Temperature Regulating and Ventilated Mattress

Team Material$

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ME 4723 A – Interdisciplinary Capstone

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Executive Summary

This report presents the design and development of an innovative climate-controlled mattress intended to enhance sleep quality and offer therapeutic benefits. The motivation stems from the limitations of conventional cooling methods, such as ceiling fans, which provide inconsistent and imprecise temperature regulation, leading to discomfort. This design specifically addresses the need for a customizable solution that can cater to individual comfort preferences while also providing benefits for athletes, hospital patients, and those recovering from illness.

The core design problem is the development of a mattress that offers effective internal climate control, providing both heating and cooling capabilities to improve sleep quality. Additional benefits may include providing therapeutic effects, such as aiding muscle recovery or preventing bedsores. Traditional methods fail to maintain consistent air temperature across the bed surface, and current market solutions offer limited thermal regulation. The primary objective of this project is to design a mattress with an internal heating and cooling system that accomplishes three main tasks:

1. Allow customizable temperature control for the user.
2. Provide continuous and evenly distributed air circulation to the user.
3. Operate safely and efficiently, with minimal power consumption.

To accomplish these goals there are a few key technical challenges associated with this project. Achieving uniform air distribution across the mattress is essential to prevent thermal gradients, but the challenge is ensuring the physical hardware does not interfere with the overall comfort of the mattress. The next challenge is developing a system that can operate reliably over prolonged periods since users will likely use it every night for several hours. Lastly, the design must ensure the safety of any integrated heating components, particularly when the user is in direct contact with the mattress.

The design process was guided by market research, the study of relevant patents, and Quality Function Deployment (QFD) charts. The team conducted several brainstorming sessions to generate and evaluate multiple concepts, aided by tools like function trees and morphological charts to assess various design solutions. Through this process, the design was narrowed down to one that incorporates an air-based system for heating and cooling. Air is drawn from the environment, conditioned to the desired temperature, and circulated through the mattress using fan units. The system includes temperature sensors and control units to allow users to customize their sleep environment and ensure its safety.

Several key performance specifications are used to define the system requirements. The temperature range is between 15 °C and 30 °C to allow for adjustable heating and cooling over a broad

temperature range. Once a temperature is selected the airflow uniformity should be within 2 °C. Materials with low thermal conductivity will be selected to minimize heat loss. The system should consume less than 2.5 kWh/night of power. To ensure reliability, the system should be capable of 12 hours of continuous operation. The system should also operate quietly and stay below 30 dB during operation.

The proof of concept for the design will be a fully functional small-scale version of the system. It will be a two-foot by two-foot prototype that can showcase the heating and cooling functions of the bed. A two-foot by two-foot specification was chosen to ensure all of the necessary electronic components would be able to fit into the system comfortably. The prototype will include all the components usually found on beds, such as the frame, mattress, and sheets. Users will be able to place their hands on the surface to feel the airflow and temperature change of the system.

A CAD model was constructed using Fusion 360, which clearly labels each layer of the bed. From here, a Bill of Materials (BOM) was synthesized and the team started purchasing materials. The team also developed the electrical assembly necessary to control the prototype's functions. The team then built the diffuser box, assembled the mattress, and added the electronic components. Then, temperature sensors were installed around the diffuser box to display a heat map of the product before and after use.

Introduction

An important factor in rest quality is having a climate-controlled sleeping environment. Without this, sleep quality can be compromised, leading to suboptimal daytime performance. Although the most common method of climate control is through a ceiling or desk fan, this method results in imprecise temperature control and may end up pushing warm air throughout the room, especially in warmer climates. Thus, a proposed solution that could significantly enhance consumers' sleep quality and comfort is a mattress with an internal cooling and heating system. Optimizing the mattress material and the air flow would not only maintain the muscular stability that a regular bed offers, but would also offer an extra level of customization that the consumer can use to maximize their comfort. In addition, this bed could assist athletes in recovery from full-body soreness, as an ultra-cooled or ultra-heated bed would act as an additional therapeutic agent to supplement their treatment during their sleep. Many athletes also suffer from inflammation and swelling, so the ventilation can help to counteract these problems. An ultra-cooled or ultra-heated bed could also help people alleviate fevers or colds and help prevent hospital patients from getting bed sores after being bedridden for extended periods of time.

This introduction outlines the current state of the art regarding cooling and heating beds, as well as the formulation of several Quality Function Deployment (QFD) charts that guided the generation of several design concepts and the selection of a main design so far.

There are two main companies in the consumer market that provide internal bed cooling: bFan® [1] and BedJet [2]. Both companies utilize a fan and a duct placed inside the bed sheets to provide ultra-quiet cooling to portions of the bed as the customer pleases. However, because the dimensions of the duct for both products are limited, the coverage area of the air flowing through the duct would lead to significant thermal gradients across the bed. For instance, if a person shifts positions many times during deep sleep, they may not experience the full effects that the duct would provide.

Various patents were studied to better understand the existing technologies incorporated in internally cooled beds. One of these patents is for “Environmentally conditioned furniture” (John Statham, EP1804616B1, 2012) [3], particularly a bed, which includes a breathable mattress on a base with a fan, duct, and heater. These work together to pull in air, adjust its temperature and humidity, and push it through the mattress for the comfort and health of the person using the bed. The system often uses a shallow tray between the mattress and frame to hold the conditioning unit, as shown in Figure 1.

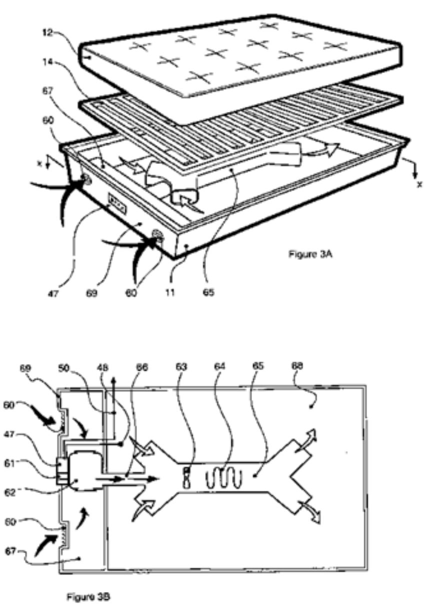


Figure 1. Exploded diagram of “Environmentally conditioned furniture”.

This technology aims to address common issues associated with traditional furniture, which often traps air pollutants like dust mites, dust, and strong manufacturing odors, potentially leading to respiratory problems. Additionally, standard furniture lacks temperature regulation, which can increase humidity levels and create ideal conditions for dust mites. By maintaining optimal humidity and temperature, this innovative design helps mitigate respiratory issues. Furthermore, it enhances user comfort with a quiet airflow system that evenly distributes air throughout the mattress.

An environmentally conditioned bed features an upholstered mattress, cushion, or bolster on top of a base that distributes conditioned air (temperature and/or humidity controlled) from an air conditioner via a forced flow system. The setup includes a specially designed tray that allows air to spread beneath the mattress, functioning as a shallow air reservoir that lets conditioned air percolate through the mattress. There are also many other notable features. For example, a "stepped profile" allows for airflow in between the mattress and the frame. A "plenum chamber" is also present, which is used to ensure even air percolation to maintain a comfortable temperature and humidity level.

Another patent studied was the Kang surface stone mattress bed for warm air, warm heat, and massage (Liu Chengyeol, Liu Jixian, CN107427133B, 2015). This invention focuses on providing a bed with a mattress that has an integrated warm air, heating, and massage system, simulating the experience of a traditional heated stone floor (kang), as seen in Figure 2. The design addresses common issues with standard mattresses, such as inadequate temperature regulation and the need for additional bedding like electric heating mats, which can be uncomfortable and prone to damage.

