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An Engineering Approach to Industrial Research and Development of Pillows

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AN ENGINEERING APPROACH TO INDUSTRIAL RESEARCH AND

DEVELOPMENT OF PILLOWS

A Capstone Experience/Thesis Project

Presented in Partial Fulfillment of the Requirements for

the Degree Bachelor of Science with

Honors College Graduate Distinction at Western Kentucky University

By

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Western Kentucky University

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ABSTRACT

Comfort during sleep, though taken for granted, involves a great amount of research and engineering. Few give it a second thought, but nearly one-third of a person's life is spent with their head on a pillow, thus making them a point for increased quality. Having been approached by a tier-1 bedding manufacturer, a team of both mechanical and electrical engineers was been tasked with the goal of creating a valid research tool that the customer, Tempur-Sealy, will utilize in the company's research and development of high-end pillows. The team sought to tackle this project utilizing tools and knowledge gained throughout our careers as an engineering student.

The goal is to create an accurate prototype model of the human head in regards to surface area, weight, heat generation, and vapor production and use this model in parallel with a data acquisition and controls system to simulate and record a pillow's thermal dissipative properties. With this tool, in-depth research into product properties can be conducted by the manufacturer. The desire is to utilize this tool for new product validation. Once a prototype for a new pillow has been proposed and the structure and filling (i.e. foam, cloth, etc.) created, the test-bed will be used to prove the product's capabilities. As with any R&D environment in industry, the data and results will be used for justification in further developments by the company.

In dedication to my parents, Chad and Angie.

Your sacrifices never went unnoticed.

ACKNOWLEDGEMENTS

To the faculty of the Western Kentucky University Department of Engineering, I thank you for making this home. By making available your facilities but more importantly your time, you have created an environment where young people from all walks of life and all backgrounds can attain an education that rivals that of the premier American universities. Specifically, I would like to thank Dr. Ashrafzadeh. I respect that you run your lab and your projects as you would in industry and just as if it were in industry you took a chance on me as a student researcher. Though only working for you in the short year that it has been, I feel as though I have grown tenfold not only as an engineer but as a future contributor to the harsh intellectual field that lies ahead.

To Dr. Chris Byrne and Professor Robert Choate, I hope this conveys to you the immense appreciation I have for you, your professionalism, and your tenacity. I believe you both saw a potential in me that I had not yet. Your guidance throughout my academic career here has been invaluable and not only from an instructional or technical standpoint. The small, ten minute conversations in the hallway about my future and graduate studies were what really pushed me forward to the idea and already it has changed my life.

I owe an immense debt to the “Human Head Modeling” team that made success in this project all but a reality. To Molly, Jeremiah, Brayan and “other Wes,” working together on this project has been a privelidge from the start. I am glad to have gotten to

know you and see you grow as industry-ready engineers. I look forward to keeping in touch to see just how big of an impact you have on the world, as I know it will be great.

Finally, to my family I owe the greatest debt of gratitude. As the first in our exceedingly large family to graduate college and walk across that stage with full honors I know you must be proud. I only hope you realize that it is a culmination of your influences on me. To my grandparents, of whom I am ever-grateful to still have, you have been some of my biggest motivators in college and life. From the time I was a boy, I remember you all telling me to get an education and make something of myself. I realize that even a high school education was impossible for some of you to attain, let alone being able to attend college. To my Papaw Leroy, your story of teaching yourself to read from the Bible as a teenager has always stuck with me and motivated me to ignore the odds of what is expected of a *redneck* from Green County and to make something of myself.

Most of all, I want to show my appreciation to my parents. I know you always regretted missing out on the opportunity to get a college education and, for that, you have always pushed me to excel at whatever I put myself towards. Had it not been for your persistence, I may have given up a long time ago. My biggest motivation in this endeavor has been to make you proud and I sincerely hope I have succeeded.

VITA

November 20, 1993…………………………………….... Born- Taylor County, Kentucky

May 2012……………………………………………..Graduated with Honors, Green County High School

Fall 2012……………………………………………… Award of Excellence Scholarship Recipient

2014………………………………………………….. Summer/Winter Internship – Sumitomo – Edmonton, KY

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Field of Study:

Mechanical Engineering

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CHAPTER 1

INTRODUCTION

Comfort during sleep, though taken for granted, involves a great amount of research and engineering. Few give it a second thought, but nearly one-third of a person's life is spent with their head on a pillow, thus making them a point for increased quality and comfort. Long have inventors attempted to find the optimal recipe for a comfortable night's sleep, changing materials and configuration of pillows and bed's to reach the perfect conditions. Though companies and consumers are far past the traditional feather or cotton-filled pillows of old, there is still competition in the industry to attain perfection. This competition effectively drives further research and development in companies, one of these being Tempur-Sealy International, known world-wide for their sales of the popular Tempurpedic mattresses. Attempting to lead the market with their line of high-end pillows, this company constantly seeks to formulate and construct new materials suited for their gold-standard name.

Project Formation & Problem Specification

With new, secret types of fillers being developed for potential mass production, it is important to executives at Tempur-Sealy to be able to back up a claim of producing the "world's most comfortable pillow" with empirical proof that will have customers all over the globe anxious to purchase their products and have their lives changed forever. Therein lies the problem, however, in that testing in this regard is a relatively new science, especially to this company who has only been producing pillow technology for a handful of years. Thus, a partnership between Tempur-Sealy's department of research and development, led by engineer Hamid Ghanei, and WKU's department of engineering was established and a team of electrical and mechanical engineers was formed with the objective of creating a means by which to test this company's pillows and produce concrete empirical evidence that will support their claims and further development of bedding products.

Before a solution to a problem such as this can be realized, it must first be understood what comfort is, or at least how it is defined by the customer in question. When an average person is asked what a comfortable pillow means, many responses would entail softness or firmness, or perhaps size would play a large factor. For many, the adage of the "flip-side of a pillow" is an all too real and often scenario in which discomfort, brought on by high temperatures and sweating, causes the user to wake up in a fit and flip the pillow in hopes of a cooler side and a few more hours of peaceful rest. We have all been there and it is this enormous market that drives innovation. In hopes of reaching pillow nirvana, developers have tried for years to change the configuration of different "soft" materials, organic and man-made alike, in hopes of utilizing their thermal dissipative properties to the consumer's advantage. However, one problem with this that consistently plagues us like a bad joke from up high is that materials that feel soft and fluffy enough to lay our precious heads upon are often some of nature's best insulators; that is, they conduct a minimal amount of heat. This is a very negative side-effect considering the human body, from a physical and biological standpoint, is essentially a thermal reactor taking ingested calories and carbohydrates and converting them into heat, our heads being one of the most prominent anatomical locales of this phenomenon. It is this circumstance that has led to the overwhelming amount of research into TempurSealy's patented foam technology utilized in their pillows. The ability of their foam to conform easily to a body's contours under loading (i.e. firmness) while being able to dissipate enough of the body's heat to keep one cool throughout the night is what makes them a new contender in the world market of high end pillows. Thus, their engineers define overall comfort of their pillows as the ability to conduct and dissipate heat in the presence of anatomical conditions including physical weight, constant thermal load, and perspiration (i.e. humidity). With this defined in terms of the scope of the project, my team and I were then able to outline and pursue a project whose goal would encompass this idea of testing standards of comfort and create a testbed that would fully satisfy the customer in question.

CHAPTER 2

TECHNICAL PROBLEM STATEMENT & PROJECT LAYOUT

Engineering Specifications

The research tool that was to be the end product desired by the customer was planned to have two general functions. This *testbed* must both replicate physical and anatomical conditions while also recording data relating to the products effectiveness at satisfying the desired parameters (i.e. heat dissipation). The human head test bed must be capable of generating and regulating the head's surface temperature and surface humidity, parameters defined by the customer as representing average anatomical characteristics. The surface temperature must be maintained at **35 ± 0.5 ºC**. The surface humidity, or moisture evaporation rate, must be maintained at **29 g/hr-m^2**. The desired set point for the head's surface temperature must be variable for the researcher to test a broad range of scenarios. The pillow is to have an attachable sensor array in order for the temperature and humidity effects from the *head* resting on the pillow to be observed. For convenience and communication between the data acquisition tools, controls, computer and sensor array, a graphical user interface (GUI) would also be integrated into the system. The GUI should acquire these sensor measurements and illustrate them for real-time visualization as well as logged by the GUI into some type of databank for future use. A further specification that was deemed *in-scope* by the team members and industrial contact was robustness against various room temperature, and humidity, and line-voltage-source variations. These initial specifications were then used to further develop project goals and design.

Teamwork Allocation

Teamwork is a central pillar in engineering. In industry, engineers are often appointed to teams or action committees in order to satisfy company goals in a fraction of the time it would take an individual employee to do. Time isn't the only factor that plays a role in team matters, however. Often, engineers with different strengths and backgrounds will work together in order to accent and complement one another. This idea was explicitly used when undertaking this project, using teamwork and planning skills learned in the classroom and gained with workplace experience to run an efficient operation consistent with what is expected in an industrial atmosphere. Weekly meetings with team members, the faculty advisor, and industrial contact were held to discuss project planning, scheduling, and designs. From these, documents such as a Gant Chart and Project Macro Plan (see Appendices Figure 16) were developed and ensured timely progression through the two-semester-long project was maintained and accountability amongst all stakeholders in the project was upheld.

