac{n_{new} * 6}{71 * I_{new}} \tag{21}$$

$$K_m = K_m * \frac{n_{new} * I_{new}}{71 * 6} \tag{22}$$

Current Calculation

$$I = \frac{(V - (S_m * DT))}{R_m} \tag{23}$$

Heat Moved

$$\dot{Q} = (S_m * T * I) - (0.5 * I^2 * R_m) - (K_m * DT); \tag{24}$$

https://thermal.ferrotec.com/technology/thermoelectric-reference-guide/thermalref11/

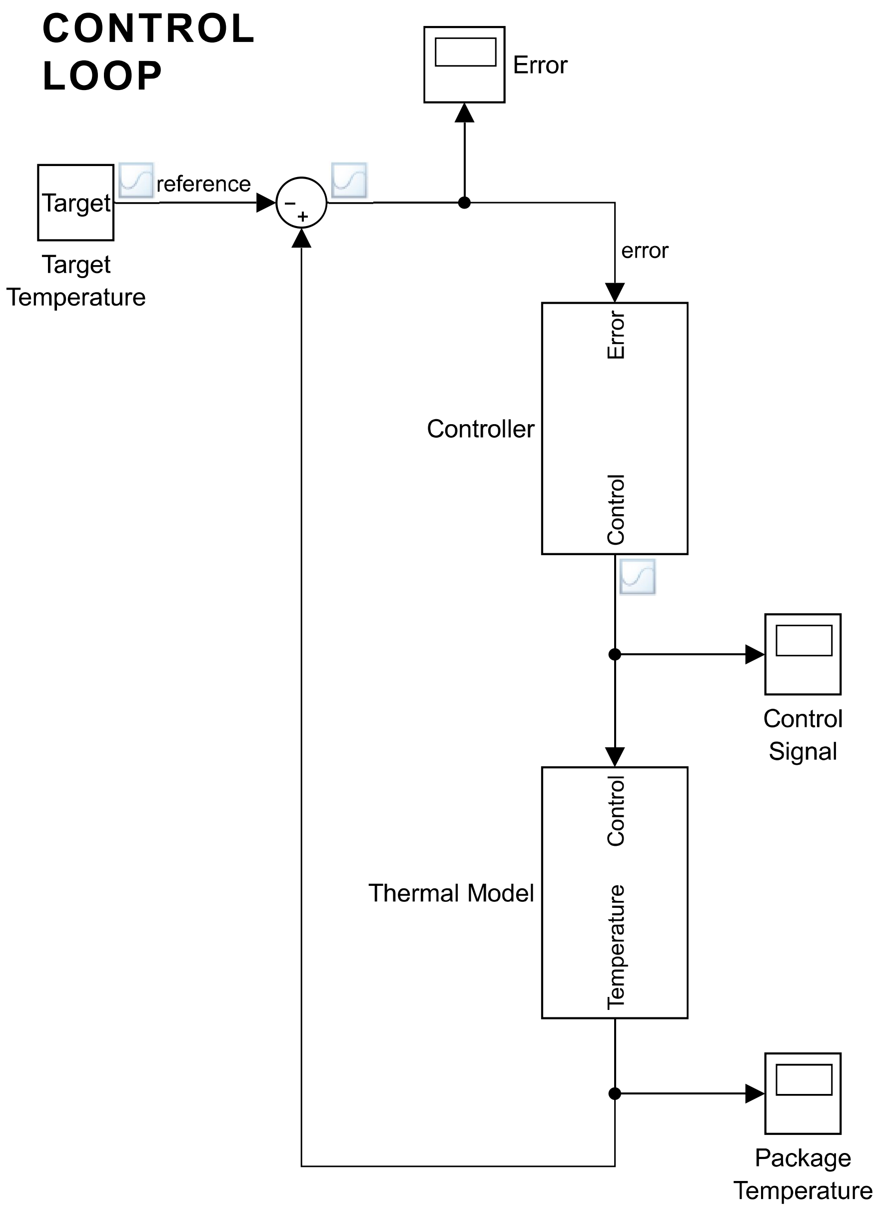
F Simulink Theoretical Model

This appendix contains complete documentation of the Simulink models. While the model is not perfect, it considers many different aspects of the system.

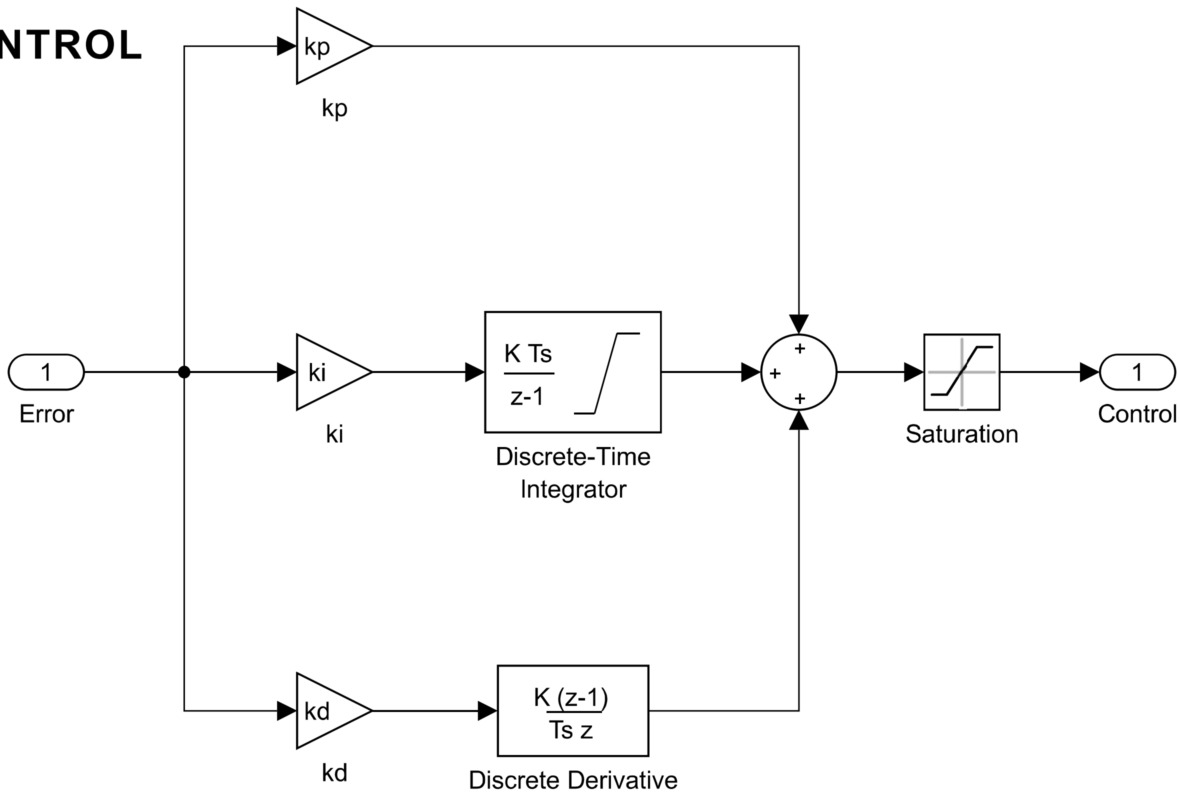
- Rate of heat moved by the TEC
- Rate of heat into the package
- Package energy and heat capacity
- Heatsink masses and thermal resistances
- Heat into the system through the heatsinks when unpowered
- Nonuniform temperature distribution in heatsinks