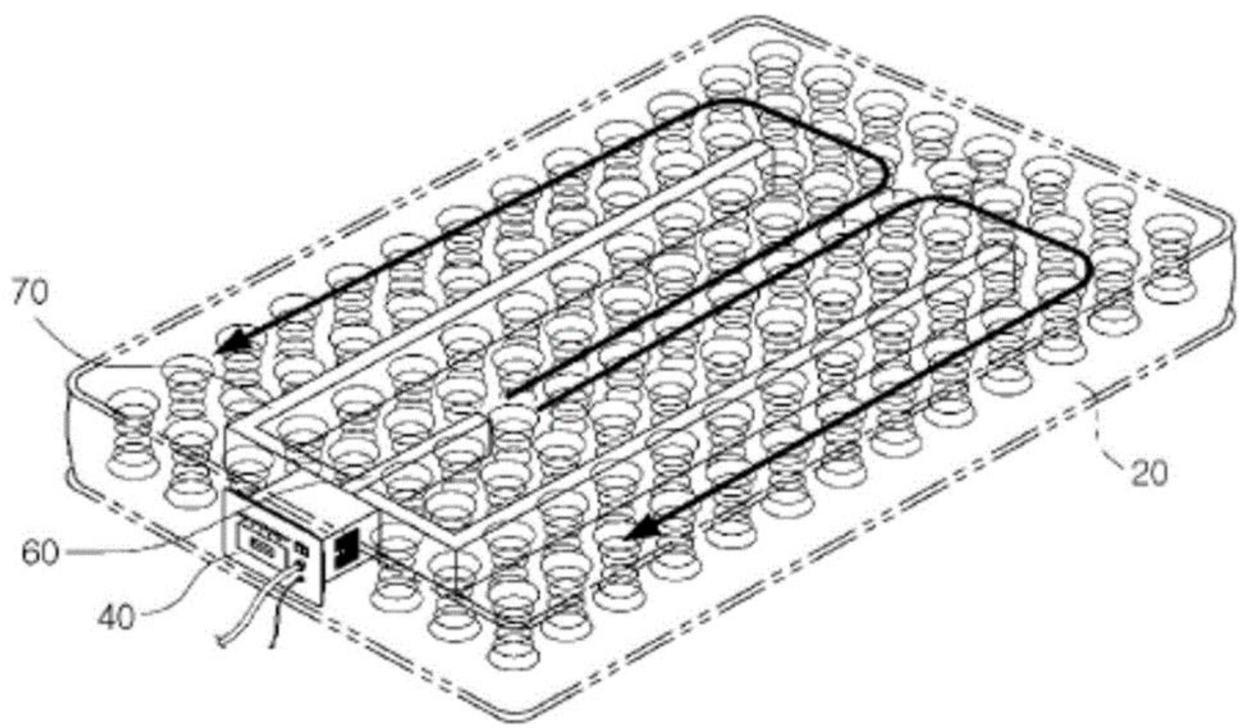


Figure 2. Kang surface stone mattress bed for warm air, warm heat, and massage.

The system incorporates a warm air generation unit, a warm air discharge unit, and warm air guide members that distribute warm air evenly across the mattress. The air is filtered and sterilized with a built-in ultraviolet sterilizing lamp and a filter system, designed to eliminate dust mites and other allergens. The warm air circulates throughout the mattress, dehumidifying and heating it efficiently.

Additional features include a remote control with multiple operational settings, such as temperature, time, speed, and sterilization. A massage unit with roller massage tables can be folded for storage, and the bed is supported by a frame with integrated shock absorbers to enhance durability and comfort. The system also includes safety mechanisms like overheating prevention and a triple safety control feature to ensure safe operation.

The innovation behind this technology lies in its ability to provide a more controlled, comfortable sleeping environment while addressing issues of air circulation, temperature regulation, and user health by combating allergens and moisture buildup.

Another patent examined involves an improved temperature-regulating mattress system that dynamically adjusts temperature to enhance user comfort during sleep (TRIPLEPOINT VENTURE GROWTH BDC CORP, US11241100B2, 2019). This mattress incorporates a comfort layer and an intake layer, with air passages and permeable covers that enable airflow across the bed's surface, as seen in Figure 3. The system is designed to maintain a stable microclimate around the user, offering temperature control, humidity regulation, and biometric monitoring.

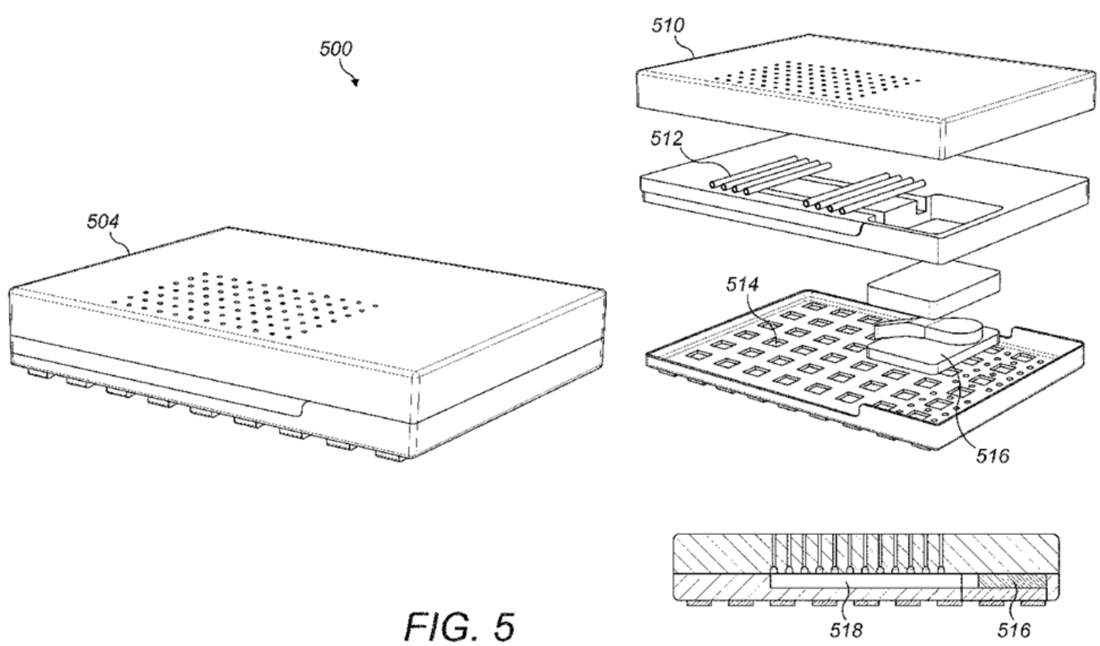


Figure 3. Exploded diagram of "Temperature-regulating mattress".

Key features include dual-zone temperature regulation with individual controls for each side of the mattress, allowing customization for multiple users. The system uses smart controls with app integration, enabling users to set custom profiles and connect to smart home devices. It also includes surface sensors embedded in the mattress that measure temperature, humidity, and user presence, enhancing biometric data collection and optimizing sleep conditions based on user activity.

Additionally, the mattress base is equipped with expandable segments and airboxes that distribute heated or cooled air efficiently. The airbox system uses a network of channels to circulate air, ensuring that both torso and foot zones are well-regulated. The system also features a biometric sensor embedded in the mattress base, which tracks heart rate, breathing rate, and motion to further fine-tune temperature adjustments.

This patent addresses common sleep disturbances caused by improper temperature regulation, offering a sophisticated solution that enhances sleep quality through continuous real-time adjustments tailored to individual user needs.

Societal, Environmental, and Sustainability Considerations

From a societal standpoint, the product was designed and developed for use by many potential groups. For one, patients in hospitals could benefit, due to the fact they are often restricted to staying in bed. Hospital patients are prone to bed sores, and infections due to moisture that may form at the interface of the bed and the skin. With this temperature regulated, ventilated bed, moisture formation from sweat and trapped air can be mitigated and the increased airflow can minimize bed sores as well. This product can also assist in therapeutic treatment for athletes or others struggling with back pain or muscle soreness. Thus, the benefits for many demographics were considered in the development of this product.

From an environmental and sustainability perspective, the foam can be shredded and reused to make other foam products [1]. This increases the sustainability of the materials utilized. Furthermore, many pieces of the bed are composed of wood, which is a biodegradable material. Finally, the team designed the bed to be modular, so that many of the components can be reused in other electronics or so that components could be replaced easily.

Design Requirements

As this is a product that will integrate itself into the daily lives of the user, customer requirements and design specifications are prioritized. The intended purpose of the invention is to allow for temperature regulation, so naturally, it is also a major design requirement. However, because users will be physically in contact with this surface which contains heated components underneath, safety is also a strong consideration. Other performance demands include uniform air distribution, continuous operation, and power efficiency. From a structural perspective the bed should also be durable. Finally, the bed should be able to be controlled by users.

Table 1. Stakeholder chart for temperature regulating mattress system

	High Influence	**Low Influence**
High Interest	**Satisfy** • Capstone Group • Professors	**Manage** • Sports Organizations (NFL, NBA, Team USA, NCAA, etc.) • Hospital Systems • Senior Homes
Low Interest	**Monitor** • Consumer Product Safety Commission • BBB	**Inform** • Retailers (Amazon, Walmart, Mattress Firm, etc.)

