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Team 510: Climatic Camera

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Abstract

Danfoss Turbocor specializes in making HVAC compressors. The electronic parts of the compressors are tested in an environmental test chamber, with temperatures that range from -40 °C to 160 °C. The design of the chamber makes it difficult to see the parts inside during testing. In order to achieve better failure detection, our team is designing a thermal housing to allow a camera to be placed inside the chamber.

Tests inside the chamber can last up to 80 days, so basic insulation alone is not enough. Typical cameras work between 0 °C to 45 °C. To meet the necessary temperatures, we are using basic insulation and constant air flow to help regulate the temperature inside the camera enclosure. Constant airflow through the enclosure removes and adds heat as needed, keeping the camera operational.

The camera records videos of the parts and stores them for later use. Camera angles are adjustable for specific tests. With our design, Danfoss employees can determine when and how the parts fail.

Disclaimer

Our sponsor, Danfoss Turbocor, does not require a disclaimer.

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1.1 Project Scope

Project Description

The objective of this project is to design a product that will maintain operation of a recording device at extreme temperatures. The product will have to sustain extreme oscillatory temperatures inside a climate-controlled testing chamber that is currently used for testing the longevity of Danfoss equipment. The customer has specified his interest in a borescope camera as the recording device and would prefer a flexible location for the device inside the chamber.

Key Goals

The goals of the design solution are to make a product that is affordable, heat and cold resistant, movable, and safe for its users. The design must take an existing camera and maintain its functionality inside a climatic chamber with temperatures ranging between -70 to 180 degrees Celsius. The goal of this project is to improve Danfoss's failure detection when testing equipment through extreme climatic condition. The customer expressed interest in being able to monitor the equipment up-close and to access the camera feed remotely.

Markets

The primary markets of this product are end users of climatic chambers. The device is intended for the people who perform tests at extreme climatic conditions as mentioned above under a controlled environment. The secondary market includes but it is not limited to extra-terrestrial research, engine testing monitoring, and Antarctic research, or any type of monitoring that would be subjected to extremely hot and/or cold conditions.

Assumptions

It is assumed that the device will be able to operate at the limit temperatures of the climatic chamber and not only at the test temperatures. The solution will be a secure and permanent device that cannot be removed without proper equipment. The device will be connected to an existing nearby computer through cable connection. It is assumed that the remote access for other devices will be implemented by Danfoss personnel.

Stakeholders

The stakeholders of this project are the investors, people with interest in the project, and people with control over the project. Danfoss Turbocor is a stakeholder in this project due to their financial involvement. Dr. Shoele is also a stakeholder due to his interest and involvement in this project. Lastly, Dr. McConomy is a stakeholder due to his ability to control the aspects of the project.

1.2 Customer Needs

Questions, Answers, and Interpretations

To accurately find the customer's needs, a series of questions were formed. We asked our customer (Vinayak Hedge) a series of questions in order to find what was important in the products design. Below are the questions that were asked to the customer. The full table of customer needs with their interpretations can be found in Appendix C.

Questions:

- How do you currently monitor the environmental test?
- How long does the test last?
- How would you like to control the test monitoring?
- Would you like to be able to put away or move around this product?
- How would you like to power this product?
- What size would you like the monitoring device (camera) to be?

- What conditions will the monitoring device be subjected to?
- Do you have any size constraints for this product?
- Is anything else inside the chamber other than the test subject?
- What would you like this product to do? Time of failure or…? What kind of feedback do you want? Only visuals?
    - Does the device need audio?
- Is there lighting inside the chamber?
- Is there a desired angle for the recording device?
- Do you want us to use a standard recording device or develop a new one?
- What does the vibrational test consist of?
    - Do floor and/or walls vibrate?
- Is the chamber operated from a computer or the chamber itself?
- At what height are the test subjects tested?
- How big/How much space are we allowed to use in the wire opening space?
- How do you currently isolate the wire opening in the chamber?
- Is there only one subject tested at a time?
- Is there access to Wi-Fi on laptop for remote access?
- Is the inside of the chamber magnetic?

By analyzing the customer's needs, the team determined that each question has unique characteristics for the desired product. Vinayak Hedge, reliability engineer manager for Danfoss, desires a monitoring device that sustains the climatic chamber conditions. The device needs to have video recording capabilities. The video recordings need to be accessible live and stored for future access. The model numbers for the two climatic chambers that are used were recorded to have the recommended manufacturers specifications. Also, the vibrational chamber model number was taken to understand how the device works and what specifications it has.

Overall, the needs that the team were able to interpret from the customer data were directly related to one another. The final product will be able to accommodate the primary and secondary markets as much as capable.

1.3 Functional Decomposition

Functional Decomposition Description

To determine the functions necessary to have a monitoring device inside the climatic chamber, the group split up the basic processes that the proposed solution would need to have. The group developed a few potential solutions, existing and brainstormed, to guarantee the chosen functions could apply to differing alternatives. Each system was then determined by breaking down the general processes that any of these solutions demanded. The monitoring device referred to as "climatic camera" from here forward was broken down into the following systems: support, monitor, isolate, and provision.

The system, support, is the first step that contains a mounting mechanism for the climatic camera. The camera needs a stable housing for visuals to be optimal. In addition, the support needs to be movable when needed and but secure when no movement is desired. The specific verbs used to describe the functions in this system include "provide", "prevent", and "secure." Provide implies that the device will provide stability for the camera. Prevent implies avoiding/dampening vibrations for the most stable and consistent video images. The final verb, secure is separated into two functions; the first implies securing the position of the device in the x, y, and z axes, the second implies securing rotational angles for desired recording orientation.

The system, monitor, is the only feedback that is generated from the device. The monitor system consists of the camera itself and the computer interface. The system captures the visuals, transmits, and archives them. The stored visuals can either be transmitted remotely to a home network to be viewed off site-site or displayed on the adjacent computer. This gives the user the ability to reference the time of failure and relate them to the corresponding parameters of the chamber.

The system, isolate, is the primary design feature or the device. The device needs to be protected from the various condition inside the climate controller to maintain the camera's recommended operating temperature. With extremely hot and cold fluctuating temperatures, this system is the primary focus of the project and will take the most considerable design. The isolation also keeps the device safe from humidity related inconveniences (such as fog) or failure.

The system, provision, is the power source for the device. This system provides the camera with stable power to be operated the entire duration of the test. The power supply is regulated, keeping the device safe from overheating or incurring excessive stress on its sensitive components. It also allows for a more compact design inside the chamber due to absence of an attached power supply. The user also does not have to be as involved with the process since the power source is run externally.

Task Analysis

The task analysis describes step by step procedure that could apply to any solution. In order to properly understand the desired outcomes for the product, the group needed to understand each action that is performed within the process. The group attempted to boil down what the solution must do to its most basic actions, and realized the product had 6 distinct actions in order to fulfill its purpose. First, the device needs to be mounted. Once mounted at the desired position, the device needs to be powered. Then, the device needs to be connected to the computer interface to power the device and provide a means for data transfer. Once connected, the device can begin to collect data, then transmit said data to the computer interface. Finally, the device needs to store the data that has been recorded for potential future access.

Hierarchy Chart

As explained in the functional decomposition description, the defined systems of the climatic camera were placed with the functions mentioned and compiled into a hierarchy chart as shown in appendix B.

Cross Reference Table

The table in appendix B shows the four main systems on the top row. The left column contains the functions of those systems. If a function corresponds to a system, that box is marked with an "x".

As mentioned previously, the most important system is "isolate." Without isolation the system would not work, because of this, the functions that are under isolate are given top priority. It can be seen from the table that some of the functions are applicable to more than one system. The functions that fall under more than one system are considered to have priority in the functionality of the device. All functions that are alone within their respective systems are crucial to fulfill in that stage. Using the cross-reference table allows for imperative functions to be seen easier across different systems.

1.4 Targets and Metrics

After conducting the functional decomposition, the targets and metrics were determined and can be seen in : Target Catalogue

Table 14. Appendix D: Target Catalogue shows other targets and metrics that were not included in the functional decomposition.

Each function above was associated with a target and a metric to verify the final product is successful. The first set of functions deal with position of the device. Some functions have harder targets to measure, for example “Provide Stability,” refers to having the recording device in an unchanging location. This function could be measured with a sensor inside the enclosure of the recording device to check the acceleration within the device (e.g. accelerometer). As mentioned in previous activities, the nature of the test is continuous for days to even months (up to 71 days), so access to the device only occurs prior to the commencement of the test and at culmination. Having a stable frame for recording purposes, the function “Secure Position” is also related to stability of the device, but this time the function is centered in a specific area of the climatic chamber. The target given to this function was in the units of translational distance (meters). For the most stable image the camera should not move (in the x, y, and z directions). The third metric “Translation,” deals with securing the recording device ensuring it does not move, with units in meters. The function “Secure Rotational Angle,” serves a similar purpose as the previous function to secure the desired angle in degrees with a 0-degree change. The difference being that the recording device has a different degree of freedom, this time around, rotational.

The functions that deal with visuals are associated with data handling. The function “Capture Visuals,” deals with recording the test subjects and how often the device takes a picture. This target is heavily dependent on how precise Danfoss needs to be when determining time of failure. 1 frame per second will give enough without requiring excessive data logging reflect time. The previous target greatly affects the following: Store Visuals and Record Time. The function “Store Visuals,” as the name suggests is where the captured visuals are stored into the computer and available for future access. The memory capacity will depend on the computer in use or storage capacity available through other means in Danfoss (e.g. memory drive, cloud, etc.). The record time also has an effect on the amount of data generated. Again, the duration for current Danfoss tests can go up to 71 days, so the device must be able to record for 71 days continuously. The two functions involving data handling for "Transmit Visuals," and "Replay visuals" are binary. Transmit visuals implies that the device should not have its own data logger, but instead attached to a computer to be replayed and examined to determine where and when the failure occurs.

Under the function "isolate" there are 2 parameters which need to be met. Controlling the temperature is a target for the device to be operable. The test chambers range from -40°C to 160°C, and 5-95% relative humidity so the device must be isolated from this extreme environment for operation. Since zero heat transfer is not thermodynamically possible, the insulated device can have a range temperature from $0°C \leq T \leq 45°C$. The range of temperature $0°C \leq T \leq 45°C$ and 0-50% Relative Humidity are "acceptable" operating ranges for a camera.

The device is not powered by a battery so sufficient power must be provided from the computer. A USB can put out 2.5 Watts of Power.

Upon observation of the chambers in person additional targets were noticed. There is a chamber cable opening that cables can be run through. This diameter is roughly 10cm which is a constraint on the amount of constant access into chamber. The cables must also have a minimum length in order to reach the computer. This length was calculated to be 2 meters. For the device to record quality images, condensation on lens should be minimized, ideally 0 mL. The device was also requested to be inexpensive. Research on borescope type cameras ranged from $30 for low range cameras with waterproofing to several thousand dollars for specialty furnace and cryogenic cameras. Based on these extremities, the camera was decided to be less than $100. There is limited space inside the climatic chamber; the dimensions are 97x97x97cm. If testing subjects are considered when in operation, the device must be significantly smaller as a physical constraint.

Methods of Validation

Majority of validation will be done during the prototyping and design phase. For the function “support” there should be no visible image issues within the playback. This can be validated physically by measuring any camera movements using a caliper and its original position. However, just because the camera moves, doesn’t mean that the image will. The end product is the quality of the image, so this will be validated by a computer to see if the image is stable and the amount of fluctuations between frames. Adobe Premier pro is a sufficient software for video editing and image stabilization.

Capture Visuals, Transmit Visuals, Store Visuals, Replay Visuals, and Record Time are all parameters that are considered with the recording device selection. These will be validated by the manufacturer’s specifications.

Control Temperature and Control Humidity will both be validated in simulation using Finite Element Methods (FEM) as well as physically during prototyping. Temperature can easily be measured using a thermocouple or similar temperature obtaining device. Humidity would be measured using a hygrometer.

Critical Targets

The targets that are critical in this project are those for the functions*: Record time, Control temperature*, and *inexpensive*. These targets are marked with asterisk in : Target Catalogue

Table 14. Record time is a very critical target due to the duration of the tests. 71-day tests mean that longevity of the components will have to be considered. The climatic chamber cannot

be opened during testing to replace any broken or malfunctioning parts. Control Temperature is also a critical target. Standard cameras/ recording devices are not able to be operated in the temperature range of the climatic chamber. Without an operational camera the project is not complete and therefor all other targets are unobtainable and valid. Inexpensive is the final critical target. The purpose of the senior design project is to make a generic device work in said extreme conditions. If the camera itself was too expensive, then there would be no market for the device, and one would simply purchase an expensive existing camera that can work in said environment. If these three functions fail to meet the target, the device would not fulfill the project objective.

Table 1- Critical Targets

Need	Target	Metric
Record Time	71 Days	Time
Control Temperature	$0 \leq T \leq 45\ ^{o}C$	Temperature
Inexpensive	≤ $100	Price

1.4 Concept Generation

Concept Generation Tools

In order to generate an array of concepts, various technical tools and methods were employed. First, individual research and brainstorming was performed by the group members, once each member had a few ideas and knowledge on functionality of the design such as, insulation techniques, types of camera's, mounting, and general knowledge about what it is desired to accomplish. Then, the group gathered and engaged in a brainstorm session where roughly twenty concepts were devised. Eight relatively functional ideas were developed, which became the foundation for further analysis. The group then considered biomimicry, relating the cooling process that can be seen in humans for other sources of inspiration to model. The group examined how the body regulates the temperature inside in order to keep stability within. Also, the attachment for the enclosure was envisioned by tracing how an octopus can attach itself through its tentacles. The group then tried the Anti-problem method, by thinking about ways to increase heat transfer to the device. Examples such as fins, conductive fluids and large surface areas all came to mind. The opposite should be taken to reduce heat transfer (flat surface, vacuum insulation and small surface area). To come up with various design options, a morphological chart was created. The group developed a set of variations for each system to achieve a higher number of possible designs. Categories varied in the source for securement, insulation technique, temperature regulation, type of camera, and condensation prevention. A total of 162 concepts were devised from the morphological chart. However, out of these, there were various redundancies as well as illogical designs, so only the fifty most realistic were kept in the concept list. See Table 2: Morphological Chart below to see the variations applied in the systems mentioned.

