University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects - ASEN 4018

Systematic Testbed Apparatus for Thermal Infrared Sensors (STATIS)

Conceptual Design Document

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1 Information

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2 Project Description

Team STATIS will be working with Ball Aerospace corporation with the intent to design, build and validate the functionality of a test bed that will characterize a range of commercial off the shelf (COTS) non-contact infrared temperature sensors, by testing their accuracy and precision over variable distance and on different target surfaces when compared to contact based temperature sensors, in a simulated space environment. Specific requirements for these parameters will be defined further in Sections 2.4 and 3.

2.1 Project Purpose

The motivation for this project is twofold; the project stems from the complex wiring systems currently used for recording temperature data aboard spacecraft as well as an inability of current sensors to record accurate temperature data where direct contact is not an option. Currently contact based sensors are used aboard space systems to sense all temperatures required for mission success. Contact based sensors present problems specifically at moving interfaces on spacecraft, as they require complex wiring systems and flexible circuits to span over moving parts and joints. The use of these complex wiring systems requires expensive and time consuming reliability testing as well as introducing many sources of risk into the system, which is directly correlated to additional expense and time. Single-point failures are one risk associated with contact based sensors that can be mission ending. Additionally contact based sensors cannot be used in certain applications where direct contact would mar and reduce the overall effectiveness of the surface. Mirrors used for space telescopes are a prime example of these surfaces where direct contact is not possible as the mirror would not function correctly with particulates on it let alone an entire sensor. For additional application and previous work in the area refer to the Preliminary Design Document for the STATIS project.

2.2 Functional Block Diagram

A functional block diagram was created to better understand the interfaces and data relay of the STATIS system. The following describes the command system setup. Once the test bed is installed inside and the thermal chamber has been pumped down to a pressure less than 1.0e-5 torr, the tester will initiate a set of commands from the control software of the test station computer. The commands will consist of a target temperature and sensor temperature commands (in the range of 250-350K and 275-325K respectively), a target selection (5 target materials), and a separation distance command in the range of 7-76 mm. This information will travel by wire to the digital-to-analog converter (DAC) through the test chamber cable pass-through. A depiction of this process is shown in Figure 1 .

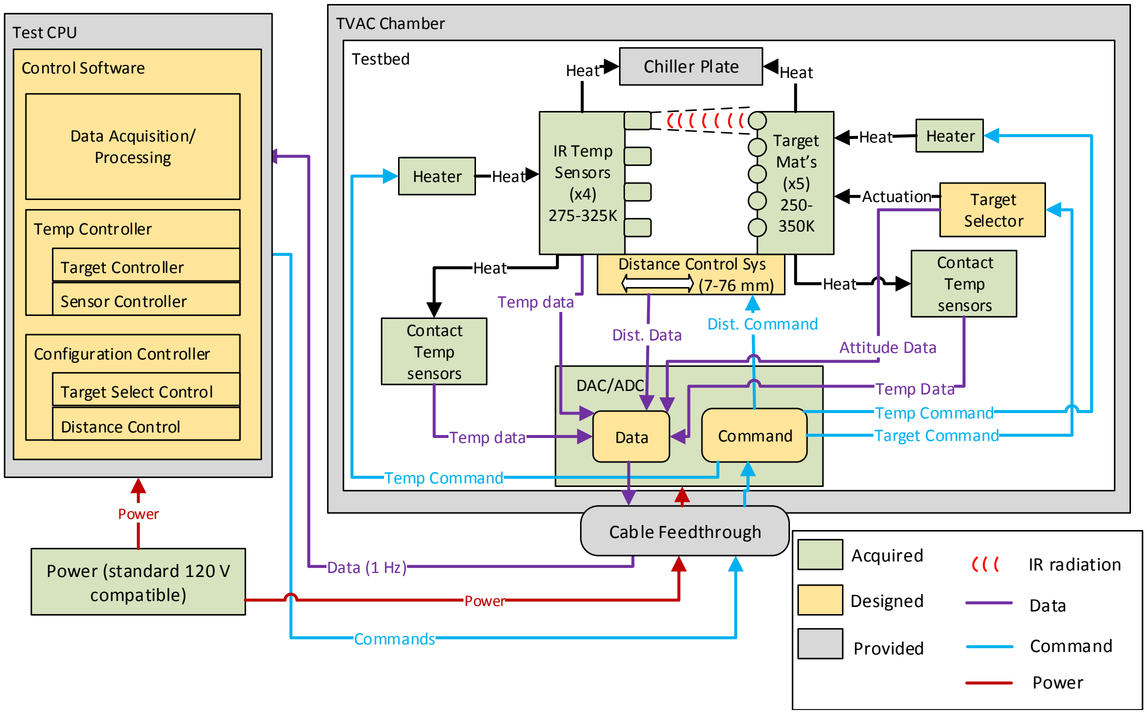

Figure 1: Function Block Diagram

2.3 Concept of Operations

The concept of operations shown in Figure 2 highlights the major steps required to operate STATIS, from integration into the thermal vacuum, through testing of our various parameters and finally removal from the chamber and data analysis. The general procedure will be interfacing with the chamber, depressurizing the chamber, varying parameters of interest and data collection, re-pressurizing the chamber, and removal of the testbed from the chamber along with data analysis. The CONOPS below additionally mentions the potential for future work.

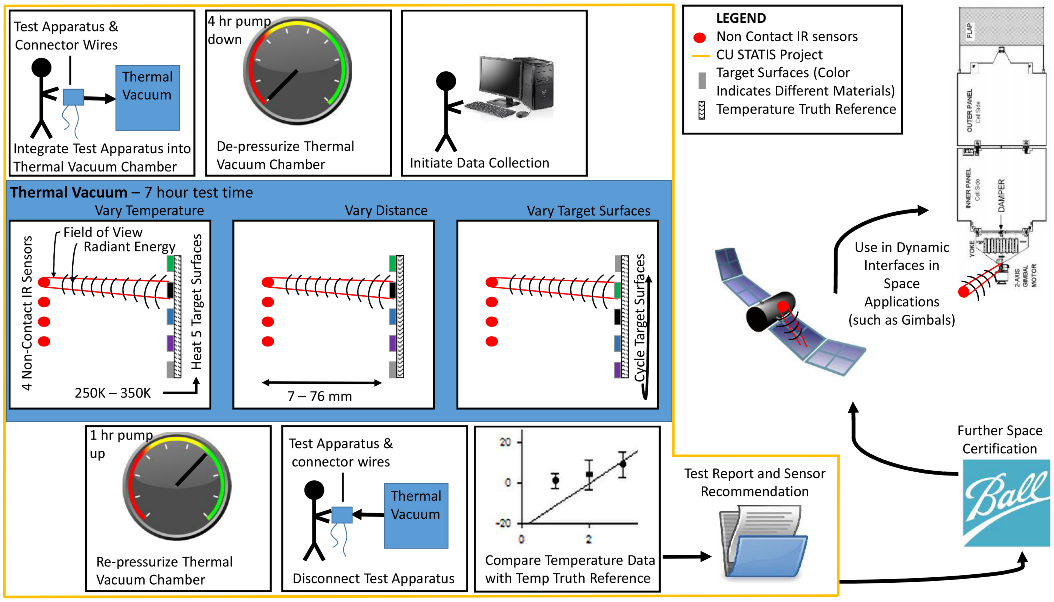

Figure 2: Concept of Operations

2.4 Functional Requirements

Functional Requirements have been established which will lead to design requirements and specifications. The functional requirements consist of three requirements which cover various aspects of the testbed. **FR 1** examines the testbed functionality, **FR 2** examines data collection, and **FR 3** covers integration into the TVAC.

FR 1 STATIS shall vary parameters relevant to characterizing the performance of COTS non-contact infrared temperature sensors.

FR 2 STATIS shall collect measurement data required to characterize the performance of the COTS IR sensors.

FR 3 STATIS shall be designed for use within Ball Aerospace's thermal vacuum chamber.

3 Design Requirements

FR 1 STATIS shall vary parameters relevant to characterizing the performance of COTS non-contact infrared temperature sensors.

DR 1.1 The distance between the target surface and non-contact infrared temperature sensor shall be adjustable through user input commands.
Motivation: The intent is to determine whether distance is a contributing factor to temperature accuracy of the non-contact IR sensors.
V&V: Successful verification of **DR 1.1.1** through **DR 1.1.4**.

DR 1.1.1 The minimum distance between the target surfaces and non-contact IR sensors shall be 7mm.
Motivation: The intent is to eliminate the risk of collision between the non-contact IR sensors and target surfaces as one method of heat transfer in a vacuum is conduction, that could result in measurement errors from the non-contact IR sensors. Additionally launchh vibrations resulting in contat must be considered as this could damage sensors.

V&V: Inspection - Ensure that the minimum distance from target surface to tip of non-contact IR sensors is 7mm by using calibrated calipers outside of Thermal Vacuum chamber before test cycles begin.

DR 1.1.2 The maximum distance between the target surfaces and non-contact IR sensors shall be 76mm.
Motivation: The intent is to replicate the expected maximum distance between the non-contact IR sensors and target surfaces in the intended applications of non-contact IR sensors on space systems, such as measuring the temperature of a pointing mirror.
V&V: Inspection - Ensure that the maximum distance from target surface to tip of non-contact IR sensors is 76 mm by using calibrated calipers outside of Thermal Vacuum chamber before test cycles begin.

DR 1.1.3 The distance between the target surfaces and non-contact IR sensors shall be modified by three incremental steps by the mechanical-bearing ball-screw linear stage with an A3200 software-based machine controller (both provided by Ball Aerospace).
Motivation: The intent is to test the full range of distances between 7mm and 76mm in the intended applications while conducting the test in the allotted time.
V&V: Demonstration - The stage shall demonstrate its capabilities to control distance at the chosen steps outside of the Thermal Vacuum with calibrated calipers.

DR 1.1.4 The distance between the target surfaces and non-contact IR sensors shall be modified with an accuracy of ±6 micrometers, as prescribed by the accuracy of the linear stage.
Motivation: The intent is to have an absolute knowledge of what distance the sensor is at relative to the target surface.
V&V: Demonstration - The stager specifications shall be verified with the use of calibrated calipers.

DR 1.2 The temperature of the target surface shall be adjustable through user input commands.
Motivation: The intent is to represent a range of temperatures that surfaces would be exposed to in a space environment in order to investigate whether the non-contact IR sensors are accurate over this range. Commanding capability is necessary to adjust the target temperatures while the test bed is inside the thermal vacuum chamber.
V&V: Successful verification of **DR 1.2.1** through **DR 1.2.2**.

DR 1.2.1 During steady state control of the target materials, the variance of the temperature data shall remain within 0.1K in an interval of 30 seconds.
Motivation: The intent is to control the target surfaces to at least the uncertainty of the temperature truth sensor.
V&V: Test - The standard deviation of the steady state data will be evaluated in rolling 30 second intervals to confirm compliance.

DR 1.2.2 The target surfaces shall be commandable in temperatures ranging from 250 - 350K.
Motivation: The intent is to maintain temperatures within a range that components on a thermally controlled spacecraft must withstand.
V&V: Test - Examine data received from the contact ‘temperature truth’ reference sensors.

DR 1.2.2.1 The target surfaces shall increase in temperature at a minimum rate of 20K/hr.
Motivation: The intent is to test the apparatus in the allotted time based on limited access to the thermal vacuum chamber.
V&V: Test - Calculate rate from recorded temperature and time stamp data.

DR 1.2.2.2 The target surfaces shall decrease in temperature at a minimum rate of 5K/hr.
Motivation: The intent is to test the apparatus in the allotted time based on limited access to the thermal vacuum chamber.
V&V: Test - Calculate and confirm rate from recorded temperature and time stamp data.

DR 1.2.2.3 The temperature of the target surfaces shall be modified in incremental steps of 10K.
Motivation: The intent is to test the full range of temperatures between 250K and 350K to determine if/when sensors begin to lose accuracy while conducting the test in the allotted time.
V&V: Test - Examine data recorded to ensure it maintains the requirement in **DR 1.2.2** and is at the designated target temperature.

DR 1.3 Every target surface temperature will be measured by every non-contact IR temperature sensor during the allotted test time.
Motivation: The intent is to determine how well a non-contact IR sensor measures temperatures on different materials commonly found on spacecraft.
V&V: Successful verification of **DR 1.3.1** and **DR 1.3.2**.

DR 1.3.1 Five target surfaces shall be integrated into STATIS.
Motivation: The intent of using five targets is cover a significant sample of common materials used in spacecraft. Due to time, budget, and spatial constraints (see **DR 3.5**) this number must be limited to five.
V&V: Inspection - Five target surfaces will be verified to be the proper surfaces as specified by **Spec 1.3.1**.

Spec 1.3.1 The surfaces shall be Anodized Aluminum, Chromated Aluminum, Standard Graphite Composite, Glass and, Z306 Emissive Paint.

DR 1.3.1.1 The area of the target surfaces shall be large enough such that the FOV of each non-contact IR sensor is spanned completely by the target surfaces at the maximum separation distance of 76 mm. The size of the targets must also be compatible with the chamber volume, see **DR 3.5**.
Motivation: The intent is to ensure the target material spans the entire field of view of the non-contact IR sensors in order to isolate only the radiation emitted from the target under test. This is critical to ensuring the temperature readings are properly measured.
_V&V:_ Test/Inspection - The sizes of the target surfaces will be determined mathematically given the FOV specification of the non-contact IR sensors and the maximum separation distance of 76 mm; the resulting sizes and cuts will be verified by measurement through the use of calibrated calipers prior to STATIS entering the thermal vacuum chamber.

DR 1.3.2 Four non-contact IR temperature sensors shall be integrated into STATIS.
Motivation: The intent is to use multiple sensors in order to get a sample of the available technology and compare data from different non-contact IR sensors in order to validate performance.
_V&V:_ Inspection - Four non-contact IR sensors will be verified to be within the testbed before STATIS enters into the thermal vacuum chamber.

FR 2 STATIS shall collect measurement data required to characterize the performance of the COTS IR sensors.

DR 2.1 The temperatures of the target surfaces shall be collected using conventional contact sensors.
Motivation: The intent is to know the target surface temperatures as accurately as possible in order to find the error of the infrared temperature sensors' measurements. This is achievable using reliable and accurate contact sensors.
_V&V:_ Successful verification of **DR 2.1.1** and **DR 2.1.2**.