The model is run iteratively at a time differential of one second. Discrete iterators are used to accumulate the heat transfer (Watts) into energy values (Joules), which are converted into temperatures (Kelvin) using $Q = mC_pT$. The current draw of the system was also passed through an iterator to get a current capacity output, measured in amp hours.

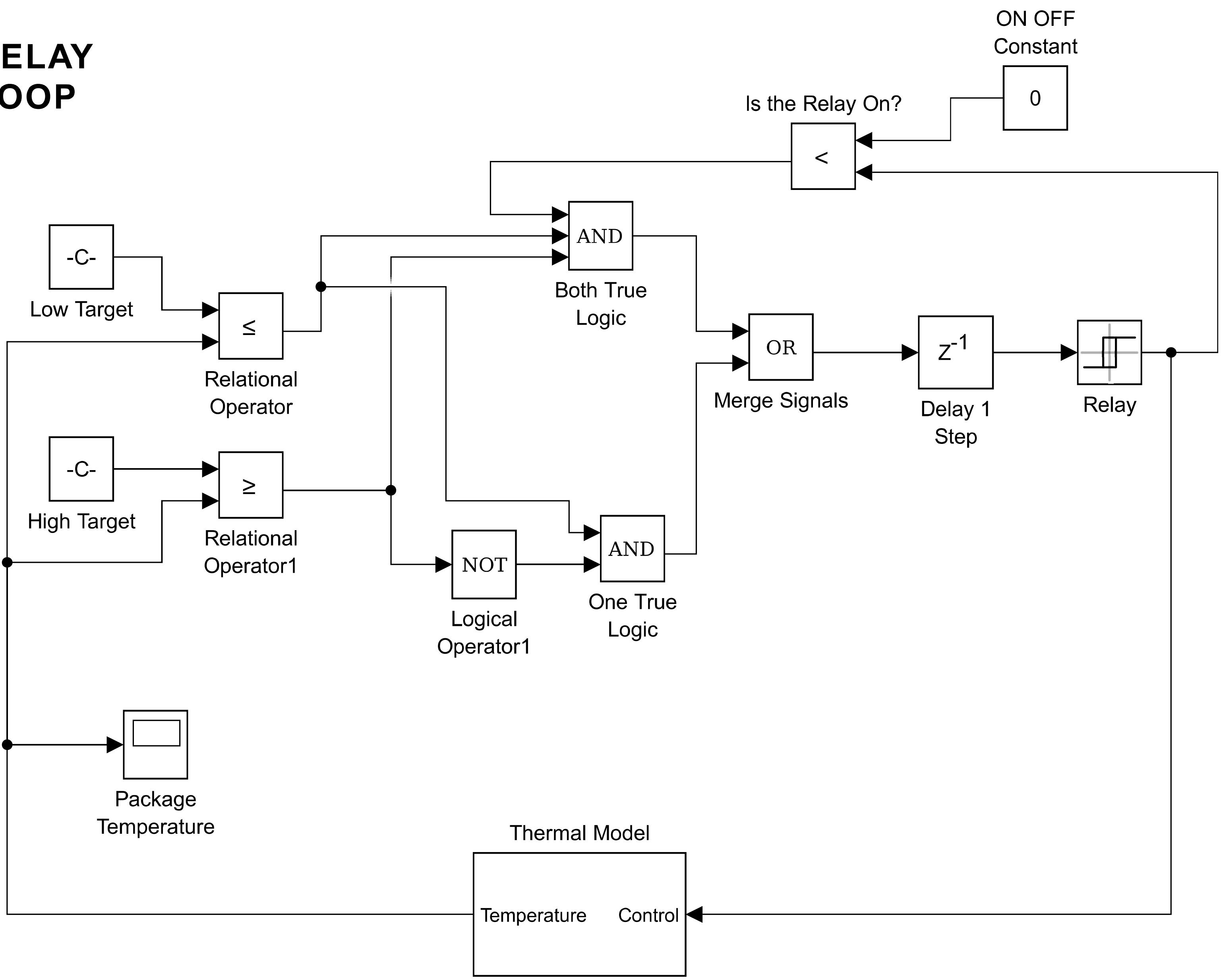
The model was used to test different methods of control. The relay loop and the PID function are two different programs but include the same thermal model functions. Each model's constants were found using experimental data from Design 2.0. Some of the constants were adjusted to account for discrepancies with measured results. Ultimately there are some avenues of heat transfer missing from the model, but it still provides an internal comparison between different scenarios.