Table 2: Morphological Chart

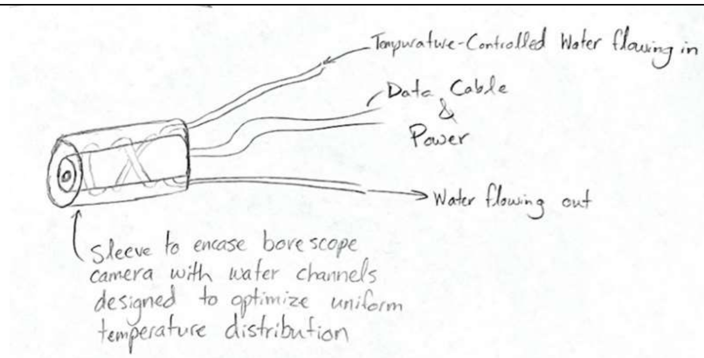
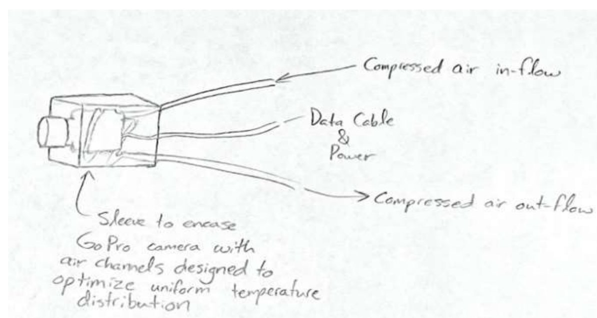
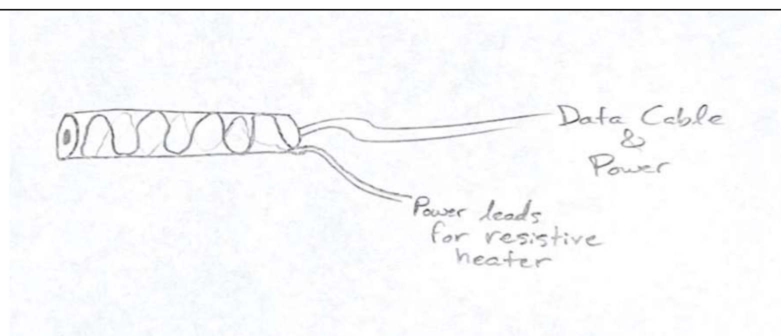
Temperature Regulation	Securement Method	Camera Type	Insulation Technique	Condensation Prevention
No Temperature Regulation	Clamp	Borescope	No Insulation	Resistive Heater
Compressed Air	Suction Cup	Infrared	Vacuum	Constant warm air flow over interior
	Velcro Strap	FireCam™	Polyurethane	Hydrophobic Coating

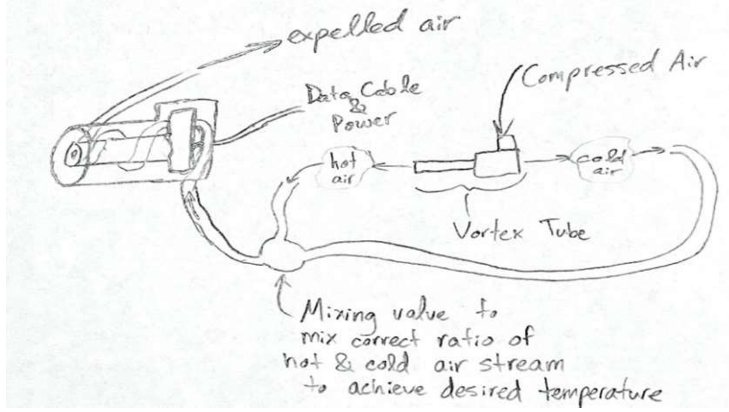
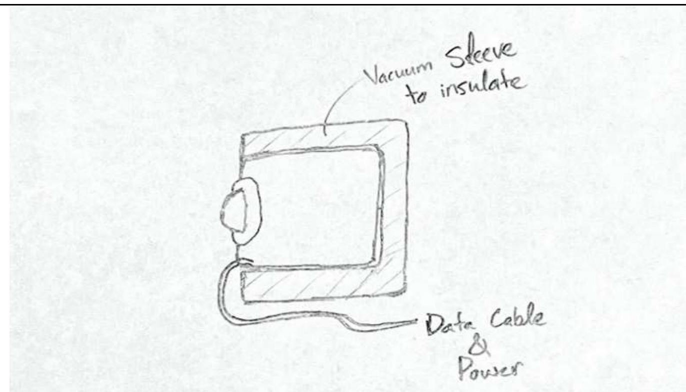
A full list of one hundred concepts was devised using the methods mentioned and can be found in Appendix E: Generated Concepts

Medium Fidelity Concepts

The *Water-Cooled Borescope* concept in Table 3: Medium Fidelity Concepts utilizes an inexpensive borescope camera as the viewing the device. To maintain the device in operating temperature and prevent condensation, water channels would be guided around the camera. The *Compressed-air cooled GoPro™ Camera* concept uses a traditional GoPro™ as the recording device. This camera is resistive to the elements already, but in order to maintain operating temperature and prevent condensation it will be cooled by compressed air channels. The *Borescope Camera with resistive heater* concept utilizes a special borescope that can withstand hot temperatures. To protect it from the cold temperatures a resistive heater will be put around the camera. This will also prevent condensation accumulation around the lenses. The *FireCam™ with vortex tube* uses a small camera that is capable of temperatures up to 482 degrees Celsius. To protect the device from the cold temperatures, a vortex tube is used to channel hot compressed air around the FireCam™ The *Infrared Camera* concept is an infrared camera that is maintained at operating temperature through vacuum insulation, a special lens would be required in order to minimize the difference in temperatures captured by the camera (considering polarized lens or similar effect lens).

Table 3: Medium Fidelity Concepts

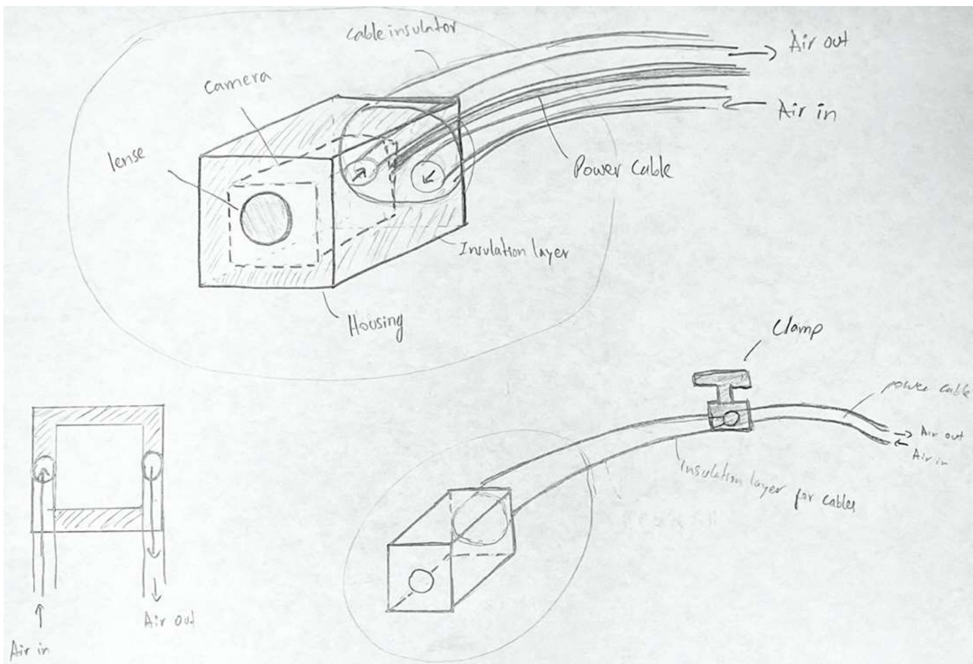
Water Cooled Borescope	
Compressed air-cooled GoPro™ Camera	
Borescope Camera with resistive Heater	

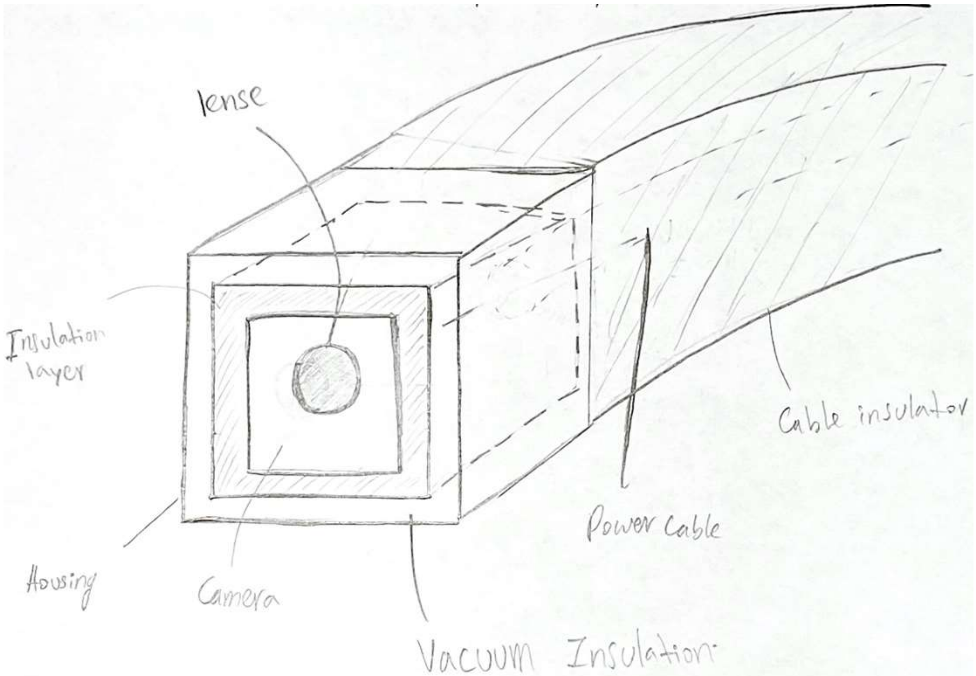
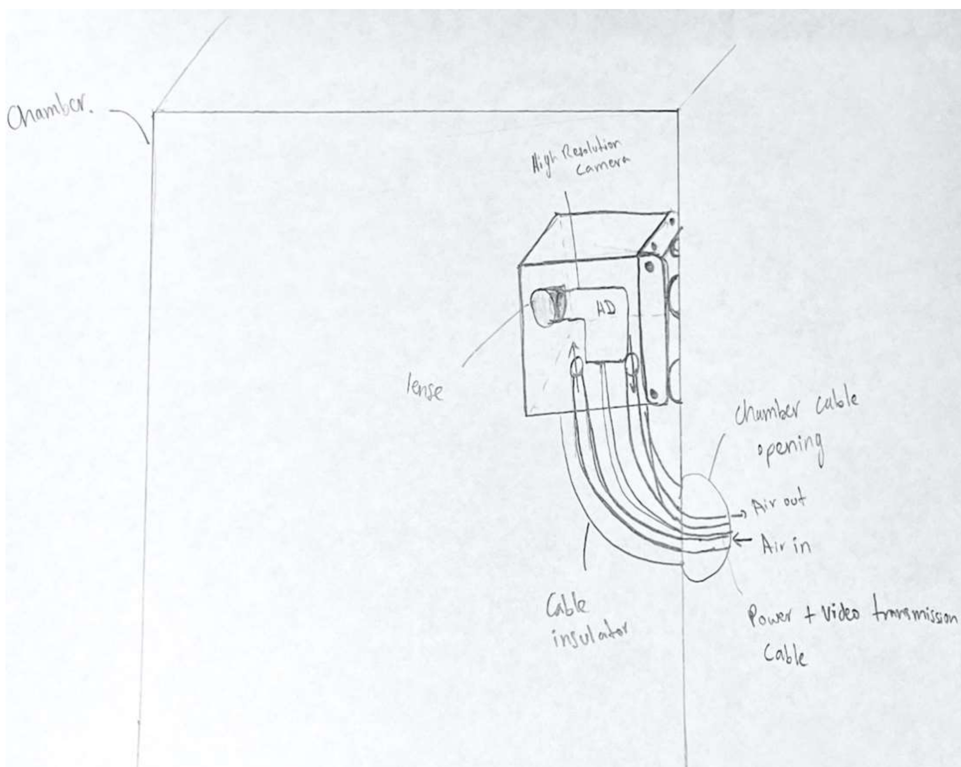
FireCam™ with vortex tube	
Infrared camera with vacuum insulation	

High Fidelity Concepts

The *Compressed Air, clamped, borescope with USB power* is an inexpensive borescope camera, in this design the temperature is controlled by using compressed air channels. The compressed air channels will prevent any condensation build up. The camera will be powered by a USB cable which will also be used for data transfer. The clamp will secure the device to the racks with minimal movement. The *Vacuum insulated, clamped, borescope with USB power* is an inexpensive borescope camera that prevents heat transfer by having a vacuum wall. The vacuum layer will prevent any condensation build up. The camera will be powered by a USB cable which will also be used for data transfer. The clamp will secure the device to the racks with minimal movement. The *Vacuum and compressed air, suction cup, borescope with USB power* an inexpensive borescope camera that maintains temperature by compressed air channels and a vacuum insulated wall. The vacuum layer will prevent any condensation build up. The camera will be powered by a USB cable which will also be used for data transfer. The clamp will secure the device to the racks with minimal movement. The high-fidelity concepts are in Table 4: High Fidelity Concepts.

Table 4: High Fidelity Concepts

Compressed Air, clamped, borescope with USB power	

Vacuum insulated, clamped, borescope with USB power	
Vacuum insulated with compressed air, suction cup, high resolution camera, with USB power	

1.5 Concept Selection

House of Quality

The purpose of the House of Quality (HoQ) is to translate the customer requirements into quantifiable design variables. This is done by relating the said requirements to engineering characteristics. The customer requirements were selected from a summary of the customer needs done earlier in the project. To determine the important weight factor of each customer requirement, a binary comparison chart was made. The requirements were compared to one another by asking the question "Is the row better than the column?". If this was true a 1 was put in that place, but if false a 0 was placed. The numbers were then mirrored over the diagonal and the sums of each row and column was calculated. To confirm this was done properly, the following equation was used on each row and column pair:

Equation 1: $$T_1 + T_2 = n - 1$$

where n is the number of customer requirements, T_1 is the total of the row, and T_2 is the total of the column. The binary comparison chart performed on this project is shown below.

Table 5: Binary Comparison Chart

Customer Requirements	1	2	3	4	5	6	7	8	9	10	11	12	13	Total 1
1. Remote Accessibility	-	0	0	0	1	0	0	0	1	0	0	1	1	4
2. Continuous Monitoring	1	-	1	1	1	1	0	0	1	0	1	1	1	9
3. Computer Connection	1	0	-	0	1	0	0	0	1	0	0	0	0	3
4. Mobility When Required	1	0	1	-	1	1	0	0	1	0	1	1	1	8
5. Versatile Power Source	0	0	0	0	-	0	0	0	0	0	0	0	1	1
6. Compact	1	0	1	0	1	-	0	0	1	0	1	1	1	7
7. Functionality During Testing	1	1	1	1	1	1	-	1	1	1	1	1	1	12
8. Doesn't Affect Integrity of Chamber	1	1	1	1	1	1	0	-	1	0	1	1	1	10
9. Temp and Time Recording	0	0	0	0	1	0	0	0	-	0	0	0	0	1
10. Clear Visibility	1	1	1	1	1	1	0	1	1	-	1	1	1	11
11. System Connections fit Through Porthole	1	0	1	0	1	0	0	0	1	0	-	1	1	6
12. Inexpensive	0	0	1	0	1	0	0	0	1	0	0	-	0	3
13. Safe	0	0	1	0	0	0	0	0	1	0	0	1	-	3
Total 2	8	3	9	4	11	5	0	2	11	1	6	9	9	12

The Total 1 column of the binary comparison chart was extracted and used as the importance weight factor in the HoQ. The engineering characteristics were selected as those which encompassed the entirety of the targets and metrics. Once put into place, each characteristic was rated on a 1,3,9 scale for its importance in the customer requirement. The sum of the product of each column was found (importance weight factor x characteristic rate summed across the column), then ranked for its weight compared to the total raw score. The resulting HoQ is shown below.