DR 2.1.1 The temperature of the targets shall be collected 30 times over a 30 second period at equal intervals.
Motivation: The intent is to collect enough data to determine any temperature drift in the system.
_V&V:_ Demonstration - 30 measurements will be taken over a 30 second period.

DR 2.1.2 The absolute temperature of the targets shall be collected with an accuracy of 1K or less.
Motivation: The intent is to have a reliable measurement within 10% of the temperature change described in **DR 1.2.2.3** from which to compare temperature data.
_V&V:_ Demonstration - The temperature truth reference will be calibrated based on the product calibration charts provided by the supplier.

DR 2.2 The distance between the non-contact infrared temperature sensors and targets shall be known.
Motivation: The intent is to determine if the distance between the IR sensor and the target has an effect on IR sensor accuracy; the distance must be known to verify any correlation.
_V&V:_ Successful verification of future requirements.

DR 2.3 The sensor under test (SUT) and target under test (TUT) pair (STP) shall be known.
Motivation: The intent is to properly correlate data with each test, therefore the STP must be known while taking data.
_V&V:_ Successful verification of **DR 2.3.1** through **DR 2.3.3**.

DR 2.3.1 Each sensor shall be assigned a unique sensor ID, which shall be collected when taking data from sensor.
Motivation: The intent is to have absolute knowledge of which sensor is being tested such that data is correlated with the appropriate sensor.
_V&V:_ Demonstration - STATIS shall show knowledge of the sensor's unique ID.

DR 2.3.2 Each target shall be assigned a unique target ID, which shall be collected when taking data from target.
Motivation: The intent is to have absolute knowledge of which target surface is being tested such that data is correlated with the appropriate surface.
_V&V:_ Demonstration - STATIS shall show knowledge of the target's unique ID.

DR 2.3.3 The STP under test shall be correlated with each measurement of the targets.
Motivation: The intent is to compare the data from each STP, the STP must be correlated with the data in order to understand it.
_V&V:_ Demonstration - STATIS shall demonstrate data relay for the given STP prior to entry into the thermal vacuum.

DR 2.4 Upon completion of any test sequence, a file shall be created that contains data requested in **DR 2.2** and **DR 2.3**.
Motivation: The intent is that data are only useful if it can be stored for later analysis in a form that is generally

accessible.
V&V: Successful verification of **DR 2.4.1** & **DR 2.4.2**.

DR 2.4.1 The file output shall be in a UTF-8 encoded comma separated value text file.
Motivation: The intent is that data collected must be in a universally accessible format.
V&V: Demonstration - The testbed software will have the capability of outputting data collected into a file.

DR 2.4.2 The testbed software shall be capable of creating a data file at any time during testing.
Motivation: The intent is to create a file with any amount of collected data as a test sequence is not a defined amount of data.
V&V: Demonstration - The testbed software will have the capability of creating a data file at any time.

DR 2.5 All data shall be timestamped relative to the start of each test sequence.
Motivation: The intent is to correlate data with the correct environmental conditions.
V&V: Successful verification of **DR 2.5.1** & **DR 2.5.2**.

DR 2.5.1 Data shall be time-stamped with a resolution of 100ms or better.
Motivation: The intent stems from the highest frequency of collection which is 10Hz, therefore timestamps must have a resolution of 100ms.
V&V: Inspection - The internal clock counter of the DAQ will have a precision of 100ms or better.

DR 2.5.2 Data shall be time-stamped with an accuracy of ±50ms or better from the start of a test cycle.
Motivation: The intent is that relative time of data measurements within each test shall be within the range of the resolution in **DR 2.5.1**.
V&V: Inspection - The internal clock of the DAQ will not have a drift parameter greater than 50ms over the course of the maximum test duration.

FR 3 STATIS shall be designed for use within Ball Aerospace's thermal vacuum chamber.

DR 3.1 All required electronic connections between STATIS and test computer shall be compatible with the thermal vacuum cable pass-through.
Motivation: The intent is to ensure that all connections are efficiently fed through in a manner that protects the data, STATIS, and the thermal vacuum chamber.
V&V: Successful verification of **DR 3.1.1** through **DR 3.1.3**.

DR 3.1.1 The pass-through electrical interface must be able to connect to 3 37 pin round connectors or 2 25 pin D connectors.
Motivation: The intent is that these are the connections available on the thermal vacuum chamber to be used as prescribed by the integration control document.
V&V: Inspection - STATIS is able to physically connect to the provided 3 37 pin round or 2 25 pin D connector interface.

DR 3.1.2 STATIS shall be able to transmit the necessary data via the 3 37 pin round or 2 25 pin D connector interface.
Motivation: The intent is that the interface must relay the proper data back to the DAQ from the interior of the thermal vacuum chamber.
V&V: Test - STATIS is able to transmit data from the interior of the thermal vacuum chamber to the DAQ system.

DR 3.1.2.1 STATIS shall not communicate at frequencies above 7.5MHz with the feed through system.
Motivation: The intent is that at frequencies above 7.5MHz, a 2 meter cable is a significant proportion of the wavelength (λ/20).
V&V: Demonstration - Data sent through the chamber will not exceed 7.5MHz.

DR 3.1.2.2 STATIS shall be capable of sending analog and digital signals, within the voltage and current specifications of the TVAC chamber, with the feed through system.
Motivation: The intent is that signal levels, both voltage and current, cannot exceed the ratings of the connectors and wires.
V&V: Demonstration - Voltages and currents will be within the connector and wire specifications.

DR 3.1.2.3 The resistance of wires carrying analog signals connected through the TVAC chamber shall be known to within 3Ω.
Motivation: : The intent is that temperature measurements need to have an accuracy of 1K, an unknown cable resistance of greater than 3Ω will break this requirement for thermistors. (Calculations in separate document)
V&V: Inspection - Pass through cables will be measured by an ohmmeter with better than 3Ω accuracy.

DR 3.1.3 All electrical connectors shall be grounded as prescribed by the thermal vacuum chambers integration control document.
Motivation: The intent is that the electrical setup must be safely integrated with the thermal vacuum chamber in order to prevent damage to the thermal vacuum chamber or STATIS.
V&V: Inspection - STATIS grounding connections will be checked and cross referenced to the thermal vacuums grounding as prescribed by the thermal vacuums integration control document.

DR 3.2 The IR temperature sensors shall remain within the temperature range of 275 to 325K.
Motivation: The intent is to ensure that all IR temperature sensors will remain within the temperature range required for normal operation.
V&V: Test - A temperature truth reference reading will be taken within the insulating mechanism for the IR temperature sensors to monitor their temperatures and ensure they remain within in the range specified.

DR 3.3 The electronics package in the test chamber shall remain within the operating temperature range of the most temperature sensitive device.
Motivation: The intent is to ensure that all electrical components will remain within the temperature range required for normal operation.
V&V: Test - A temperature truth reference reading will be taken within the insulating mechanism for the electronics package to monitor the temperature of all components and ensure it remains within in the range specified.

DR 3.4 All STATIS components entering the thermal vacuum chamber shall operate within the vacuum environment.
Motivation: The intent is to mimic the pressure and temperature differentials the non-contact IR sensors would encounter in space with a thermal vacuum chamber.
V&V: Successful verification of **DR 3.4.1** and **DR 3.4.2**.

DR 3.4.1 All components shall operate at pressures less than 1e-5 torr.
Motivation: The intent is to mimic the 1e-5 torr pressures a spacecraft would experience in Low Earth Orbit (LEO). The altitude for low earth orbit ranges from 200km to 2000km[1].
V&V: Demonstration - STATIS will be placed in the thermal vacuum chamber and provide operation results similar to the ones obtained when STATIS is run at ambient pressure.

DR 3.4.2 All STATIS components entering into the thermal vacuum chamber shall meet the standards prescribed by Ball Aerospace's integration control document with respect to outgassing.
Motivation: The intent is to outgas molecules that could interfere with the tests being conducted by STATIS or contaminate the chamber.
V&V: Inspection - All specifications sheets will be cross referenced with Ball Aerospace's integration control document to ensure only allowed materials enter the thermal vacuum chamber. Or unallowed materials will undergo the ”bake out” out process as prescribed in Ball Aerospace's integration control document in a bake out chamber prior to STATIS entrance into the thermal vacuum chamber.

DR 3.5 Testing operations performed by STATIS shall be elected and organized so that testing may be completed within 12 hours inside a thermal vacuum chamber.
Motivation: The intent is to conserve time and resources, as thermal vacuum testing can be extremely time consuming and expensive.
V&V: Demonstration - STATIS shall be tested and utilized in a thermal vacuum chamber during a 12 hour window.

DR 3.6 The testbed shall fit within the operating environment of the cylindrical thermal vacuum chamber.
Motivation: The operating volume of the thermal vacuum chamber is finite and limited to the dimensions provided.
V&V: Successful verification of **DR 3.6.1** through **DR 3.6.3**.

DR 3.6.1 STATIS shall not exceed a width of 0.720 m as provided by Ball Aerospace's thermal vacuum chamber integration control document.
Motivation: See **DR3.4**.
V&V: The width of STATIS shall be measured by a meter stick.

DR 3.6.2 STATIS shall not exceed a depth of 1.829 m as provided by Ball Aerospace's thermal vacuum chamber integration control document.
Motivation: See **DR3.4**.
V&V: The depth of STATIS shall be measured by a meter stick.

DR 3.6.3 STATIS shall not exceed a height of 1.3308 m as provided by Ball Aerospace's thermal vacuum chamber integration control document.
Motivation: See **DR3.4**.
V&V: The height of STATIS shall be measured by a meter stick.

4 Key Design Options Considered

In order to start the discussion of how to design and build STATIS, methods for fulfilling each one of the design requirements should be examined and reviewed. STATIS can be broken down into four main subcategories of design. Figure 3 is a design tree created in order to break up the areas of STATIS that could have multiple and succinctly different design options. The flow down of this tree is created in such a way that along each branch, decisions must be made in a way that meets the needs of the project. The four main subcategories are, sensors, thermal, mechanical, software/electrical. The sensors category is directly correlated with an initial analysis as to what considerations to look into further regarding COTS non-contact infrared sensors and contact based sensors. The thermal category deals with how the temperature of the sensors (contact, non-contact) and target surfaces will be regulated and controlled with in the thermal vacuum environment. The mechanical category includes design options that include how to vary the distance between the non-contact sensors and the target surfaces and how to cycle or swap through the various combinations of four non-contact IR sensors and five target surfaces. The software and electrical design options are to a larger extent independent of the other design option subcategories. This category deals with how the electrical and software components meet the functional and design requirements specified in Section 3.

When approaching the design problem, an initial set of design studies was performed for each of the four subcategories mentioned above. Each category was examined in terms of methods which would allow for different solutions in the specified category. For example, different types of heaters are discussed in the thermal section. Following the subcategory discussion, three concepts were pulled together using the various category's design options. The concepts were formulated in a way that combined the subcategory ideas such that each component would interface well with the others. For example, patch heaters work better than cartridge heaters in certain situations. This sort of analysis is considered in the discussion below. Additionally, it was determined that the software/electrical components should be considered separately through this entire process, as the method for electrical and software control is almost entirely independent of the thermal/mechanical considerations. Interfacing is the only component that will depend on the mechanical/thermal concept chosen, and that is a trivial component at this point in the design. For this reason, the software/electrical category has its own pros and cons as well its own trade study towards the end of the report. The following design discussion overviews each of the 4 subcategories, the two electrical/software concept ideas, and the three mechanical/thermal concept ideas formulated.

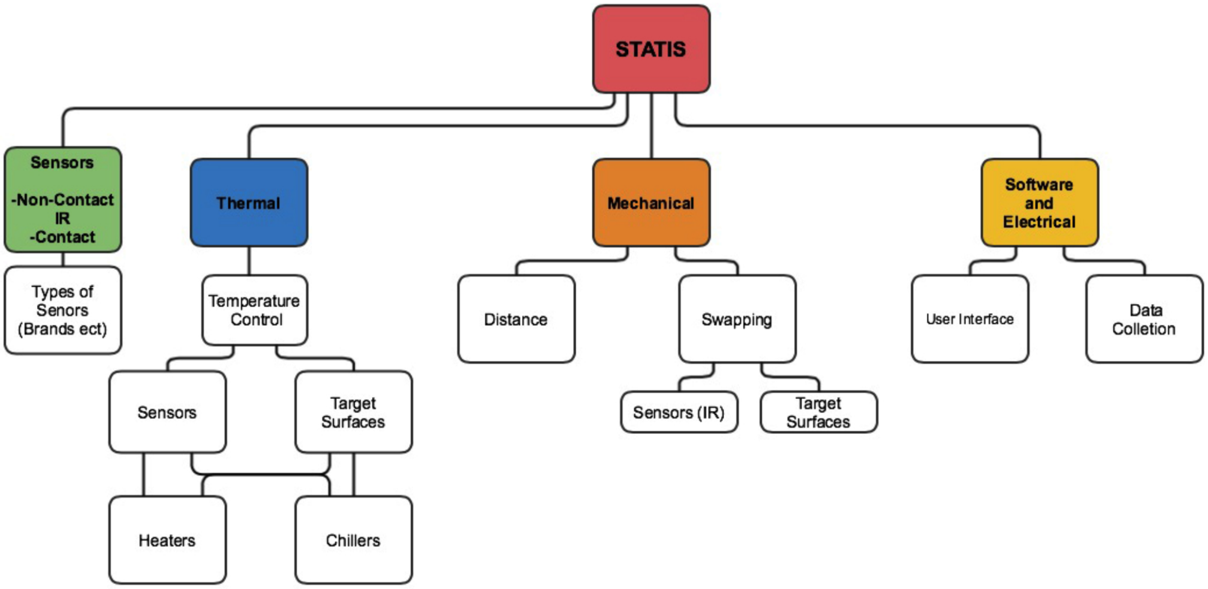

Figure 3: STATIS Design Tree

4.1 Subsystem Analysis

4.1.1 Mechanical

The mechanical elements of the design stem from **FR 1**, which states that STATIS needs to be able to change the distance between the IR sensors and the targets as per **DR 1.1** and that each target will be measured by each sensor in one TVAC test cycle per **DR 1.3**.