For the student engineers associated with the project, a generalized list of roles and responsibilities was identified (see Figure 1) and allocated towards each member's strength or specialty, though roles tended to utilize multiple members as the project progressed. Having an industrial contact nearly 500 miles meant that communication would be vital to project success, hence special roles that would generally not be considered traditional engineering related though important nonetheless. Finally, as a means of establishing and confirming these roles as well as team conduct, a list of Norms and Expectations (see Appendix) was signed by all members and validated by faculty advisors as a way of defeating the "free-rider effect" before it became an issue altogether.

Role:	Name / Organization
Literature review and providing tech. options (two or three possible solutions)	Molly Shircliff (EE)
Responsible for team communication (with team, FA (faculty advisor), etc.)	Wesley Russelburg (ME)
Building the head	Wesley Russelburg (ME)
Sensor specification and selection	Brayan Pena (EE)
Design of close loop systems,	Jeremiah Genet (EE)
Design of virtual UI and data acquisition system	Molly Shircliff (EE)
System test and validations	Wesley Patterson (ME)
Time management overseer	Molly Shircliff (EE)
Stand design and development	Wesley Patterson (ME)
**Roles are subject to change as project progresses	

Figure 1 – Roles and Responsibilities

Per the terms of the project in accordance with faculty advisors and industrial contact, the entire scope of the project was to last approximately two (2) semesters with the final deliverable of a functional testbed being finished and ready for testing by mid-May, 2016. Thus, the project was broken into two phases by the team – the design and research phase of the first semester and the building and implementation phase in the second. This was to give adequate time for members to ensure competence in the final design and deliverable.

CHAPTER 3

RESEARCH AND DESIGN APPROACH

Literature Review

One of the first phases of the project before concrete designs were approached was to research current technology already implemented in industry. Because the idea of a thermally and anatomically accurate testing tool was new to our team, we sought inspiration from any current technology being used, attempting to avoid potentially flawed designs that may have been attempted by others before us or by other industries altogether.

The most promising technology currently in use was found to be thermal mannequins. Thermal mannequins are primarily used in testing in the clothing and automotive industries. Several off-the-shelf options are available for purchase, as well as several mannequins that have been developed in universities and can be rented out to the corporate sector. For off-the-shelf options that could potentially be implemented in our system, Thermetrics offers a full body thermal mannequin named Simon, as well as head-only versions [1]. These mannequins range from $65,000-$70,000. Another company in Denmark, PT Teknik, [2] also offers a wide selection of thermal mannequins, but they do not have sweating capabilities. The National Institute for Occupational Safety and Health

(NIOSH) has developed a thermal mannequin that sweats [3]. Boise State University has a thermal mannequin in their lab that web clients can conduct experiments with in real-time through a video stream [4]. This mannequin is inflatable and uses an air flow system to pump heated air into the dummy. Sweating is not included in this model.

Holmer [5] provides an in-depth review on the history and current innovations in thermal mannequins. He discusses the different materials used for mannequins – copper, aluminum, and most recently plastic – and the newer capabilities of sweating and breathing. Designers also design gender specific mannequins for more accurate results. Richards [6] introduces a sweating and mobile thermal mannequin named SAM. SAM is capable of producing sensible and insensible sweating – pads can be placed on the sweat outlets to create insensible sweat. The surface temperature can be maintained constant through constant power. The maximum power provided to the system, which corresponds to maximum physical exertion, is 1.2 kW. SAM's sweat rate (evaporation rate of water) is determined through weight measurements. The sweat rate and temperature of the mannequin's surface are measured at 1 minute intervals. With these different approaches to accomplishing essentially the same goal as our project had in mind, we were able to have a general idea of the design route we would embark on.

Design Approach

If teamwork is a key pillar to engineering, than surely design is the foundation it all rests upon. Design of the entire system involves approaching each technical specification and potential problem with a solution that will eventually be implemented.

For the overall, rudimentary design of the test system, the entire team created individually-inspired designs. After the beginning stage when the scope of the project and the design requirements were designated, the team met to brainstorm different ideas for accomplishing the tasks. Initial designs were proposed by all teammates and illustrated with sketches and computer aided design (CAD) drawings for ease of sharing. Once presented, each design was meticulously dissected for attributes and potential shortcomings. During this, proposals for additions and improvements were discussed leading to more refined designs. Through these discussions, certain criterion for judging designs was created. These were derived from member preferences as well as project scope and customer requirements. For example, a vertical degree of freedom for the "head" was required in order to simulate weight distribution on the product according to the industrial contact's specifications. Thus, the range of motion and means by which it was accomplished were points of debate and discussion during review. Though every design differed in how this motion was achieved, it had to be present to be considered a valid choice. Such attributes were therefore present in every member's preliminary design. Figure 2 shows the comparison and ranking of the submitted designs by the team using a Pugh matrix, a prominent tool in engineering design. A well-defined criterion is important as it provides a standard for the designs to meet in order to be competitive as a potential choice for implementation. Such benchmarks included ease of assembly, adaptability, simplicity of use, as well as others, all having some merit to future stages of the project such as construction, final delivery, and laboratory use by the final recipient.

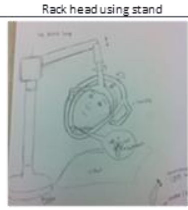
HHM Overall System: Pugh Matrix							Oct. 16, 2015	
	Options	Criteria						
		Compact	Easy-to-use	Ease of Assembly (For Customer)	Adaptability	Consistency	Fast/Easy to Build (For Team)	Overall Weight
Base Measurement	 Vertical head movement from ceiling connect	0	0	0	0	0	0	0
	 Pivot head movement, 90° freedom	-1	0	0	0	0	0	-1
	 Vertical head movement from side connect	+1	0	0	0	0	0	+1
	 Rack head using stand	0	0	0	0	0	0	0
	 Swinging head (like dentist lamp)	+1	0	0	0	-1	0	0
	 Adjustable raise/lower head from side connect	0	0	0	0	0	0	0

Figure 2 - Pugh Matrix of Initial Designs

Subsystem Approach

Due to the nature of this project and its many parts coalescing into one unified system, it was broken into several different subsystems. This allowed for better allocation of resources and manpower to each as well as maintaining a level of division between areas better suited for electrical engineers from those tailored for a more mechanical approach. The downside to this method is that, without constant communication between leaders of the different subsystems and designs, it would be quite difficult to expect their seamless integration with one another once they were completed by their respective parties. Thus, teamwork and planning methods were immensely useful in this stage and onward.

Stand Subsystem Design

The test stand was a straightforward design process, though it was not without it's own hurdles. A significant lack of physical limitations such as weight, size, and complexity gave nearly unlimited freedom for the design of the structure. The stand serves the function of a skeleton that supports the weight of and allows the desired motion of the model head model. At the same time, it acts as a channel for the circuitry used in data acquisition and controls. The frame was designed with lightweight extruded aluminum in mind which, for its standardized slots and fasteners, has become commonplace in industry. This adds a level of versatility and robustness that, though not explicitly required, opens the testbed to future development and improvement at little to no extra expense to the customer. This also added the benefit of time saved from lack of construction and fabrication the team would need as the material need only be cut to length and fastened with standardized tooling and hardware readily available.

Design of the motion apparatus was much more involved. Once the general design of angular motion was picked by the team, the industrial contact added a preference that the head unit only have a degree of vertical motion perpendicular to the base of the test stand. Because of this, a dual arm pivot mechanism, a specific type of four-bar linkage, was designed which would achieve just that. Next, because of the potential of the fragile head structure to fall when not supported by test material, it was requested that a damper be added to the system to slow its rapid descent. This would also serve to provide an opposing vertical force to offset any overage in desired weight of the head, a safeguard to any miscalculations that could have occurred when dealing with the complex geometry of the head unit. Figure 3 shows a preliminary simulation of the stand design before implementation.