There are a few constraints that must be kept in mind when designing the mattress. For one, the temperature regulation must be uniformly distributed throughout the mattress, meaning that any setup that could lead to the formation of a temperature gradient must be avoided. To quantify this, the temperature control system must maintain a customizable range between 15 °C and 30 °C, with uniform airflow within 2 °C across the mattress to cater to individual preferences. This is essential for user comfort. In the same, the layout of the components within the mattress should not interfere with the overall comfort.

Materials with low thermal conductivity are required to minimize heat loss and ensure effective temperature regulation. The thermal conductivity of at least the material surrounding the heated components should be less than 0.4 W/mK, to prevent the addition of heat from the mechanical system. From a noise perspective, the mechanical system should also generate less than 30dB of sound, to ensure user comfort.

Also, the system must show reliability, durability, and efficiency, as it is expected to be operated nightly over a long period of time. Specifically, the mattress must be capable of continuous operation for at least 4 hours at one time, which would encompass one night of use. The design also needs to be efficient in terms of power consumption, operating below 2.5 kWh to ensure cost-effectiveness and sustainability.

Safety is another concern, especially regarding the integrated heating elements, which must be safe for users in direct contact with the mattress. To quantify this, the mattress must be able to withstand a temperature of up to 70°C for 1000 hours. Though it is not expected to reach this temperature, this adds an extra layer of safety check. A summary of these specifications and constraints are displayed in Figure 4.

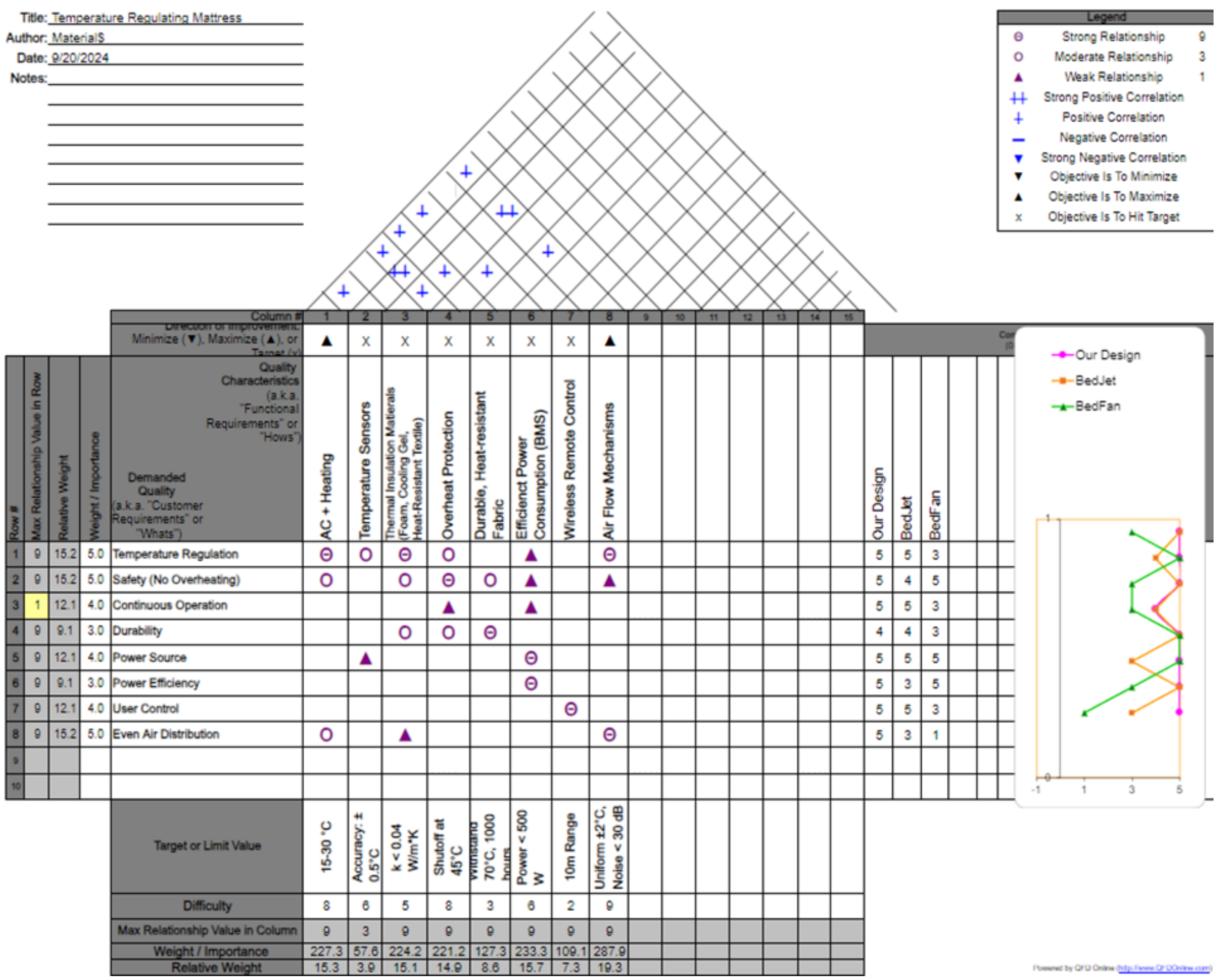


Figure 4. House of Quality for temperature regulating mattress system.

Figure 5 illustrates a function tree for the mattress. The main functions are detecting the current temperature, adjusting the temperature by heating or cooling to a temperature setpoint, and maintaining the setpoint. The most important and complex subfunction is diverting the airflow from the heated to cooled section (and vice versa), as this requires a feedback system to quickly and automatically switch a valve or damper according to the temperature reading.

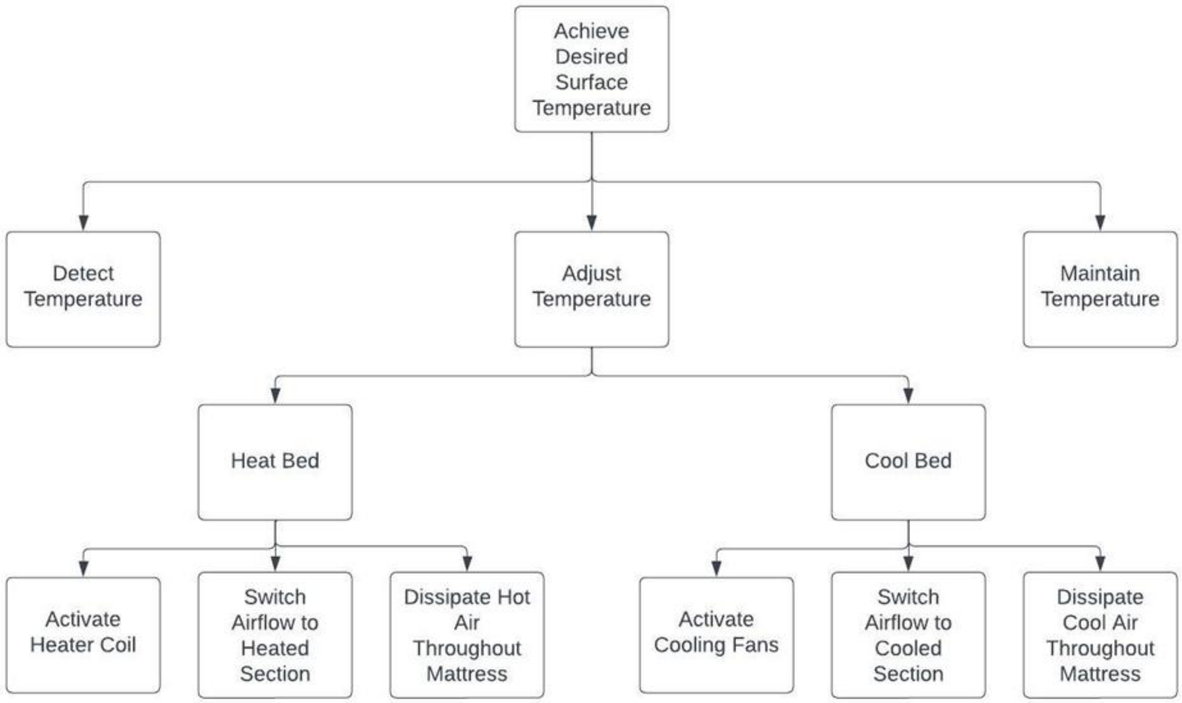


Figure 5. Function tree for temperature regulating mattress system.