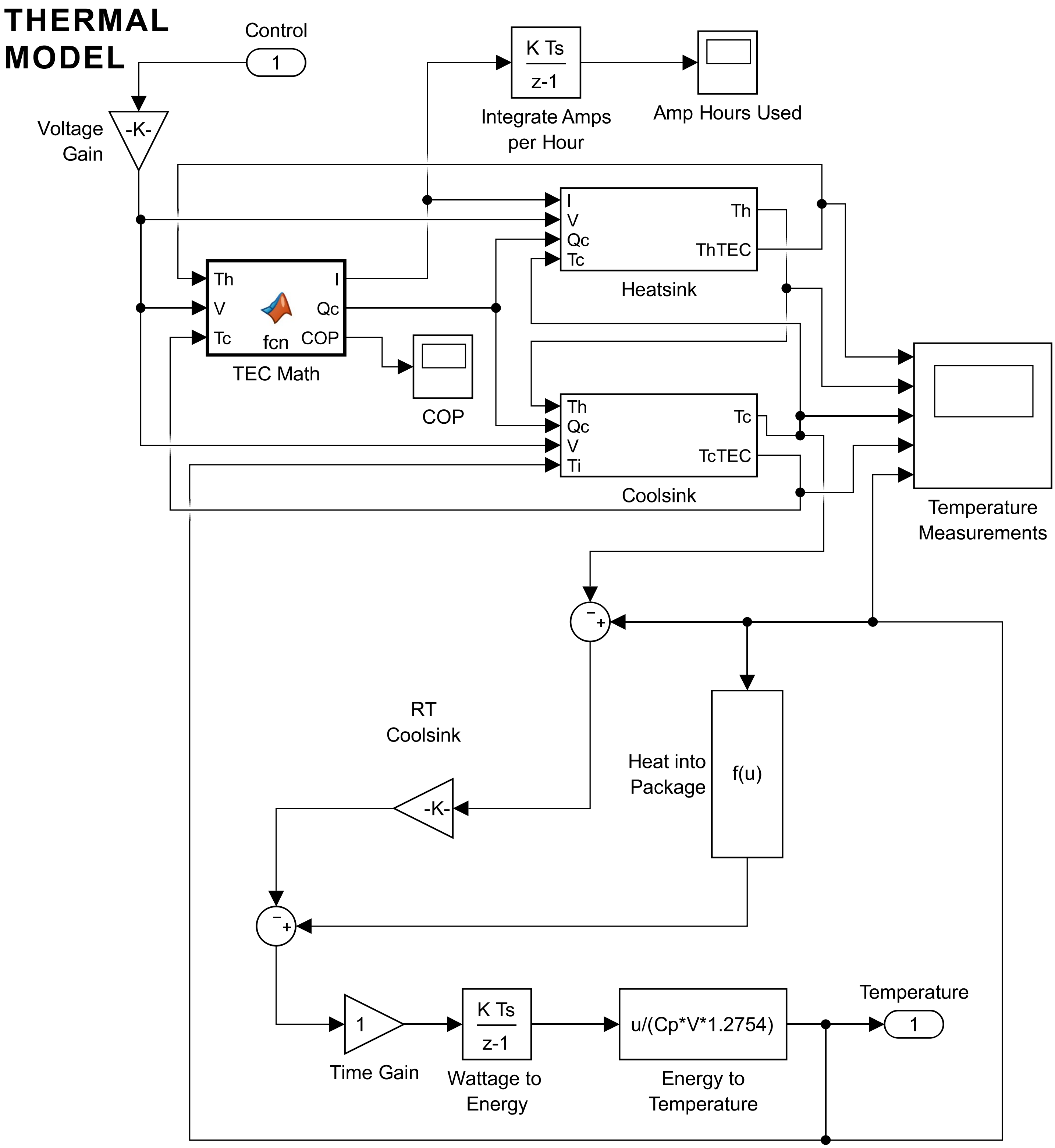

CONTROL
LOOP
Error
Target
reference
Target
Temperature
error
Error
Controller
Control
Control
Signal
Control
Thermal Model
Temperature
Package
Temperature