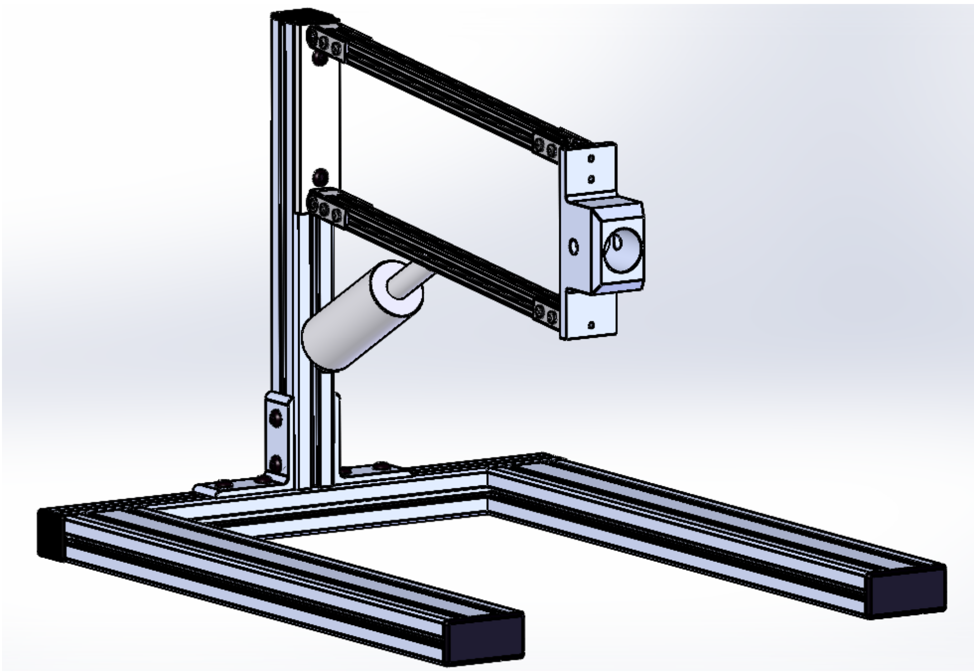


Figure 3 - Preliminary Stand Design

Head Subsystem Design

This sub system requires heat and moisture generation to the specifications outlined previously. The other essential requirement is the size. The size and shape of the head should be similar to a human head in the 95th percentile. In order to achieve these requirements, design concepts learned through a site visit to Tempur-Sealy were utilized. The method to generate heat and moisture will utilize a bladder made of polytetrafluorethylene. This material, known in the industry as Gore-Tex®, is a vapor permeable material which allows vapor molecules to pass through the fabric at a *porosity* rate of approximately 30-40 g/h-m^2. The containment shell of the head would thus serve two functions: humidity regulation and heat conduction. The shell was designed with voids in the surface that direct the moisture to the desired testing areas which are the side of the head and the back of the head that makes contact with the pillow. Holes can be plugged or more holes can be made during post-manufacturing so that the precise water evaporation rate is met especially if that rate needs to be changed for varying test parameters.

The liquid inside of the bladder is deionized water and will be maintained at the specified temperature to simulate heat generation similar to the human head. To generate the heat similar to a human head, the water is circulated through a resistance heater with a built in pump. It was important to utilize an off-the-shelf heater readily available for purchase in the case that the heater experience failure in the future. This way Tempur-Sealy will be able to purchase and replace the heater independently with little effort. Using a 1 KW heater and modeled with a simplified heat transfer model (see appendices Figure 21) we ensured that the time for the head to reach the desired temperature will be less than 10 minutes. Again, this was not a requirement set by the customer, but rather an added benefit that the team determined was beneficial for the primary stakeholder.

The bladder inside the head was designed in a U shape so that each surface, the back and sides, will be exposed to both heat and moisture transfer. This shape also allows for a compartment in the very center of the head unit to contain the heater and necessary equipment for fluid flow. This design was chosen because having all the fluid carrying components centralized in close proximity to the bladder minimizes the heat loss from the coil housing to the bladder where it is utilized. Moreover, what losses do exist are centered in the head and therefore must radiate outwards, still being used to mimic the anatomy of a head. Control valves were connected to the inlets which will be sewn to the bottom of the bladder in specified locations. The control valves allow for selection of the proper inlet depending on orientation of the head during testing. Figure 4 and Figure 5 show exploded solid models of the head assembly.

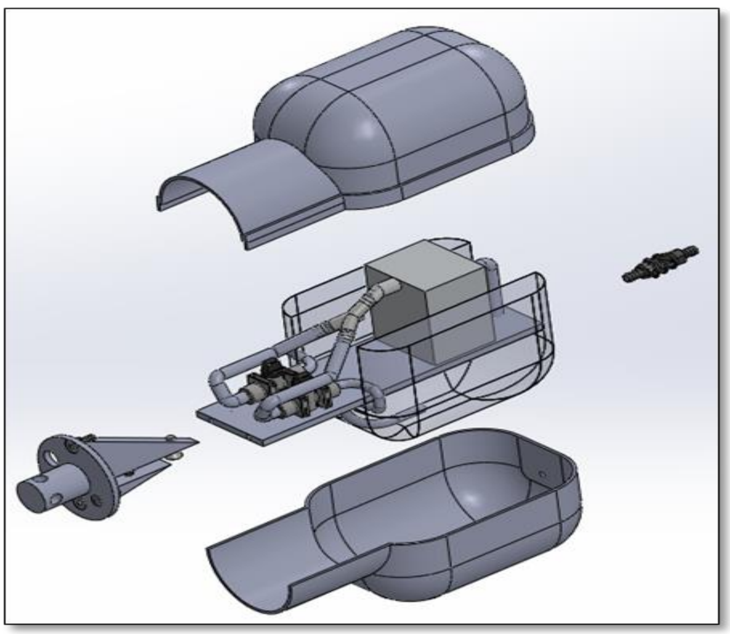


Figure 4 - Exploded Head Design View

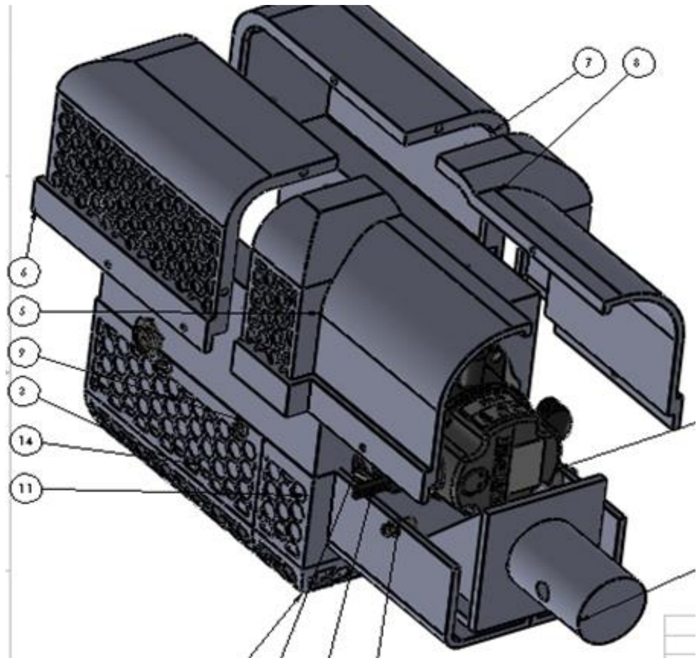


Figure 5 - Updated Head Design View

Sensor Array Subsystem

Temperature and humidity work hand in hand to effect comfort during sleep. For the sensor array subsystem, two preliminary tests were conducted to visualize and better realize the sensor apparatus needed to satisfy the customer's needs. In the first test, an IR camera was used to capture the temperature change induced by a human head across the test material surface. Results from this can be seen in Figure 6 and Figure 7.

Although humidity might not be as intuitively felt as temperature, it is just as important when monitoring the effects on quality and comfort of a product. Thus, not only did temperature across the surface of the pillow need to be measured, but also humidity. The second test implemented the use of the Sensirion Evaluation Kit EK-H4 provided by the customer to include relative humidity with temperature. Three SHT2x sensors were secured to the surface of the test material and were located at the center of the material-head contact region, at the boundary of material-head contact region, and approximately three inches beyond the contact region boundary.

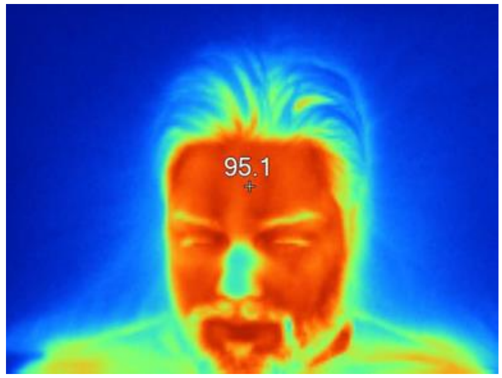


Figure 6 - IR picture of head laying on pillow

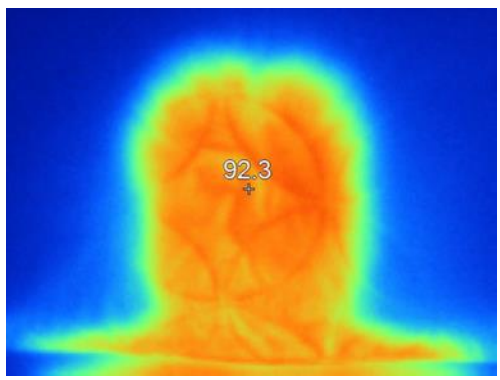


Figure 7 - IR picture of pillow with head absent

Results from both test indicated very a small temperature and relative humidity gradient from the center of the contact region to the boundary of the contact region and three inches beyond the boundary of the contact region the temperature gradient was steep, staying at nearly ambient conditions for the duration. An array of sensors placed at the surface of the test material would allow for collecting temperature and relative humidity readouts at known points on the surface relative to the material-head contact region and the ambient conditions. This translates to real-time mapping of the test material's temperature and local humidity. The sensors were to be secured to a flexible, porous, mesh-sheet material with adjustable straps, achieving a universally compatible, secure coupling between all test materials and the array. Based on the preliminary tests and the dimensions of the test materials provided, the dimensions of the array sheet were calculated and would result in the need for 17 – 25 sensors, depending on further testing during construction.