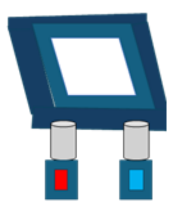
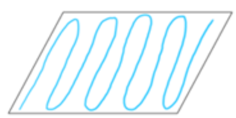
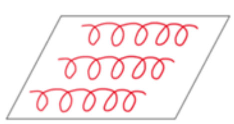
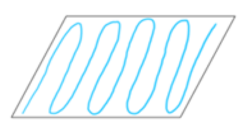
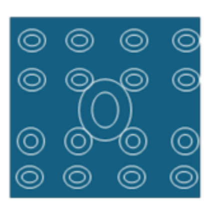
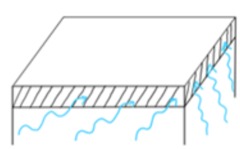
Concept Ideation

The desired solution must fulfill several fundamental design functions. The system must enable heat transfer to and from the user. This can take the form of either an air- or water-based system. An air-based system would intake air from the surrounding environment, heat or cool it to the desired temperature, then circulate it through the mattress to regulate the temperature of the user. A water-based system would operate like the air-based system, but instead have a closed loop of water circulating through the bed. The system must also have a way to measure the temperature and enable the user to control the temperature of the bed. To solve these challenges, multiple brainstorming sessions were held to develop concepts that could fulfill each of these functions.

For an air-based system, one or more fan units located under the bed can be used to intake air into the heating or cooling mechanism. The fluid can be heated or cooled to the correct temperature by utilizing a few different processes. An electric heating coil that connects to a power supply plugged into a standard wall outlet may be used for heating. A standard air conditioning unit can be used for cooling. A fan or pump can be used to circulate fluid through the system. An air-based system would use a perforated cover to allow air to flow towards the user, while a water-based system would place the loop close to the surface to allow heat transfer.

Sensing and control systems are also essential for proper functionality of this system. The heating and cooling modules should include temperature sensing capabilities. This can be in the form of a thermometer, thermistor, or thermocouple. This can connect to an electronic system that can control the thermal capabilities, which the user must be able to control the electronics. This can be accomplished using buttons directly on the system or a wireless remote control. A mobile app could also be developed to control the system from the user's phone. Additional capabilities like programming the bed to automatically change the temperature based on a schedule may also be used.

Table 1. Morphological chart of solutions to each core function of a temperature regulating mattress.

Function	Solutions			
Cooling	A/C 	Water loop 	Fans (no active cooling) 	
Heating	Heating coil in mattress 	Heating coil in separate unit 	Water loop 	
Air intake and circulation	Fans 	Perforated cover and fan 	Vents in bedframe 	
Sensing	Relative settings	Flow meter	Thermometer	

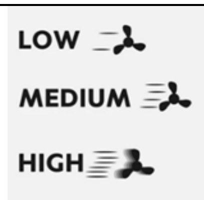
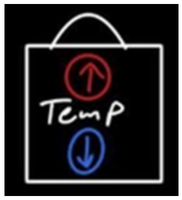
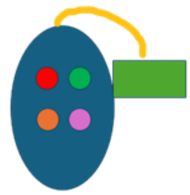
				
System control	Remote control 	App on phone 	Buttons to PCB 	Scheduled 

Table 1 is a morphological chart that illustrates several design concepts that could fulfill the various functions of the temperature-regulated mattress. Each concept is a distinct approach to fulfilling the specified function of the system. Brainstorming these concepts will help ensure that the final design considers all possible solutions to the problem. The individual concepts for each function can be combined into integrated designs.

Figure 6 shows an air-based integrated design that combines several of the functions from the morphological chart. Fans are used to intake air which is heated using coils. The air is then passed upwards to the user using vents in the mattress. A remote control can be used to control the temperature of the bed.

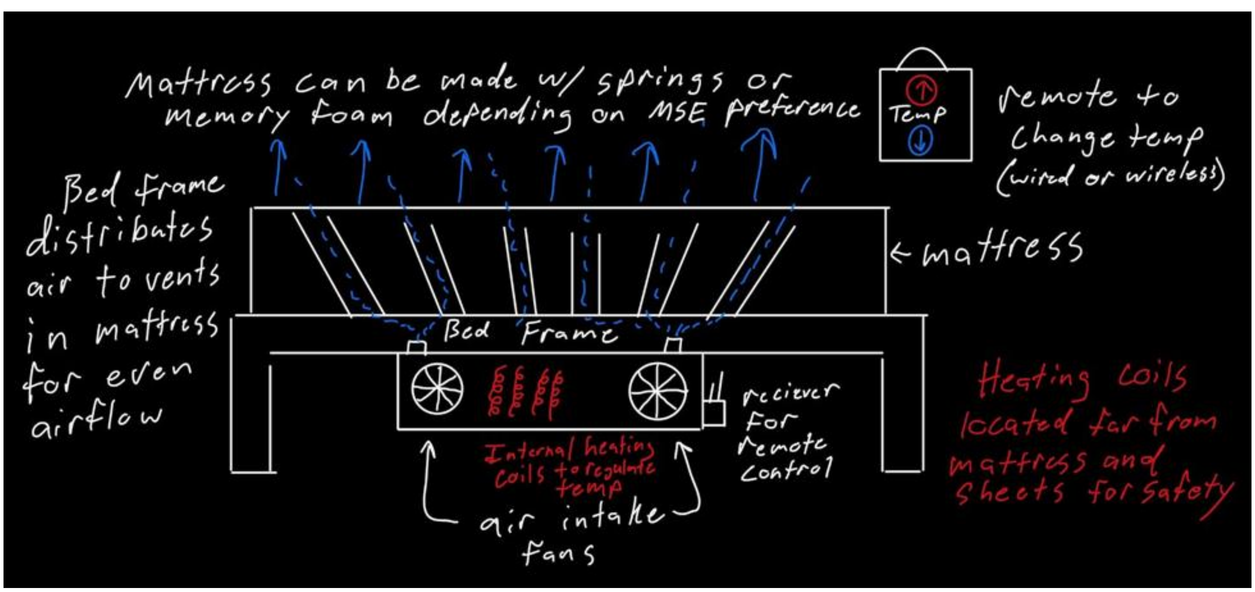


Figure 6. Air-based integrated concept.

Figure 7 showcases a water-based system that utilizes a closed water loop. This loop is connected to a heating and chiller unit to control the temperature. A three-way solenoid valve is used to control the flow between the heater and chiller. A pump and flow meter are also used to monitor and operate the system.

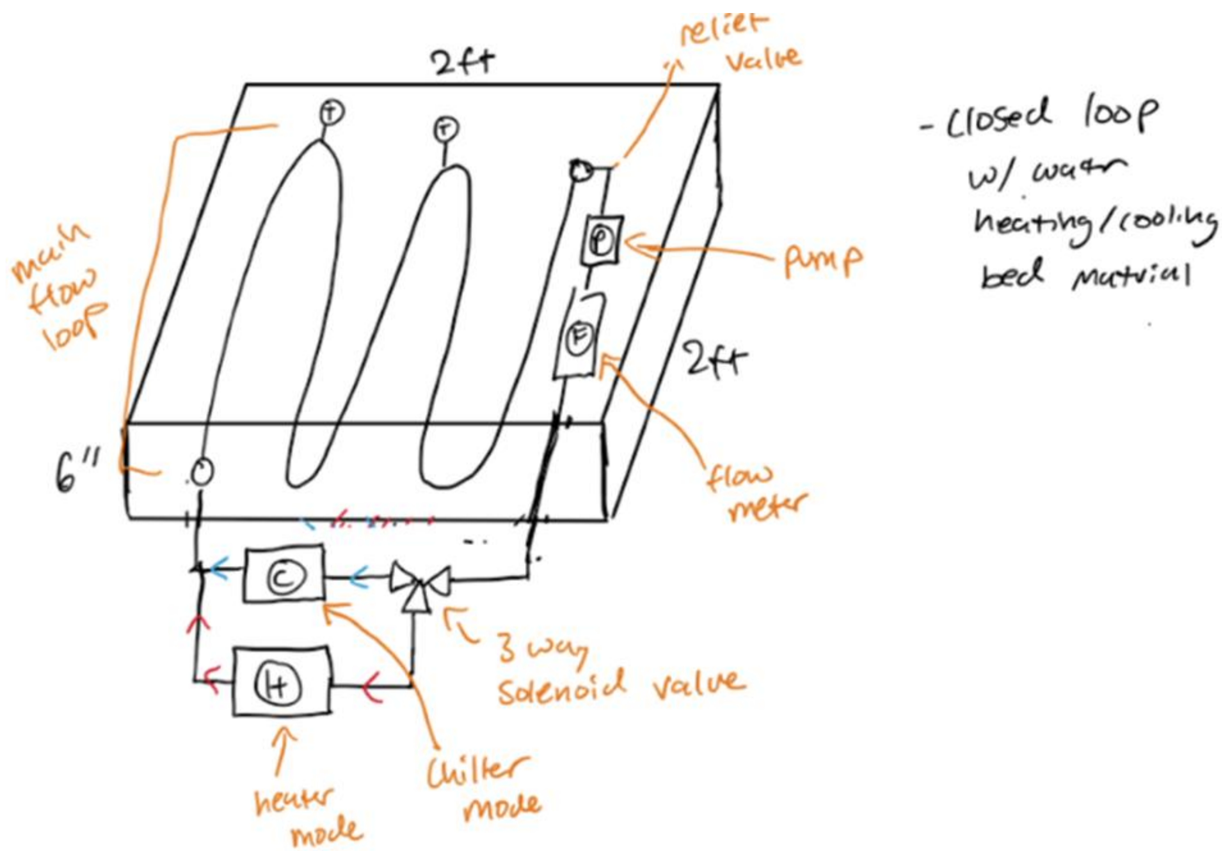


Figure 7. Water-based integrated concept

These integrated concepts will be further developed, and the design will be finalized using a decision matrix. The feasibility and risks with the design must also be considered during this process.