PID CONTROL

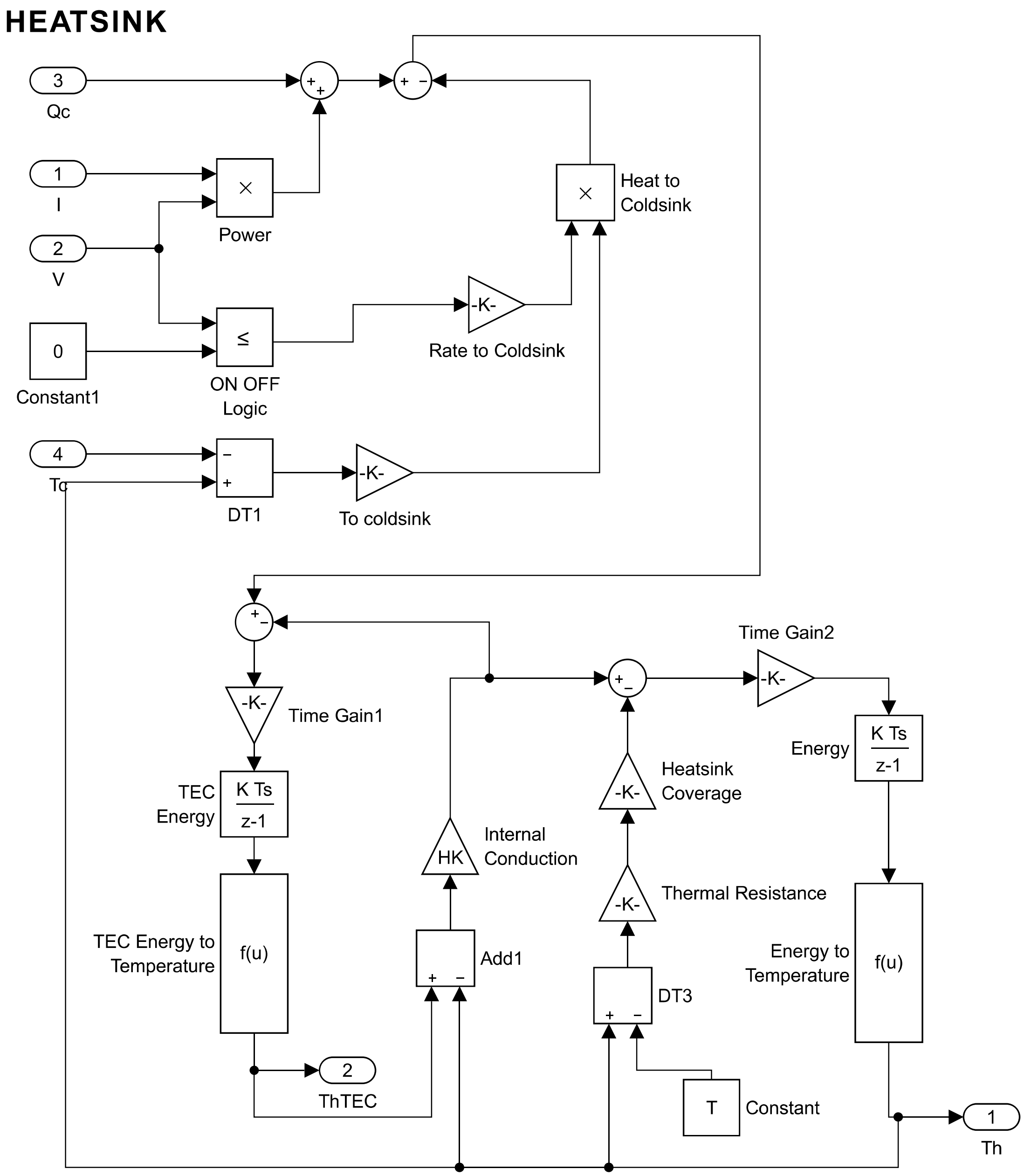

kp
kp
1
Error
ki
ki
K Ts
z-1
Discrete-Time Integrator
+
+
+
Saturation
1
Control
kd
kd
K (z-1)
Ts z
Discrete Derivative

RELAY LOOP

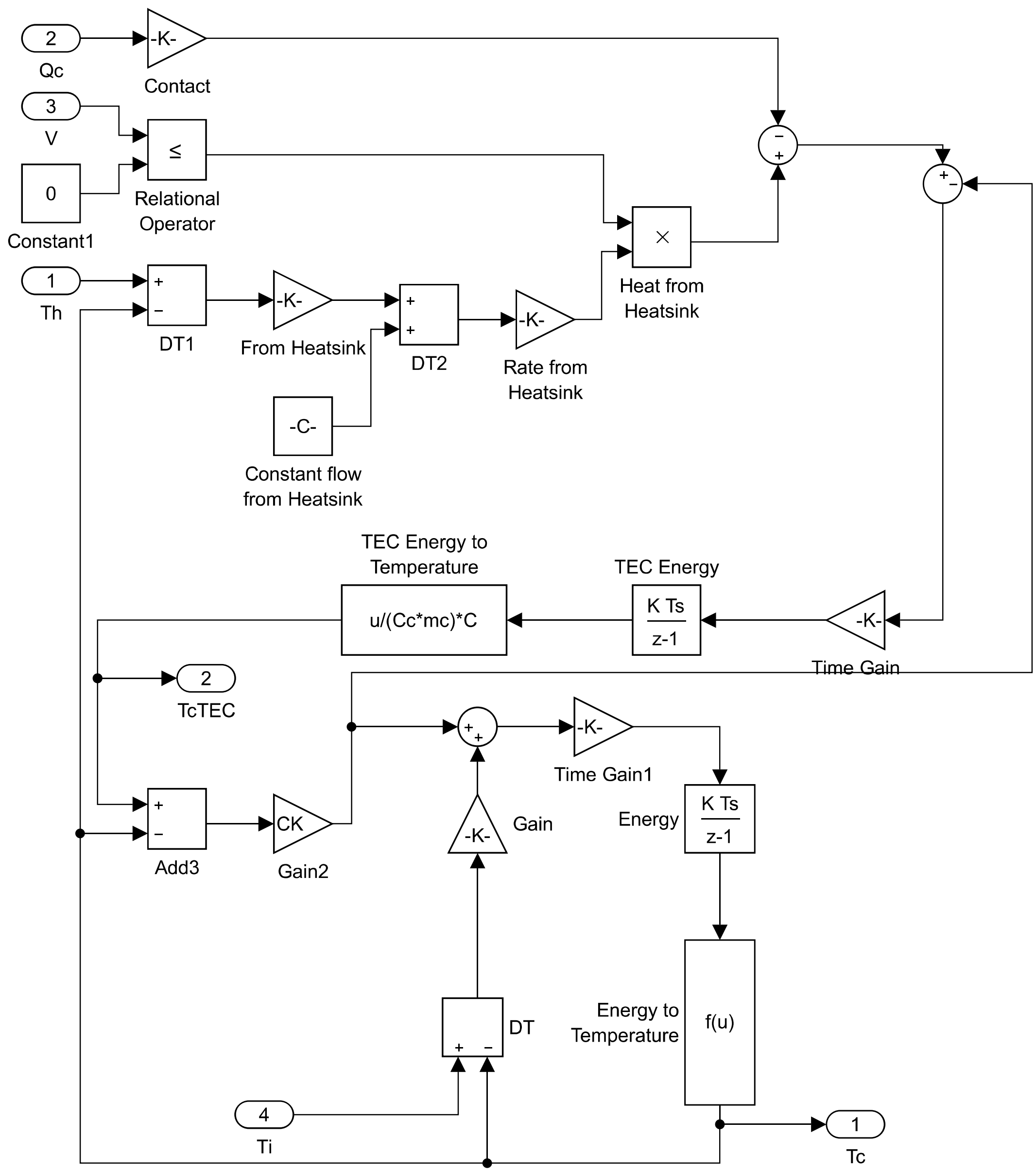

ON OFF Constant
0
Is the Relay On?
<
-C-
Low Target
≤
Relational Operator
AND
Both True Logic
OR
Merge Signals
z^{-1}
Delay 1 Step
Relay
-C-
High Target
≥
Relational Operator1
NOT
Logical Operator1
AND
One True Logic
Package Temperature
Thermal Model
Temperature
Control



THERMAL
MODEL
Control
1
Voltage
Gain
-K-
K Ts
z-1
Integrate Amps
per Hour
Amp Hours Used
I
V
Qc
Tc
Th
ThTEC
Heatsink
Th
V
Tc
I
Qc
COP
fcn
TEC Math
COP
Th
Qc
V
Ti
Tc
TcTEC
Coolsink
Temperature
Measurements
RT
Coolsink
-K-
Heat into
Package
f(u)
1
Time Gain
K Ts
z-1
Wattage to
Energy
u/(Cp*V*1.2754)
Energy to
Temperature
Temperature
1