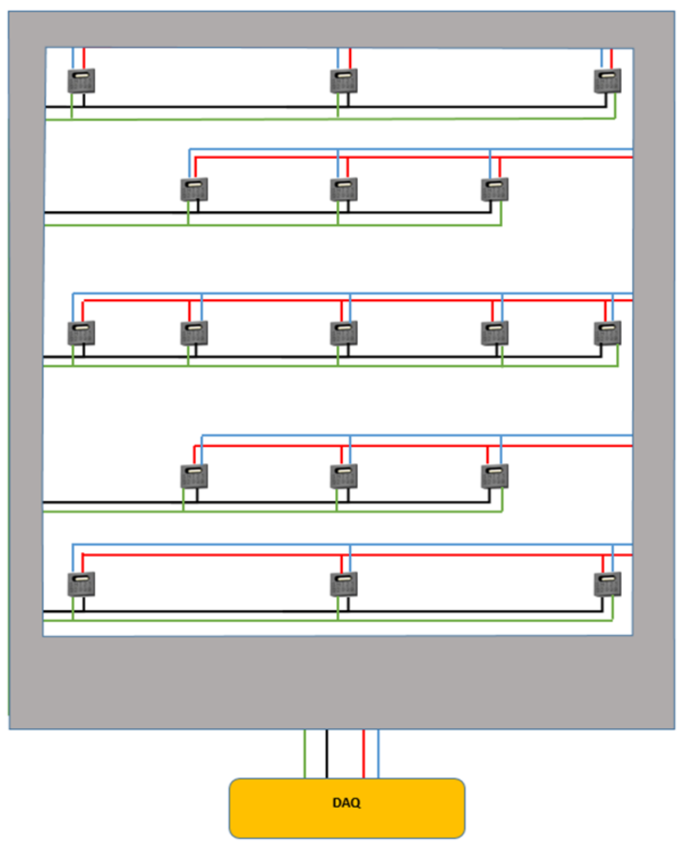


Figure 8 - Proposed sensor array layout example

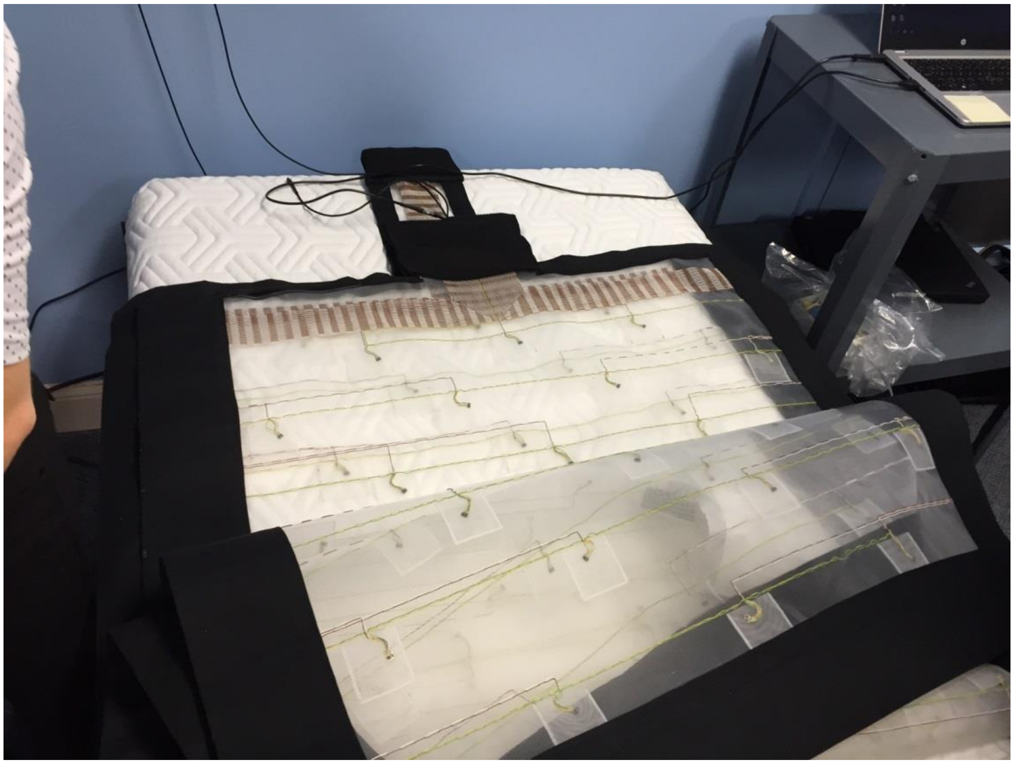


Figure 9 - Similar sensor array currently implemented

Data Acquisition and GUI Subsystem Design

Data acquisition and control was to be accomplished through data acquisition hardware. Measurements from the head and pillow sensors is acquired through the DAQ and logged into the computer where the data will be illustrated in real time as well as saved for the user in a directory. The measurement data will be displayed in real-time in Excel which is utilized for the entire graphical user interface (GUI). The values from the head surface's sensors will be used to create a feedback PID control of the head surface temperature. PID, or a proportional-integral-derivative, controller is what is used to accurately maintain the output temperature of the head unit. This has a significant advantage over traditional on/off type controllers (see Figure 23 & 24 in appendices), especially in a system such as this where the environment and pillow will constantly be drawing heat away from the thermal mass being controlled. Again, this control functionality is programmed in Excel's VBA programming language which was chosen primarily because of its availability. This means that any computer with a Microsoft package can operate the testbed's program, an effective advantage over the costly laboratory software available for purchase. Figure 10 and Figure 11 show a sketch of the GUI in Excel and its operations.

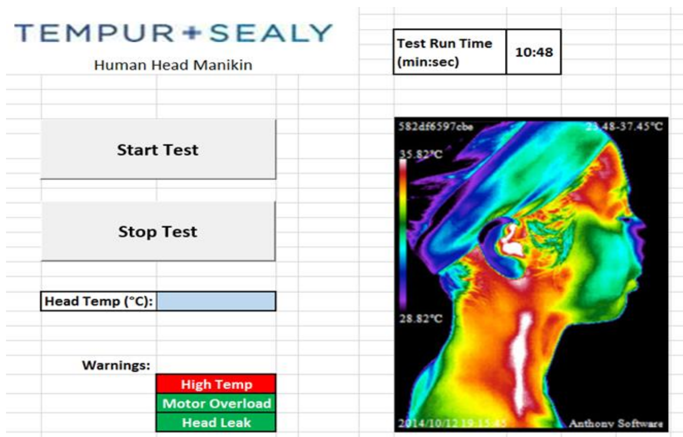


Figure 10 - Example GUI design

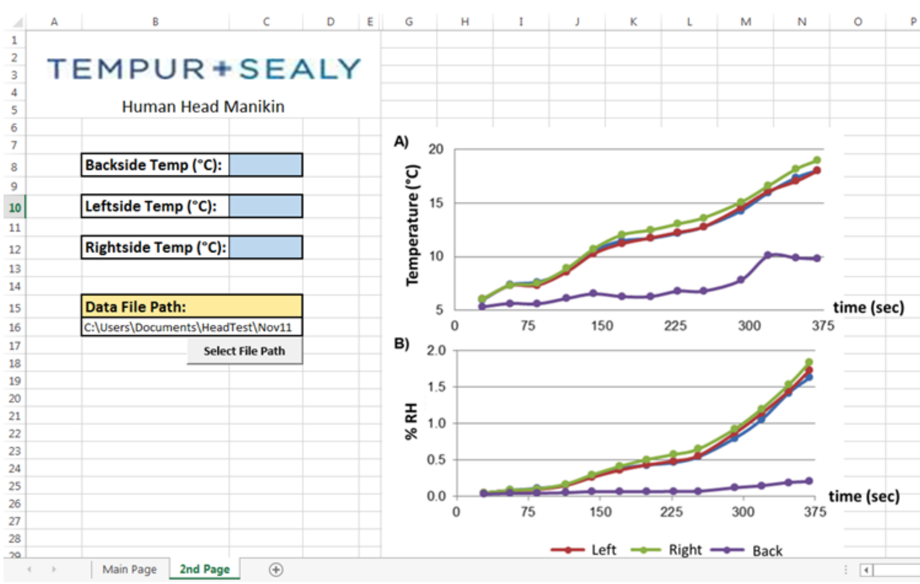


Figure 11 - Second page of sample GUI

Start and Stop buttons on the Main Page allow the operator to begin and end tests easily. The results from the pillow array sensors are displayed in a thermal image for easy visual interpretation of the tests in real time. The *Main Page* will also display warnings, such as high temperature or failure of heater or pump. The second page (Figure 11) will let the operator see the current temperatures of the head surface. It also provides graphs of the temperature and humidity measurements. The user can also choose the file path for the data logging, a useful measure for sharing gathered data with associates.