Table 6: House of Quality

		Engineering Characteristics										
Improvement Direction		↓	↓	↓	↑		↑		↑	↓	↓	
Units		m/s^2	m	Δ Degrees	frame/s	n/a	GB	n/a	hh:mm:ss	°C	%	n/a
Customer Requirements	Importance Weight factor	Provide Stability	Secure Position	Secure Rotational Angle	Capture Visuals	Transmit Visuals	Store Visuals	Replay Visuals	Record Time	Control Temp.	Control Humidity	Supply Power
1. Remote Accessibility	4					9	3	9	3			
2. Continuous Monitoring	9				9	3			1			3
3. Computer Connection	3				3	9	9	9				
4. Mobility When Required	8	3	3	3						1		3
5. Versatile Power Source	1									3	3	9
6. Compact	7	1	1	1		1				3	1	3
7. Functionality During Testing	12				9	9			1	9	9	3
8. Doesn't Affect Integrity of Chamber	10		3							9	3	
9. Temp and Time Recording	1				1	3	3		9	1		
10. Clear Visibility	11	3	1	1	9	3		9		9	9	3
11. Aux System fits Through Porthole	6					9				3	1	1
12. Inexpensive	3	1	1	1		1	3			1		
13. Safe	3					3				9	3	9
Raw Score (1870)		67	75	45	298	307	51	162	42	378	262	183
Relative Weight %		3.58	4.01	2.41	15.94	16.42	2.73	8.66	2.25	20.21	14.01	9.79
Rank Order		8	7	10	3	2	9	6	11	1	4	5

The information gained from the House of Quality determined the ranked importance of each engineering characteristic. The most important (1) was found to be "Control Temperature," while the least important (11) was "Record Time". The rankings were then used in Pugh Charts to determine the best design of the selected concepts.

Pugh Chart

The Pugh Chart was utilized to identify the best concepts. With the aid of the House of Quality chart above, we were able to generate the most important evaluation criteria (engineering characteristics). These engineering characteristics can be seen on the far-left column of the Pugh Chart. Next, we chose nine of the most promising concepts from the 100 generated concepts. These nine concepts can be seen on the top row on the Pugh Chart.

The concepts were compared to an existing product (Datum). The "ChamberCam," Dynamic Intelligent Solution (DIS) product, was chosen as the datum for comparison. Each of the nine concepts were then compared to the datum for their capabilities in the engineering characteristics. If the engineering characteristic of the concept is better than the datum that block gets a "+", worse gets a "-", and equal gets an "S". After evaluating all concepts, the positives and negatives were totaled at the bottom of the chart. The first Pugh Chart, which compares the nine chosen concepts to the datum, is shown below.

Table 7: First Pugh Chart (8 Concepts)

		Concepts								
Engineering Characteristics	ChamberCam	Comp. Air Clamped Borescope	Vacuum Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera	Infrared Camera, Vacuum	FireCam w/ Vortex Tubes	Borescope, Resistive Heater	Compressed Air Cooled GoPro	Water Cooled Borescope	Slider Linkage, Comp Air HD Camera
Control Temperature		S	-	S	-	S	-	S	S	S
Transmit Visuals		S	S	S	S	S	S	S	S	S
Capture Visuals		-	-	S	+	-	-	-	-	-
Control Humidity		S	-	S	S	S	-	S	S	S
Supply Power		S	S	S	S	-	S	-	S	S
Replay Visuals	Datum	-	-	-	S	-	-	-	-	-
Secure Position		+	+	+	-	S	S	S	S	+
Provide Stability		S	S	S	S	S	S	S	S	+
Store Visuals		-	-	-	-	-	-	-	-	-
Secure Rotational Angle		+	+	+	S	S	S	S	S	+
Record Time		S	S	S	S	S	S	S	S	S
# of Pluses		2	2	2	1					3
# of Minuses		3	5	2	3	4	5	4	3	3

After completing the first Pugh Chart, the concepts were narrowed down to perform a second iteration. The concepts with the most minuses and least number of pluses were eliminated (See concepts highlighted in yellow). These included the FireCam with Vortex Tubes, Borescope with Resistive Heater, Compressed Air-Cooled GoPro, and the Water-Cooled Borescope. A new datum was then picked from the remaining concepts based off the most satisfactory distribution. Slider linkage with Compressed Air HD Camera (highlighted in green) was chosen because it has even number of pluses and minuses and overall highest number of pluses in comparison to the other concepts. The second Pugh Chart was completed with the four remaining concepts.

Table 8: Second Pugh Chart (4 Concepts)

		Concepts			
Engineering Characteristics	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum, Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera	Infrared Camera, Vacuum
Control Temperature	New Datum	S	-	S	-
Transmit Visuals		S	S	S	S
Capture Visuals		-	-	S	+
Control Humidity		S	-	S	-
Supply Power		S	S	S	S
Replay Visuals		-	-	S	S
Secure Position		S	S	S	-
Provide Stability		S	S	S	S
Store Visuals		S	S	S	S
Secure Angle		S	S	S	-
Record Time		S	S	S	S
# of Pluses					1
# of Minuses		2	4		4

Following the completion of the second Pugh Chart, the best three designs were chosen to move forward to the Analytical Hierarchy Process (AHP). The concepts selected (highlighted in green) were the Compressed Air, Clamped Borescope, Vacuum + Compressed Air, Suction Cup Attached HD Camera, and the previously selected datum the Slider Linkage with

Compressed Air HD Camera. Each of these concepts has a high value to solve the design challenges. They were further analyzed to determine which one was best for our product.

Analytical Hierarchy Process

Following the House of Quality, the Analytical Hierarchy Process (AHP) was done to guarantee there was no bias in the concept selection process and to determine the best overall product. The first step in the AHP was to do determine the weight of the engineering characteristics through pairwise comparison. Similar to the binary comparison done earlier, the pairwise uses reciprocals rather than ones and zeroes. The pairwise comparison was performed and is shown below.

Table 9: Criteria Comparison Matrix

Development of Candidate Set of Criteria Weights {W}											
Criteria Comparison Matrix [C]											
	Provide Stability	Secure Position	Secure Angle	Capture Visuals	Transmit Visuals	Store Visuals	Replay Visuals	Record Time	Control Temp	Control Humidity	Supply Power	Sum
Provide Stability	1	1	1	5	0.33	0.33	0.33	0.14	9	7	1	26.13
Secure Position	1	1	1	5	0.2	0.2	0.33	0.14	9	7	1	25.87
Secure Angle	1	1	1	3	0.33	0.14	0.14	0.11	7	5	0.33	19.05
Capture Visuals	0.2	0.2	0.33	1	0.2	0.14	0.2	0.11	0.33	0.33	1	4.04
Transmit Visuals	3	5	3	5	1	0.2	0.33	0.2	5	7	5	34.73
Store Visuals	3	5	7	7	5	1	3	1	9	9	3	53
Replay Visuals	3	3	7	5	3	0.33	1	0.2	7	5	3	37.53
Record Time	7	7	9	9	5	1	5	1	9	9	5	67
Control Temp	0.11	0.11	0.14	3	0.2	0.11	0.14	0.11	1	0.33	0.2	5.45
Control Humidity	0.14	0.14	0.2	3	0.14	0.11	0.2	0.11	3	1	0.33	8.37
Supply Power	1	1	3	1	0.2	0.33	0.33	0.2	5	3	1	16.06

Once complete, the sum of each column was found and used to create the normalized matrix shown below. This was done by dividing each element in the column by the column's sum.

Table 10: Normalized Criteria Comparison Matrix

Development of Candidate Set of Criteria Weights {W}												
Normalized Criteria Comparison Matrix [Norm C]												
	Provide Stability	Secure Position	Secure Angle	Capture Visuals	Transmit Visuals	Store Visuals	Replay Visuals	Record Time	Control Temp.	Control Humidity	Supply Power	Sum
Provide Stability	0.038	0.038	0.038	0.191	0.013	0.013	0.013	0.005	0.344	0.268	0.038	1.000
Secure Position	0.039	0.039	0.039	0.193	0.008	0.008	0.013	0.005	0.348	0.271	0.039	1.000
Secure Angle	0.052	0.052	0.052	0.157	0.017	0.007	0.007	0.006	0.367	0.262	0.017	1.000
Capture Visuals	0.050	0.050	0.082	0.248	0.050	0.035	0.050	0.027	0.082	0.082	0.248	1.000
Transmit Visuals	0.086	0.144	0.086	0.144	0.029	0.006	0.010	0.006	0.144	0.202	0.144	1.000
Store Visuals	0.057	0.094	0.132	0.132	0.094	0.019	0.057	0.019	0.170	0.170	0.057	1.000
Replay Visuals	0.080	0.080	0.187	0.133	0.080	0.009	0.027	0.005	0.187	0.133	0.080	1.000
Record Time	0.104	0.104	0.134	0.134	0.075	0.015	0.075	0.015	0.134	0.134	0.075	1.000
Control Temp	0.020	0.020	0.026	0.550	0.037	0.020	0.026	0.020	0.183	0.061	0.037	1.000
Control Humidity	0.017	0.017	0.024	0.358	0.017	0.013	0.024	0.013	0.358	0.119	0.039	1.000
Supply Power	0.062	0.062	0.187	0.062	0.012	0.021	0.021	0.012	0.311	0.187	0.062	1.000
Criteria Weight	0.055	0.064	0.090	0.209	0.039	0.015	0.029	0.012	0.239	0.172	0.076	

After normalizing the comparison table, the columns were averaged to produce the row on the bottom of the table. This is the critical weight vector, which will be used to determine the best concept. To determine if the critical weight vector is void of bias, a consistency check must be done. The equations used to find the necessary values include:

Equation 2: $$\{W_s\} = [C].* \{W\}$$

Equation 3: $$\{Cons\} = \{W_s\}./\{W\}$$

Equation 4: $$CI = \frac{\lambda - n}{n-1}$$

Equation 5: $$CR = \frac{CI}{RI}$$

where $\{W_s\}$ is the weighted sum vector, [C] is the criteria comparison matrix, {W} is the criteria weight vector, {Cons} is the consistency factor vector, CI is the consistency index, λ is the average consistency factor, n is the number of criteria, CR is the consistency ratio, and RI is random index value. Matrix operations were performed where they apply, and RI was retrieved from an index table. The following table shows the consistency check for the engineering characteristics critical weight vector, {W}.

Table 11: Consistency Check

Consistency Check (n = 11)		
Weighted Sum {Ws}	Criteria Weight {W}	Consistency Factor (Cons.)
0.71	0.055	12.94
0.80	0.064	12.50
1.09	0.090	12.11
2.73	0.209	13.06
0.43	0.039	11.03
0.19	0.015	12.51
0.33	0.029	11.53
0.15	0.012	12.56
3.21	0.239	13.43
2.30	0.172	13.37
0.89	0.076	11.71
Average Consistency Vector (λ)		12.43
Consistency Index (CI)		0.143
RI Value (11 Criteria)		1.51
Consistency Ratio (CR)		0.09

Since the consistency ratio was less than 0.1, the critical weight vector was deemed valid and could therefore be used to calculate for the best concept. Before this could be done, the final rating matrix had to be determined. This was done by repeating the AHP with the three selected concepts for each of the engineering characteristics, a total of eleven times. Once completed, each design alternative priority vector {Pi} was placed into the final rating matrix. The matrix was then transposed and is shown in the following table.

Table 12: Final Rating Matrix (Transposed)

Final Rating Matrix (Transposed)											
Selection Criteria											
	Provide Stability	Secure Position	Secure Angle	Capture Visuals	Transmit Visuals	Store Visuals	Replay Visuals	Record Time	Control Temp	Control Humidity	Supply Power
Slider Linkage, Comp Air HD Camera	0.63	0.33	0.33	0.45	0.33	0.33	0.45	0.33	0.14	0.2	0.33
Comp. Air Clamped Borescope	0.26	0.33	0.33	0.09	0.33	0.33	0.09	0.33	0.14	0.2	0.33
Vacuum + Comp. Air, Suction Cup, HD Camera	0.11	0.33	0.33	0.45	0.33	0.33	0.45	0.33	0.71	0.6	0.33

With the final rating matrix, one last equation was done to calculate the alternative value using matrix multiplication.

Equation 6: $$Alternative\ Value = [Final\ Rating\ Matrix]^T .* \{W\}$$

In this equation, the transposed final rating matrix is matrix multiplied with the critical weight vector, {W} from the AHP of the engineering characteristics. The results were formed in the following table.

Table 13: Final Alternative Values

Final Alternative Value	
Concept	Alternative Value
Slider Linkage, Comp Air HD Camera	0.31
Comp. Air Clamped Borescope	0.20
Vacuum + Comp. Air, Suction Cup, HD Camera	0.48

From this table it was determined that the Vacuum shell with compressed air, suction cup attached HD camera was the best concept that met the design criteria. All other concept comparison matrices, normalized criteria matrices, and consistency check tables to reach the final decision are shown in

Final Concept

All three of the final concepts that were analyzed have the potential to meet the design challenge we are facing. Due to the inexistent products, we had to speculate on their performance. Further analyzing the "best concept," (the Vacuum shell with compressed air, suction cup attached HD camera) we were able to see some potential flaws. For one, suction cups may not remain attached to the chamber walls, or stay in place, as humidity, temperature, and pressure change. We considered having a lever suction cup, but with increasing temperatures, the air inside the suction cup may expand and the device could fall. We considered the other two concepts attachment mechanisms (Slider linkage and Clamps). The vacuum part of the design relies on ideal conditions on construction of the device, however in practice manufacturing a perfect vacuum is difficult considering the circumstances. A slightly positive pressure could be used inside the camera chamber to keep moisture out of the enclosure in case of any leaks, this avoids potential risk of damaging the electronics. Through prototyping and testing we will be able to see which mechanism can work best for our design. Also, the compressed air line would need a filter to have dry air (preventing moisture inside the camera chamber) at room temperature to circulate inside the enclosure. All the final comparison designs have the mobility qualities that a borescope camera would have but contain variations in mounting and high definition cameras. Using all the methods for process selection, the final design to move forward with is a combination of the elements in the top three concepts analyzed. Again, through prototyping, testing, and consulting engineering professionals, the team will determine which design will be most effective for our project.

1.6 Spring Plan

Error! Not a valid bookmark self-reference. below contains a Gantt chart for the expectations of the project for Spring. This chart shows the predicted times the group will spend on each section. The final prototype must be completed by April 24, as that is engineering design day.