4.1.1.1 Distance Actuation

In order to remain within budget, hit the range (**DR 1.1.1** & **DR 1.1.2**), and precision (**DR 1.1.4**) required, the customer will provide a TVAC rated stage for STATIS. Should this stage not be available, STATIS will do all other operations and manually change the distance in between TVAC test cycles.

4.1.1.2 Target Cycling

The testing also requires actuation to allow each IR sensor to take a reading from each target as outlined in **DR 1.3**. In order to begin looking at cycling, the STATIS team first researched different methods of actuation. The three methods that are commonly used in TVAC testing are a manual push-pull, pneumatic, and electric motor based mechanical movement.

4.1.1.2.1 Manual Push-Pull

Manual push-pull was a method that was seen in other TVAC test beds but was thrown out after talking with Ball. Several companies sell mechanisms that use billows and magnets to allow a rod to be controlled from the outside of the chamber, go through the wall, and then cause a distance change inside the chamber. This method is simple and much cheaper than other options. That being said, it was thrown out as a feasible design option upon finding out that none of the Ball TVAC chambers have the required flange that is necessary to install the push-pull mechanism. Thus, opening the chamber and physically moving components would be the only way to manually change the test setup.

4.1.1.2.2 Pneumatics

A pneumatic actuator inside the chamber would be connected to existing ports on the TVAC chamber. On the outside of the chamber would be a connection with a valve that would cause the pneumatic piston to move up or down depending on the pressure of gas supplied. Linear potentiometers, standard cheap sensors that produce a voltage difference proportional to displacement distance, may be used to measure the distance traveled by the pneumatic actuator. This method is shown in the linear rail design in section 4.2.2 on page 20.

Table 1: Pneumatics Pros & Cons

Pros	Cons	Unknowns
TVAC chambers already have ports which allow gasses into the chamber.	Leaking pneumatic gasses in TVAC chambers because of bad connections is a potential problem. This would cause the TVAC chamber pressure to increase and the desired position to start drifting.	Approximate cost estimates - Vendors were contacted and are either unresponsive or unwilling to give an estimate in preliminary design phase.
All of the valves would also be outside of the TVAC chamber, which means that they would not have to have the same cleanliness ratings as the components inside of the chamber and thus the cost would be lower.	Cannot be easily used for rotational movement.	

4.1.1.2.3 Electric Motor

An electric motor was the final mechanical actuator considered. Motors require an electronic interface to control when and how far they are operated. The use of a stepper motor removes the need for an additional rotation sensor since it can be calibrated to rotate through a predetermined angle and thus was the primary focus in preliminary design concepts. The degrees of rotation per step can be used to calculate how many peaks in a square wave are necessary for commanding the desired actuation when the gearing is precisely designed. This method is used in both the pentagonal cylinder and annular array concept designs in sections 4.2.1 on page 17 & 4.2.3 on page 23.

Table 2: Electric Motor Pros & Cons

Pros	Cons	Unknowns
Stepper motors can be used in conjunction with a rail system for linear motion or provide torque to a wheel to create rotational motion.	Very expensive to buy stepper motors that are TVAC compatible. The cheapest found thus far is over $2000.	Non stepper motors might need to be coupled with additional sensors to ensure the correct position is reached.
Only interface needed is for it to be mounted and for electrical signals to go through the existing electrical ports on the TVAC.	The cheaper the motor the less power it provides which means the cost could drive how fast the apparatus would be able to move and the mass of the apparatus.	

4.1.2 *Thermal*

The thermal elements of the STATIS project will regulate the temperatures of the targets as per requirement **DR 1.2** and maintain temperatures of the IR sensors and support electronics in an operable temperature range as per requirements **DR 3.2** & **DR 3.3**. Temperature control revolves around controlling the thermal flux into and out of the system of interest such that a desired equilibrium temperature may be attained. The testbed system of concern is depicted below in Figure 4 .

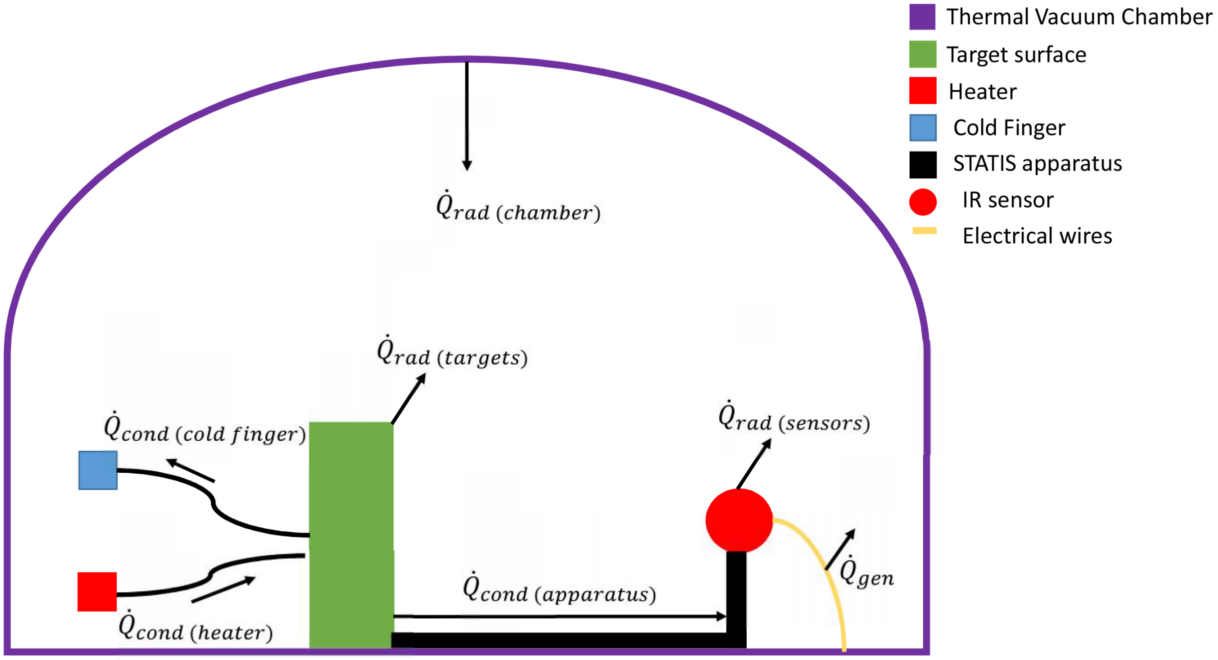

Figure 4: Thermal simplification of testbed

The traditional approach to thermal control involves the use of heat sinks to remove more thermal energy than the system creates and heaters to supply thermal energy back into the system. For steady state analysis (a valid assumption if **DR 1.2.1** is met),

$$\dot{Q}_{gen} + \dot{Q}_{in} - \dot{Q}_{out} = 0 \tag{1}$$

where the rates in and out of the system are a combination of the contributing factors of conduction, convection, and radiation. In a vacuum, however, there is no convective fluid and so the convection is negligible providing a final thermal flux balance equation shown in Eq. 2 .

$$\dot{Q}_{gen} + \dot{Q}_{in,cond} + \dot{Q}_{in,rad} = \dot{Q}_{out,cond} + \dot{Q}_{out,rad} \tag{2}$$

$\dot{Q}_{gen}$ accounts for heat that is generated due to the operation of electronics and motors as the tests are performed. As a simplifying assumption, $\dot{Q}_{rad}$ will consider only radiation from the target surfaces, sensor and chamber at this phase in the design as they are the largest contributors in size. $\dot{Q}_{cond}$ considers conduction that occurs via thermal straps and via the structure of the testbed itself.

4.1.2.1 Conductive Heat Sink Feasibility

It is critical that the thermal system is able to keep the target surfaces at a steady state temperature in the 250-350K range during data collection as per **DR 1.2**. This preliminary thermal model approximates the rates of heat transfer in each of the three considered design concepts. The thermal model used to analyze the steady state heat transfer of the targets considers 3 paths: radiation between the target surfaces and the surrounding chamber shroud, heat conduction into the targets from a heater, and heat rejection to the chamber cold finger by conduction as in Figure 4 on page 11.

With regard to heat transfer by radiation, the temperature of the thermal vacuum chamber wall is approximated at 290K because a large volume of air at room temperature surrounds the chamber. Based on the estimated surface area of the targets and an internal wall temperature of 290K, the rate of heat transfer by radiation is calculated. The targets are treated as black bodies (emissivity equal to unity) to provide an upper limit approximation for the rate of heat transfer between the targets and chamber wall. When the targets must be held at a steady 250K the surrounding chamber will radiate energy into the targets at the maximum rate; this minimum temperature steady state condition therefore drives the steady state requirement for heat rejection.

The rate of heat transfer out of the system by conduction must be equal to the total heat transfer into the system (via radiation from the shroud and conduction from the heater). This will achieve equal and opposite rates of heat transfer. Heat rejection is accomplished by conduction to the cold sink of the TVAC chamber, maintained at a steady 50 K. The required cross-sectional area of the conducting material, A_{xsect}, can be estimated using basic 1D heat conduction analysis. It is assumed throughout that the separation distance between the target and cold sink is 1 meter to analyze a ”worst case” scenario. With the heater completely off and the targets at 250 K, the heat rate balance and required A_{xsect} are expressed by Eqs. 3 & 4 :

$$A_{targets}\sigma(T_{wall}^4 - T_{target}^4) + \dot{Q}_{gen} = \frac{kA_{xsect}}{L}(T_{target} - T_{cold}) \tag{3}$$

$$\dot{Q}_{gen} = 0W \rightarrow A_{sect,min} = \frac{LA_{target}\sigma(T_{wall}^4 - T_{target}^4)}{k(T_{target} - T_{cold})} \tag{4}$$

Figure 5 plots the required cross-sectional area of the conducting path (1 meter in length) for a given target surface area at the 250 K steady state condition:

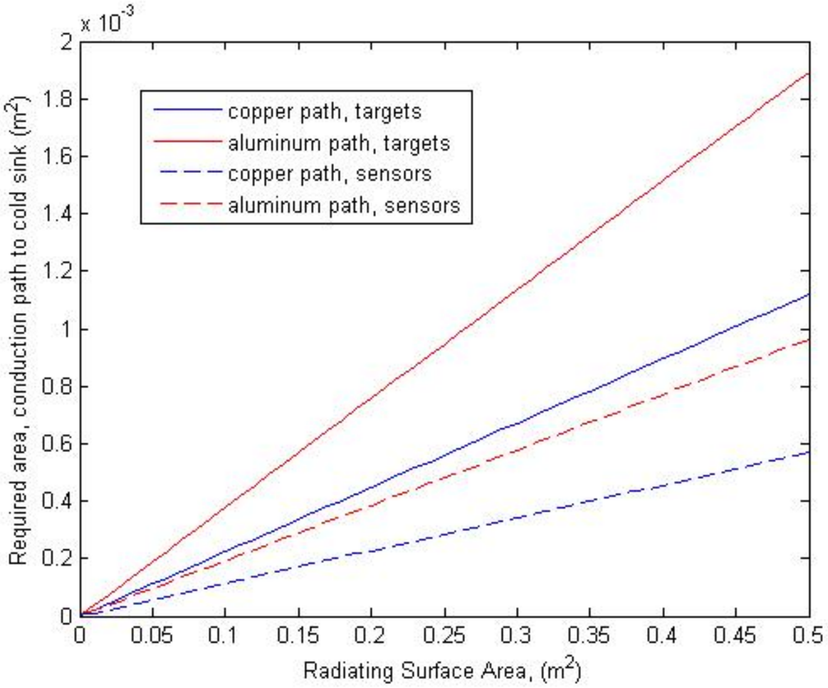

Figure 5: Required Area of Cold Sink Conduction Path vs. Radiating Surface Area

Based on the estimated surface area of the targets, $A_{targets}$, in each design concept, the value of A_{xsect} was calculated. With this value set, the rates of heat transfer by radiation and conduction with the cold sink was calculated for any desired steady state temperature in the 250-350 K range. The resulting net rate of heat transfer out then determines the required power that must be produced by the heater/s to balance the energy rates. This same exact analysis can be applied independently to the sensor housing, which must be kept between 275 and 325K. This smaller temperature range enforces different requirements for heat rejection from the sensors, hence the separate lines plotted in Figure 5 on page 12. This simple preliminary thermal model is the basis for quantifying rates and testing the feasibility of temperature control in each design concept.

It is important to note that this preliminary model only considers heat transfer requirements at steady state, and that system mass was not a factor. Future thermal models must address the behavior of the system during transient periods in order to finalize a design capable of changing temperature at the rates specified in **DR 1.2.2.1** and **DR 1.2.2.2**. Mass is a critical variable regarding the temperature stability of the system. The testbed must be capable of both changing temperature and holding temperature constant. With respect to changing the temperature, the system mass must be small enough such that the rates specified in **DR 1.2.2.1** and **DR 1.2.2.2** are met. The system mass also must be large enough such that temperature control system is able to meet **DR 1.2.1**; the control system will be incapable of handling the speed and sensitivity of temperature change if the system mass is too small. This balance between stability and changeability will be a critical point for consideration in future analysis.

Given the time constraints on testing set forth in **DR 3.4**, it is critical that the system is capable of being test ready as soon as the TVAC finishes the pump-down process. This means that the thermal system will need to be at the starting temperature by that time to most efficiently utilize TVAC resources. Given the challenges cooling the system poses relative to heating the system, it is most advantageous to use the pump-down time to cool the system to a starting temperature of 250K. Thus, the thermal design will need to be capable of cooling the system from ambient temperature to 250K by the time the TVAC finished depressurizing.

An estimate for the rate of thermal rejection required for can be obtained by dividing the total amount of thermal energy needed to be transported off the system by the time the chamber depressurizes.

$$\dot{Q} = \frac{\Delta Q}{t_{max}} \tag{5}$$

ΔQ can be estimated as

$$\Delta Q = c\rho V \Delta T \tag{6}$$

where c is the specific heat of the system material, ρ is the density of the material, V is the volume of material cooled, and ΔT is the temperature difference between ambient and 250K.