Design Finalization & Continuation

As designs were finalized at the end of the first term, they were reviewed by the faculty overseeing the progress as well as the industrial contact. Here, final revisions and comments were made and certain aspects were approved and further evaluated. Permission for construction and purchasing components was given and the project progressed as initially planned. It is important to note, however, that as with any large scale design project such as this, designs and preferences are subject to change, as was the case here. Though final prototypes do and will resemble initial designs that were given approval, the projects and much of its documentation and dependency are very much "living," a term referring to the fact that they are subject to review and change at any point until completion and delivery of the project.

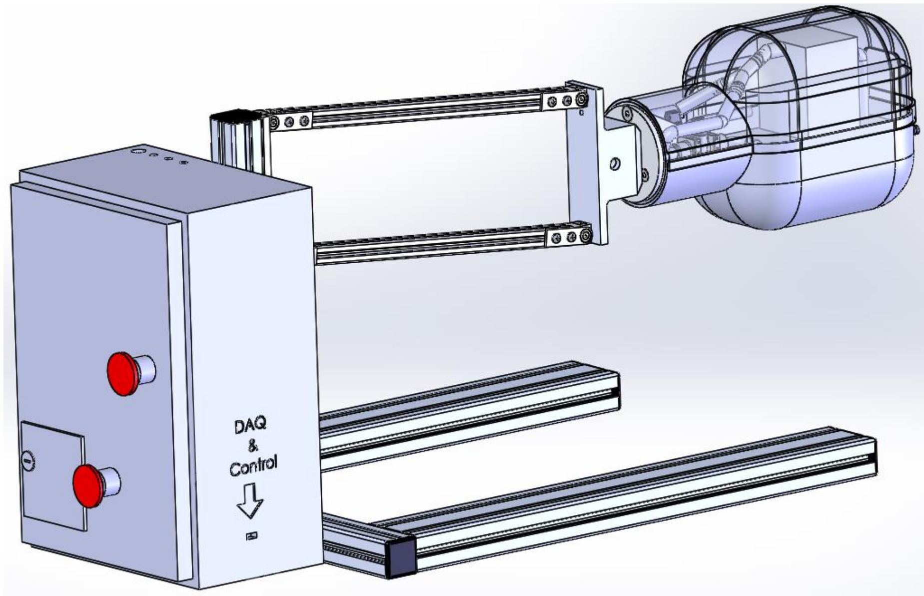


Figure 12 - Preliminary CAD model of testbed

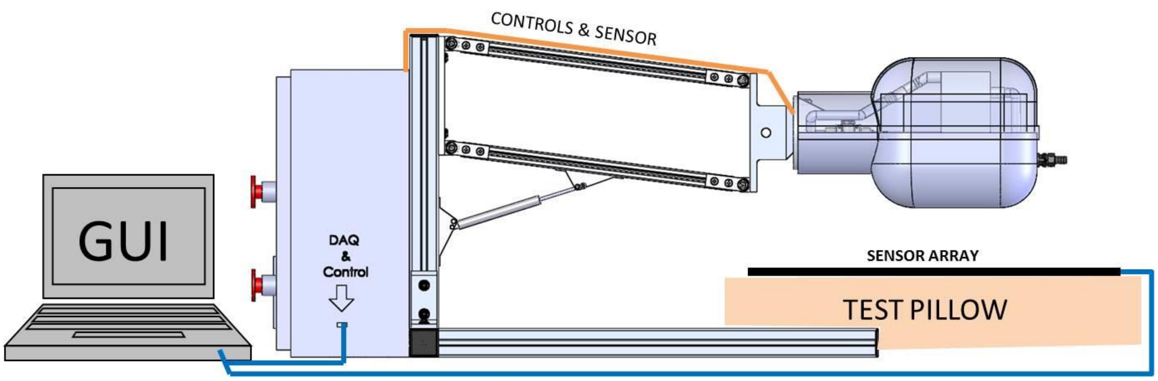


Figure 13 - Full System Diagram

CHAPTER 4:

DESIGN IMPLEMENTATION & CONCLUSION

Current Progress & Looking Forward

A primary tool used for continual improvement of the system was that of the FMEA. FMEA, or Failure Mode Effects Analysis, is a system introduced at the beginning of this project by the engineers at Tempur-Sealy. The tool has a long history in industry, though first conceived by the military and later NASA. As seen in Figure 30, it is used to predict all possible modes of failure, rank them by severity as well as other important parameters, and then used as a template for finding solutions to negate the future failures from ever occurring. Continuously revisiting this document helped our group to come up with several design changes and component implementations. An example of a change brought about by the FMEA was within the head subsystem. Leaks or stoppages in the tubing and bladder in the head could cause catastrophic failure in a two ways. First, lack of a moving fluid across the heating element will result in heat being retained in the pump unit, resulting in burning out the element and pump altogether. Secondly, leaks could flood the electronics or cause shock if exposed to live wires. Therefore, to negate this, a flow meter was added to the channels circulating the water. If the controls system picks up a significant drop in flow, errors will be initiated and power will be cut to the system until visited by the technician. This is just one of the many benefits brought on by implementing an engineering tool such as this.

Few changes have come about with the design since they were confirmed at the end of phase 1, however. The biggest changes have been to the head design. Though given approval of the design and the go-ahead on construction, concern about the large hexagon-shaped pores allowing exposure of the Gore-Tex® to the air surrounding the head arose from the industrial contact. The pattern, chosen for its excellent packing density as opposed to round holes, had the potential to refrain from conducting enough of the heat coming from the head to transfer to the pillow. Moreover, there was concern in regards to over-exposing the sensors on the array to direct humidity, negatively affecting the system by giving false readings about the local humidity surrounding the head-pillow interface. However, expecting possible changes or modifications to the design, it was decided to use more simple geometry for the shell of the head in order to utilize additive manufacturing, or 3-D printing, to build new components with the ability to do so in-house for a host of benefits: quick turn-around time, cost effectiveness, local accountability, and little-to-no fabrication work by a team member. Figures below show examples of the parts created using this method. See Appendices for more pictures of the advancement of construction.

Figure 14 - 3-D printed pattern for head shell

Figure 15 - 3-D printed shell components

At the time of this document's completion, the first full prototype of the testbed is nearing completion, currently at approximately 80%. As planned, nearly all of the fabrication took place in the department, using our tools and prototyping skill developed from years of projects. The full prototype is expected to be operational by the initial delivery date of May 7, 2016. In the end, our team came in under budget at just over $5000 USD and, barring any unforeseen circumstances, will have completed the projects original scope in its entirety. From here, we will finish final preparation of the deliverable by end of the term. Once completed, it will stay on WKU's campus were student researchers will use it for testing pillow samples sent by our new industrial partner, a relationship I hope will continue for quite some time.

Reflection

The first phase of the project went smoothly and was quite successful. Looking back at the first semester, the only negative reflection I have about project organization was to have had the first-person contact with our cooperating engineer at Tempur-Sealy much sooner. However, this was a problem that really couldn't have been helped due to the long distance between us. Having the project description fully defined by the industrial contact at the very beginning of the semester would have also given us more time to work on the project. Again, this was only compounded upon by the distance.

In the second phase, it may have been more beneficial to outsource more of the fabrication. Of course there were benefits to doing the majority in house including cost, reliability and accountability, and having the ability to make any necessary changes on the fly. However, this also took time from myself and my teammates that could've been allocated to other endeavors. This also resulted in setbacks that may have not been experienced if outsourced such as delay in meeting fabrication deadlines due to department machinery being down for maintenance or identifying and fixing leaks in the handmade bladder.

Overall, I am pleased with my team and our progress in this endeavor. As a whole, I learned many invaluable engineering skills and how to implement the tools and knowledge gained in my years in the classroom. The biggest takeaway from a project of this magnitude is the fact that engineering is more than mathematics and physical models, but is also about working professionally and with colleagues of different backgrounds and roles to meet a common goal, a practice I believe applicable to many industries. I look forward to completing this project and hearing of its progress and activity after I depart from the university.

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[5] I. Holmer, "Thermal manikin history and applications," European Journal of Applied Physiology, vol. 92, pp. 614-618, 2004.