Design Overview

Figure 8 below shows the CAD of the bed section. It features 4 distinct layers; the comfort foam (CF) layer, the high-density foam (HDF) layer, the wooden diffuser box, and wooden bed frame. The CF layer features 100 holes of 0.25 in diameter that allows flexible tubes of the same outer diameter to be inserted. These tubes will run through both the CF and HDF layers so that the air in the diffuser box is properly channeled towards the top of the bed. The CF and HDF layers will be stitched together using normal sewing threads, and the HDF layer and the diffuser box will be attached via adhesive spray. The diffuser box will be attached to the bed frame through regular wood screws and corner brackets.

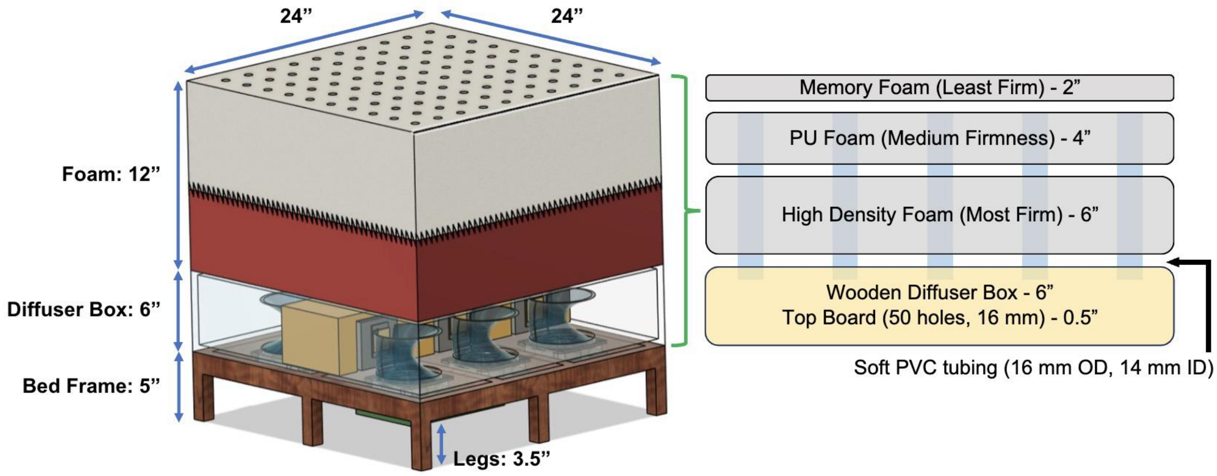


Figure 8: TempMattre$$ Design Overview

The diffuser box contains several critical components and geometries, seen in Figure 9. On the bottom side, there are six ducts of 4.7 in diameter for the fans to channel air through. On top of these ducts are six air diffusing channels within the box. These channels are designed so that the entering air will be effectively directed over the thermoelectric cooling (TEC) module, then channeled outward towards the top edges and corners of the box after the air passes over the module. This air will then be directed upward into the array of tubes that carry the heated or cooled air toward the top of the mattress. These TEC modules are attached to aluminum heat sinks so that when current is supplied to the module, the heat sinks dissipate the excess heat away from the air flow. These heat sinks serve the same function when the current is reversed, and the module is used to heat the incoming air.

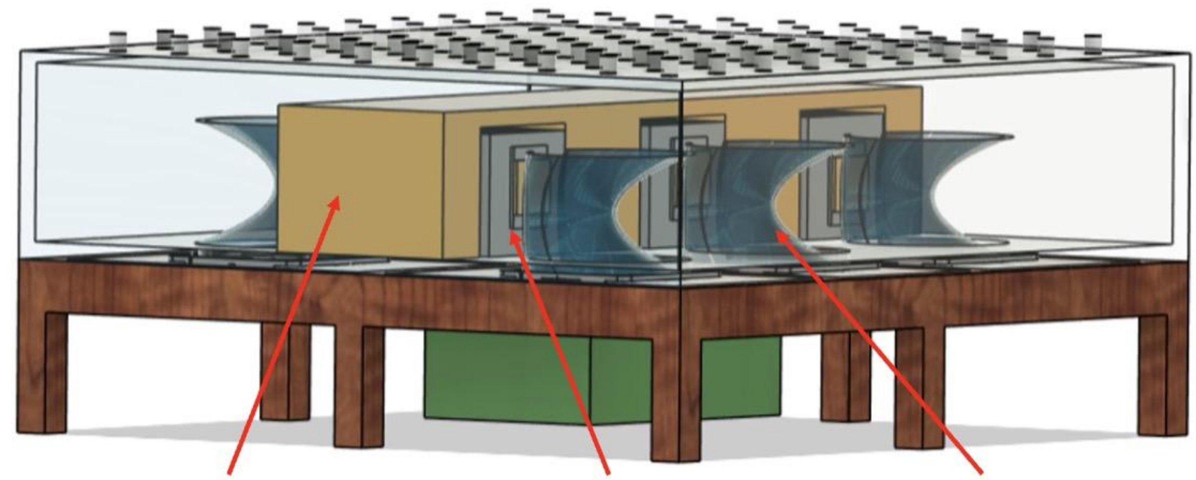


Figure 9: Internal View of Diffuser Box

Figure 10 below shows the bottom-side view of the TempMattre$$ design. The main components are the computer fans, which direct the air through the ducts. These computer fans are approximately 4.7” x 4.7”, supply 108 cubic feet per minute (CFM), produce 45 dB of noise, and consume up to 5.76 W each. Additionally, the Electronics Control Box, which has dimensions of 3” x 6” x 9”, houses the power unit and controllers for the six computer fans, six TEC modules, and temperature sensors placed throughout the mattress.

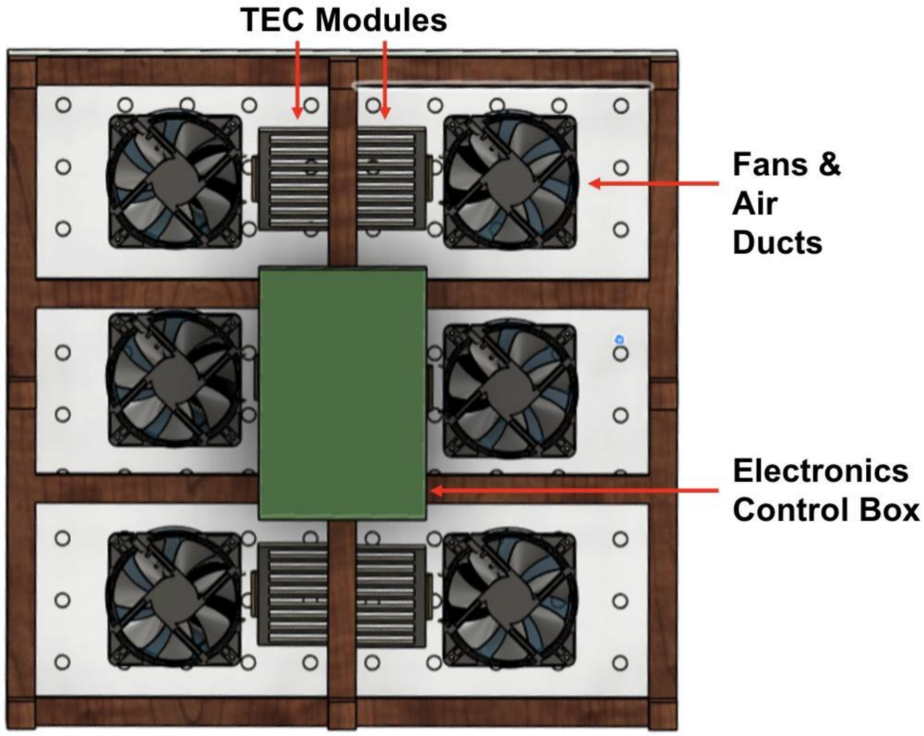


Figure 10: Bottom-Side View of TempMattre$$

Design Analysis - Chassis

The main objective when constructing the system was to ensure even ventilation and temperature regulation across the bed. Six ducts were chosen due to space constraints and to ensure even coverage. The team then decided to utilize six fans, one attached to each duct, because it would be difficult to channel the air into six ducts from one fan. Six thermoelectric coolers (TEC) that utilize the Peltier effect were attached to each fan, and each TEC has a heat sink attached, which allows for better heat dissipation and prevents overheating. These TECs intake air from the fans and form a thermal gradient, which allows the air to selectively heat or cool the bed. A system of diffusers and an array of medical grade plastic tubes will allow for the air to flow through vertically and provide heating/cooling on top of the mattress.