An upper bound on the thermal rejection rate required is obtained by assuming the entire testbed structure will need to be cooled by ΔT. Thus, ΔQ must be summed across all components of the testbed.

$$\Delta Q = \Delta T \sum_{i=1}^{N} c_i \rho_i V_i \tag{7}$$

4.1.2.2 Contact Temperature Sensors

Achieving requirements **DR 1.2.2** and **DR 2.1.2** is not trivial since many contact sensors do not have both an accuracy of 1K and a precision of 0.1K. Analog components for temperature measurement include thermistors, thermocouples and resistance temperature detectors (RTD). After researching potential sensor candidates that meet the requirements, thermistors proved to be the most practical option. Thermocouples generally do not meet the minimum operating temperature and precision required and RTDs are generally not accurate enough and used for commercial applications. Analog solutions using a precision thermistor include a Wheatstone bridge circuit and a precision current source circuit (See Figure 6). Digital solutions include analog temperature ICs and simple ADC sampling but are prone to electrical noise around 0.1K. From preliminary calculations, a major source of error in absolute knowledge is ADC accuracy, however, this error can be reduced by ADC calibration for temperature measurements. Other sources of error include reference sources and resistors as seen in the equations for voltage measurement, however an accuracy of 1K is achievable. An actual implementation may use a combination of these solutions so that measurements can be compared to each other.

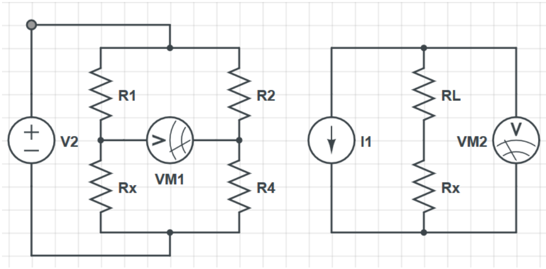

Figure 6: Thermistor Circuit

4.1.2.3 Heater Options

The two ways heaters useful in TVAC applications are patch heaters and cartridge heaters. ”The patch heater consists of an electrical-resistance element sandwiched between two sheets of flexible electrical insulating material such as Kapton. The cartridge heater consists of a wound resistor enclosed in a cylindrical enclosed in a cylindrical metallic case.”[2] Both types of heaters need to be in direct contact with the surface it is trying to heat. The patch heater is normally stuck on to the surface using some sort of adhesive, the cartridge heater normally has a hole drilled into the material that it is going to heat for it to rest in, or it can be clamped on to the surface.

Figures 7 & 8 depict patch and cartridge heaters.

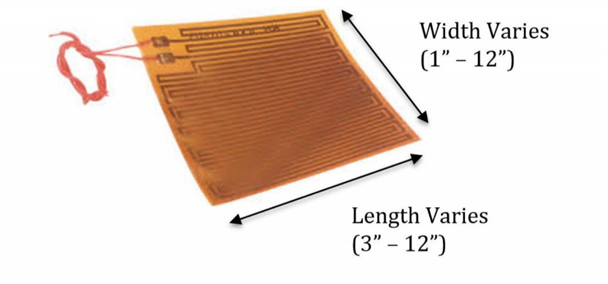

Figure 7: Patch Heater[3]

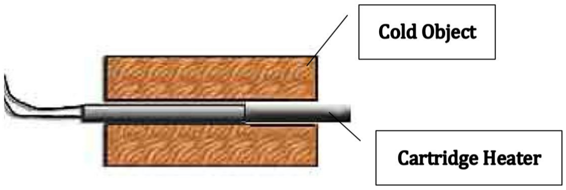

Figure 8: Cartridge Heater[4]

The pros and cons of each heater option are in Table 3 & Table 4 below.

Table 3: Patch Heater Pros & Cons

Pros	Cons
Readily available from manufactures with small lead times and low cost.	May be made of materials, which do not met Ball Aerospace’s Thermal Vacuum out gassing standards.
Ease of electrical integration (simple circuit design).	Requires adhesive that if not applied properly could create air bubbles that would expand and damage the heater and STATIS during the pump downprocess of the Thermal Vacuum Chamber.

Table 4: Cartridge Heater Pros & Cons

Pros	Cons
Readily available from manufactures with small lead times and low cost.	Must be fitted properly into the target surfaces either through a clamp or by drilling a hole into the target surfaces.
Ease of electrical integration (simple circuit design).	Larger and bulkier and requires more design effort to integrate into the target surfaces.

4.1.3 Electrical

4.1.3.1 COTS Electrical Hardware

The electrical design concepts are evaluated independently since the electric and software subsystem is not dependent mechanically on the rest of the system. Likewise, a design conclusion in this subsystem does not constrain any other system.

The electrical design for this project is dependent on many variables; especially the interfaces between IR sensors, heaters, contact temperature sensors, and other components that may have unknown characteristics , which may need to be bought in order fulfill the testbed's capability. The first electrical design option promotes buying COTS electrical hardware designed to accommodate project demands such as data acquisition (DAQ), analog-to-digital conversion (ADC), and control. These components come with predesigned circuit hardware and embedded firmware (See Figure 9 below).

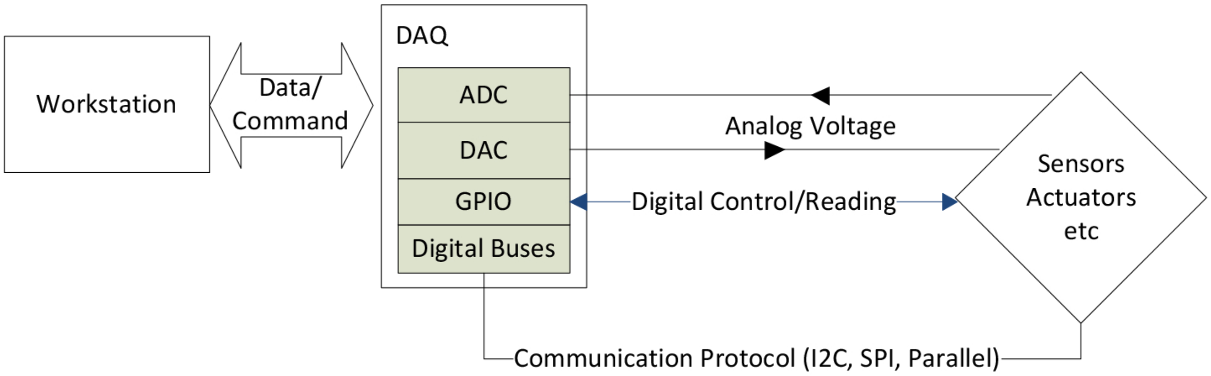

Figure 9: COTS Electrical Hardware FBD

Buying preassembled COTS electrical hardware such as a DAQ system might reduce schedule risk because a COTS DAQ is already made and has well-defined literature about its functionality. However, some DAQ systems are extremely expensive; the more capable the DAQ is, the more expensive (i.e., up to $11,085). Purchasing a COTS DAQ system with capable of satisfying a plethora of integration possibilities with unknown components, as mentioned above, increases budget risk. Furthermore, identifying this design option as a high cost risk and low schedule risk is not a complete conclusion, because there is potential for great schedule risk involved with buying COTS electrical hardware if the COTS electrical hardware does not accommodate the variety of electrical components (sensors, heaters, etc.) bought to satisfy testbed functionality, and must be redesigned before important testing deadlines. As is the case for almost every project in existence, schedule and budget risks must be traded.

Many of the unknown electrical components that need to be bought are being shopped for right now, but the conceptual design of the electronics subsystem of the testbed is heavily dependent on these unknown components: flexibility and modularity will be crucial to the success of this project. The pros and cons discussed for this design are summed up in Table 5 below.

Table 5: COTS Electrical Hardware Pros & Cons

Pros	Cons
Less hardware development - might reduce schedule risk.	Less modular - might not be able to accommodate a wide variety of interfacing possibilities between unknown (to-be-bought) components i.e., IR temperature sensors.
Well defined functionality - manual/specs that define how hardware works - might be quicker to learn - might reduce schedule risk.	Expensive
Knowledge that the system will work when used as specified.	Limited to what is available on the market
	Limits our intellectual capability - easier to think-and-buy than to think-and-build

4.1.3.2 Custom External Control Board

A custom external control board made to interface with all the sensors and actuators in the TVAC chamber including ADC/DAC functions is another option as shown in Figure 10 on page 16.

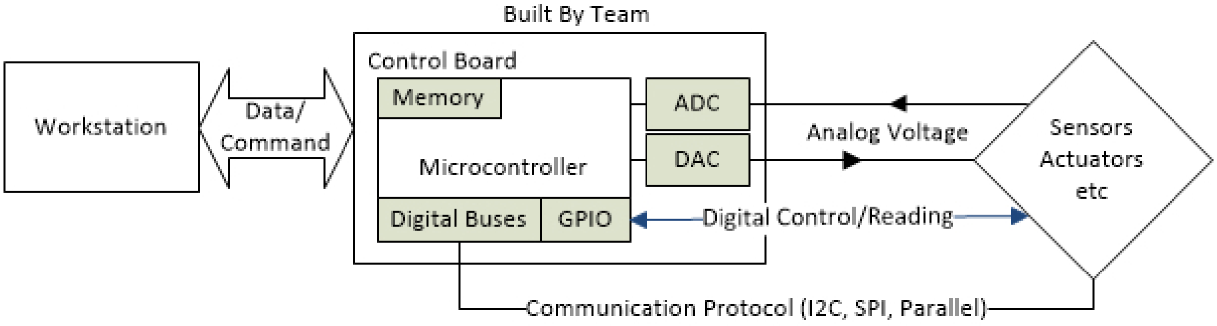

Figure 10: Custom External Control Board FBD

The hardware will be designed such that any amount of control could be programmed into the control board and offload control from the workstation if necessary. In addition, the control board could carry out a variety of functions such as digital processing and temporary data storage. Since the control board is custom made, any variety of digital and analog interfaces can be accommodated in the design. This makes the design extremely modular and flexible and allows for fast prototyping or quick implementation of design changes. The flexibility means there will be very little restrictions on temperature sensor or actuator selection as well. The price for prototyping and printing a final circuit board is approximately $200. A disadvantage to making a custom board is development time. The design process includes part selection, breadboard testing, PCB layout and PCB printing; all of which may take a few weeks. However, if the full schedule cannot be accommodated, design could stop at the breadboard level. Beyond the custom built board, the workstation would be purchased separately. Since this design is flexible, the workstation interface to the control board can be variable depending on the capabilities of the workstation. Full PC workstations can use an USB interface and other solutions such as a Raspberry Pi could use a low level serial protocol. Since the workstation choice does not constrain this design, it is not considered a major part of this study.

Table 6: Custom External Control Board Pros & Cons

Pros	Cons
Control flexibility (real time control)	Hardware development time
Sensor/Actuator interface flexibility	Firmware development time
Low cost	
Guarantee no data loss/ accurate time stamping	

4.1.4 Additional Considerations

4.1.4.1 IR Sensors Selection

The purpose of the testbed is to characterize IR temperature sensors in the vacuum environment. The STATIS team is researching COTS IR temperature sensors so that a thorough trade study can be conducted as soon as possible in order to choose at least 4 of them. Designing a budget will be critical to this decision, because of how variable the cost for each sensor is; each subsystem of the testbed must have an appropriate budget so that the testbed capability is not violated, so as soon as this is resolved, sensor selection will be easier to decide on.

4.1.4.2 Time Considerations

Requirement **DR 3.5**, driven by the availability of the thermal vacuum chamber for student testing, states that tests must be completed in a 12 hour test window. The TVAC requires a 4 hour pump down period and a 1 hour pump up period, leaving 7 hours of testing. Another set of requirements (**DR 1.2.2.1** and **DR 1.2.2.2**) require a minimum of 20K/hr decrease in temperature of the target surface and a 5K/hr increase in temperature. These two requirements were provided by the customer as minimum requirements necessary for practical testing. These two rates were used to calculate the amount of testing we could perform. Requirement **DR 1.2.2.3** states that we will vary the temperature in incremental steps of 10K and vary the temperature of the target surfaces from 250-350K. This requires a 100K difference in temperature. If it is assumed that STATIS first heats to the warmest temperature and then decreases the temperature in steps of 10K down to 250K, this will require 5 hours of temperature changes (100/20K/hr), leaving only 2 hours for actual tests to be performed. Additionally if 30 seconds of data are recorded for each test with an additional 5 seconds to account for movement/rotation of the device and another 5 seconds for linear movement, and there are 5 combinations (5 target surfaces) this requires 3.33 minutes of testing per each temperature or distance test. If 11 temperature steps are required, this will take 36.6 minutes. The overall amount of time required for the tests can be calculated as in Eq. 8 below.

$$\Delta\text{time} = (\#\text{ of targets})(\#\text{ of distance steps})(\#\text{ of temp steps}) \tag{8}$$

Solving that equation for the number of distance steps results in only 3.27 steps. This initial analysis, assuming all "worst case" scenarios, shows there is only time to test three different distances. As designs move forward this analysis will become more realistic. Initial estimates have shown that, with the materials to be used and the heating power options available, a rate of 20K/hr should be greatly surpassed.

4.2 Conceptual Designs

4.2.1 Pentagonal Cylinder

In this design concept, all five targets are located on a single housing unit. The housing unit is an aluminum pentagonal cylinder with a hole drilled through the center. Each of the cylinder's five sides are covered by a different rectangular target of different material. The cylinder is supported by a stand, with the center hole mounted on one side by the drive shaft of a step motor. The center hole on the opposite side is supported by a short shaft integrated with a bearing such that the cylinder can rotate. The orientation angle will be controlled using the step motor and the rotation angle will be measured with an encoder. Heat is added using a cartridge heater that spans the middle portion of the cylinder's center hole (with sufficient room on each side of the hole to insert the motor shaft and bearing). Reference temperature measurements are recorded by thermistors located on each target.