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Appendices

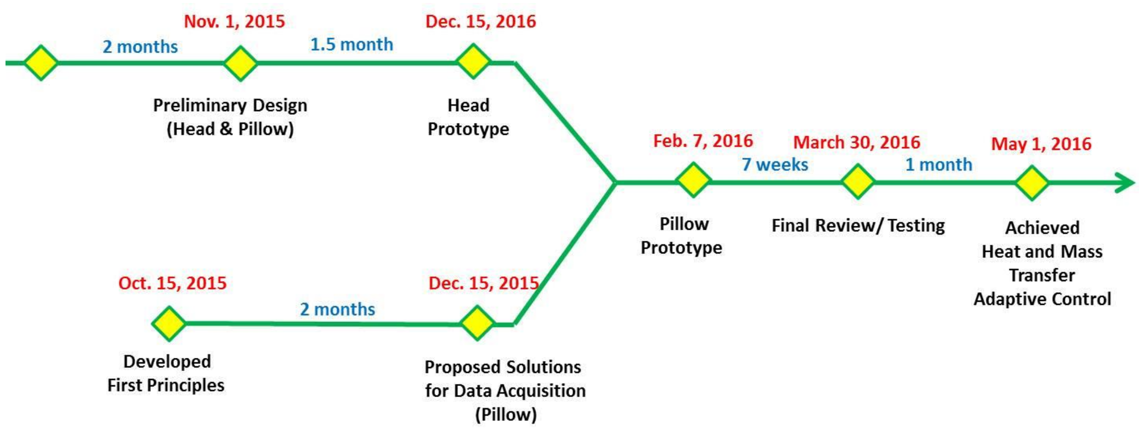
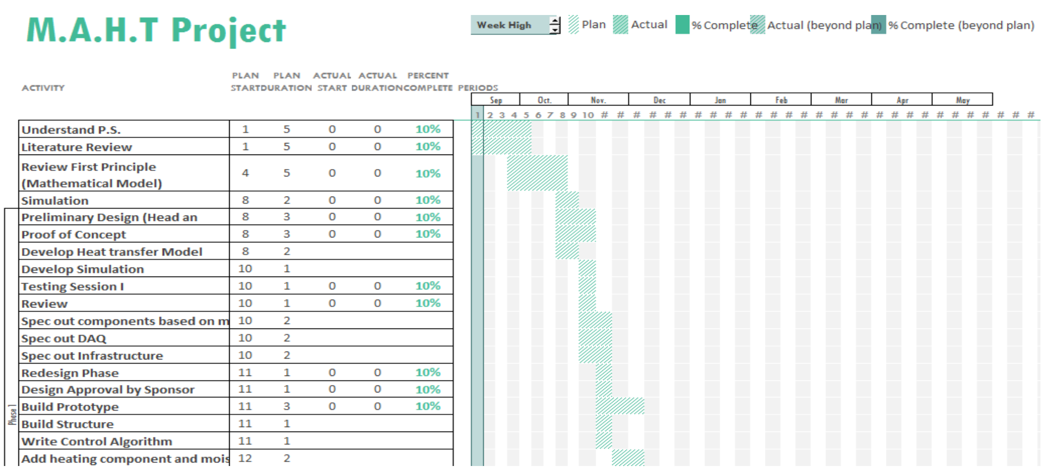


Figure 16 - Phase 1 Macro Plan



M.A.H.T Project

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Understand P.S.	1	5	0	0	10%
Literature Review	1	5	0	0	10%
Review First Principle (Mathematical Model)	4	5	0	0	10%
Simulation	8	2	0	0	10%
Preliminary Design (Head an	8	3	0	0	10%
Proof of Concept	8	3	0	0	10%
Develop Heat transfer Model	8	2			
Develop Simulation	10	1			
Testing Session I	10	1	0	0	10%
Review	10	1	0	0	10%
Spec out components based on m	10	2			
Spec out DAQ	10	2			
Spec out Infrastructure	10	2			
Redesign Phase	11	1	0	0	10%
Design Approval by Sponsor	11	1	0	0	10%
Build Prototype	11	3	0	0	10%
Build Structure	11	1			
Write Control Algorithm	11	1			
Add heating component and mois	12	2			