HEATSINK
3
Qc
1
I
2
V
0
Constant1
4
Tc
Power
Heat to Coldsink
-K-
Rate to Coldsink
≤
ON OFF Logic
DT1
To coldsink
Time Gain1
Time Gain2
TEC Energy
K Ts
z-1
Energy
Heatsink Coverage
Internal Conduction
HK
Thermal Resistance
TEC Energy to Temperature
f(u)
Add1
DT3
Energy to Temperature
2
ThTEC
T
Constant
1
Th

COOLSINK



2
Qc
-K-
Contact
3
V
0
Constant1
≤
Relational Operator
1
Th
DT1
-K-
From Heatsink
DT2
-C-
Constant flow from Heatsink
-K-
Rate from Heatsink
×
Heat from Heatsink
TEC Energy to Temperature
u/(Cc*mc)*C
TEC Energy
K Ts
z-1
-K-
Time Gain
2
TcTEC
Add3
CK
Gain2
-K-
Gain
-K-
Time Gain1
Energy
K Ts
z-1
DT
4
Ti
Energy to Temperature
f(u)
1
Tc

```
function [I, Qc, COP] = fcn(Th, V, Tc)
%{
TEC Math
This function runs TEC math to get the current draw, the heat transfer
rate, and the coefficient of performance.

Parameters: temperature hot side, voltage, temperature cold side

Returns: current, heat transfer rate, coefficient of performance

Evan Bosia
%}

n = 127;    %number of TEC couples in new TEC
Inew = 4.8; %Imax of new TEC

%Constants for TEC with 71 couples and Imax of 6 amps
s1 = 1.33450 * 10^-2;
s2 = -5.37574 * 10^-5;
s3 = 7.42731 * 10^-7;
s4 = -1.27141 * 10^-9;

r1 = 2.08317;
r2 = -1.98763 * 10^-2;
r3 = 8.53832 * 10^-5;
r4 = -9.03143 * 10^-8;

k1 = 4.76218 * 10^-1;
k2 = -3.89821 * 10^-6;
k3 = -8.64864 * 10^-6;
k4 = 2.20869 * 10^-8;

%Temperature difference between hot and cold side
DT = (Th-Tc);

%Equations dependent on temperature difference
if(DT == 0)
    T = Th;
    Sm = s1 + s2*T + s3*T^2 + s4*T^3;
    Rm = r1 + r2*T + r3*T^2 + r4*T^3;
    Km = k1 + k2*T + k3*T^2 + k4*T^3;
else
    Smh = s1*Th + (s2*Th^2)/2 + (s3*Th^3)/3 + (s4*Th^4)/4;
    Smc = s1*Tc + (s2*Tc^2)/2 + (s3*Tc^3)/3 + (s4*Tc^4)/4;
    Sm = (Smh - Smc)/DT;

    Rmh = r1*Th + (r2*Th^2)/2 + (r3*Th^3)/3 + (r4*Th^4)/4;
    Rmc = r1*Tc + (r2*Tc^2)/2 + (r3*Tc^3)/3 + (r4*Tc^4)/4;
    Rm = (Rmh - Rmc)/DT;
```

```
    Kmh = k1*Th + (k2*Th^2)/2 + (k3*Th^3)/3 + (k4*Th^4)/4;
    Kmc = k1*Tc + (k2*Tc^2)/2 + (k3*Tc^3)/3 + (k4*Tc^4)/4;
    Km = (Kmh - Kmc)/DT;
end

%Convert to new TEC
Sm = Sm * (n/71);
Rm = Rm * (n/71) * (6/Inew);
Km = Km * (n/71) * (Inew/6);

%Current
I = (V - (Sm * DT))/Rm;

%Heat transfer rate
Qc = ((Sm * Tc * I) - (0.5 * I^2 * Rm) - (Km * DT));

%Power
P = I*V;

%If the current is negative, set power to a high value
if(P <= 0)
   P = 1000000;
end

%If the TEC is unpowered, set Qc to the -temperature differential * Rt, I
%to 0 and COP to 0
if(V <= 0)
    Qc = -DT/1.6;
    I = 0;
    COP = 0;
else
    COP = Qc / P;
end

end
```

```
function Qc  = fcn(To,Ti,Th)
%{
Heat Transfer Program
Runs heat transfer analysis on a cylindrical package with internal
insulation. Finds the heat into the package relative to ambient temp and
heatsink temp.

Evan Bosia
%}

%Material Thickness
ti = 1 * 0.0254;
ts = 0.625/2 * 0.0254;

rs = 4 * 0.0254; %inner radius of structural pipe

h = 5.5 * 0.0254; % height of the structural container

v_air = 0;

%Material conduction coeff
ki = 0.05; %insulating material ~ Neoprene 0.05
ks = 0.19; %structural material ~ ABS = 0.10
           %PVC = 0.19

%Heat transfer analysis
Qw = heat_cylinder(rs, ti, ts, v_air, ki, ks, To, Ti, h);

%Heat through top cap (function does 2 equal caps)
Qc1 = 0.5 * heat_caps(rs, ti, ts, v_air, ki, 0.1, To, Ti);

%Heat through bottom cap (related to heatsink temp)
Qc2 = 1.4 * heat_caps2(rs, ti, 0.004, ki, 0.1, Th, Ti);

%Total heat transfer
Qc = Qw + Qc1 + Qc2;

end
```

```
%{
Heat Transfer Through Bottom Cap Function
Determines the conduction heat transfer through the bottom of the cylinder.
This takes into account the heat of the heatsink.

Params: radius, thickness of insulation, thickness of structure, external
air velocity, conduction coeff of insulation, conduction coeff of
structure, external temperature, internal temperature.

Returns: Heat transfer into the system (watts)

Evan Bosia
%}

function Qc = heat_caps2(rs, ti, ts, ki, ks, To, Ti)
%Inner edge
h1 = 10.5- 4 + 10 *sqrt(4);

%Cap heat resistance insulation
Rcdi = ti/(pi*(rs-ti)^2*ki);

%Cap heat resistance tube structure
Rcds = ts/(pi*(rs)^2*ks);

%Convection heat resistance internal
Rcv1 = 1/(pi*(rs-ti)^2*h1);

%Total thermal resistance
Rt = Rcv1 + Rcdi + Rcds;

Rt = Rt * 0.5;

%Heat transfer through 2 caps
Qc = (To-Ti)/Rt;
end
```

```
%{
CONSTANTS
This file contains the constants used for Simulink modeling. It is
automatically loaded prior to running the Simulink model.

Evan Bosia
%}

clear all;

%PID constants
kp = 5;
ki = 0;
kd = 0;

%PID target
Target = 275;

%Relay target bounds
Up_Target = 280;
Low_Target = 278;

%Ambient Temperature
T = 293;

%Mass of heatsink and coolsink adjusted for uneven heating
mh = 0.293/2; %0.293 BALTO 2.0 HEATSINK
mc = 0.113/2; %0.113 BALTO 2.0 COOLSINK

%Conduction coefficient for heatsink and coolsink
Ch = 9100;
Cc = 9100; % AL 9100, CU 3900

%Initial energy of heatsink and coolsink
Qh = Ch * mh * T;
Qc = Cc * mc * T;

%Thermal resistance of heatsink and coolsink
Rth = 0.152;
Rtc = 0.7;

%Internal conduction of heatsink and coolsink
HK = 5;
CK = 2;

%Size of TEC area adjacent to heatsink and coolsink
%Used to get TEC temperature difference ~ the smaller the more accurate
H = 10;
C = 10;
```

```
%Package RT ~ heat loss included due to imperfections included
Rtp = 6.25*0.9;

%Package volume
V = .0015;

%Package air initial energy
Cp = 718;
Qp = Cp*V*1.2754*T;

%Coverage of heatsink and coolsink on TEC (not 100%)
Hcov = 0.7;
Ccov = 0.6;

%Voltage input for relay
Voltage = 7.4/11.1*5;

%Heat back into package when off
H_const = 0.00;

%Conduction through TEC
HTC = 0.5;
```