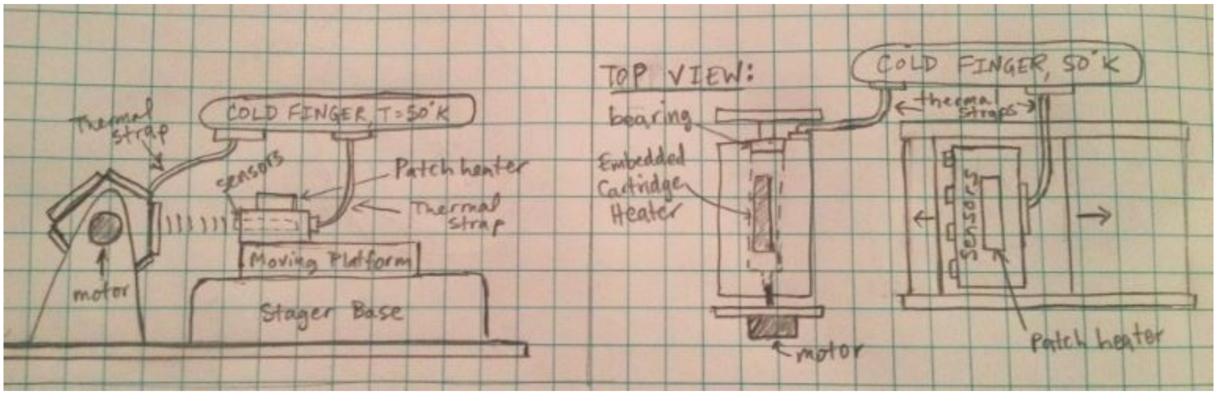

Figure 11: Pentagonal Cylinder Concept Design

The sensor housing is a rectangular box made of aluminum, with 4 sensors inserted inside and oriented in a horizontal line. The horizontal length of the rectangular targets must span the entire field of view of the 4 in-line sensors. From research, it was determined that IR sensors operate with a distance to diameter ratio of 2:1 in the worst case[5]. This means every inch of separation between the sensor and target corresponds to half an inch of diameter added to the field of view. At the maximum separation distance of 3 inches, each sensor's field of view will span a 1.5 inch diameter circle on the target surface. In order to ensure the field of view of each sensor is independent and completely spanned by the target material, each sensor will be separated 2 inches apart with a 2 in. by 2 in. target area. This constrains the size of each target rectangle to 2 in. by 8 in. Because the target spans the field of view of all 4 sensors, the sensors will be tested against the same target simultaneously. This is a huge advantage because of the limited time available to conduct tests inside the chamber.

After a test is completed for a certain material, a user input will command a new target material. Voltage will be sent to the motor to apply a torque, rotating the cylinder through the correct angle such that a new target face is oriented perpendicular to the sensors. Step motors rotate a fixed angle each time a pulse is applied. This type of motor makes actuation control simple because the required rotation (72 degrees for each target change) can be achieved by determining the number of steps required to rotate 72 degrees based on the motor specifications, and supplying the motor with a square wave containing an equal number of voltage peaks. Depending on the reliability of the motor, actuation of the target cylinder may not require any form of closed loop control.

The sensor housing is mounted on the top platform of a linear stager mechanism supplied by Ball Aerospace, designed and used specifically for thermal vacuum testing. The stager is provided with a customized controller that will move the top platform according to user input commands. The structure that supports the target cylinder must be sufficiently tall to position the targets level with the sensors. Also, the target structure must be sufficiently close to the edge of the platform such that the sensors can satisfy the minimum separation distance requirement and get within 7 mm of the target.

In this design, heat rejection will be accomplished using copper wire thermal straps that connect the target cylinder and chamber cold sink (maintained at 50 K). The length of the thermal strap is approximated as 1 meter. The thermal model outlined in section 4.1.2.1 was used to assess the thermal requirements of this specific design concept. Using Eq. 4 and a radiating target surface area of 80 in.^{2} (5 targets*16 in.^{2} /target, equivalent to .05163 m^2), a suitable cross sectional area of copper wiring was determined to be 1.334e-4 m^2 (5 copper wires of gauge size 3, 26.67 mm^2 each)[6]. With this result, $\dot{Q}_{rad}$ and $\dot{Q}_{cold}$ (rate of heat transfer due to radiation and rate of heat transfer by conduction to the chamber cold sink, respectively) can be determined, as well as the required value of $\dot{Q}_{heater}$ in order to balance the heat rates and achieve steady state. These values are plotted for the entire required temperature range in Figure 12 below. The maximum required power from the heater is only about 40 Watts:

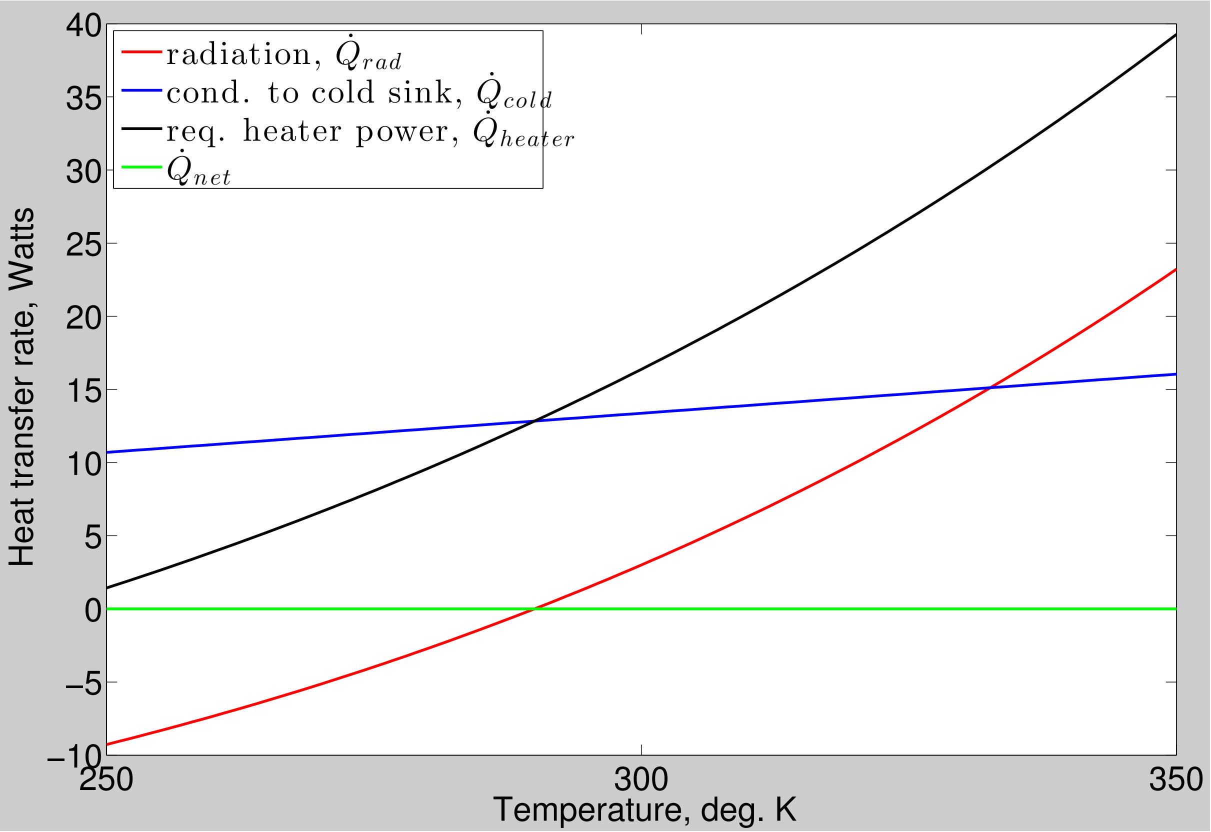

Figure 12: Rates of Heat Transfer vs. Steady State Temperature, Targets

This same analysis was applied to the sensor housing. The sensor housing in this design was approximated as 1in.x8in.x4in.. The 8in. dimension is determined based on the same field of view restriction used to constrain the width of the targets. The 1 inch height is based on an upper limit for the sensor diameter, determined to be about 0.6 in. from the IR sensors researched[11]. The 4in. dimension was based on an upper limit for the sensor length, also determined from IR sensor research[8]. Since the IR sensor housing must reach a minimum temperature of only 275K, a suitable value for A_{xsec} of the thermal strap was determined to be 5.275e-5 m^2 (5 copper wires gauge size 7, 10.55 mm^2 each)[6]. The resulting plot of $\dot{Q}_{rad}$, $\dot{Q}_{heater}$, and $\dot{Q}_{cold}$ versus temperature is shown below. In this case, less than 20 W are required from the heater at the hottest steady state temperature:

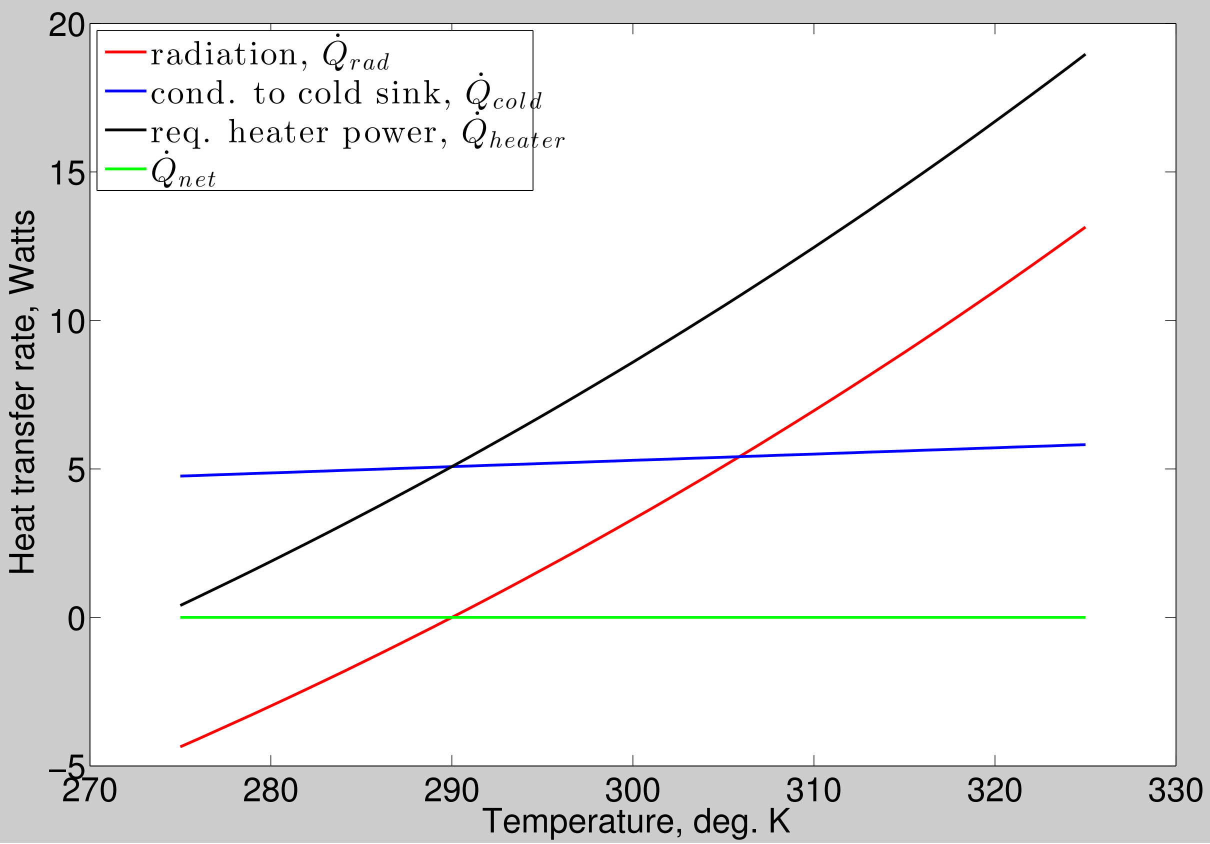

Figure 13: Rates of Heat Transfer vs. Steady State Temperature, Sensor Housing

A critical element to this design is the ability to rotate the target cylinder using torque supplied by a motor. Some preliminary calculations were made to verify the feasibility of this design option for changing the target. The torque applied to the cylinder must be capable of overcoming the resistive frictional moment present in the bearing. This frictional moment can be estimated using the following equation, where μ is the coefficient of rolling friction in the bearing, P is the load supported by the bearing, and d is average diameter of the bearing[7]:

$$\tau_{bearing} = \frac{\mu P d}{2} \tag{9}$$

Based on a table listing approximate ranges for several different types of bearings, the upper limit on the bearing friction coefficient is determined to be μ= .0035[7]. The weight of the cylinder is estimated using the volume of the cylinder (ignoring the center hole) and the density of aluminum, resulting in P= 23.8 N, The diameter of the bearing is estimated to be 0.5 in. (12.7e-3 m). Based on a preliminary quote from Empire Magnetics, the cheapest vacuum-rated motor ($2200) currently identified from research produces 0.18 Nm of torque. With these values determined, the rotation capability can be estimate by Eq. 10 below:

$$\tau_{motor} - \tau_{bearing} = 0.1795Nm = I_{cylc}\alpha - > \alpha \approx 79rad/s^2 \tag{10}$$

This resulting value of angular acceleration is more than sufficient to rotate the cylinder from target to target in a very short amount of time.

Table 7: Pentagonal Cylinder Pros & Cons

Pros	Cons
All sensors are testing at the same time.	The lead wires of the cartridge heater must extend out of the target cylinder without interfering with the motor or bearing.
The system does not require a high torque motor.	These wires, the thermistor wires, and the thermal straps must smoothly rotate with the cylinder without being damaged or causing interference with the motion.
The thermal model supports the feasibility of maintaining a steady state temperature in the range of 250-350K for the targets and 275-325K for the sensor housing. Values for required the heater input (W) and thermal strap area are reasonable.	In the real case, 1 cartridge heater won't be sufficient to control each of targets to the same temperature value.
Only one heater is used to balance the heat rates for steady state control.	
The design fits well inside the design space.	

4.2.2 Linear Rail

In the linear rail concept design, all five targets are attached to an aluminum sheet. Each target material is in a 2in. by 8in. rectangle as in Figure 14 on page 21. The sensors are mounted in a row to a 2in. by 8in. aluminum plate that faces the targets and is supported at its ends by cylindrical rails. The sensor's mounting plate is vertically actuated along the rails by a pneumatic driver. Patch heaters and thermistors are attached to the back of both the target and the sensor mounting panels to control temperature. The sensor mount structure and the electronic system are mounted to the stage provided by Ball Aerospace and are translated closer to and farther away from the targets.

The sensor housing for the linear rail design is identical to that used in the pentagonal cylinder as the dimensions of the targets are identical. This has the similar advantages as all 4 sensors may be tested at once.