Figure 17 - Snip of Phase 1 Gant Chart

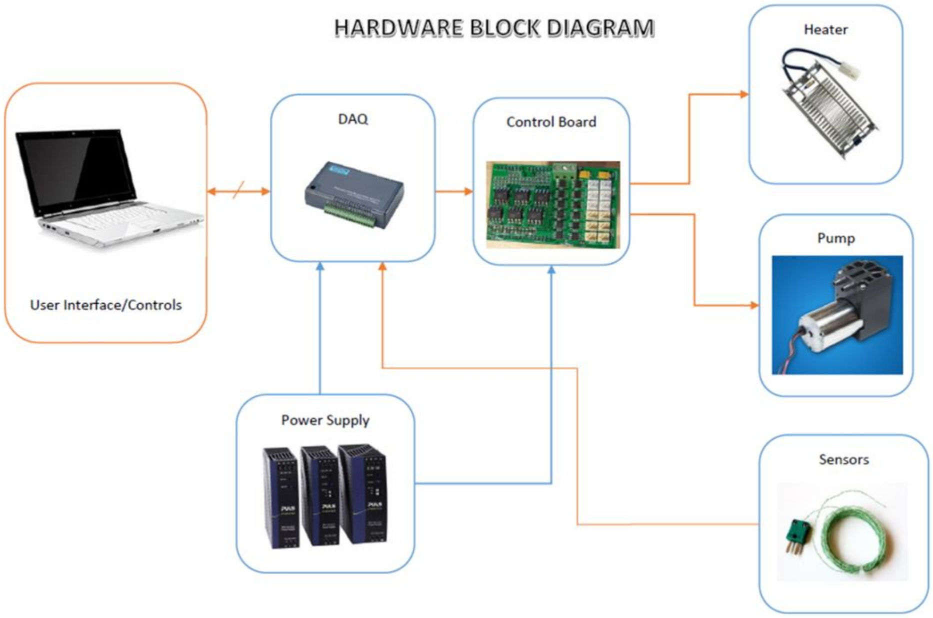


Figure 18 - Hardware block diagram

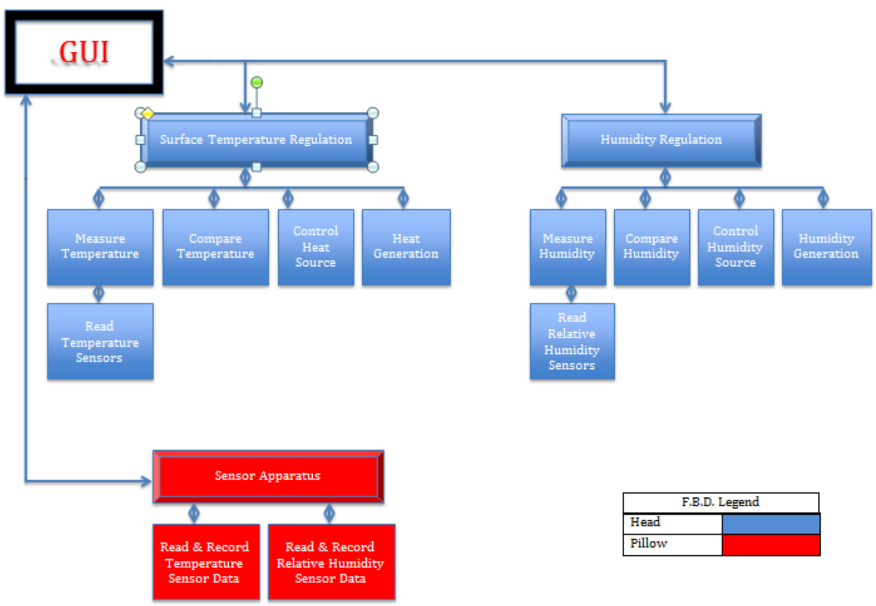


Figure 19 - System Block Diagram

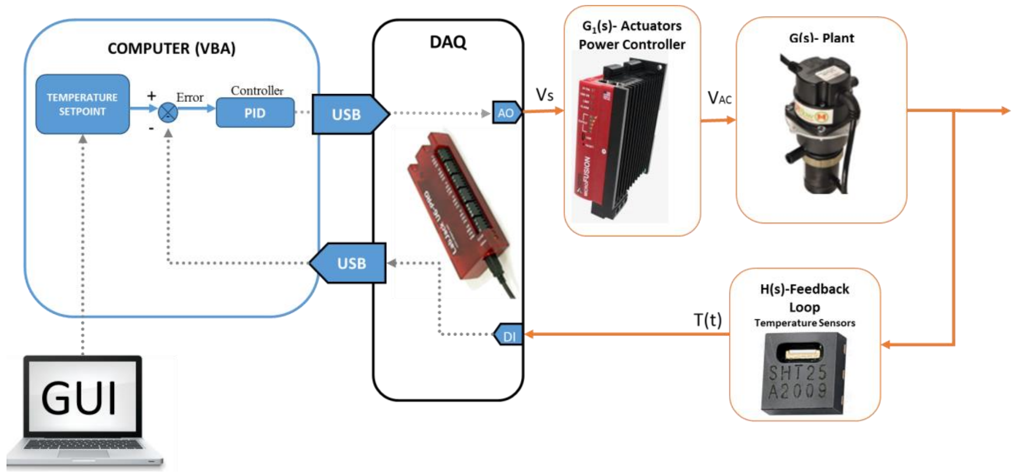


Figure 20 - Control Loop Diagram

$$V\rho c_p \frac{dT_{tank}}{dt} = Q_{heater} - hA(T_{amb} - T_{tank})$$

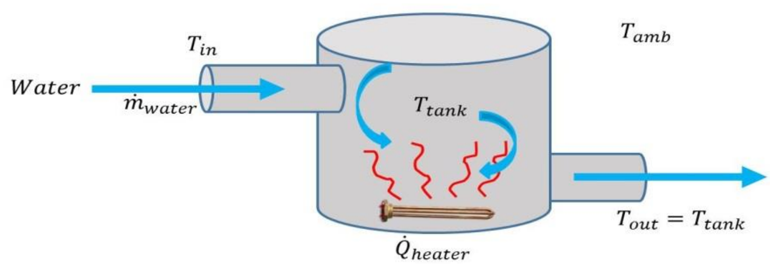


Figure 21 - Heat Transfer Model

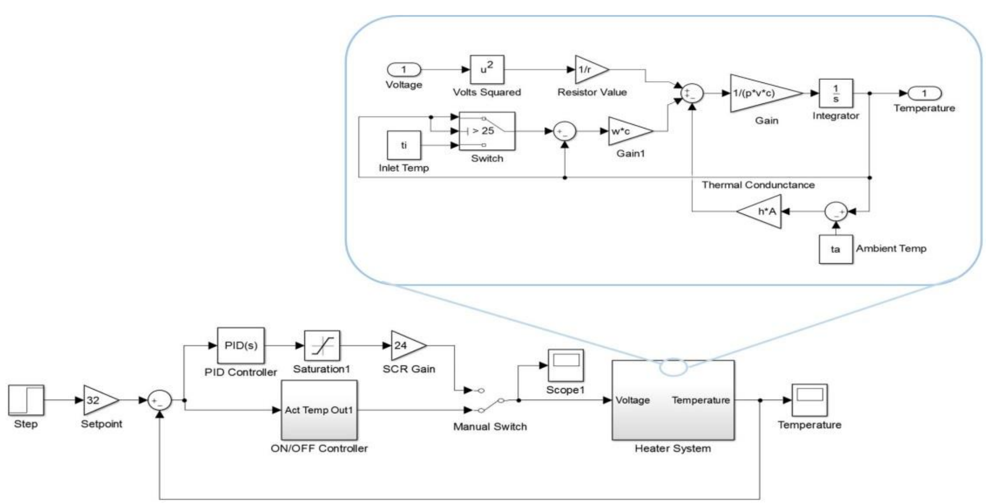


Figure 22 - Heat Transfer Simulink Model

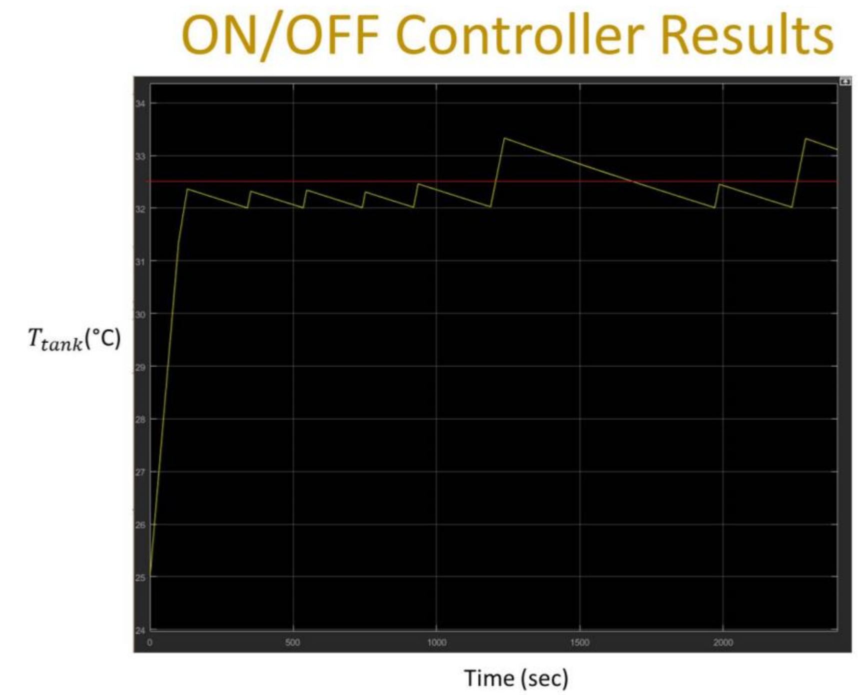


Figure 23 - Temperature Control via ON/OFF

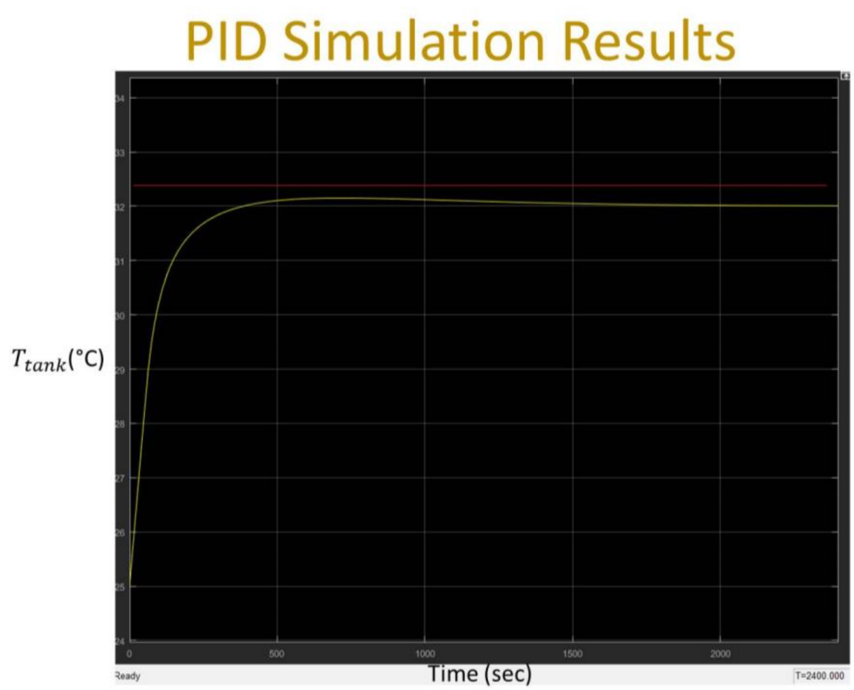


Figure 24 - Temperature Control via PID

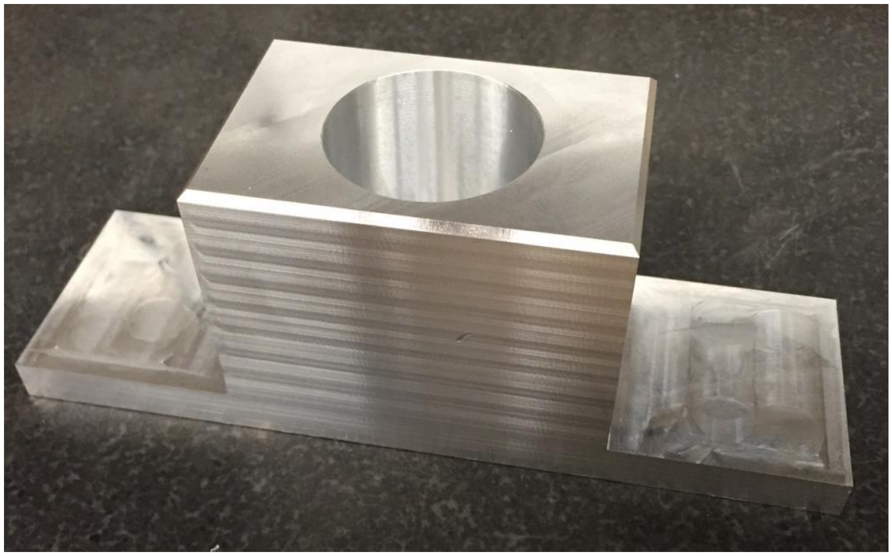


Figure 25 - Neck Reciever Plate after CNC machining

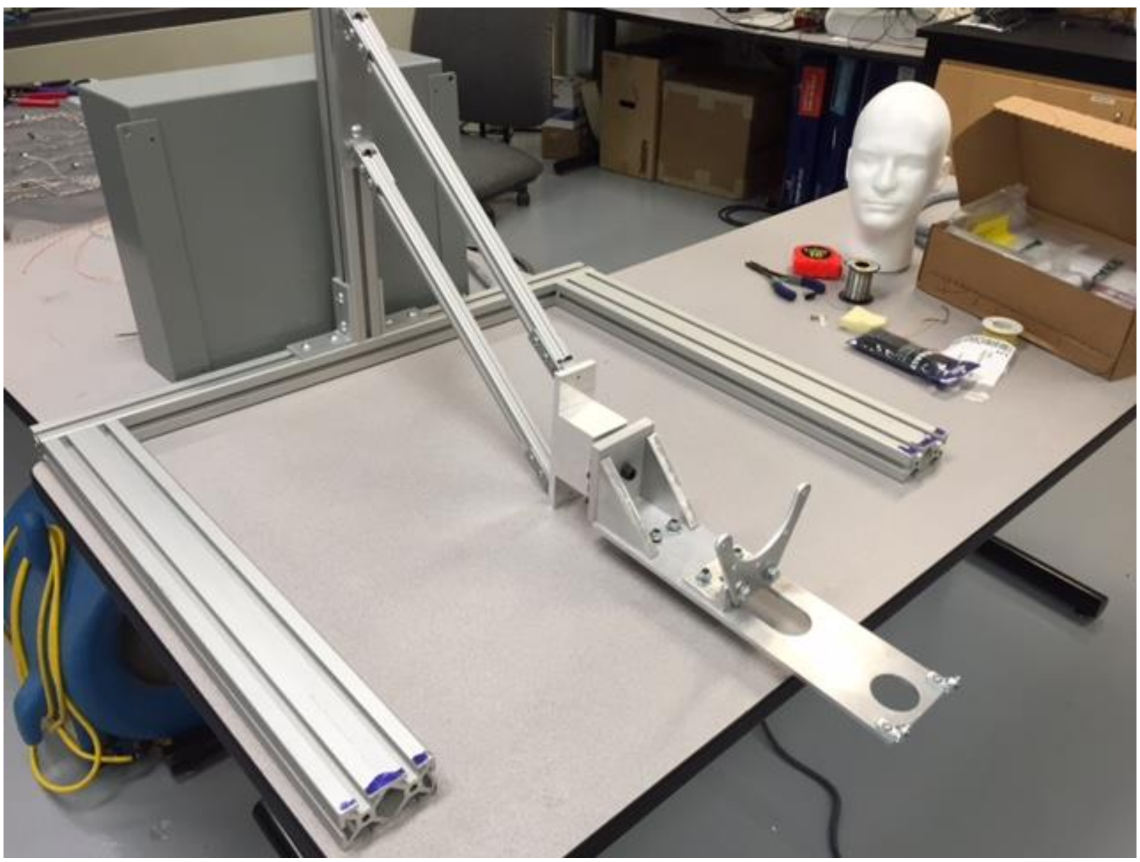


Figure 26 - Stand under construction

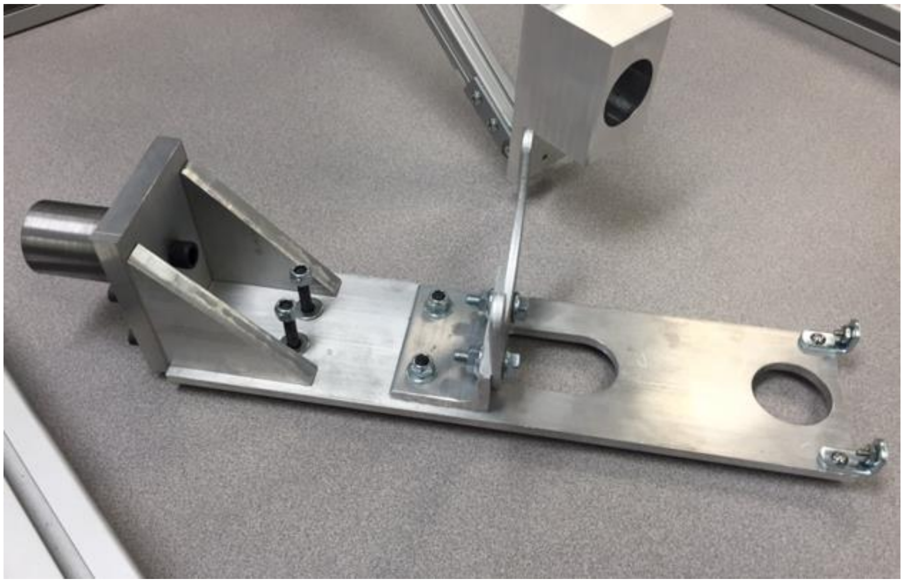


Figure 27 - Head Mounting Plate

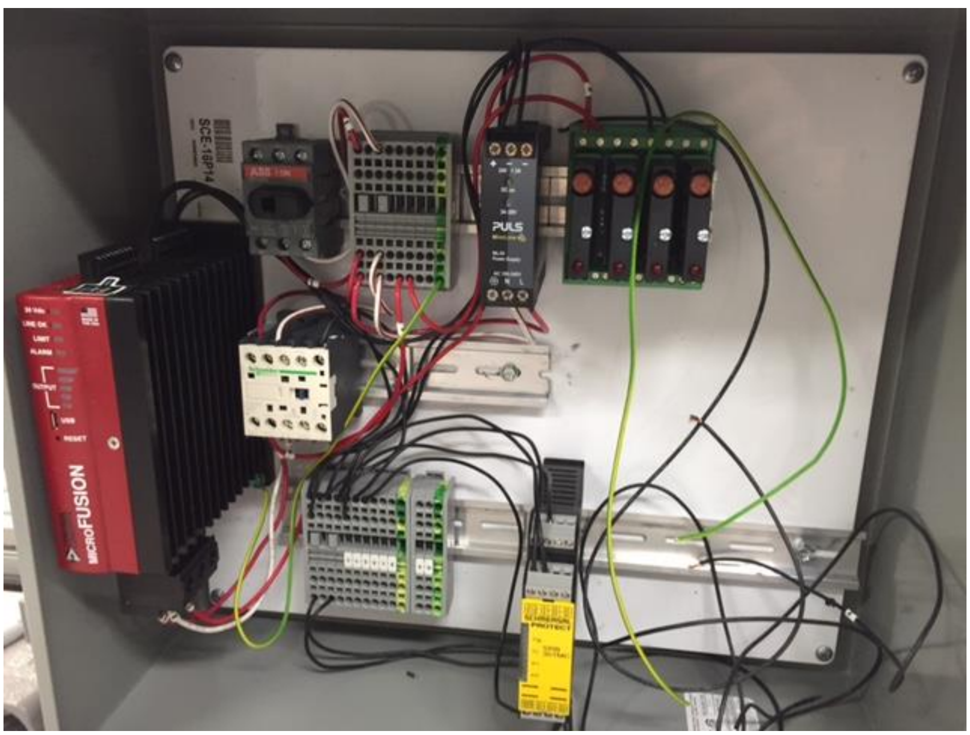


Figure 28 - Control Box under construction

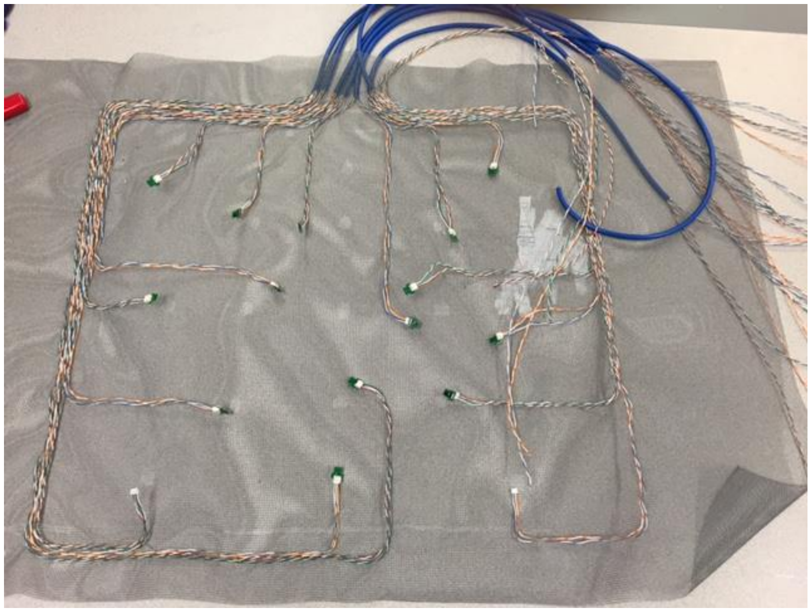


Figure 29 - Sensor array under construction

Item:	Head Manikin				**Responsibility:**		W. Russelburg			
Model:	First Model				**Prepared by:**		M. Shircliff			
Core Team:	J. Genet, B. Pena, W. Patterson, W. Russelburg, M. Shircliff									
Process/Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Class	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Process Controls	Detec	RPN	Recommended Action(s)
Stand - holds manikin head for easy maneuverability	Stand cannot support head	Stand falls over, bows	9		Head too heavy, stand not heavy enough or not structurally sound	1		1	9	Fasten to a more sturdy base
Heater - heats head to set temperature point	Overheats	Burns user, Melts head material, Ruins sensors on head	9		Controller overshoots, product malfunction	5		2	90	Add warning to GUI if overheat occurs sensed by temp and current sensors
	Does not heat	Wasted test time	4		Product malfunction	5		2	40	Add temp sensors to GUI
	Electric shock	Injures user	9		Wires short	4		1	36	Utilize Insulated wires that and the body is grounded
Pump - pumps water through head	Stops pumping	Causes overheat	9		Product malfunction	5		2	90	Put warning on GUI if pump stops sensed through flow switch
Head - thermal manikin that houses heater and pump	Bladder leaks	Ruins equipment, inaccurate data	7		Not sewn properly, not proper seal at tube inputs	4		1	28	
	Too hot to touch	Burns user	7		Heater overheats, heater is too close to head surface	5		2	70	Test before fully building head
									0	

Figure 30 - Snip of FMEA

Figure 31 - "Human Head Modeling" Team on site visit