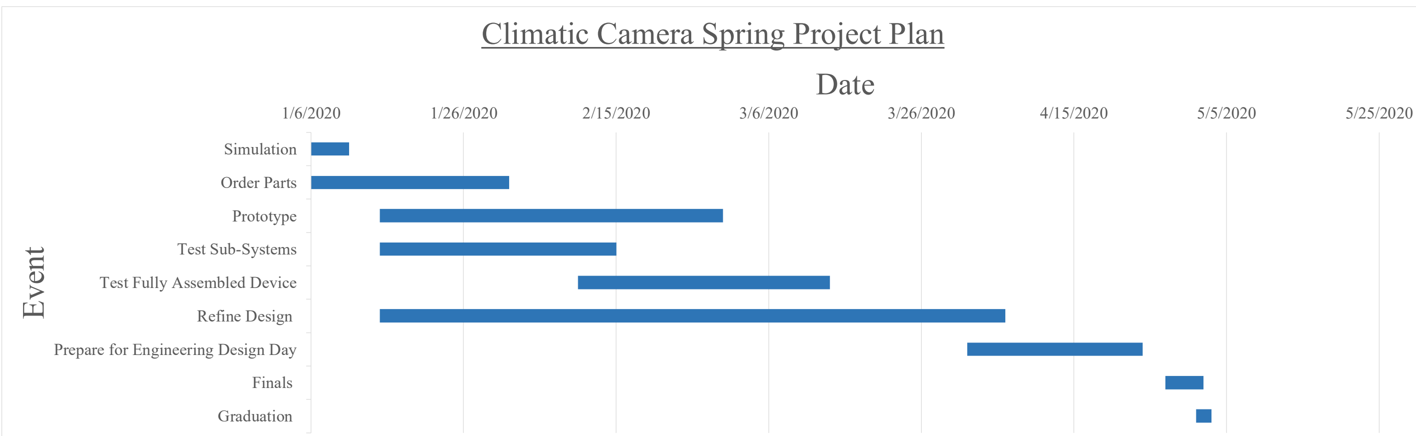


Figure 1: Spring Gant Chart

Chapter 2: EML 4552C

2.1 Restated Project Definition and Scope

Project Description

The objective of this project is to design a product that will maintain operation of a recording device at extreme temperatures. The product will have to sustain extreme temperatures inside a climate-controlled testing chamber that is currently used for testing the longevity of Danfoss equipment. The customer has specified his interest in a borescope camera as the recording device and would prefer a flexible location for the device inside the chamber.

Key Goals

The goals of the design solution are to make a product that is affordable, heat and cold resistant, movable, and safe for its users. The design must take an existing camera and maintain its functionality inside a climatic chamber with temperatures ranging between -40 to 160 degrees Celsius. The goal of this project is to improve Danfoss's data acquisition when checking equipment malfunctions when extreme climatic condition tests are performed. The customer expressed interest in being able to monitor the equipment up-close and to access the camera feed remotely.

Markets

The primary markets of this product are end users of climatic chambers. The device is intended for the people who perform tests at extreme climatic conditions as mentioned above under a controlled environment. The secondary market includes but it is not limited to extra-terrestrial research, engine testing monitoring, and Antarctic research, or any type of monitoring that would be subjected to extremely hot and/or cold conditions.

Assumptions

It is assumed that the device will be able to operate at test temperatures with a tolerance of 10 degrees Celsius. The solution will be a secure device that cannot be removed without proper equipment. The device will be connected to an existing nearby computer through cable connection. It is assumed that the remote access for other devices will be implemented by Danfoss personnel. Also, there is an ample supply of compressed air that can be used for temperature regulation in Danfoss facilities.

Stakeholders

The stakeholders of this project are considered to be the investors, people with interest in the project, and people with control over the project. Danfoss Turbocor is a stakeholder in this project due to their financial involvement. Dr. Shoele is also a stakeholder due to his interest and involvement in this project. Lastly, Dr. McConomy is a stakeholder due to his ability to control the aspects of the project.

2.2 Results and Discussion

Ideally, the group would like to of fully completed their prototype to gain accurate results and validation. However, due to unforeseen circumstances and not being able to order all parts, the group was only able to simulate the results for validation.

Testing Methods

Before the device could be tested for functionality, a simulation was done to see the required air flow for maintaining the temperature within the operational range. To do so, a model was setup in COMSOL using the L-VEL turbulence model for the computational fluid dynamics (CFD) part of the simulation, and the convective and conductive heat transfer were modeled in the steady state. Steady state was chosen for analysis due to the fact that the temperature difference between the camera and the extremes of the testing chamber will be at a minimum in steady state.

Boundary conditions for the CFD part of the simulation include the pressure at the inlet and outlet of the device. The inlet pressure was varied to examine the effects of doing so and to determine what the minimum pressure is to maintain operational temperatures for the camera. The pressure at the outlet was taken to be at ambient pressure, i.e., the gauge pressure was zero at the outlet of the device.

The boundary conditions for the heat transfer part of the simulation include: natural convection on all surfaces of the device exposed to the environment of the testing chamber, the air entering the housing is at ambient temperature, the air exiting will carry thermal energy out of the system with it, and the heat generation of the camera is negligible.

Results

Figure 2 illustrates the flow of air inside of the designed housing. Half of the housing was removed along the major axis for better viewing.

The air enters uniformly on the right side of the figure and makes its way to the helical sweep near the left side of the figure. The incoming ambient temperature air wraps around the camera and then it exits the air channel in the very front near the sight glass. The air then spirals towards the back of the device where it is exhausted to ambient conditions outside of the testing chamber. This spiraling effect of the air is a result of the helical sweep and aids in mixing the air inside of the device, avoiding any stagnant air pockets. Another advantage of the helically swept air channel is that it maximizes the surface area for heat transfer to occur between the ambient temperature air flowing through the channel and the camera it wraps around. This maximizes the heat transfer that will effectively regulate the temperature of the camera. Furthermore, once the close-to-ambient temperature air exits the helical air channel it acts to regulate the temperature of the other components, keeping them from exceeding their temperature limits before the air exits the system completely.

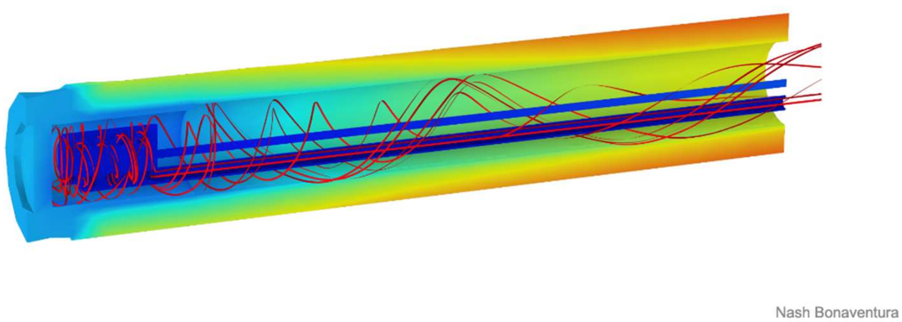


Figure 2 Streamlines showing the velocity field of the air within the housing.

Figure 3 and Figure 4 show the temperature distribution of the housing and its components for the four cases of interest. The simulations were tested at the high and low temperature extremes of 160 °C and -40°C, respectively. For each temperature extreme two different inlet pressures were tested to establish an acceptable lower bound for the pressure demand of the device for proper operation. The gauge pressures of 0.1 psi and 1.0 psi were selected based off of the results of abstract models and hand calculations.

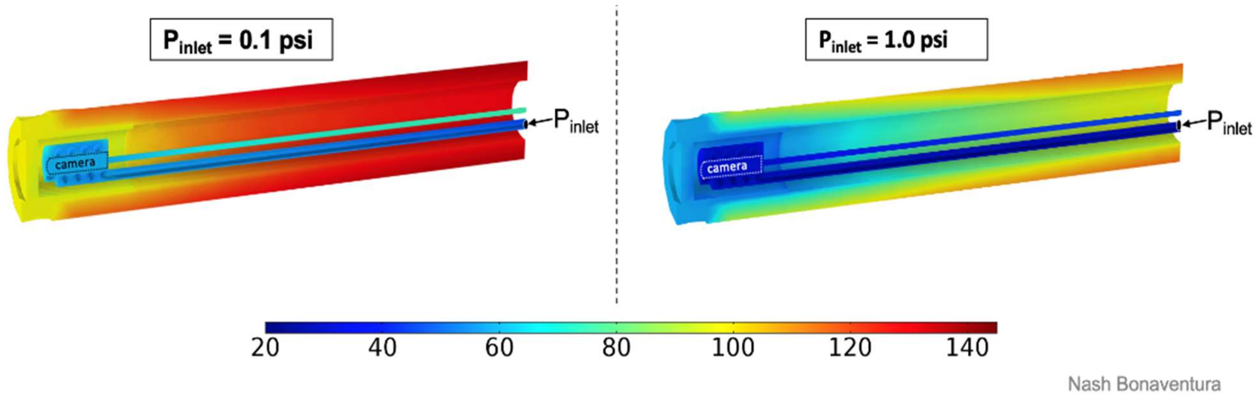


Figure 3 Temperature distribution at 160°C.

The effects of increasing the air flow through the device are well observed in the figures and follow the findings of the initial abstract models.

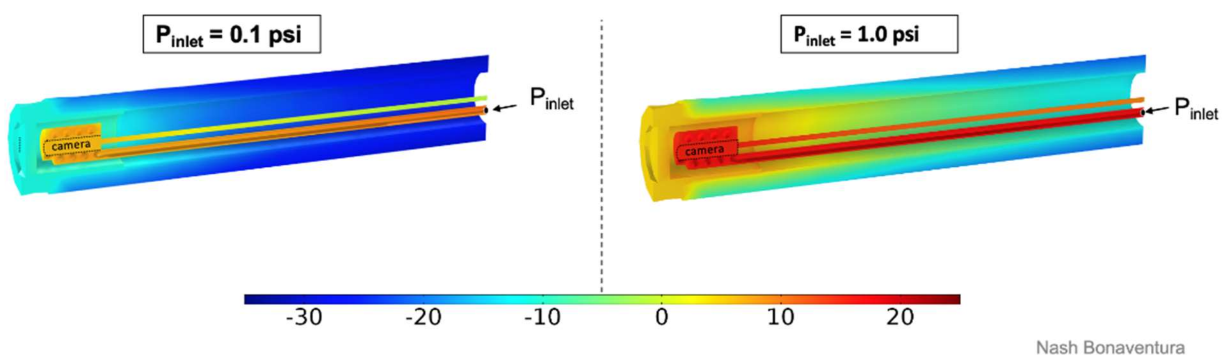


Figure 4 Temperature distribution at -40°C.

Figure 5 shows the bare camera and its temperature distribution for each case tested. This was the primary metric used to validate the design of the device. The target value for the camera temperature ranges from 0°C to 45°C. It may be derived from the figure that when the testing chamber is at the extreme cold temperature, the lower bound for the supply pressure may be reduced further than the lower supply pressure bound of the extreme hot temperature. These findings suggest the implementation of an active control scheme to monitor the temperature and throttle the pressure accordingly. However, this option was not investigated as it was slightly out of the scope of this project.

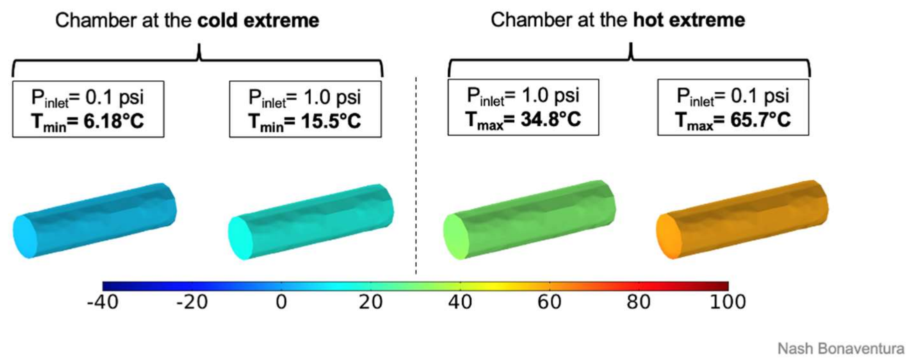


Figure 5 Camera temperature distribution for all cases.

2.3 Conclusion

Though we weren't able to build the physical prototype due to unforeseen circumstances, it was proven through COMSOL simulations that our proposed device can withstand the extreme temperatures of the environmental test chamber. Positive pressure and constant air flow inside the camera housing, allow our device to expel any unwanted moisture from potential leakages. Eliminating the threat of internal lens condensation. With constant air flow and a pressure 1.0 *psi* it was modeled that the surface of the camera stayed well within operational levels. The surface temperature of the camera at the chamber extreme temperatures (-40 and 160 °C) was simulated to be 15.5°C and 34.8°C respectively as seen in Figure 10. With our device, live continuous monitoring is possible without physical presence. Through our results, we have proven a successful design that will help improve components failure detection for the Reliability Department at Danfoss during environmental chamber testing.

2.4 Future Work

The Climatic Camera was not finalized for the physical prototype. Due to the COVID-19, the items requested for building the final prototype were not ordered. As this was out of our hands, we left instructions on how to build the prototype as well as the items needed to build it. The project budget was unknown to the team, but the parts requested totaled $ 531.66 without extra shipping considerations. Given that projects usually are between $1,000-$2,000, the team was satisfied with the overall cost of the project. The conference paper and operation manual show how the set-up was envisioned. There were reflective issues with the housing lens and the camera LED’s. There were two solutions proposed to fix or alleviate the reflection; The first solution is to change the housing lens to anti-reflective glass; this would reduce the reflection to less than 0.5% (Lens on housing has about 8%). The second solution is to have a source of light outside the environmental test chamber. Figure 6 shows the assembled housing for the camera; however, the rest of the prototype is missing and therefore, falls in this section for future work.

Figure 6: Prototype of Camera Housing

The housing consists of a stainless-steel body. Inside of the housing is a helically swept air channel. The inner wall of the helical air channel is to be in contact with a solid copper sleeve, which is in contact with the body of the endoscope camera (Figure 7). The copper interface between the camera and the air channel will create an efficient thermal connection between the ambient temperature air flowing through the channel and the camera. The copper sleeve is to be manufactured at the machine shop in Danfoss or at the college of engineering once the situation normalizes, or when Danfoss chooses to continue with the project. The copper sleeve will enhance the uniformity of the temperature distribution of the camera. Figure 7 shows proposed housing. The helical air channel was built with a 3-D printer (ABS material), in theory the helical air channel would be able to sustain the temperatures of the tests. However, it is recommended that the air channel be printed with a metal 3-D printer.