G MATLAB Testing Code

This appendix includes complete documentation of the MATLAB code used for measuring package temperature. Some of the constants were changed to examine different values in the system. Each separate function is started by a commented header file explaining...

- the title of the code segment
- what the code segment does
- input parameters if a function
- output returns if a function

The system takes three temperature measurements simultaneously. For most testing cases, the temperatures measured were the heatsink, the coolsink, and the package internal temperature.

```
%{
Temperature Log Program
Reads in voltages from Arduino, converts to temperature, then displays on
graph. Program runs for a set period of seconds denoted by the time
variable, and the loop iterates at one second intervals.

Evan Bosia
%}

clear all; close all;

%Link to Arduino
a = arduino('com5', 'uno');

%Temperature arrays
temps = [];
temps2 = [];
temps3 = [];

%Length of time the program runs in seconds
time = 3600;

%Stores time data
x = [];

%Set axis of plots
axes('xlim',[1,time],'ylim',[0,30]);

%Iterate the temperature readings
for i=1:time
    x(i) = i;

    %Read voltages from analog inputs on Arduino - convert to temperature
    temps(i) = (readVoltage(a, 'A0') - 1.1449)/0.0523;
    temps2(i) = (readVoltage(a, 'A1') - 1.1449)/0.0523;
    temps3(i) = (readVoltage(a, 'A2') - 1.1449)/0.0523;

    %Realtime plot of temperatures
    plot(x,temps,x,temps2,x,temps3);

    %Iterate the loop a every second
    pause(0.99);
end

%Create new figure
figure;

%Plot temperature data with axis labels
plot(x, temps, x, temps2, x, temps3);
```

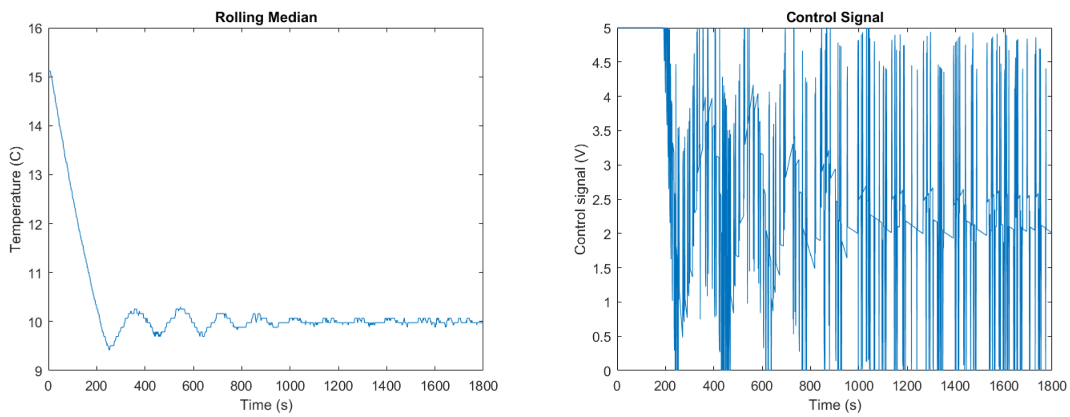
```
xlabel('Time (s)');
ylabel('Temperature (C)');
```

H PID Testing Data

This appendix includes the control graphs developed by testing the package using an operational amplifier to use PID control. The changes in the graphs was caused by different methods of smoothing the signal (running median vs mean) and different PID constants.

Median Temperature

The first data smoothing method examined was taking a running median of 10 data samples. The target temperature set for tests was 10 degrees Celsius. This is shown in Figure 58. The result was a stable temperature, but extremely noisy control signal.