From a structural standpoint, the bedframe will be fabricated from wood due to its durability, common use for this purpose, and because it can dampen noise that could be generated from the equipment. Wood will also be used to make a base that will hold the diffuser system. Screws and corner brackets will be used hold the wood together. For the mattress layers, foam will be utilized. A high-density foam will give the mattress stability and will be placed directly above the wooden diffuser box.

For comfort, a memory foam layer will be attached on top of this with a combination of adhesive and stitching.

Bill of Materials							
BoM Level	Part #	Vendors	Description	Qty	Units	Unit Cost	Cost
1	1A	FoamOnline	Memory Foam (2" thick) (2' x 2')	1	ea	$ 41.00	$ 41.00
1	1B	FoamOnline	PU Foam (4" thick) (2' x 2')	1	ea	$ 29.00	$ 29.00
1	1C	FoamOnline	High Density Foam (6" thick) (2' x 2')	1	ea	$ 66.00	$ 66.00
1	1D	McMaster Carr	Medical Grade PVC Tubes, 1 ft	50	ea	$ 2.81	$140.25
1	1E	Home Depot	Wooden Plank with 50-hole grid cutout (2' x 2')	1	ea	$ 12.39	$ 12.39
2	2A	Home Depot	Box Side Pieces (2' x 0.5')	4	ea	$ 3.10	$ 12.39
2	2B	Home Depot	Wooden Plank with 6-hole cutout (2' x 2')	1	ea	$ 12.39	$ 12.39
3	3A	In-house	3D Printed Duct	6	ea	$ 3.50	$ 21.00
3	3B	Amazon	Computer Fans	6	ea	$ 20.00	$120.00
4	4A	Home Depot	Spray Foam	6	oz	$ 0.21	$ 1.28
4	4B	Home Depot	Insulation Board (4" x 4")	3	ea	$ 0.55	$ 1.65
4	4C	Home Depot	Insulation Board (4" x 2')	1	ea	$ 0.83	$ 0.83
5	5A	Home Depot	Corner Brackets	4	ea	$ 2.49	$ 9.97
5	5B	Home Depot	Screws	32	ea	$ 0.08	$ 47.04
5	5C	Home Depot	Hinges	2	ea	$ 1.47	$ 2.94
6	6A	AdaFruit	TEC modules	6	ea	$ 34.95	$209.70
6	6B	Amazon	Temperature Sensors	6	ea	$ 4.30	$ 25.80
6	6C	Amazon	Switch Power Supply	1	ea	$ 29.88	$ 29.88
6	6D	Amazon	Terminal Distribution Block	1	ea	$ 24.99	$ 24.99
6	6E	Amazon	MOSFET	4	ea	$ 6.33	$ 25.32
6	6F	Amazon	Microcontroller	1	ea	$ 3.00	$ 6.00
6	6G	Amazon	Step-Down Buck Converter	2	ea	$ 5.00	$ 10.00
6	6H	Amazon	Breadboard	1	ea	$ 6.99	$ 6.99
6	6I	Amazon	Wiring	9	ft	0.70/ft	$ 6.30
Total				**135**			**$863.11**

Figure 11: Bill of Materials

Design Analysis – Electronics Overview

Figure 12 showcases the final design of the electronic circuit responsible for powering the entire bed. Note that the ground pictured on the bottom and the ground from the power supply are separate, where the bottom ground serves as common reference for all PWM signals and the top ground for the power converters and TEC LED Driver. Overall, the system features a total of 20 subsystems:

- 2 TEC module subsystems
- 6 Bed fan subsystems

- 6 TEC fan subsystems
- 6 Temperature sensor subsystems

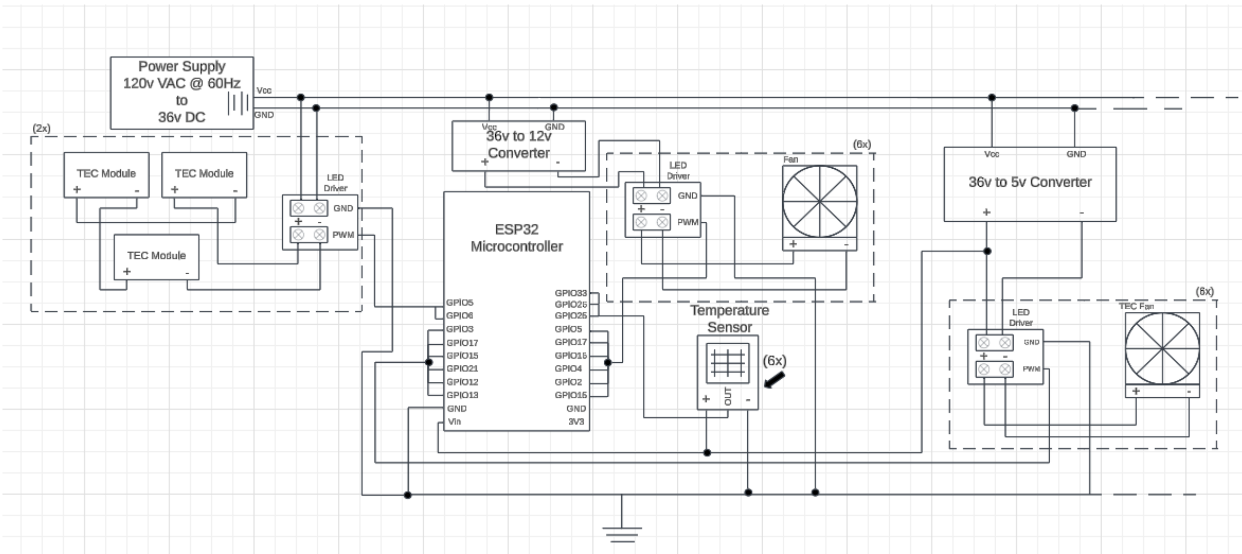


Figure 12: Finalized Electrical Design of the Bed

The system utilizes a 36V 10A switch power supply, Figure 13, to convert main power provided by a standard 110-240VAC @ 60Hz outlet to 36V DC, thus powering all components. It's equipped with a 6-point safety system with the following features:

1. Short circuit protection
2. Electromagnetic wave protection
3. Overcurrent protection
4. Over temperature protection
5. Over voltage protection
6. Quality microchip

The power supply also features an adjustable yellow knob visible in Figure 14 that can be used to adjust the voltage up to 39V DC down to 32V DC. Also pictured in Figure 14 is the wiring method necessary to route power from an outlet to DC components at 36V up to 10A, where a set of 3, 14-gauage wires (green, white, black) corresponding to ground, neutral, and live respectively are clamped in the power supply's provided screw terminals. 12-gauge red and black wire outputs positive +36V DC and ground from the terminals.

Figure 13: Aclorol's 36V 10A 360W Switch Power Supply

Figure 14: Switch Power Supply Wiring Methods

A Terminal Block Distribution Module with a current and voltage rating of 30A 48V is shown in Figure 15. The terminals labelled A and B are input from the +36V DC and ground 12-gauge wires connected to the power supply and provide a parallel connection to all A-B terminal sets. For instance, terminals A4 and B4 power one component at 36V, terminals A5 and B5 power another component, etc. This module routes power from the linear power supply to all 4 electronic subsystems that are powered directly from this main line. As read from left to right in Figure 12, this includes both TEC (thermoelectric cooling) subsystems, a 36V to 12V buck converter, and a 36V to 5V buck converter.