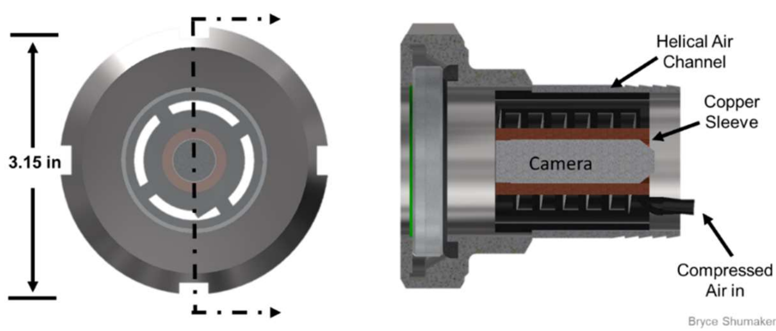


Figure 7 : CAD render of camera housing: Left: Front view. Right: Cross section view with highlighted components

Since the team couldn't complete the physical prototype, the following schematics are the proposed design for the project, the bill of materials can be found in Appendix H: Bill of Materials. The purchase and assembly of these parts falls in future work and be seen by their feature below.

Temperature Regulation

To keep the camera within its operating temperature range (0°C to 45°C), active temperature regulation is needed. Since the camera is exposed to both hot and cold temperatures, compressed air is used as a medium to add or remove heat as needed. Compressed air is provided by Danfoss's central compressed air system. The compressed air is routed towards an air-drying system. The air-drying system consist of a desiccant filter to remove residual moisture from the air, and a built-in regulator to step down the main line air pressure to a desired pressure. This is then followed by a safety shut off ball valve which is connected to vinyl tubing to run to the camera housing. The schematic diagram of the internal connections of the system can be seen in Figure 8.

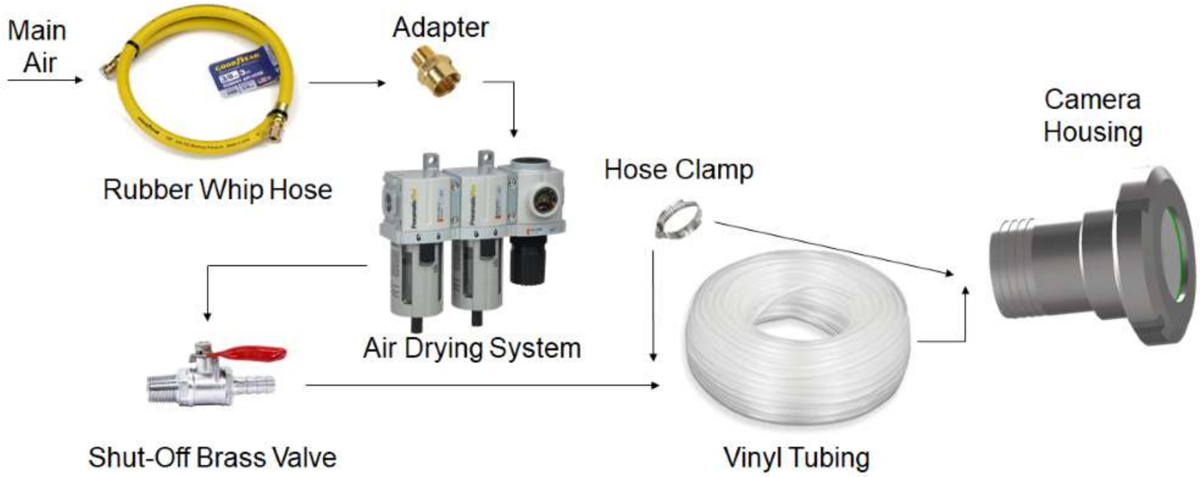


Figure 8: Component breakdown of the air supply for the Climatic Camera.

For exterior insulation, the housing is attached to a suction and discharge hose that serves as the path for the air in and out of the housing, removing any unwanted heat. The discharge hose is used to prevent leakages into the environmental testing chamber. Both the hose and the housing are to be wrapped in melamine foam pipe insulation, leaving the sight glass as the only exposed part. Melamine foam has isolation temperature that works for both extreme cold and hot temperatures (-40°C to 176°C) with a resistance R-value of 5.12 and thermal conductivity k-value of 0.25. The pipe insulation is used to slow down the rate of heat transfer between the climatic chamber conditions and the walls of the housing. Figure 9 shows the schematic diagram for external temperature regulation.

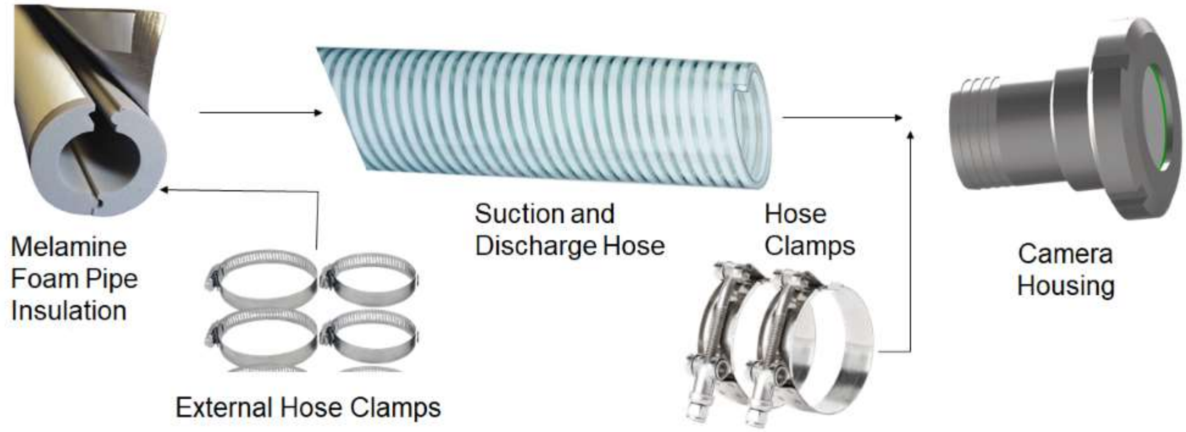


Figure 9: Component breakdown for outside temperature regulation (Insulation).

External Support

To improve failure detection, it was required that the device be fixed at a desired location with a set view angle and distance. To do this we propose a 783 Newton (176 pound-force) steel magnetic base threated to a goose neck that can sustain up to 2.5 pounds at its maximum stress point. The goose neck is to be attached to a stainless-steel plate with hose clamps that will be attached to the device to position at the desired location. Figure 10 shows the schematic diagram for the external support of the proposed solution.

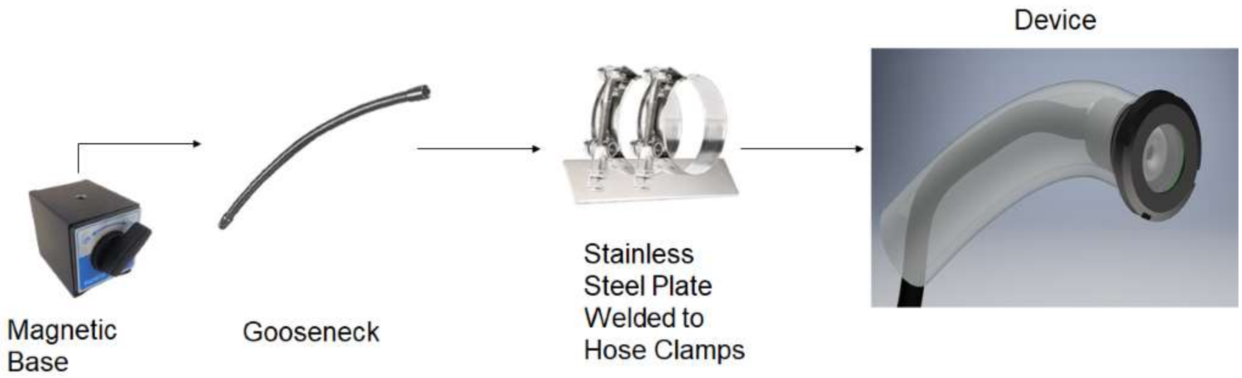


Figure 10: External support for fixed visuals.

Failure Detection

Finally, in order to ensure the device will be at operational temperatures through testing, a simple failure detection system is proposed. A micro-controller Arduino UNO is to be connected to the main computer where the test takes place. The micro-controller is connected to small temperature sensors that are placed inside the camera housing. Air exiting the housing is assumed to be the temperature of the camera. If such temperature gets within 5°C of operational limits (5°C to 40°C) an alarm speaker will be activated to indicate that visuals are at risk. Figure 11 shows the schematic diagram for the failure detection system proposed.

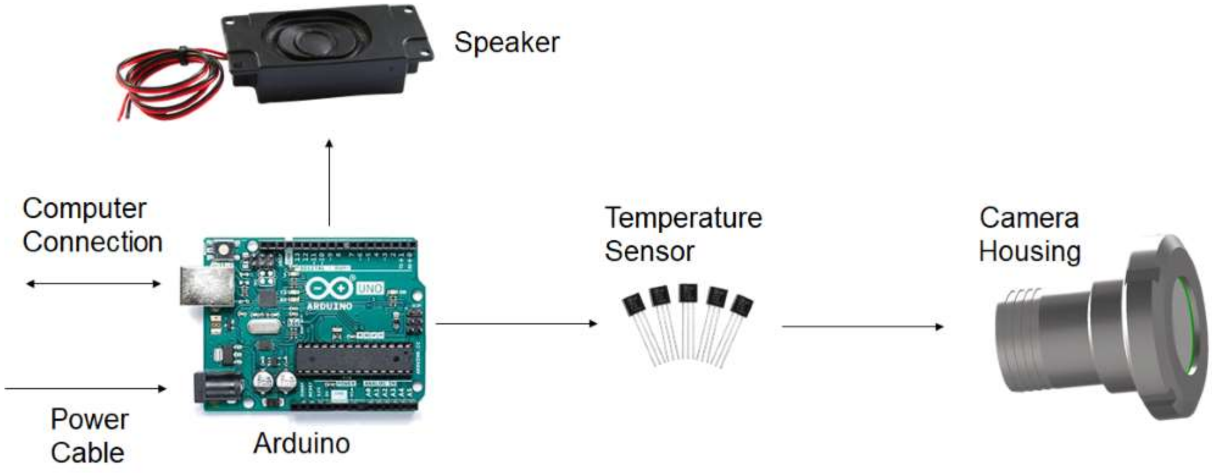


Figure 11: Device temperature failure detection.

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Appendices

Appendix A: Code of Conduct

Mission Statement

The Danfoss Climatic Camera Team is dedicated to work together in a positive environment through the entirety of this project. Each team member will always be respectful and professional with other team members. Each member will utilize his or her strengths in order to contribute as much as possible to this project.

Team Member Roles

Project Manager – Bryce Shumaker

The Project Manager will ensure that each team member is aware of his or her responsibilities through every stage of the design project. He will also make sure that all members are completing assigned tasks in a timely manner. The Project Manager is responsible for editing each deliverable before the submission deadlines. This includes all reports, presentations, and any other documents required by the project. Once the Project Manager has edited a deliverable, he will be in charge of submitting it on time. Lastly, the Project Manager will always inform the other team members of the project's progress. The Project Manager will be the main contact between the senior design team and the sponsor.

Simulation Engineer – Nash Bonaventura

The Simulation Engineer will be in charge of the technical part of the project. This includes data analysis, programming, and any calculations that need to be done. The Simulation Engineer will be held responsible for these tasks even when the work is done by another team member. In the event that another team member does any calculations, the Simulation Engineer will thoroughly check their work for correctness.

Design Engineer – Diego Gonzalez

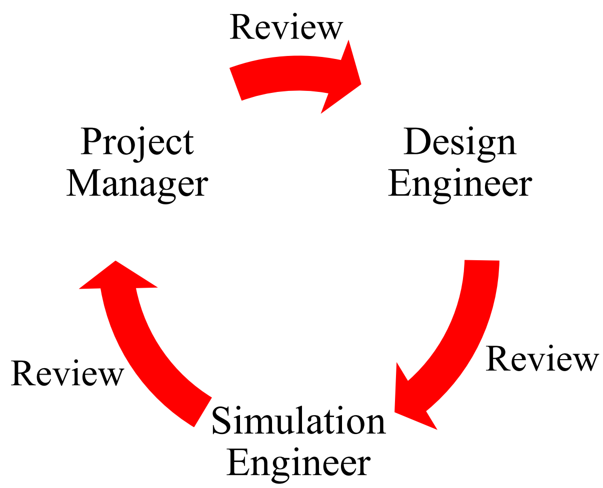
The responsibilities of the Design Engineer are but not limited to ensuring that the wants and needs of the customer are well understood, ensuring that the sponsor is aware of the current state of the project, and providing the sponsor with feedback and answering/ finding the answers to any questions that may come up. The Design Engineer will be tasked with creatively designing the project prototype. He will also ensure the safety of the prototype. All parts will be made by the Design Engineer considering the machinability and cost of the process. All part drawings will be done by the Design Engineer, and he will schedule drawing reviews with all team members before any submissions or purchases. The Design Engineer will also maintain and update the website.

Organizational Chart

	Team Member Roles		
Team Member Names	Simulation Engineer	Design Engineer	Project Manager
Nash Bonaventura	X		
Diego Gonzalez		X	
Bryce Shumaker			X

All Team Members:

- Contribute equally
- Listen and be open-minded to others' ideas
- Review each other work
- Deliver on commitments



Communication

Communication between team members will be done in person on Tuesdays and Thursdays in class, through SMS/MMS text messaging, and on Trello when preparing presentations and papers that we will all collectively be collaborating on. If a member of the team is having difficulty with communication, (i.e. not responding to messages/ not doing their part) The other two group members will consult the 3rd during class. If this is a continuous problem, it will be addressed with Dr. McConomy.

Communication between the senior design team and the sponsor at Danfoss will be done mostly through email and scheduled face-to-face meetings. Meeting will be scheduled so all team member may be present. Each team member will be CC'd on emails.

Team Dynamics

Each team member will have their own responsibilities during the project. They are in charge of making sure their portion of the project is progressing in a timely manner and are ultimately responsible for making sure it is completed by the specified deadline. One of the most important things is that a team member should communicate with the team if they are having difficulty completing a task.

Ethics

The team will be adhering to the National Society of Professional Engineers' Code of Ethics. Team members are required to model their behavior to the highest standard of honesty and integrity for the benefit of the client, the team and the profession.

Dress Code

During presentations, team members will be expected to dress in business professional attire. Sponsor meetings will be held in business casual attire. There will be no required dress code for routine team meetings. All dress code expectations are subject to change with a unanimous team decision.

Weekly and Biweekly Tasks

Weekly meetings will be held between team members during class time. In these meetings, the group will make sure all the team members are up to date on the progress of the project. Project updates and any new information will be discussed here. At least one meeting per week with all team members will be expected with strict attendance.

Decision Making

All decisions will be made together as a team. Ideally, in the event that two group members disagree, an intelligent conversation would be had including all team members, leading to a resolution. If there is still a disagreement, a vote would be taken amongst team members. We have an odd number of group members so this should solve the issue.

Conflict Resolution

If the team members have any discord, the following steps will be employed:

· Ideas will be discussed with all members to analyze the pros and cons.

· The leader of each department will decide what the final result will be.