The pneumatic actuation method was chosen because of its easy implementation in this vertical movement application. The pneumatics would push or release a bar vertically up or down a rail. Mounted to the bar would be the IR sensors so that moving it up and down will meet **DR 1.3** regarding the cycling of targets and IR sensors. It would also contain contact sensors to monitor the temperature of the system as required by **DR 2.1**, and heaters to ensure that the IR sensors remain within the range required by **DR 3.2**.

In order to determine baseline feasibility of the method, an approximate force required from the pneumatic actuator was calculated. The basis of the analysis was to set up the worst case scenario for all parameters involved. With that in mind, the IR sensor weight used (m_{IR}) was 226 g because the OS137 series IR sensor was the heaviest currently being researched[8]. Likewise, the heaviest patch heater found in preliminary research was an ULTRAMIC vacuum rated contact heater with a mass (m_h) of 0.0706g[9] . The mass of the thermocouple (m_{tc}) came from weighing a 24 gauge 3.2 meter long thermocouple out of the ITLL and came out to be 27g[6]. In order to calculate the mass of the bar (m_b) to which the IR sensors, heaters and contact sensors would be mounted, it was assumed that the dimensions were .1m x .1m x .72m. The height and width (h_b) of .1m came from the rational that 10 cm would be more than sufficient to mount an IR sensor to. The length of the bar (l_b) was assumed to be .72m because that is the exact width of the testing space which means that it is the worst case scenario as allows for no room to put the apparatus in the TVAC. The density of the bar (ρ_{AL}) was assumed to be 2.72 kg/m^3 as this is the standard density of aluminum which is a relatively cheap and lightweight material[10].

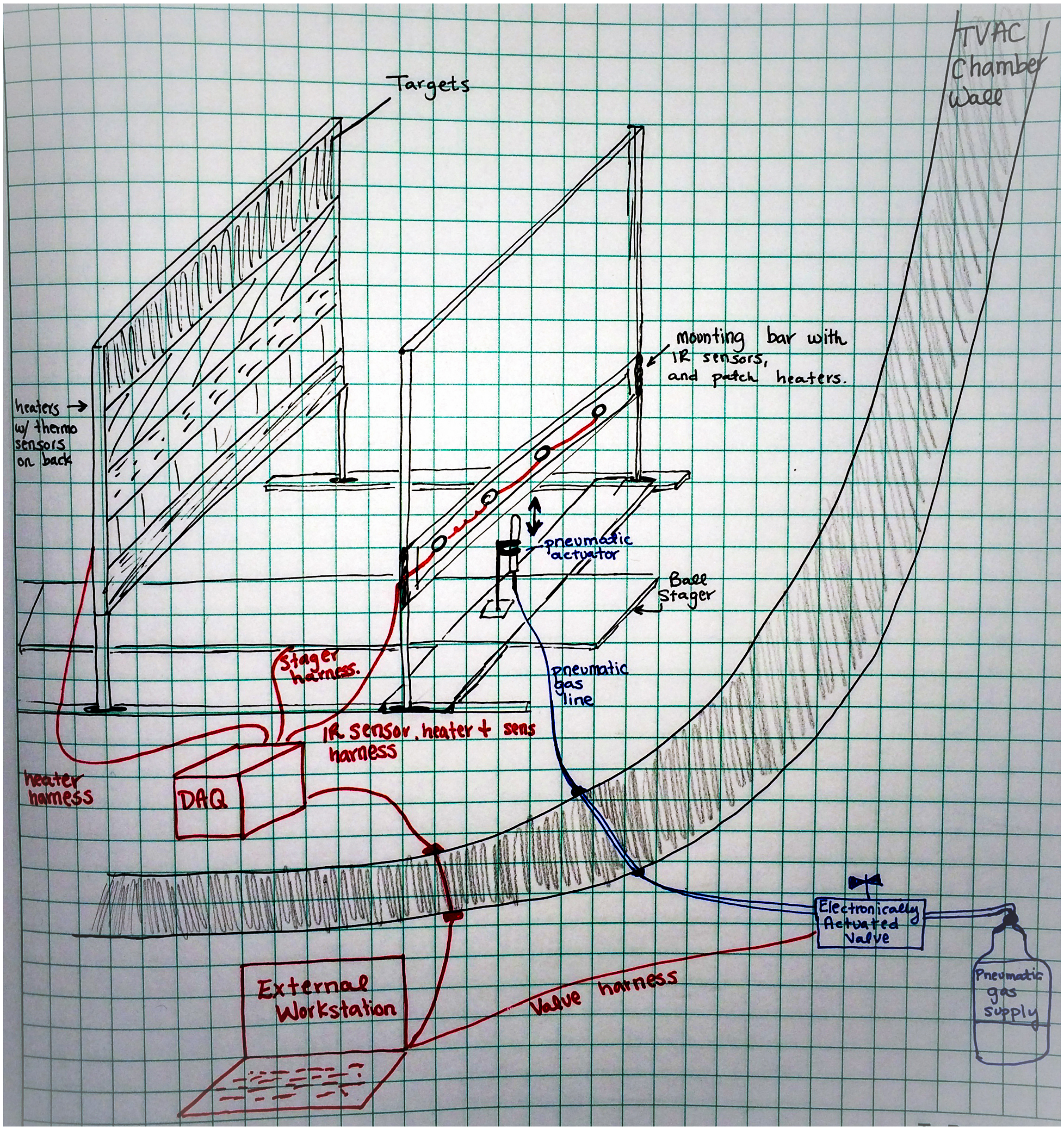

Figure 14: Linear Rail Conceptual Design Diagram

The basis of the calculation is that the force from pneumatics pushing upwards (F_p) needs to be greater than the force generated from the components and the bar (F_w) in order to push the bar upwards. There were many assumptions made in order to do this calculation including:

- Friction was assumed to be negligible in comparison to the other forces.
- The bar is said to be a rectangular prism, solid mass. This was done in order to neglect the weight of the mounting components. In reality, the bar will most likely not be a solid mass.

Given these, the worst-case scenario was calculated in the following manner:

$$F_p \geq F_w \tag{11}$$

$$F_p \geq g(m_b + 4m_{tc} + 4m_h + 4m_{IR}) \tag{12}$$

A four was multiplied to the mass of the thermocouples, the heaters, and the IR sensors because there will be four IR sensors per **DR 1.3.2** and worst case scenario would mean that each would have their own contact sensor and heater.

In order to get the mass of the bar, the dimensions and density are substituted in.

$$F_p \geq g(\rho_{Al} h_b^2 I_b + 4m_{tc} + 4m_h + 4m_{IR}) \tag{13}$$

From there the assumed values are plugged in which gives the following:

$$F_p \geq 9.81\frac{m}{s^2}\left((2.72kg/m^2)(.1m)^2(.72m) + 4(.027kg) + 4(0.0000706kg) + 4(.226kg)\right) \tag{14}$$

$$F_p \geq 10.12N \tag{15}$$

While no vendors have been willing to give a cost estimate for a pneumatic actuator that is TVAC compatible, if one is available for cheaper than the $2000 motors while supplying around 10 Newtons of force, pneumatics would be the actuation method of choice. If the motor with a screw drive ends up being the cheaper option, it can easily be implemented as well as both are capable of providing sufficient actuation force.

The preliminary thermal model outlined in section 4.1.2.1 was also applied to this design concept in order to estimate what is required for steady state heat control. Because this design uses the same horizontal sensor and target orientation as the pentagonal cylinder in section 4.2.1, The same target area estimate (2 in. by 8 in.) can be used. However, in this design, both sides of the targets are exposed and therefore the total radiative area is now doubled. The model predicts that five gauge 0 copper wires (53.47 mm^2 each) is a sufficient thermal strap to reject heat[6]. The resulting rates of heat transfer and required heater power for steady state operation between 250-350K is shown below:

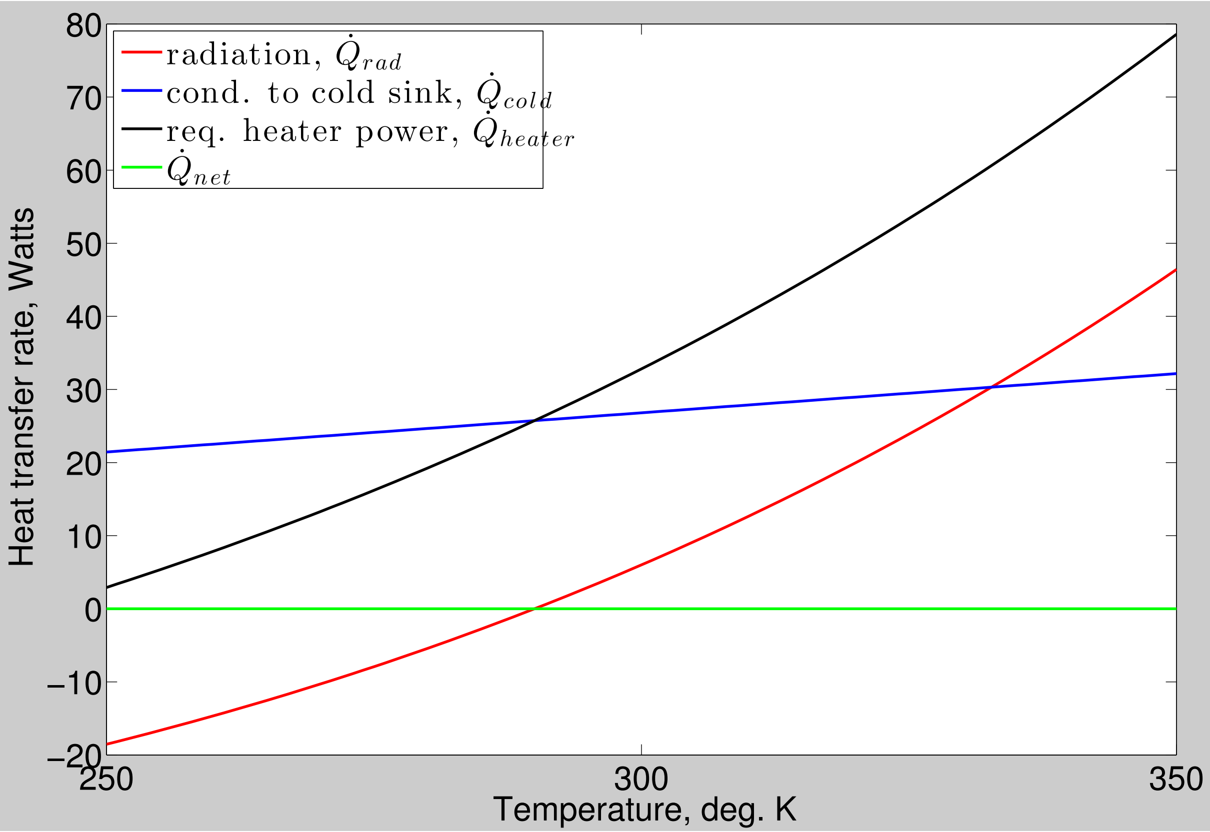

Figure 15: Rates of Heat Transfer vs. Steady State Temperature, Targets

In this design, the radiative area of the sensor housing can be estimated using the same dimensions used in section 4.2.1 describing the pentagonal cylinder concept. For this reason, Figure 13 on page 19 can be used as a good baseline estimate for the rates of heat transfer present in the sensor housing.

Table 8: Linear Rail Pros & Cons

Pros	Cons
All sensors are being testing at the same time.	Pneumatic actuator is required and at the moment may be out of STATIS' budget.
Requires 5 different heaters, which allows for better temperature commanding of the target surfaces.	If a pneumatic actuator is not viable another motor option will also be expensive to make TVAC ready.
Only the sensors need to move vertically so wiring will not have to worry about wiring twisting due to rotation.	

4.2.3 Annular Array

The annular array concept design, as in Figure 16 , uses a rotational disk-like array that contains the target materials (5 total), and a fixed orientation IR sensor cluster (4 sensors total) that is translated to change the viewing distance of each sensor. Changing targets would be accomplished by rotating the annular target array by a fixed angle, in order to supply each IR sensor a new target material for temperature measurements. This rotational actuation would be accomplished by use of a stepper motor. The 4 sensors in the IR cluster would change distance from the targets by the same amount using the stage provided by Ball Aerospace, while keeping the entirety of their field of view on the targets. The skeleton and/or supporting structure of this concept design would be aluminum, due to its moderate strength while remaining low weight, low cost, and easy to machine. Structural loads are expected to be small, due to the quasi-static nature of the test-bed and the relatively low weight of components.

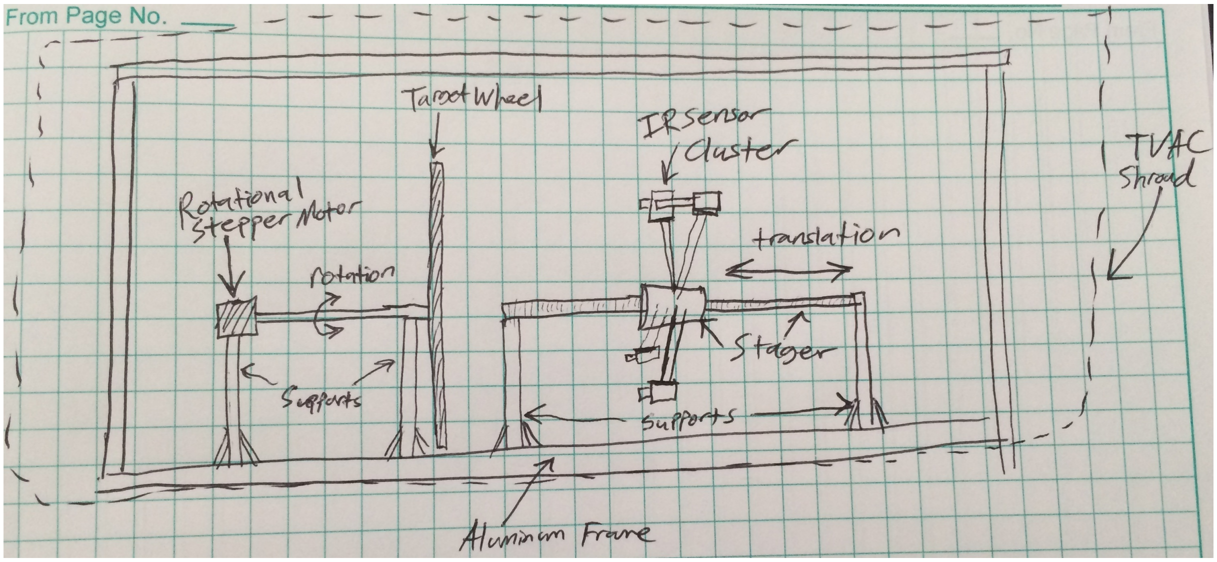

Figure 16: Annular Array Overview Diagram

By changing the targets through rotation and the viewing distance by translation, all of the mechanical or moving goals of the test-bed are accomplished.