Figure 15: Terminal Distribution Block Module

Each subsystem's (TEC, fan, and TEC fan) power is electronically adjusted via a 5V-36V 15A (maximum 30A) 400W LED driver (Figure 16), with a total of four drivers included in the design. These drivers function as PWM-controlled MOSFETs, allowing precise adjustment of input current and voltage. They operate with a PWM frequency range of 0 to 20kHz and an input voltage range of 3.3V to 20V. Power is supplied via a pair of input wires connected to blue terminal blocks on one side of the driver, while a corresponding pair of output wires routes power to the components through terminal blocks on the opposite side. The PWM signal is generated by the ESP32 microcontroller. The LED drivers were chosen for their low cost, compact size (1.34" x 0.67" x 0.47"), and high-power rating, making them ideal for this application.

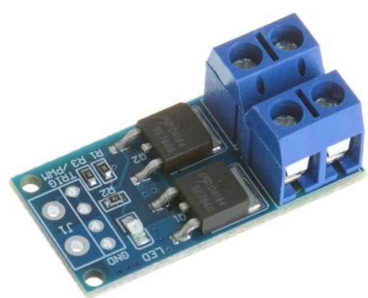


Figure 16: DC 5V-36V 15A (Max 30A) 400W Dual High-Power LED Driver (MOSFET)

The TEC assembly is shown in Figure 17. The Peltier module itself is mounted on top which is then connected to a thick aluminum heat sink to dissipate the large excess heat generated by the TEC modules when under load. To further get rid of this heat, a fan (which we denote as 'TEC fan') is mounted to the back of the heat sink which attempts to convectively cool the thermal block. The Peltier module itself is operated by 12V DC 5A for a maximum power draw of 60W. TEC fan specifications were unavailable; however, testing confirmed operation at both 5V and 12V, with 5V being selected as a precaution to prevent overcurrent damage. With 6 of these TEC assemblies total and 2 TEC subsystems, each subsystem composed of 3 TECs are wired in series, requiring an operating voltage 36V to power (refer to Figure 12) while maintaining an operating current of 5A, leading to up to 36V * 5A = 180W maximum power draw for each subsystem. 180W * 2 (for both subsystems) = 360W maximum power draw for both TEC subsystems operating at full power. The current draw of each TEC subsystem is controlled via its respective LED Driver ranging from 0V DC to 36V DC corresponding to a current range from 0A to 5A, providing a fully adjustable range.

While the Peltier modules are powered in series, the TEC fans themselves are powered individually in parallel, a design choice elaborated on in the prototyping section. Since there are 6 TEC fans that each operate on 5V with an operating current that should safely stay below .075 A, we can estimate the power draw of the TEC subsystem to be 5V * .075A = 0.375W * 6 fans = 2.25W maximum power draw from these fans, which is highly negligible.

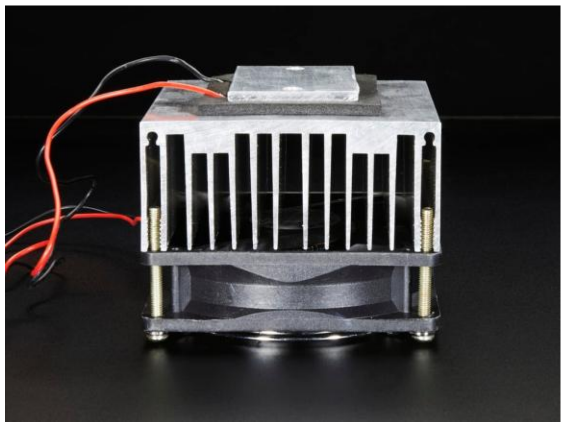


Figure 17: TEC Module Assembly

The temperature control system is managed by an ESP32 Devkit Wroom32 microcontroller (Figure 18), a versatile and cost-effective development board well-suited for this application. It is equipped with a dual-core Tensilica Xtensa LX6 processor, operating at a clock frequency of up to 240 MHz, providing sufficient computational power for real-time temperature monitoring and control operations. With 520 KB of SRAM and 4 MB of flash memory, the microcontroller offers ample storage for firmware and real-time data processing.

The Devkit Wroom32 supports multiple connectivity options essential for the project, including:

- Wi-Fi: 802.11 b/g/n standard, supporting both 2.4 GHz and 5 GHz bands, enabling wireless communication with user interfaces and external devices. It even features an access point so any device can connect to it, and it will service webpages.
- Bluetooth: BLE 4.2 (Bluetooth Low Energy), ideal for low-power connections to smartphones or other peripheral devices.

In terms of I/O capabilities, the ESP32 features 34 programmable GPIO pins, with support for ADC (analog-to-digital conversion), DAC (digital-to-analog conversion), PWM (pulse-width modulation), and UART, SPI, and I2C protocols. Specifically, the project leverages:

- PWM Outputs: To control the LED drivers for precise adjustment of TEC voltage and current.
- I2C Communication: For interfacing with temperature sensors.
- GPIO Pins: To manage fan speeds and provide system feedback.

The ESP32 operates within a voltage range of 2.3V to 3.6V, powered directly from the system's 36V supply via a 36V-to-5V buck converter, and further regulated down to 3.3V through its onboard voltage regulator. Its ultra-low-power consumption design, featuring multiple power-saving modes, ensures minimal energy use when idle, a critical factor in maintaining overall system efficiency.

With dimensions of only 2.6" x 1" x 0.2", the Devkit Wroom32 fits seamlessly within the compact design constraints of the electronic assembly. It includes integrated capacitive touch sensors, a hardware timer, and secure cryptographic modules, making it a robust choice for managing the heating and cooling bed's complex operational requirements.

Figure 18: ESP32 Devkit Wroom32 microcontroller

The 36V to 5V step-down buck converter (Figure 19) is a critical component in the system. The red-black wire pair connects directly to the terminal distribution block module and the yellow-black wire pair connects to breadboard power rails, converting power from the 36V DC line to 5V DC to power the temperature sensors and fans. This converter accepts a wide input voltage range, typically from 10V to 60V DC, making it compatible with the system's 36V power supply. It delivers a regulated 5V output with a maximum current capacity of 3A, resulting in a power output of up to 15W. It features a high conversion efficiency of up to 93%, which minimizes energy loss and heat generation. Its design includes multiple protection features, such as over-current, over-temperature, short-circuit, and over-voltage protections, ensuring reliable and safe operation of connected components. It's also encapsulated in a waterproof ABS plastic housing (rated IP67), providing excellent resistance to water and dust ingress. The compact dimensions of approximately 2.87" x 2.87" x 1.26" facilitate easy integration into the system's design.

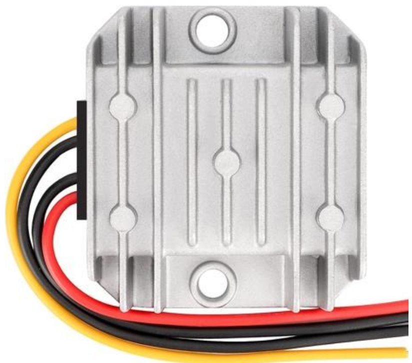


Figure 19: 36V to 5V Step-Down Buck Converter

The LM2596 step-down buck converter (Figure 20) is employed to convert the system's 36V DC supply to a stable 12V DC output, effectively powering the six bed fan subsystems. A pair of input power wires (12-gauge) are connected directly to the terminal distribution block module's 36V output power and 16-gauge wire connects the output of this buck converter to a breadboard power rail, where all the bed fans' LED Drivers are connected to tunable power. This adjustable regulator accepts input voltages ranging from 3V to 40V and delivers an output voltage between 1.23V and 37V, with a maximum load current of 3A. Operating at a fixed switching frequency of 150 kHz, the LM2596 ensures efficient voltage conversion while minimizing the size of external components.

The module features a multi-turn potentiometer, allowing precise adjustment of the output voltage to meet specific requirements. Its high efficiency, up to approximately 93%, reduces heat generation and enhances overall system performance. Additionally, the LM2596 includes built-in thermal shutdown and current limit protection, safeguarding the device and connected components from potential damage due to overheating or overcurrent conditions. The compact dimensions of the module facilitate seamless integration into the system's design, ensuring reliable operation of the fan subsystems.

Figure 20: LM2596 step-down buck converter

The 36V to 12V buck converter supplies regulated 12V DC power to the bed's six axial fans (Figure 21), each measuring 120 mm in diameter with 108 cfm. These fans are designed to efficiently circulate air through the bed structure, enhancing thermal management. Each fan operates at 12V DC with a current draw of up to 0.12A, resulting in a power consumption of approximately 1.44W per fan. Collectively, the six fans consume up to 8.64W, which is well within the buck converter's output capacity.