· If needed, the engineering manager will intervene.

· Instructor will facilitate the resolution of conflicts.

Amendment Process

This code of conduct can be amended only if all team members sign off on the amendment.

Statement of Understanding

By signing this document, the members of the Danfoss Climatic Camera Team agree to the code of conduct and understand its principles.

Amendments

10/7/19

- Changed Team Member Roles
  - Bryce Shumaker - Project Manager
  - Nash Bonaventura - Simulation Engineer
  - Diego Gonzalez - Design Engineer

Appendix B: Functional Decomposition Charts

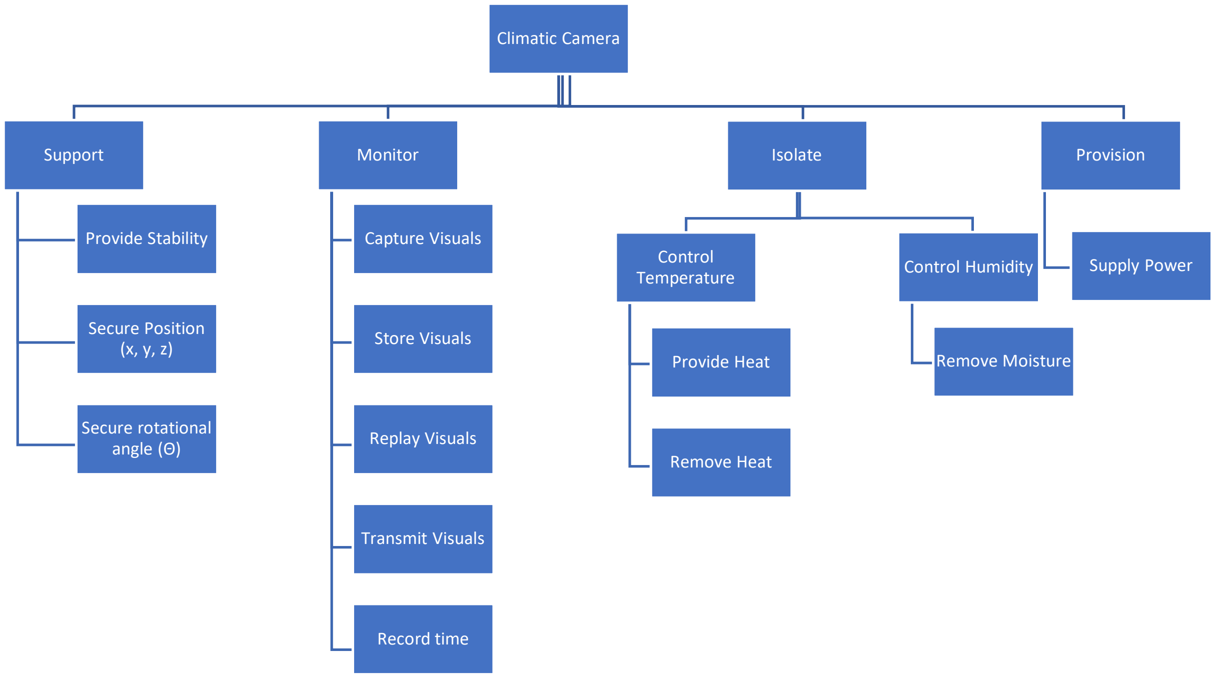


Figure b12: Flow diagram of all items in the functional decomposition.

Table 1: Functional Decomposition Cross Reference Table

	Systems			
Functions	Support	Monitor	Isolate	Provision
Provide Stability	x	x	x	
Secure Position	x	x		
Secure Rotational Angle	x	x		
Capture Visuals		x		
Store Visuals		x		
Replay Visuals		x		
Transmit Visuals		x		
Record Time		x		
Control Temperature			x	
Control Humidity			x	
Supply Power		x		x

Appendix C: Customer Needs Interpretations

Question/Prompt	Customer Statement	Interpreted Need
How do you currently monitor the environmental test?	As of now, someone has to physically go and look in from the window of the chamber and see if there is any failure or any LED off	The device can be remotely accessed
How long does the test last?	The test goes on 24/7 until failure	The device provides continuous monitoring
How would you like to control the test monitoring?	I would like a camera that can be connected to a computer	The device can be connected to a computer
Would you like to be able to put away or move around this product?	I would like a rigid fixture and mobility of the camera	The device can be movable or fixed
How would you like to power this product?	USB connection preferably	The device can be powered by an external source (outside the chamber)
What size would you like the monitoring device (camera) to be?	I want something small, like a USB Borescope camera	The device is compact in size
What conditions will the monitoring device be subjected to?	The climatic chamber test has oscillating temperatures that go from -40 to 160 degrees Celsius. We also do 10 to 90 % Relative Humidity and vibrational tests	The device operates within the parameters of the test
Do you have any size constraints for this product?	Compact device, cannot drill inside the chamber to fix camera because it would affect liability and guarantee of chamber	The device is compact and does not affect integrity of the chamber
Is anything else inside the chamber other than the test subject?	Vibrational chamber and various test subjects depending on what part we are testing	The device needs to be easily moveable
What would you like this product to do? Time of failure or…? What kind of feedback do you want, only visuals?	If possible, I would like the product to have a temperature indicator to see time and temperature at failure	The camera should know the current time and/or temperature
Is there lighting inside the chamber?	There are two bulbs inside the chamber but would like to have operational camera without bulbs, like an infrared camera	The customer would like the camera to see in the dark
Is there a desired angle for the recording device?	No, but would like the device to be movable and adjusted to desired angle	Orientation of device should not be permanent
Do you want us to use a standard recording device or develop a new one?	I want you to use an existing camera and make it work under the test conditions	The recording device is isolated from the environment

What does the vibrational test consist of?	Vibrational test is done with a smaller chamber were the surface of the chamber is the only part that vibrates	The device can avoid vibrations with proper positioning
Does the device need audio?	Don't make a difference	The device has visual capabilities
Is the chamber operated from a computer or the chamber itself?	The chamber has a control system on the chamber that regulates temperature and humidity, the computer is used to record feedback	The device provides with visual feedback
At what height are the test subjects tested?	Various heights depending on the test, there are racks to mount test subjects but on vibrational test we take them out and have the vibrational chamber inside	The device can be placed at adjustable heights and angles
How big/how much room are we allowed to use in the wire opening space?	The space available is about a fist in diameter, not much room	The device connection to the computer fit through the wire opening space
Do the floor and/or walls vibrate? More info on vibrational test	Surface vibrates, walls do not	The device can be fixed on the wall or external surfaces without vibration
How do you currently isolate the wire opening in the chamber?	We use a cork that is flexible for cables to go in and keep isolation	The device does not affect the integrity of the wire opening
Do you test the entire compressor in the climatic chamber?	We test at a sub-assembly level	The device can record smaller pieces of the test subjects
Is there only one subject tested at a time?	We test various components at a time	The device can be adjusted to video record a few test subjects or one in particular
Is there access to Wi-Fi on laptop for remote access?	Yes, we have Wi-Fi available in the room	The device can be Wi-Fi enabled
Is the inside of the chamber magnetic?	The inside is not magnetic, the outside is	The device does not rely on magnetism inside the chamber for support

Appendix D: Target Catalogue

Table 14: Targets and Metrics

Function	Target	Metric
Provide Stability	0 m/s^2	Acceleration
Secure Position	Change in x,y,z=0mm	Translation
Secure Rotational Angle	0-degree change	Degrees
Capture Visuals	≥ 1 frame/second	Frame Rate
Transmit Visuals	Yes	N/A
Store Visuals	Giga Bytes	Storage Memory
Replay Visuals	Yes	N/A
Record Time*	71 Days	Time
Control Temperature*	$0 \leq T \leq 45\ ^{o}C$	Temperature
Control Humidity	0-50%	Relative Humidity
Supply Power	2.5 Watts	Power

**identifies critical target*

Table 15 : Targets and Metrics cont.

Need	Target	Metric
Chamber Cable Opening	10 cm	Diameter
Cable Length	2 m	Length
Condensation on lens	0 ml	Volume
Inexpensive*	≤ $100	Price
Compact	≤ 97 x 97 x 97cm	volume

**identifies critical target*

Appendix E: Generated Concepts

Table 16: 100 Generated Concepts

Concept	Description
1.	Water cooled Borescope camera
2.	Compressed air-cooled go pro
3.	FireCam with Vortex tube temperature regulation
4.	GoPro with Vortex tube temperature regulation
5.	Camera with open flame heater
6.	Camera with isolated negative pressure enclosure
7.	Camera with negative pressure enclosure to exchange air with ambient environment outside chamber
8.	Large concrete bunker to create enclosure so large heat transfer with chamber environment negligible
9.	Wrap camera in a blanket
10.	Camera mounted with wheeled structure for easy maneuverability
11.	Camera mounted with magnetic mount for versatile positions
12.	Camera outside of chamber entirely
13.	Inside fan for camera
14.	PID temperature control
15.	Fan on outside of camera housing to mitigate lens condensation
16.	Triple-layer Ziploc bag housing
17.	Electric heater in housing
18.	Use natural convection flow inside housing to regulate temperature
19.	Use CO2 inside enclosure to aid in insulation
20.	Borescope camera with fiberglass insulation no temperature regulation clamp hydrophobic coating
21.	Borescope camera with fiberglass insulation no temperature regulation clamp resistive heater
22.	Borescope camera with fiberglass insulation no temperature regulation clamp compressed air flow on interior of lens
23.	Borescope camera with fiberglass insulation no temperature regulation suction cups hydrophobic coating
24.	Borescope camera with fiberglass insulation no temperature regulation suction cups resistive heater
25.	Borescope camera with fiberglass insulation no temperature regulation suction cups compressed air flow on interior of lens
26.	Borescope camera with fiberglass insulation compressed air temperature regulation clamp hydrophobic coating
27.	Borescope camera with fiberglass insulation compressed air temperature regulation clamp resistive heater
28.	Borescope camera with fiberglass insulation compressed air temperature regulation clamp compressed air flow on interior of lens

29.	Borescope camera with fiberglass insulation compressed air temperature regulation suction cups hydrophobic coating
30.	Borescope camera with fiberglass insulation compressed air temperature regulation suction cups resistive heater
31.	Borescope camera with fiberglass insulation compressed air temperature regulation suction cups compressed air flow on interior of lens
32.	Borescope camera with polyurethane insulation no temperature regulation clamp hydrophobic coating
33.	Borescope camera with polyurethane insulation no temperature regulation clamp resistive heater
34.	Borescope camera with polyurethane insulation no temperature regulation clamp compressed air flow on interior of lens
35.	Borescope camera with polyurethane insulation no temperature regulation suction cups hydrophobic coating
36.	Borescope camera with polyurethane insulation no temperature regulation suction cups resistive heater
37.	Borescope camera with polyurethane insulation no temperature regulation suction cups compressed air flow on interior of lens
38.	Borescope camera with polyurethane insulation compressed air temperature regulation clamp hydrophobic coating
39.	Borescope camera with polyurethane insulation compressed air temperature regulation clamp resistive heater
40.	Borescope camera with polyurethane insulation compressed air temperature regulation clamp compressed air flow on interior of lens
41.	Borescope camera with polyurethane insulation compressed air temperature regulation suction cups hydrophobic coating
42.	Borescope camera with polyurethane insulation compressed air temperature regulation suction cups resistive heater
43.	Borescope camera with polyurethane insulation compressed air temperature regulation suction cups compressed air flow on interior of lens
44.	Borescope camera with vacuum insulation no temperature regulation clamp hydrophobic coating
45.	Borescope camera with vacuum insulation no temperature regulation clamp resistive heater
46.	Borescope camera with vacuum insulation no temperature regulation clamp compressed air flow on interior of lens
47.	Borescope camera with vacuum insulation no temperature regulation suction cups hydrophobic coating
48.	Borescope camera with vacuum insulation no temperature regulation suction cups resistive heater
49.	Borescope camera with vacuum insulation no temperature regulation suction cups compressed air flow on interior of lens
50.	Borescope camera with vacuum insulation compressed air temperature regulation clamp hydrophobic coating
51.	Borescope camera with vacuum insulation compressed air temperature regulation clamp resistive heater
52.	Borescope camera with vacuum insulation compressed air temperature regulation clamp compressed air flow on interior of lens

53.	Borescope camera with vacuum insulation compressed air temperature regulation suction cups hydrophobic coating
54.	Borescope camera with vacuum insulation compressed air temperature regulation suction cups resistive heater
55.	Borescope camera with vacuum insulation compressed air temperature regulation suction cups compressed air flow on interior of lens
56.	FireCam with fiberglass insulation no temperature regulation clamp hydrophobic coating
57.	FireCam with fiberglass insulation no temperature regulation clamp resistive heater
58.	FireCam with fiberglass insulation no temperature regulation clamp compressed air flow on interior of lens
59.	FireCam with fiberglass insulation no temperature regulation suction cups hydrophobic coating
60.	FireCam with fiberglass insulation no temperature regulation suction cups resistive heater
61.	FireCam with fiberglass insulation no temperature regulation suction cups compressed air flow on interior of lens
62.	FireCam with fiberglass insulation compressed air temperature regulation clamp hydrophobic coating
63.	FireCam with fiberglass insulation compressed air temperature regulation clamp resistive heater
64.	FireCam with fiberglass insulation compressed air temperature regulation clamp compressed air flow on interior of lens
65.	FireCam with fiberglass insulation compressed air temperature regulation suction cups hydrophobic coating
66.	FireCam with fiberglass insulation compressed air temperature regulation suction cups resistive heater
67.	FireCam with fiberglass insulation compressed air temperature regulation suction cups compressed air flow on interior of lens
68.	FireCam with polyurethane insulation no temperature regulation clamp hydrophobic coating
69.	FireCam with polyurethane insulation no temperature regulation clamp resistive heater
70.	FireCam with polyurethane insulation no temperature regulation clamp compressed air flow on interior of lens
71.	FireCam with polyurethane insulation no temperature regulation suction cups hydrophobic coating
72.	FireCam with polyurethane insulation no temperature regulation suction cups resistive heater
73.	FireCam with polyurethane insulation no temperature regulation suction cups compressed air flow on interior of lens
74.	FireCam with polyurethane insulation compressed air temperature regulation clamp hydrophobic coating
75.	FireCam with polyurethane insulation compressed air temperature regulation clamp resistive heater
76.	FireCam with polyurethane insulation compressed air temperature regulation clamp compressed air flow on interior of lens
77.	FireCam with polyurethane insulation compressed air temperature regulation suction cups hydrophobic coating
78.	FireCam with polyurethane insulation compressed air temperature regulation suction cups resistive heater
79.	FireCam with polyurethane insulation compressed air temperature regulation suction cups compressed air flow on interior of lens