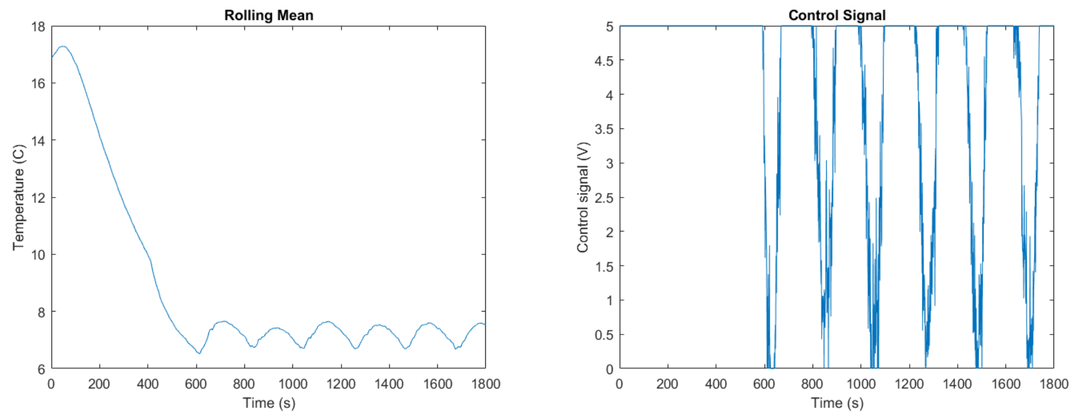
(a) Rolling median temperature

(b) Control signal to op-amp

Figure 58: Rolling median, kp = 5, ki = 0.1, kd = 50

Mean Temperature

The other method examined was taking a running mean of 10 data samples. This method was used to examine multiple PID constant values. The target of these tests was 7 degrees Celsius. The first values examined were Kp = 5, Ki = 0.5, and Kd = 50. This is shown in Figure 59. The result was an oscillating temperature an almost on-off control signal. This was not much better than on-off relay control.

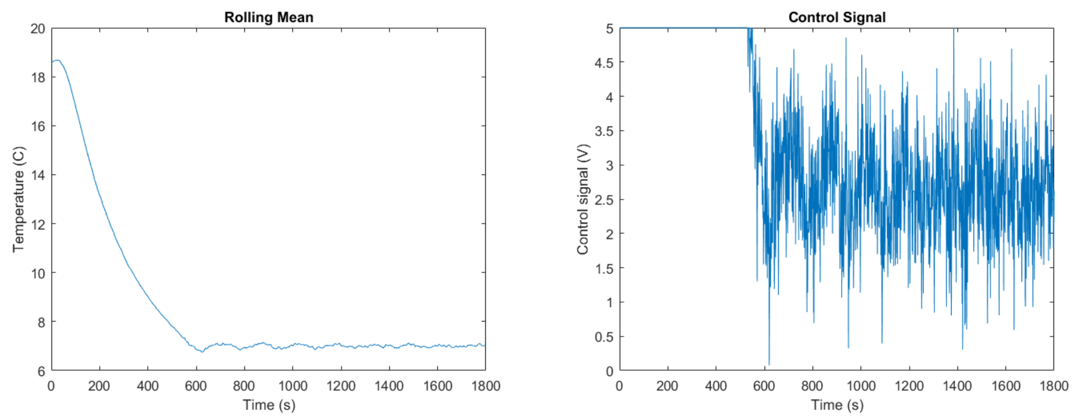


(a) Rolling mean temperature

(b) Control signal to op-amp

Figure 59: Rolling mean, kp = 5, ki = 0.5, kd = 50

The next values examined were Kp = 5, Ki = 0.1, and Kd = 50. This is shown in Figure 60. The result was an stable temperature and more-constant control signal, but still very noisy.

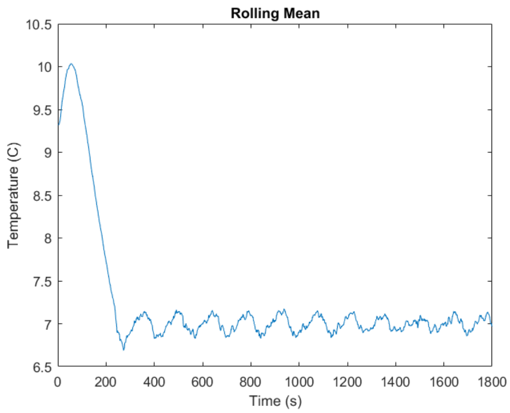


(a) Rolling mean temperature

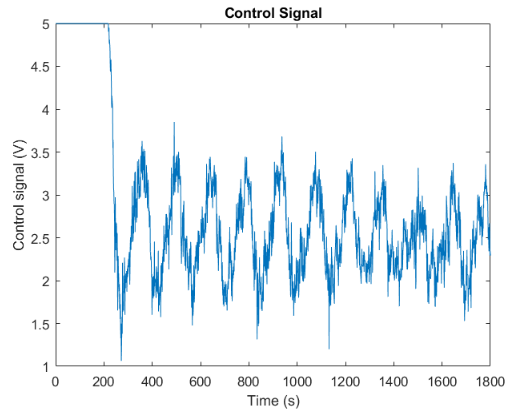
(b) Control signal to op-amp

Figure 60: Rolling mean, kp = 5, ki = 0.1, kd = 50

The next values examined were Kp = 5, Ki = 0.05, and Kd = 50. This is shown in Figure 61. The result was an stable temperature and more-constant control signal, but still very noisy.