Because of the unique number of target materials, the geometry of the annular arrangement can be determined, and the diameter of the target array may be approximated close to its maximum size based on the TVAC dimensional restrictions (30 inches of width max). Also, based on the worst case FOV (largest FOV means largest targets at the same max viewing distance which means more cost and weight) for possible COTS IR sensors (2:1), a target material size may also be determined. 5 targets at equal angular spacing means that the angle between each is 72 degrees in the array. A 2:1 FOV means that at the maximum viewing distance of 3 inches, the field of view is 1.5 inches in diameter. Based on these numbers, and giving some room for error to keep the FOV on a target, an expected geometry is shown in Figure 17 on page 24.

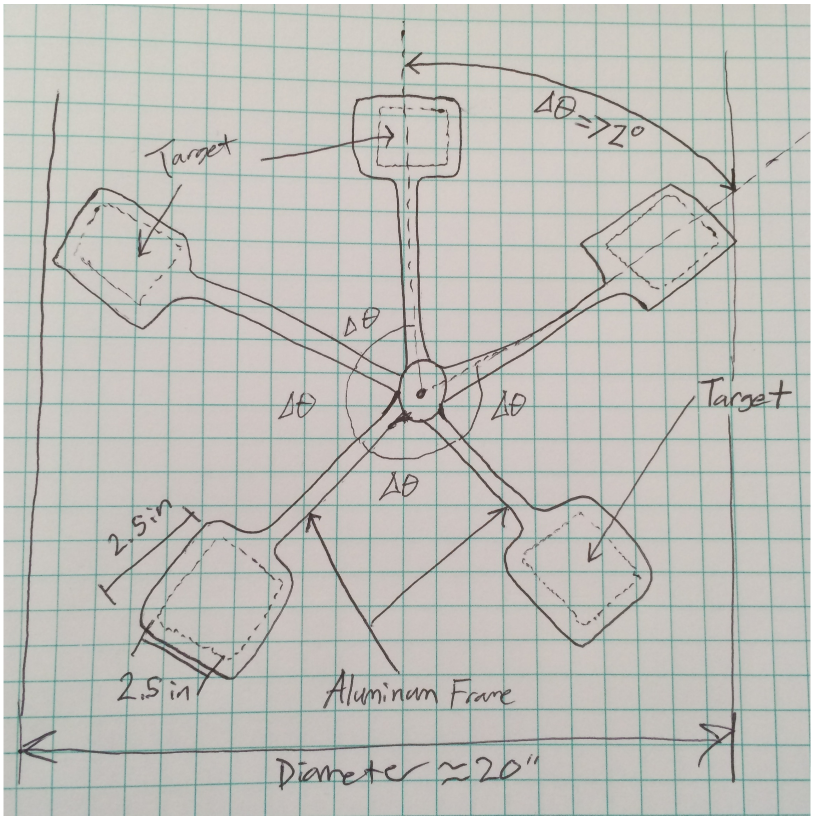

Figure 17: Annular Target Array

The thin arms on the arrangement are to save weight and to reduce the ability for heat to conduct through the support structure from target to target. The thickness of the plate-like array would also be as small as possible to save weight and cost, while still remaining strong enough and possible to machine/manufacture. Because of this arrangement of targets, the 4 sensors must also be at 72 degrees from one another (excepting an empty space, between which would be 144 degrees), mirroring the position of 4 out of the 5 targets as in Figure 18 below.

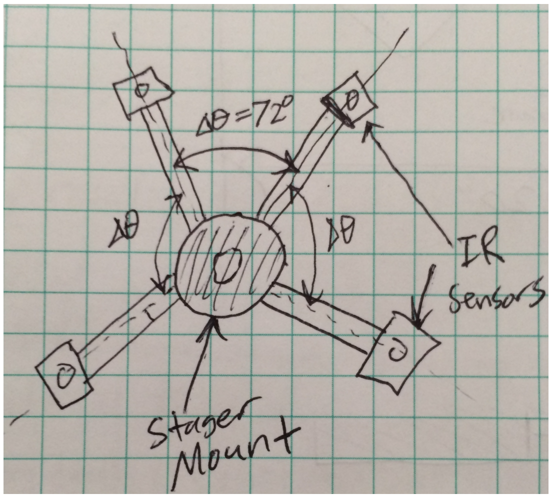

Figure 18: IR Sensor Cluster Arrangement

The method by which the targets and sensors are temperature controlled is in part based on the geometry of the arrangement. Less dependent on arrangement is the method of heat rejection, so-called thermal strapping to either the 50K cold finger, or the variable temperature chiller plate. Thermal strapping is a heat rejection method that connects temperature-controlled components to a cold temperature source by means of physical connection (copper wiring), to reject heat through conduction. This technique, along with the unavoidable radiation to the surrounding TVAC environment, will be used to cool both the targets and the IR sensors. This requires wires going from each of the targets and IR sensors to the cold source.

Heating must also take place to control the temperature, considering the targets first, which must range from 250-350K, and be measured with an accurate contact thermal sensor. The natural option in the case of the plate-like array is to use thin, light, patch heaters applied to a thin piece of target material. The less power required by the system the better, so very thin target plates are ideal in that they will change temperature much faster than a large volume of material. Within the annular array pictured above, the patch heater and material layer would be embedded within the tips of the arms, such that the material sits on top of the heater in the same cavity as shown in Figure 19 on page 25.

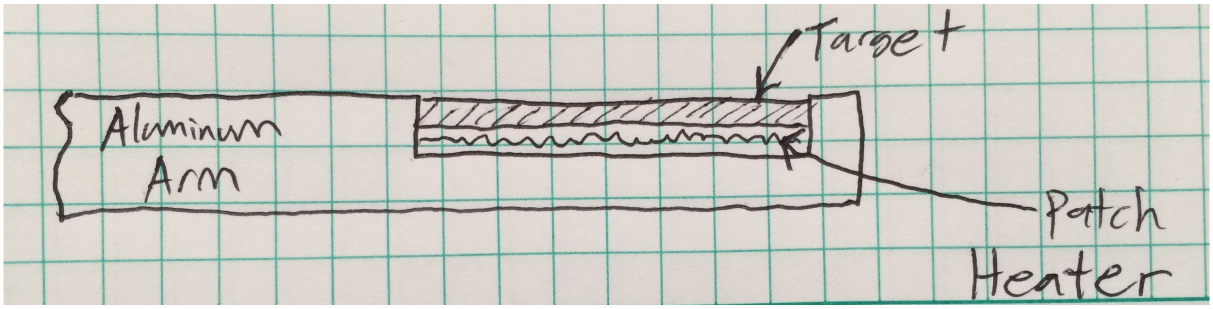

Figure 19: Heating arrangement for target materials within annular target array

Based on the 2.5 in. x 2.5 in. approximation for the target sizes, the thermal model explained in section 4.1.2.1 was applied to determine a baseline estimate for the required size of the thermal straps and required heater input. The model suggests that five gauge size 4 copper wires (21.15 mm^2 each) are sufficient to remove heat from each of the five targets (gauge reference). The resulting rates of heat transfer for steady state operation between 250-350K is shown below:

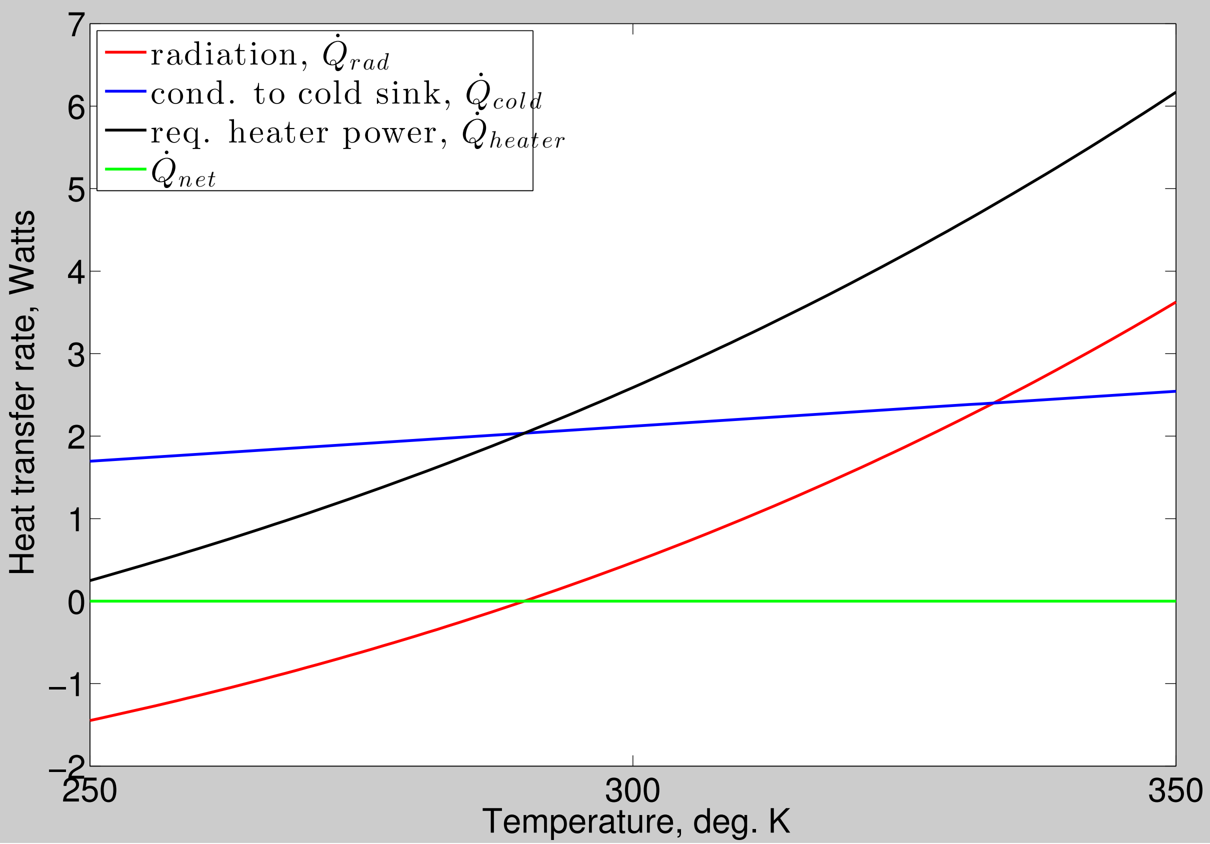

Figure 20: Rates of Heat Transfer vs. Steady State Temperature, Each Target

To supply the patch heater with power, holes/slots would need to be drilled through the aluminum arms supporting each target. Similarly, to allow the temperature of the target to be measured by a contact sensor, additional holes or access areas must allow for wiring to connect. Once again wiring is necessary for the heat rejection by thermal strapping. Each of the IR sensors will also be controlled with a patch heater strapped to the sensor mount. Also, each of the sensors mounts must be connected to the cold source by thermal strapping. Each IR sensor mount would also have a contact sensor connected to it for temperature data. An upper limit estimate for the surface area of the sensor casings was determined from 1in.x1in.x4in. volume which is a conservative estimate based on the IR sensor research[8,11]. The thermal model predicts that each sensor will require a gauge 7 copper wire (10.55 mm^2 each) to conduct heat to the cold source[6]. The resulting rates of heat transfer for steady state operation between 275-325K is shown in Figure 21 on page 26.

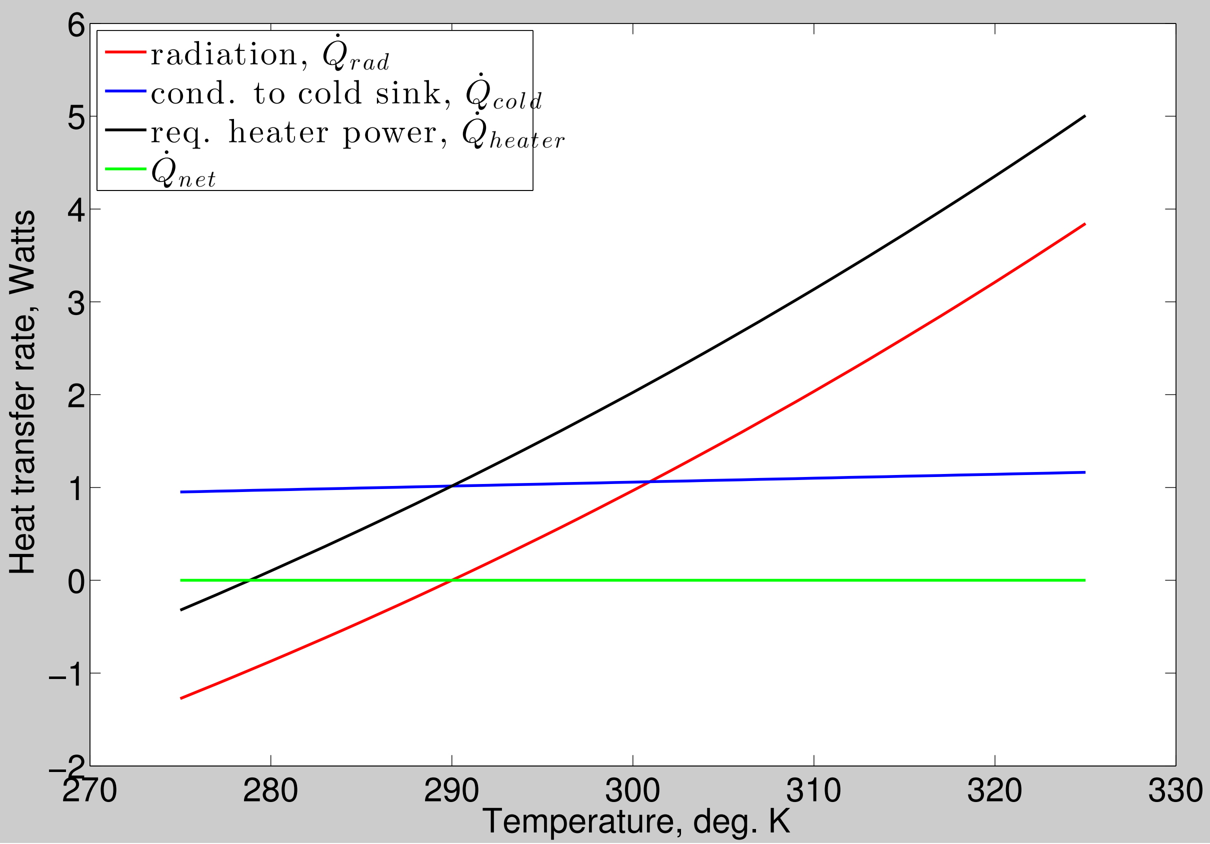

Figure 21: Rates of Heat Transfer vs. Steady State Temperature, Each Sensor

Table 9: Annular Array Pros & Cons

Pros	**Cons**
Allows for small amounts of target materials to be used.	Requires many wires connected to a rotating assembly.
Allows for low power output thermal control systems.	Requires an expensive vacuum certified motors.
Simple 1 degree of freedom step commands in target selection (sensor target pair).	Requires precise machining for annular target array.
Simple 1 degree of freedom step commands in viewing distance.	Requires many wires for each sensor and each target.
Each sensor could be taking data simultaneously of different targets.	Sensors must align properly with target array to avoid non-target objects in FOV.
The distance/target test sequences could be repeated at various target temperatures.	Without complex wiring, the target array would likely need to rotate in one direction and then in the other to show each sensor each target.