80.	FireCam with vacuum insulation no temperature regulation clamp hydrophobic coating
81.	FireCam with vacuum insulation no temperature regulation clamp resistive heater
82.	FireCam with vacuum insulation no temperature regulation clamp compressed air flow on interior of lens
83.	FireCam with vacuum insulation no temperature regulation suction cups hydrophobic coating
84.	FireCam with vacuum insulation no temperature regulation suction cups resistive heater
85.	FireCam with vacuum insulation no temperature regulation suction cups compressed air flow on interior of lens
86.	FireCam with vacuum insulation compressed air temperature regulation clamp hydrophobic coating
87.	FireCam with vacuum insulation compressed air temperature regulation clamp resistive heater
88.	FireCam with vacuum insulation compressed air temperature regulation clamp compressed air flow on interior of lens
89.	FireCam with vacuum insulation compressed air temperature regulation suction cups hydrophobic coating
90.	FireCam with vacuum insulation compressed air temperature regulation suction cups resistive heater
91.	Wi-Fi enabled camera for wireless distribution of data transfer, heat insulation by vacuum enclosure and fans inside enclosure, the source of power is an internal Battery that can last over 2 months in continuous use
92.	Housing with self-contained heat pump
93.	Mini climatic chamber to protect camera from main climatic chamber
94.	Nanotechnology Camera
95.	Wide angle lens high resolution camera mounted to inside wall of chamber
96.	Nanotechnology Camera
97.	Wide angle lens high resolution camera mounted to inside wall chamber
98.	Wiper actuated condensation removal with borescope camera
99.	Tool Holder mounted borescope camera with arm adjustment
100.	High temperature dryer vent insulation around borescope camera with clamp base tool holder

Appendix F: Generated Concepts

Criteria Comparison Matrices

Table 17: Provide Stability Criteria Comparison Matrix

Provide Stability Comparison [C]			
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera
Slider Linkage, Comp Air HD Camera	1	3	5
Comp. Air Clamped Borescope	0.33	1	3
Vacuum + Comp. Air, Suction Cup, HD Camera	0.2	0.33	1
Sum	1.53	4.33	9

Table 18: Secure Position Criteria Comparison Matrix

Secure Position Comparison [C]			
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera
Slider Linkage, Comp Air HD Camera	1	1	1
Comp. Air Clamped Borescope	1	1	1
Vacuum + Comp. Air, Suction Cup, HD Camera	1	1	1
Sum	3	3	3

Table 19: Secure Angle Criteria Comparison Matrix

Secure Angle Comparison [C]			
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera
Slider Linkage, Comp Air HD Camera	1	1	1
Comp. Air Clamped Borescope	1	1	1
Vacuum + Comp. Air, Suction Cup, HD Camera	1	1	1
Sum	3	3	3

Table 20: Capture Visuals Comparison Matrix

Capture Visuals Comparison [C]			
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera
Slider Linkage, Comp Air HD Camera	1	5	1
Comp. Air Clamped Borescope	0.2	1	0.2
Vacuum + Comp. Air, Suction Cup, HD Camera	1	5	1
Sum	2.2	11	2.2

Table 21: Transmit Visuals Comparison Matrix

Transmit Visuals Comparison [C]			
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera
Slider Linkage, Comp Air HD Camera	1	1	1
Comp. Air Clamped Borescope	1	1	1
Vacuum + Comp. Air, Suction Cup, HD Camera	1	1	1
Sum	3	3	3

Table 22: Store Visuals Comparison Matrix

Store Visuals Comparison [C]			
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera
Slider Linkage, Comp Air HD Camera	1	1	1
Comp. Air Clamped Borescope	1	1	1
Vacuum + Comp. Air, Suction Cup, HD Camera	1	1	1
Sum	3	3	3

Table 23: Replay Visuals Comparison Matrix

Replay Visuals Comparison [C]			
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera
Slider Linkage, Comp Air HD Camera	1	5	1
Comp. Air Clamped Borescope	0.2	1	0.2
Vacuum + Comp. Air, Suction Cup, HD Camera	1	5	1
Sum	2.2	11	2.2

Table 24: Record Time Comparison Matrix

Record Time Comparison [C]			
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera
Slider Linkage, Comp Air HD Camera	1	1	1
Comp. Air Clamped Borescope	1	1	1
Vacuum + Comp. Air, Suction Cup, HD Camera	1	1	1
Sum	3	3	3

Table 25: Control Temperature Comparison Matrix

Control Temperature Comparison [C]			
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera
Slider Linkage, Comp Air HD Camera	1	1	0.2
Comp. Air Clamped Borescope	1	1	0.2
Vacuum + Comp. Air, Suction Cup, HD Camera	5	5	1
Sum	7	7	1.4

Table 23: Control Humidity Comparison Matrix

Control Humidity Comparison [C]			
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera
Slider Linkage, Comp Air HD Camera	1	1	0.33
Comp. Air Clamped Borescope	1	1	0.33
Vacuum + Comp. Air, Suction Cup, HD Camera	3	3	1
Sum	5	5	1.66

Table 23: Supply Power Comparison Matrix

Supply Power Comparison [C]			
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera
Slider Linkage, Comp Air HD Camera	1	1	1
Comp. Air Clamped Borescope	1	1	1
Vacuum + Comp. Air, Suction Cup, HD Camera	1	1	1
Sum	3	3	3

Normalized Criteria Comparison Matrices

Table 26: Provide Stability Normalized Criteria Comparison Matrix

Normalized Provide Stability Comparison [NormC]				
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera	Design Alt. Priorities {Pi}
Slider Linkage, Comp Air HD Camera	0.65	0.69	0.56	0.63
Comp. Air Clamped Borescope	0.22	0.23	0.33	0.26
Vacuum + Comp. Air, Suction Cup, HD Camera	0.13	0.08	0.11	0.11
Sum	1.00	1.00	1.00	1.00

Table 27: Secure Position Normalized Criteria Comparison Matrix

Normalized Secure Position Comparison [NormC]				
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera	Design Alt. Priorities {Pi}
Slider Linkage, Comp Air HD Camera	0.33	0.33	0.33	0.33
Comp. Air Clamped Borescope	0.33	0.33	0.33	0.33
Vacuum + Comp. Air, Suction Cup, HD Camera	0.33	0.33	0.33	0.33
Sum	1.00	1.00	1.00	1.00

Table 28: Secure Angle Normalized Criteria Comparison Matrix

Normalized Secure Angle Comparison [NormC]				
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera	Design Alt. Priorities {Pi}
Slider Linkage, Comp Air HD Camera	0.33	0.33	0.33	0.33
Comp. Air Clamped Borescope	0.33	0.33	0.33	0.33
Vacuum + Comp. Air, Suction Cup, HD Camera	0.33	0.33	0.33	0.33
Sum	1.00	1.00	1.00	1.00

Table 29: Transmit Visuals Normalized Criteria Comparison Matrix

Normalized Transmit Visuals Comparison [NormC]				
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera	Design Alt. Priorities {Pi}
Slider Linkage, Comp Air HD Camera	0.33	0.33	0.33	0.33
Comp. Air Clamped Borescope	0.33	0.33	0.33	0.33
Vacuum + Comp. Air, Suction Cup, HD Camera	0.33	0.33	0.33	0.33
Sum	1.00	1.00	1.00	1.00

Table 30: Store Visuals Normalized Criteria Comparison Matrix

Normalized Store Visuals Comparison [NormC]				
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera	Design Alt. Priorities {Pi}
Slider Linkage, Comp Air HD Camera	0.33	0.33	0.33	0.33
Comp. Air Clamped Borescope	0.33	0.33	0.33	0.33
Vacuum + Comp. Air, Suction Cup, HD Camera	0.33	0.33	0.33	0.33
Sum	1.00	1.00	1.00	1.00

Table 31: Replay Visuals Normalized Criteria Comparison Matrix

Normalized Replay Visuals Comparison [NormC]				
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera	Design Alt. Priorities {Pi}
Slider Linkage, Comp Air HD Camera	0.45	0.45	0.45	0.45
Comp. Air Clamped Borescope	0.09	0.09	0.09	0.09
Vacuum + Comp. Air, Suction Cup, HD Camera	0.45	0.45	0.45	0.45
Sum	1.00	1.00	1.00	1.00

Table 32: Record Time Normalized Criteria Comparison Matrix

Normalized Record Time Comparison [NormC]				
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera	Design Alt. Priorities {Pi}
Slider Linkage, Comp Air HD Camera	0.33	0.33	0.33	0.33
Comp. Air Clamped Borescope	0.33	0.33	0.33	0.33
Vacuum + Comp. Air, Suction Cup, HD Camera	0.33	0.33	0.33	0.33
Sum	1.00	1.00	1.00	1.00

Table 33: Control Temperature Normalized Criteria Comparison Matrix

Normalized Control Temperature Comparison [NormC]				
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera	Design Alt. Priorities {Pi}
Slider Linkage, Comp Air HD Camera	0.14	0.14	0.14	0.14
Comp. Air Clamped Borescope	0.14	0.14	0.14	0.14
Vacuum + Comp. Air, Suction Cup, HD Camera	0.71	0.71	0.71	0.71
Sum	1.00	1.00	1.00	1.00

Table 34: Control Humidity Normalized Criteria Comparison Matrix

Normalized Control Humidity Comparison [NormC]				
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera	Design Alt. Priorities {Pi}
Slider Linkage, Comp Air HD Camera	0.20	0.20	0.20	0.20
Comp. Air Clamped Borescope	0.20	0.20	0.20	0.20
Vacuum + Comp. Air, Suction Cup, HD Camera	0.60	0.60	0.60	0.60
Sum	1.00	1.00	1.00	1.00

Table 35: Supply Power Normalized Criteria Comparison Matrix

Normalized Supply Power Comparison [NormC]				
	Slider Linkage, Comp Air HD Camera	Comp. Air Clamped Borescope	Vacuum + Comp. Air, Suction Cup, HD Camera	Design Alt. Priorities {Pi}
Slider Linkage, Comp Air HD Camera	0.33	0.33	0.33	0.33
Comp. Air Clamped Borescope	0.33	0.33	0.33	0.33
Vacuum + Comp. Air, Suction Cup, HD Camera	0.33	0.33	0.33	0.33
Sum	1.00	1.00	1.00	1.00

Consistency Checks

Table 36: Provide Stability Consistency Check

Provide Stability Consistency Check (n=3)		
Weighted Sum Vector {Ws}	Criteria Weights {Pi}	Consistency Factor (Cons)
1.94	0.63	3.07
0.79	0.26	3.03
0.32	0.11	3.01
Average Consistency Vector (λ)		3.03
Consistency Index (CI)		0.02
RI Value (3 Criteria)		0.52
Consistency Ratio (CR)		0.03

Table 37: Provide Stability Consistency Check

Provide Stability Consistency Check (n=3)		
Weighted Sum Vector {Ws}	Criteria Weights {Pi}	Consistency Factor (Cons)
1.94	0.63	3.07
0.79	0.26	3.03
0.32	0.11	3.01
Average Consistency Vector (λ)		3.03
Consistency Index (CI)		0.02
RI Value (3 Criteria)		0.52
Consistency Ratio (CR)		0.03

Table 38: Secure Position Consistency Check

Secure Position Consistency Check (n=3)		
Weighted Sum Vector {Ws}	Criteria Weights {Pi}	Consistency Factor (Cons)
1.00	0.33	3.00
1.00	0.33	3.00
1.00	0.33	3.00
Average Consistency Vector (λ)		3.00
Consistency Index (CI)		0.00
RI Value (3 Criteria)		0.52
Consistency Ratio (CR)		0.00

Table 39: Secure Angle Consistency Check

Secure Angle Consistency Check (n=3)		
Weighted Sum Vector {Ws}	Criteria Weights {Pi}	Consistency Factor (Cons)
1.00	0.33	3.00
1.00	0.33	3.00
1.00	0.33	3.00
Average Consistency Vector (λ)		3.00
Consistency Index (CI)		0.00
RI Value (3 Criteria)		0.52
Consistency Ratio (CR)		0.00

Table 40: Capture Visuals Consistency Check

Capture Visuals Consistency Check (n=3)		
Weighted Sum Vector {Ws}	Criteria Weights {Pi}	Consistency Factor (Cons)
1.35	0.45	3.00
0.27	0.09	3.00
1.35	0.45	3.00
Average Consistency Vector (λ)		3.00
Consistency Index (CI)		0.00
RI Value (3 Criteria)		0.52
Consistency Ratio (CR)		0.00

Table 41: Transmit Visuals Consistency Check

Transmit Visuals Consistency Check (n=3)		
Weighted Sum Vector {Ws}	Criteria Weights {Pi}	Consistency Factor (Cons)
1.00	0.33	3.00
1.00	0.33	3.00
1.00	0.33	3.00
Average Consistency Vector (λ)		3.00
Consistency Index (CI)		0.00
RI Value (3 Criteria)		0.52
Consistency Ratio (CR)		0.00

Table 42: Store Visuals Consistency Check

Store Visuals Consistency Check (n=3)		
Weighted Sum Vector {Ws}	Criteria Weights {Pi}	Consistency Factor (Cons)
1.00	0.33	3.00
1.00	0.33	3.00
1.00	0.33	3.00
Average Consistency Vector (λ)		3.00
Consistency Index (CI)		0.00
RI Value (3 Criteria)		0.52
Consistency Ratio (CR)		0.00

Table 43: Replay Visuals Consistency Check

Replay Visuals Consistency Check (n=3)		
Weighted Sum Vector {Ws}	Criteria Weights {Pi}	Consistency Factor (Cons)
1.35	0.45	3.00
0.27	0.09	3.00
1.35	0.45	3.00
Average Consistency Vector (λ)		3.00
Consistency Index (CI)		0.00
RI Value (3 Criteria)		0.52
Consistency Ratio (CR)		0.00

Table 44: Record Time Consistency Check

Record Time Consistency Check (n=3)		
Weighted Sum Vector {Ws}	Criteria Weights {Pi}	Consistency Factor (Cons)
1.00	0.33	3.00
1.00	0.33	3.00
1.00	0.33	3.00
Average Consistency Vector (λ)		3.00
Consistency Index (CI)		0.00
RI Value (3 Criteria)		0.52
Consistency Ratio (CR)		0.00

Table 45: Control Temperature Consistency Check

Control Temperature Consistency Check (n=3)		
Weighted Sum Vector {Ws}	Criteria Weights {Pi}	Consistency Factor (Cons)
0.43	0.14	3.00
0.43	0.14	3.00
2.14	0.71	3.00
Average Consistency Vector (λ)		3.00
Consistency Index (CI)		0.00
RI Value (3 Criteria)		0.52
Consistency Ratio (CR)		0.00

Table 46: Control Humidity Consistency Check

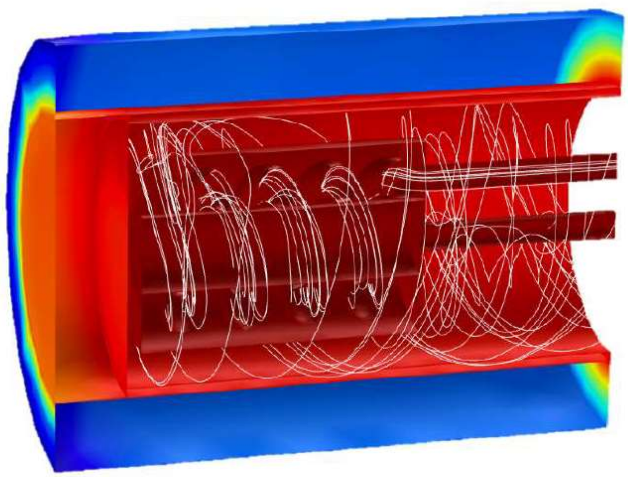
Control Humidity Consistency Check (n=3)		
Weighted Sum Vector {Ws}	Criteria Weights {Pi}	Consistency Factor (Cons)
0.60	0.20	3.00
0.60	0.20	3.00
1.80	0.60	3.00
Average Consistency Vector (λ)		3.00
Consistency Index (CI)		0.00
RI Value (3 Criteria)		0.52
Consistency Ratio (CR)		0.00

Table 47: Supply Power Consistency Check

Supply Power Consistency Check (n=3)		
Weighted Sum Vector {Ws}	Criteria Weights {Pi}	Consistency Factor (Cons)
1.00	0.33	3.00
1.00	0.33	3.00
1.00	0.33	3.00
Average Consistency Vector (λ)		3.00
Consistency Index (CI)		0.00
RI Value (3 Criteria)		0.52
Consistency Ratio (CR)		0.00

Appendix G: Operation Manual

Climatic Camera



Operation Manual

2020 Edition

1

Overview

The Climatic Camera is designed to be used inside an environmental test chamber. Each climatic Camera is unique and should be installed by a qualified technician. All instructions should be read before using the climatic camera. Use at your own risk.