(a) Rolling mean temperature

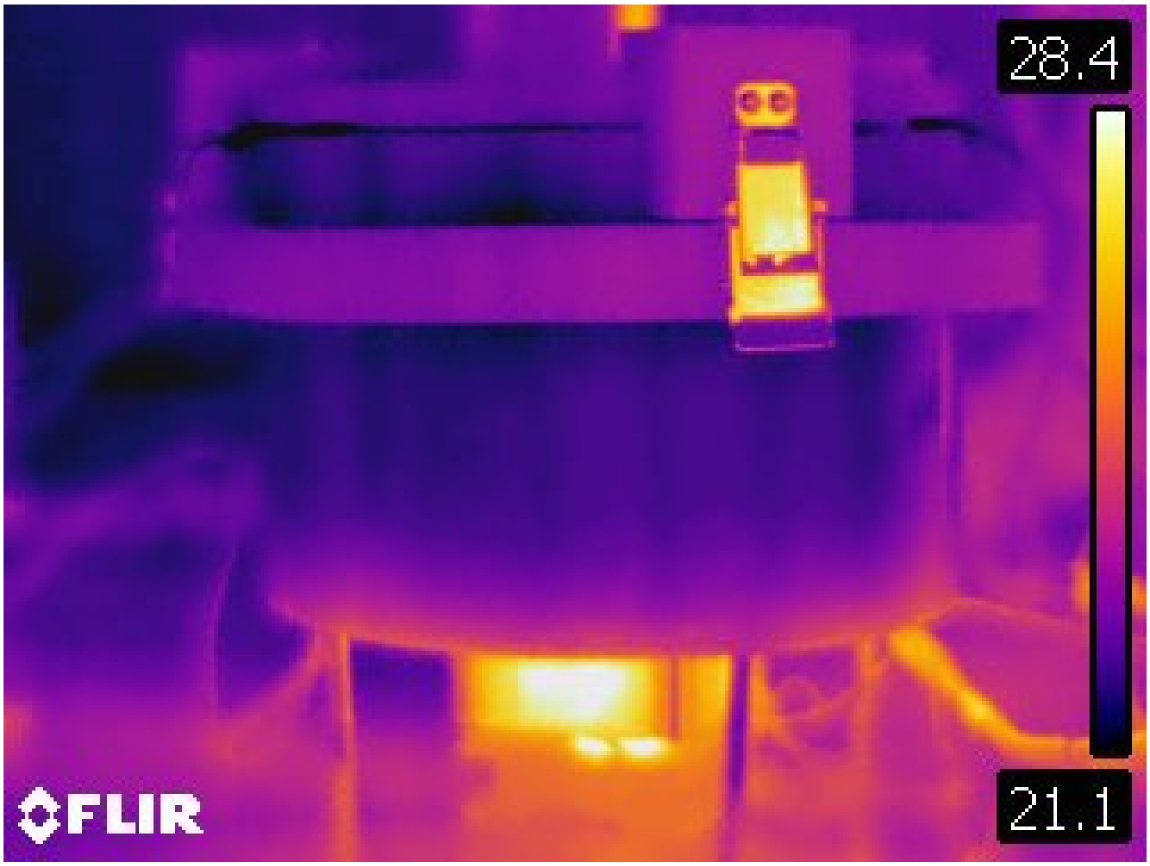


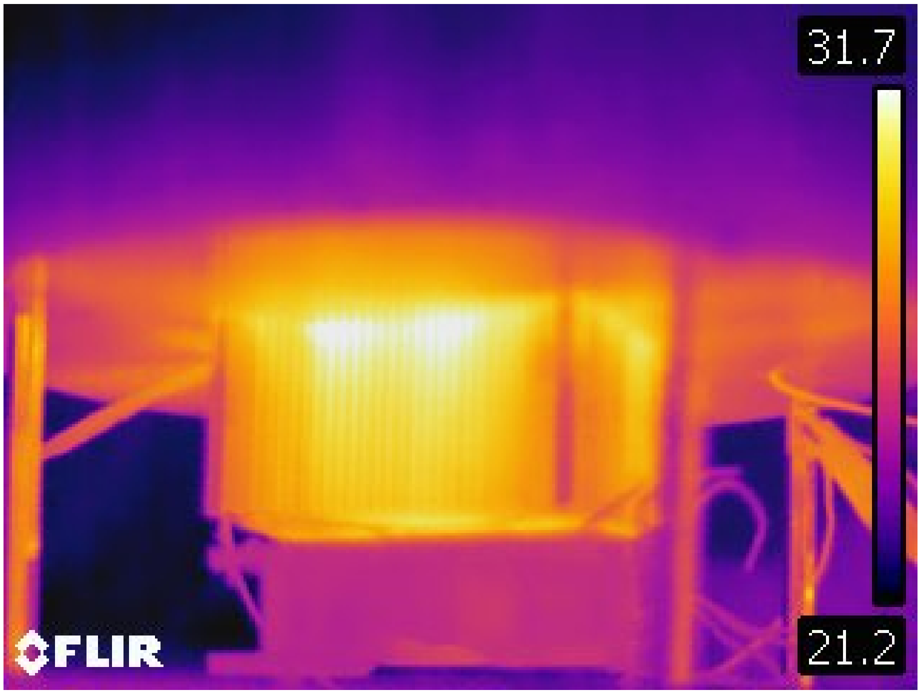
(b) Control signal to op-amp

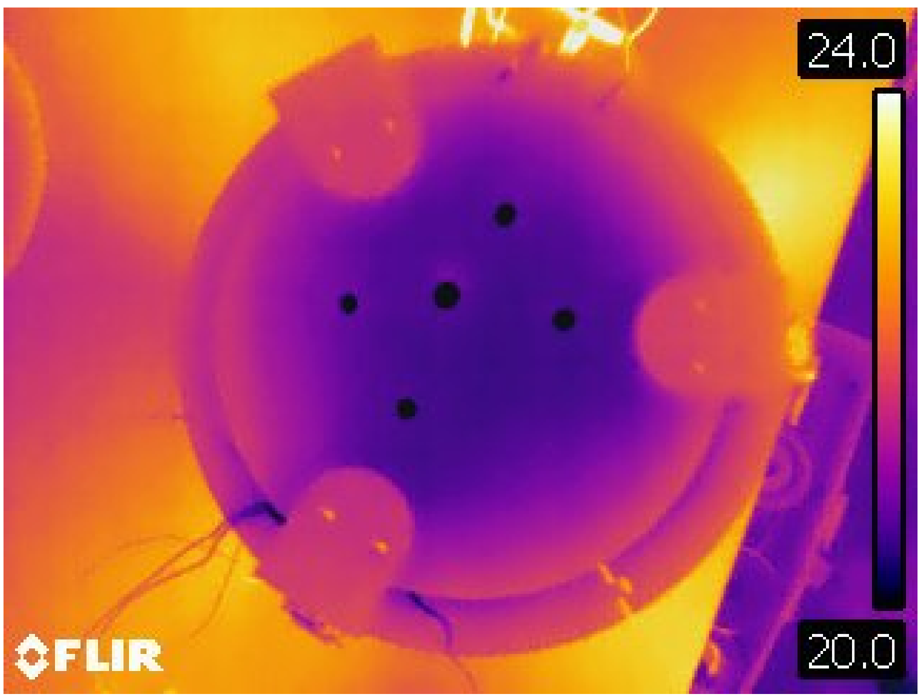
Figure 61: Rolling mean, kp = 5, ki = 0.05, kd = 10

I FLIR Thermal Images

This appendix includes the thermal imaging tests for Design 2.0. A FLIR thermal imaging camera was used to create the images. These were used to find leaks in the system.




31.7
21.2
FLIR


24.0
20.0
FLIR