5 Trade Study Process and Results

A final in-depth trade study was conducted over the three final test bed structural concept designs and the final two electrical control systems designs for STATIS. The discussion below highlights the structural concept designs considered: the pentagonal cylinder design, the linear rail design, and the annular array design. The second trade study addresses the two electrical control system concept designs: COTS hardware built electronic control, and custom built hardware electronic control.

5.1 Structural Design Trades

5.1.1 Trade Elements

Five categories were defined for consideration in the structural trade study: size and mass, mechanical components, thermal control feasibility, wiring schematic, and manufacturability. The descriptions below define each category in more detail. Additional Consideration was not given to thermal modeling, the availability and size of the target surface materials, and overall cost of the various designs. Thermal models, while a major component to the design of STATIS, were not considered in the trade study as they would be similar models for each design. Each thermal model would consider both the transient and steady state thermal conditions of the testbed; slight modifications would exist depending on the hardware configuration, but the bulk of the analysis process would be similar. The availability and size of the target surfaces likewise was not considered as, regardless of design, access to the materials of interest is required for success. The customer has provided small sections of the materials of interest, though for some of the designs more material will be required. Cost was also not considered in the trade study for the structural concept designs but rather incorporated in the selected trade elements. Budget will be a large factor in any design, as the motors required for any design will likely be around $1-2K. Budgetary constraints were considered in more depth in each category used.

5.1.1.1 Size and Mass

The size and mass of the STATIS testbed were considered in this trade study because both have a direct correlation to the cost of building and manufacturing STATIS. Size considered how much material would have to be purchased and if the design was feasible to fit inside of the size constraints provided by the useable dimensions of Ball Aerospace's Thermal Vacuum Chamber. The mass consideration looked at how heavy the system is. The heavier the system, the more torque needed to move the system from the motors, thusly the motors will become more expensive. A high number here showed that the design was not very large and would not require a significant number of materials to be purchased in order to construct the test bed, and that cheaper motors could be used. A lower number showed that the design was larger and had a significant mass, thusly costing more money to build STATIS.

5.1.1.2 Mechanical Components

The mechanical aspects of STATIS were considered in this design trade study in order to sort out which designs were the simplest in terms of mechanical design and integration. The main considerations in this section were motors. Motors have to be readied for the thermal vacuum environment and componenets such as dry lubrication have to be considered all of which drives up the cost of STATIS depending on which motors are selected. The mechanical category also looked into how complex building the structures to support the motors and movement of the targets is, if required and how easily a platform for holding the sensors could be integrated into Ball Aerospace's stager for varying the distance. The higher the number correlated to the design that would require motors that were not as expensive and structures to support motor movement that would be simpler. The lower the number, the more expensive the motor and complex the structure.

5.1.1.3 Thermal Control Feasibility

The thermal category looked into aspects such as how easy would it be to integrate patch heaters versus the cartridge heater to each design. How easily thermal straps could be utilized as a heat rejection system. Heating time and equilibrium time were taken into consideration, seeing as STATIS has to come to temperature equilibriums throughout the various temperature ranges within 12 hours in order to collect the data needed as defined by **DR 3.5**. Another aspect taken into consideration was the number of heaters used in each design. Five separate heaters for each of the target surfaces offer more precise temperature control compared one heater on all surfaces, which is essential to meeting **DR 1.2.1**. All of these components affect the test time and functionality of STATIS. A high number in this category means that the design was simpler in terms of heating and heat rejection integration and had more precise commanding control of the target surfaces. A lower number in this category correlated with worse temperature control and more complicated integration of heaters and heat rejectors.

5.1.1.4 Wiring

The wiring was considered in this trade because in many of the designs wires are rotating and being moved about in ways that add complexity to STATIS. Wiring is also extremely important because it has to fit within the cable pass throughs provided by Ball Aerospace's Thermal Vacuum Chamber and wiring is how data will be transmitted from the STATIS testbed back to the computer. The wiring needs to be considered in each design in order to maintain the integrity of data collected, if wires are twisted and pulled in a way that causes movement then the design may not be the best. A higher number indicates that the design has a simpler wiring system. A lower number indicates that the design has a lot of rotating parts and a high risk of wire signal degradation.

5.1.1.5 Manufacturability

The manufacturability category took into account what resources the STATIS team has available to manufacture and fabricate the parts that are needed for each design. Based upon limited time, budget and skill sets some design aspects may be outside of what should be considered feasible for the STATIS project as a whole. A higher number in this category means that the design was feasible in all the aforementioned area and the STATIS team had the time and skill set necessary to build and fabricate these components. A lower number in this category means that the design would not be as feasible for the STATIS team to build and fabricate.

5.1.2 Trade Study

In the table below, the scale for any score ranges from 1 to 5 where 5 is a more favorable score and 1 is a less favorable score. Weighting was assigned to each of the above categories ranking the importance of the sections. Mechanical and thermal were ranked the highest, at 30%, as this is likely where most of the design hours and efforts will be made. Wiring and manufacturing each were ranked at 15% as they are not major design considerations rather they flow down from thermal and mechanical considerations. Size and mass is ranked the lowest as it is primarily dependent on how components are manufactured.

Table 10: Trade Study Table

Trade Element	Weighting	Pentagonal Cylinder (4.2.1)	Linear Rail (4.2.2)	Annular Array (4.2.3)
Mechanical	30%	3	4	5
Thermal	30%	3	2	4
Wiring	15%	5	3	3
Manufacturability	15%	2	1	4
Size and Mass	10%	2	2	5
Totals	100%	3.05	2.6	4.25

5.2 Electrical Design Trades

5.2.1 Trade Elements

Four categories were defined for consideration in the electrical trade study: initial design cost, initial design time, redesign cost risk, and redesign time risk. The descriptions below define each category in more detail. Additional Consideration was not given to workstation computer setups, electrical modeling, sensor selection and integration. They were not considered because they either did not constrain the design or their implementation would be the same for either the COTS or custom made system. These trade elements were selected under the assumption that once all components, subsystems, mechanisms, and capabilities of the testbed are purchased and/or designed, some components, subsystems, mechanisms, and capabilities of the testbed will need to be redesigned in order to accommodate project design evolution. This assumption was derived from individual team member experiences on aerospace projects with complex systems engineering practices.

5.2.1.1 Initial Design Cost

The Initial Design Cost criterion is based on a 1-5 scale with each increment corresponding with a percentage of the electrical budget. As the scale increases from 1 to 5, the lower the percentage of the electrical design budget is expected to be used. When there is a large percentage of the budget used for the initial design there is less flexibility for redesigning the electrical system to acclimate to the overall project design evolution; therefore, spending more money than needed is less desirable.

5.2.1.2 Initial Design Time

The Initial Design Time criterion is based on a 1-5 scale with each increment corresponding with the number of hours projected to be spent on completing the initial design. Taking a longer amount of time to complete the initial design is less desirable because there will be less time for redesign which will increase schedule risk.

5.2.1.3 Redesign Cost Risk

The Redesign Cost Risk criterion is based on a 1-5 scale with each increment corresponding with a percentage of the electrical budget, equivalent to the Initial Design Cost criterion. The larger the percentage of the budget needed for redesign, the risk to complete the project within budget increases.

5.2.1.4 Redesign Time Risk

The Redesign Time Risk criterion is based on a 1-5 scale with each increment corresponding with the number of hours projected to be spent on completing the redesign of the electrical system from the inevitable project evolution. The Redesign Time Risk criterion scale covers less time (10 hour intervals) compared to the Initial Design Time criterion (25 hour intervals), because when elements of the electrical system need to be redesigned the schedule of the project will be closer to critical milestones than at the start of the project; thus, the interval size is smaller for the Redesign Time Risk criterion.

5.2.2 Trade Study

In the table below, the scale for any score ranges from 1 to 5 where 5 is a more favorable score and 1 is a less favorable score. Weighting was assigned equally among the trade elements as they had the same magnitude of importance.

Table 11: Trade Study Table

Trade Element	Weighting	COTS Electrical Hardware (4.1.3.1)	Custom Electrical Hardware (4.1.3.2)
Initial Design Cost	25%	1	4
Initial Design Time	25%	4	3
Redesign Cost Risk	25%	1	5
Redesign Time Risk	25%	3	4
Totals	100%	1.95	3.60

6 Selection of Baseline Design

6.1 Structural Baseline Design

The results of the structural trade study revealed that of the three concept designs considered, the annular array (4.2.3 on page 23) is the most suitable choice. With the weights applied, it out ranked both the linear rail and pentagonal cylinder designs by 1.2 and 1.65 respectfully. The STATIS team has decided to move forward with the annular array design.

The pentagonal cylinder concept (4.2.1 on page 17) was clearly the least desirable based on the characteristics that were traded. Due to the solid mass of the pentagonal cylinder block that would form the basis of the wheel and thermal distribution system, it was found that the system failed in two categories. In mass, the system was far heavier than any other. This led to the moment of inertia becoming prohibitively high in respect to the proportional price of torque for a TVAC rated motor. For thermal aspects, it was found that the time required to heat the entire mass from one temperature to another would take longer than it would for the other methods. Most critically, it was realized that the wiring of this concept would require feeding wires through a solid block in which manufacturing errors could perpetuate errors into the thermal conduction models. Failing these heavily weighted categories made it the least desirable design.

The second highest scoring design was the linear rail concept (4.2.2 on page 20). This concept centered on using linear motion instead of rotational; which would simplify of the wiring configuration. However, it was found through the course of the trade study that to make the system properly slide would require the creation of slides like those used in compact disk drive. These slides would have to be strong enough not to bend under the weight of the platform holding the infrared sensors. Additionally, the tolerance in the angle between the two slides would have to be exceptionally small to prevent binding. To prevent this would require additional screw calibrations which would increase the mechanical complexity of the system. Had the slide mechanism on the linear rail concept been successfully dealt with, there would still be the issue of the slides that would allow the platform to move along the slide bars and the pneumatic actuation system that would position it. Leaks can be extremely difficult to detect, especially leaks which only form under high gauge pressures. What such a leak would mean to the system once it was within the TVAC chamber was a serious concern. Alleviating such a fear would require the use of higher tensile and thus more costly materials. Ultimately the concept was found to be too heavy, too costly and too complex to score well within the trade study.

The annular array concept (4.2.3 on page 23) ranked the highest in the structural trade study that the STATIS team performed. The trade study showed that the annular array concept scored high in all areas - exempting wiring - considered by the study. It ranked highest in mechanical due to the simplified nature of the design which limited itself to only a single motor and moving contact point. While this is also true for the pentagonal cylinder, the annular array is projected to weigh less, requiring a smaller and cheaper motor. The annular array's lower projected mass also requires less heating, thus allowing the system be transferred from one steady state temperature to another much more quickly. Although low mass is considered an advantage of this design, future analysis will make sure that the stability of the system is such that a control system can achieve **DR 1.2.1** during steady state control. Furthermore, because the annular array will rely on five independent patch heaters as opposed to a single cartridge heater, it will be possible to more finely tune and control the temperature of the individual targets. The trade study revealed that the annular array concept was the least desirable with regards to wiring criterion because the use of a large harness with rotational motion is expected to pose future design restrictions. This issue, however, was insufficient to outweigh the favorable attributes previously mentioned. While the STATIS team will continue to research alterations to the design which could reduce cost and risk, the annular array design concept will be the main focus of future calculations and designs.

6.2 Electrical Baseline Design

The electrical design trade study evaluated two options: a COTS solution and a custom built solution. The trade study results from section 5.2 on 28 indicate the custom built solution is the best design choice. Custom hardware's design flexibility and low cost characteristics contributed greatly to its score. Since the board is custom designed, it will not constrain any component choices including the IR temperature sensors. Electrical components are on the order of a few dollars each, making it a low cost solution. PCB printing is also not costly. The custom hardware solution scored low on time of development since the hardware will be unique and require a significant amount of time. While COTS hardware may require less time for development, its rigidness is a risk to the project and the cost is prohibitive on the budget. Research into COTS hardware, such as National Instrument DAQs, indicated a price range of $500 or more for the predicted needed capability of the system, a large percentage of the project budget. Since other vacuum rated components needed in the testbed are also expensive and required, this expense is critical. Also, if a design change is needed with the electrical system, COTS hardware, such as a new DAQ, may be needed which will increase cost substantially. Overall, the custom hardware option scored better than COTS hardware, because of its modularity, inexpensive production, and more flexibility for mid-project redesign to satisfy the testbed's capability and requirements.

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