Components

Item #	Item Description	Qty
1	Borescope Camera	1
2	Glass Housing	1
3	Housing Body	1
4	Clamp for Housing	1
5	Clamp set	1
6	Goose neck	1
7	Magnet base	1
8	Pipe Insulation	1
9	Inside pipe	1
10	Anti-reflective glass	1
11	Supply Air Hose	1
12	Desicant Air Dryer	1
13	Main Line to supply adapter	2
14	Ball Valve	1
15	Copper Sleeve	1

Integration

The Climatic Camera is preinstalled and set up for the specific application of Danfoss. **Do Not** attempt to modify any existing parts without consulting the designers. Camera software is to be installed on the user's computer. The Software can be downloaded at http://gto.so/echd.apk. The operation manual for the camera is included with installation and more instructions on how to download the software.

Operation of Climatic Camera

Check air hoses for any signs of degradation or wear. If there are any signs or abnormalities, do not use the climatic camera and replace damaged parts or contact customer service (designers).

1. Verify camera operation
   →Run camera software on user's computer to confirm camera operation.
2. Adjust desired position for the device
   →Open thermal chamber and adjust camera so that the computer screen shows what you want to record.
3. Turn on main ball valve parallel to pipe (shown below)

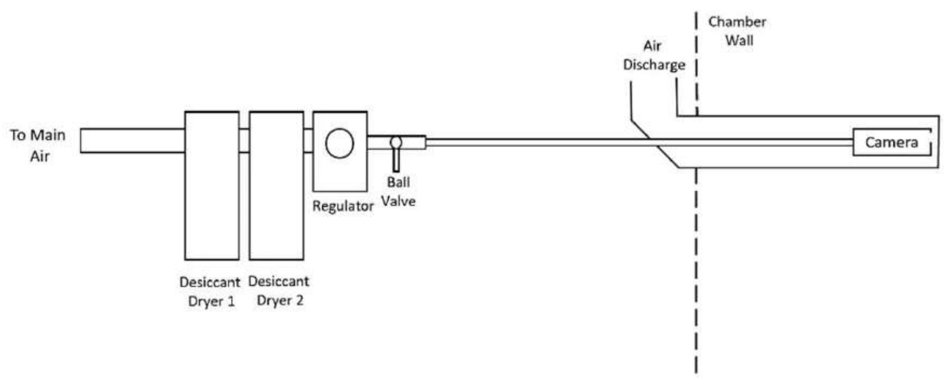
4. Check for any air leakage. If no air is exiting the tube contact service.
5. Verify proper tightness for insulation and clamps along the device.
6. Close thermal Chamber and lock door.
7. Run Climatic chamber test.
8. Periodically check the thermometer and or warning lights to verify the device is in operating temperatures (0 to 45 °C).

After Use: Turn Ball valve Perpendicular to pipe

CAUTION! Camera or any parts located inside the chamber are extremely hot or cold. DO NOT touch without proper PPE.

Troubleshooting

Air Leakages: if there is an air leakage along the air flow pipe, adjust and tighten all pieces to make sure device is airtight. If leakages continue, contact service or designers (likely, parts will have to be changed). An air hose diagram is pictured bellow



Camera not Working: Please verify connection to computer is stable, avoid turning the cable as much as possible. The camera has a waterproof level IP67, if camera stops working and is properly connected it's likely that the temperature exceeded operational values. Try checking for proper operation without chamber test. If camera still doesn't work, a replacement should be ordered. (Air Leakages could affect temperature inside the camera housing, please read our section on Air Leakages in Troubleshooting)

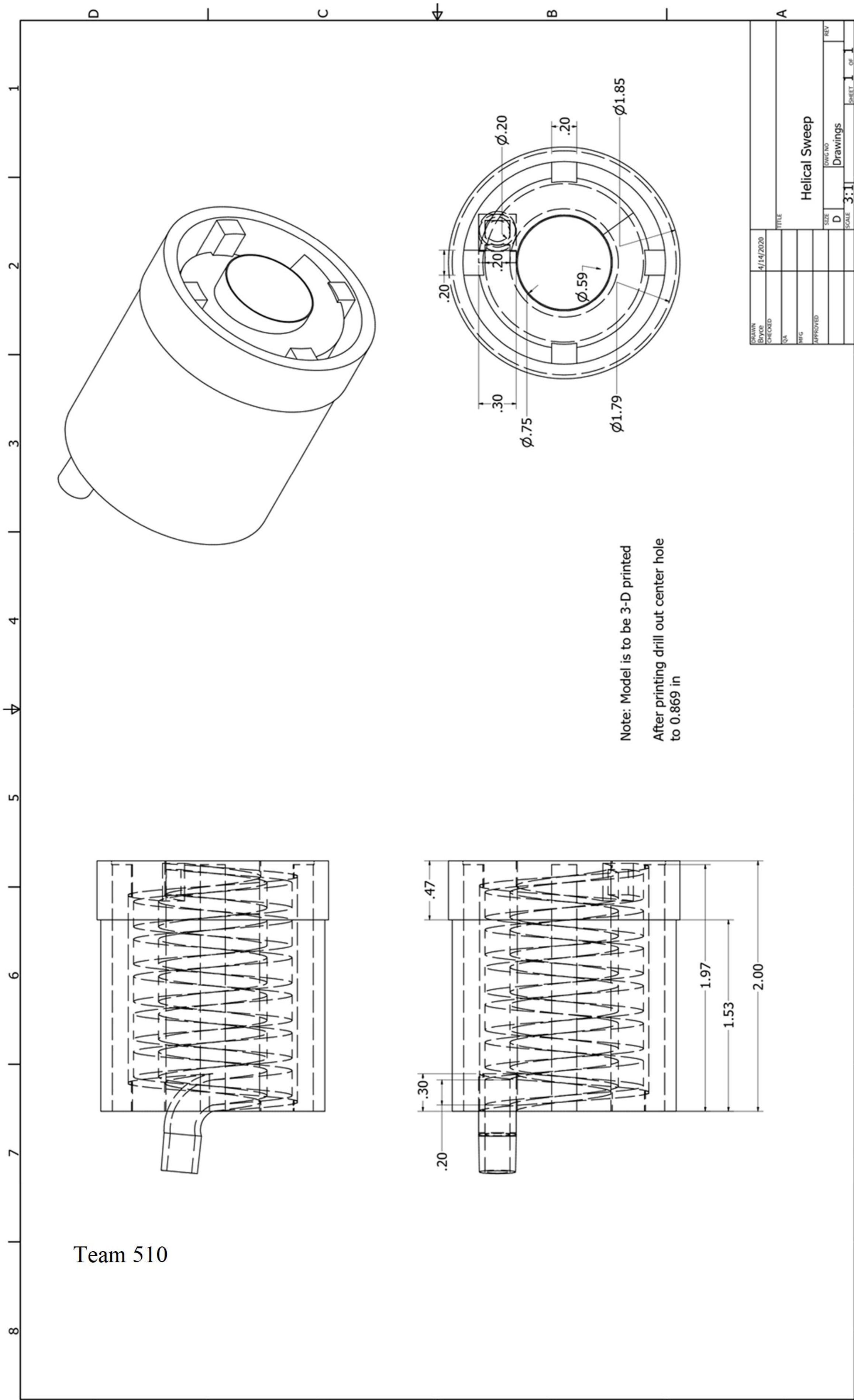
Camera Link: https://www.teslong.com/USB-Endoscope?product_id=195

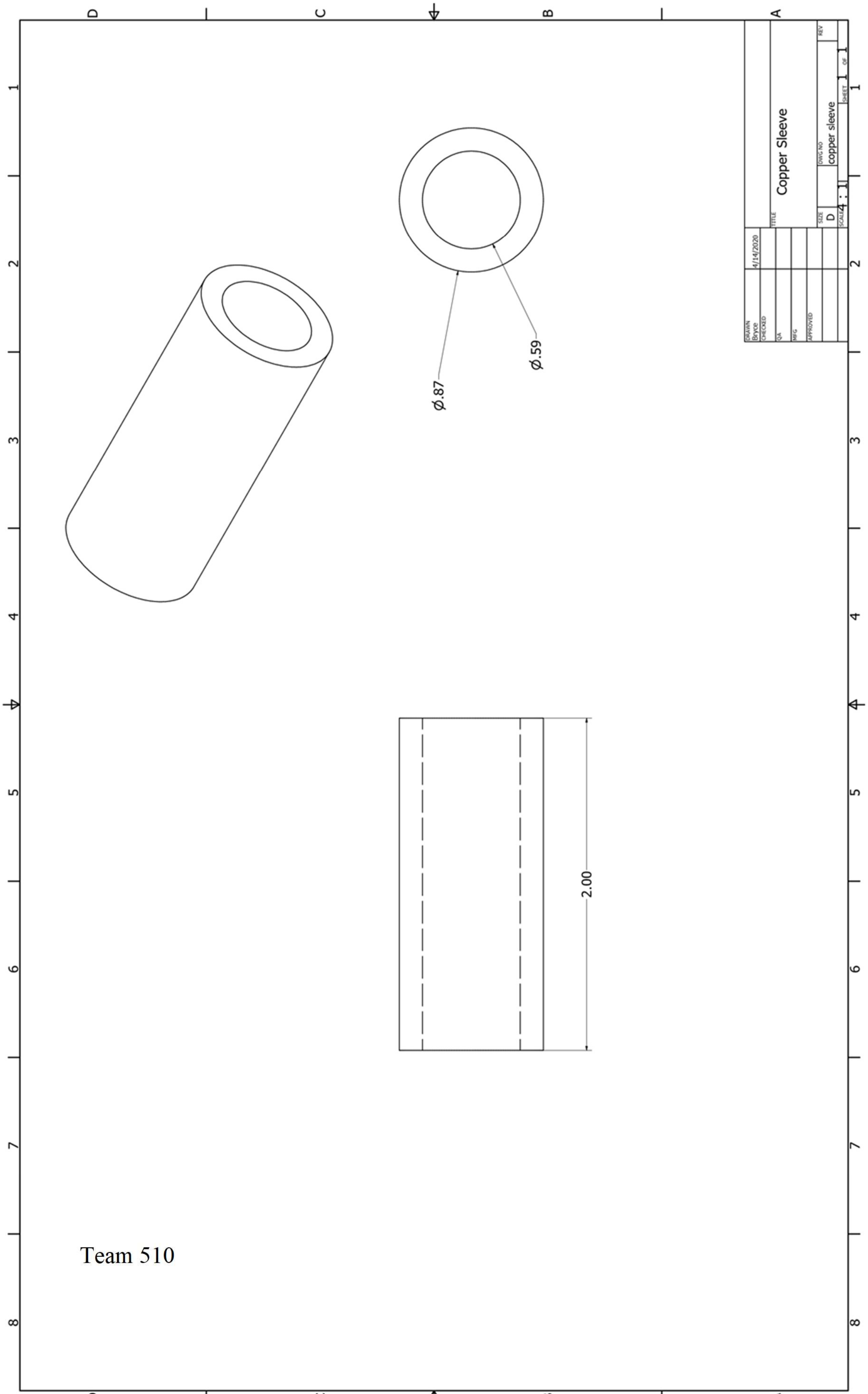
Appendix H: Bill of Materials

Item #	Item Description	Quanti	Price
1	Borescope Camera	1	49.99
2	Glass Housing	1	22.52
3	Housing Body	1	12.22
4	Clamp for Housing	1	$11.39
5	Clamp set	1	$11.90
6	Goose neck	1	$9.95
7	Magnet base	1	$16.99
8	Desicant Air Dryer	1	$129.99
9	Shut-Off Brass Valve	1	$8.98
10	Brass Reducer	1	$3.79
11	Vynil Tubing	1	$9.97
12	Copper rod	1	$25.49
13	Smaller Hose Clamps	1	$2.99
14	ABS Filament	1	$21.99
15	Rubber Whip Hose	1	$8.62
16	Arduino	1	$19.99
17	Temperature sensor	1	$9.99
18	Speaker	1	$11.99
19	Teflon Tape	1	$4.99
20	Pipe Insulation	1	$47.92
21	Inside pipe (Tigerflex)	60	$30.00
22	Anti-reflective glass	1	$60.00
			$531.66

Appendix I: Part Modifications and Engineering Drawings

Part Modifications		
Number	Item Description	Modification
3	Housing Body	Remove Lip from end (1/4”) to leave only ribs
6	Goose Neck	Retap current thread to M8x1.25
11	Vinyl Tubing	Cut to Length
12	Copper Rod	See Engineering Drawings
14	ABS Filament	Used to print Helical Sweep See Engineering Drawings
20	Pipe Insulation	Cut to Length
21	Inside Pipe (Tigerflex)	Cut to Length
22	Anti-Reflective Glass	Cut to 60mm Diameter Circle


Note: Model is to be 3-D printed
After printing drill out center hole to 0.869 in
Ø.20
.20
Ø1.85
.20
.20
Ø.59
.30
Ø.75
Ø1.79
.47
1.97
1.53
2.00
.30
.20
DRAWN
Bryce
4/14/2020
CHECKED
QA
MFG
APPROVED
TITLE
Helical Sweep
SIZE
D
DWG NO
Drawings
REV
SCALE
3:1
SHEET 1 OF 1


Copper Sleeve
DWG NO
copper sleeve
SIZE
D
SCALE
4 : 1
SHEET 1 OF 1
REV
DRAWN
Bryce
4/14/2020
CHECKED
QA
MFG
APPROVED
TITLE
Ø.87
Ø.59
2.00