To modulate the fans' speed and airflow, the system employs LED Drivers. These drivers receive PWM signals from the ESP32 microcontroller, allowing precise control over the fans' operating voltage and speed. By adjusting the duty cycle of the PWM signal, the system can vary the fans' speed to match cooling requirements, optimizing both performance and energy efficiency. This configuration ensures effective thermal regulation within the bed while maintaining operational flexibility.

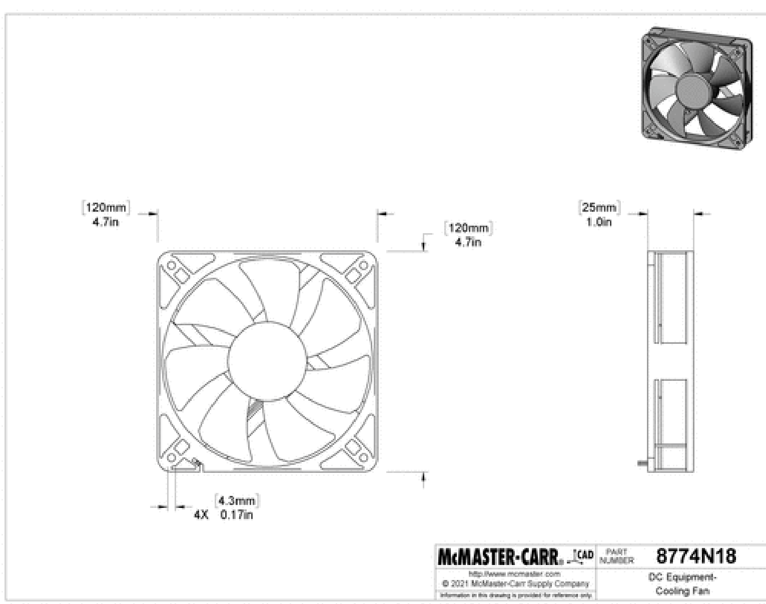


Figure 21: Bed Fans

The system employs six DS18B20 digital temperature sensors, each connected to the 5V breadboard power rail, to monitor and regulate the bed's thermal environment. These sensors operate within a voltage range of 3.0V to 5.5V, making them compatible with the 5V supply. They communicate with the ESP32 microcontroller via a unique 1-Wire interface, which allows multiple devices to share a single data line, thereby simplifying wiring complexity. Each DS18B20 sensor has a unique 64-bit serial code, enabling precise identification and data retrieval from each sensor on the shared bus.

The DS18B20 sensors offer user-selectable resolution from 9 to 12 bits, corresponding to temperature increments of 0.5°C down to 0.0625°C, respectively. They provide accurate temperature measurements over a range of -55°C to +125°C, with an accuracy of ±0.5°C in the -10°C to +85°C range. The sensors' compact design and minimal wiring requirements make them ideal for integration into the bed's control system, ensuring precise and reliable temperature monitoring.

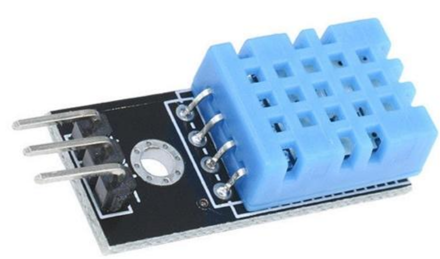


Figure 22: Temperature Sensor

Design Analysis – Electronics Operation

The temperature is continuously monitored by the temperature sensor, which will provide instantaneous feedback to the ESP32 via a GPIO pin. If the temperature exceeds the pre-programmed maximum 30° C threshold within the main channel-, the ESP32 throttles the TEC to prevent overheating and adjusts the fan speed accordingly. The Peltier module subsystem operates at 36V DC with a maximum of 5A externally supplied current, which can safely be adjusted between 0A to 5A. However, to meet efficiency demands, the Peltier should never draw more than 33% of its maximum output current. Therefore, the actual output amperage per Peltier module is not expected to exceed 1.65-1.7 A. The

ESP32 manages this much larger current via a LED driver which allows for a safer PWM input current sent by the microcontroller to the driver to control the current across the load (Peltier module). Bed fan and TEC fan speed are controlled via LED drivers, which provides flexible and efficient control based on temperature feedback or user settings.

The system also integrates a web-based application to provide users with full control over bed settings. The app interface (Figure 23) is user-friendly, featuring buttons to turn the system on or off, toggle between manual and automatic modes, and set the desired temperature. A number input field allows users to specify the target temperature in degrees Celsius, which is then sent to the ESP32 microcontroller to dynamically regulate the TECs and fans. The user simply must turn the system on and connect to its Wi-Fi via the input *Mattress* as the SSID input field *117658* as the password input field.

In automatic (auto) mode, fan speeds are adjusted dynamically for optimal cooling without requiring user intervention. In manual mode, users have granular control over individual fan speeds, both for the bed fans and TEC fans, using intuitive sliders. Each slider adjusts the PWM duty cycle, which the ESP32 translates into precise fan speed control via the LED drivers. Real-time feedback from the sliders ensures accuracy, displaying the selected speed value alongside the slider. Additionally, the app includes a live sensor data chart powered by Chart.js, which updates every 5 seconds. This chart displays temperature readings from all six sensors, providing a comprehensive view of the thermal conditions across the bed. These features collectively ensure the system remains both highly functional and user-friendly.

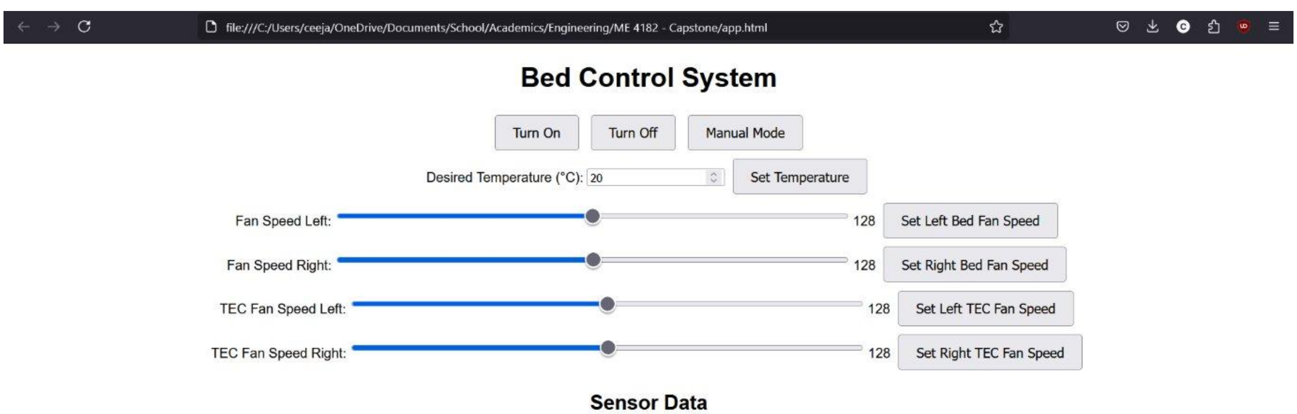


Figure 23: Bed Control System App Interface

Prototyping

Initial Design and Components

Here's what was originally planned regarding the electrical design process:

The electronic components to be implemented into the design and fit within the control box's enclosure include the microcontroller (ESP32), LED drivers, H-bridge, and Breadboard, as well as miscellaneous wires and resistors. Components outside of the control box include the fans, temperature sensor, and Peltier (TEC) module. The overall circuit design is illustrated in Figure 24, consisting of 6 fan subsystems, each with an LED driver to control fan speed, and 6 temperature control systems each with 3 H-bridges since each H-bridge can be responsible for 2 Peltier modules. All subsystems will be wired in parallel. The ESP32 as well as the Peltier and fan system is powered by a 12 Vcc source, and the temperature sensor(s) and H-Bridge are powered by a 3.3 Vcc source, all connected to a common ground. The H-Bridge is utilized to reverse current flow through the Peltier module which permits both heating and cooling effects to occur on one side. Controlling the DC current rather than using a PWM signal generated by the EPS32 (which causes severe interference and efficiency loss), the ESP32 ensures consistent, reliable cooling and heating performance. The LED drivers accept input current from the 12 Vcc and ground and feed a variable amount of it into the fans controlled by 6 GPIO pins on either side of the EPS32. Similar operation applies to the temperature control system, where the LED drivers utilize 6 GPIO pins to control the magnitude of the temperature gradient across the module.

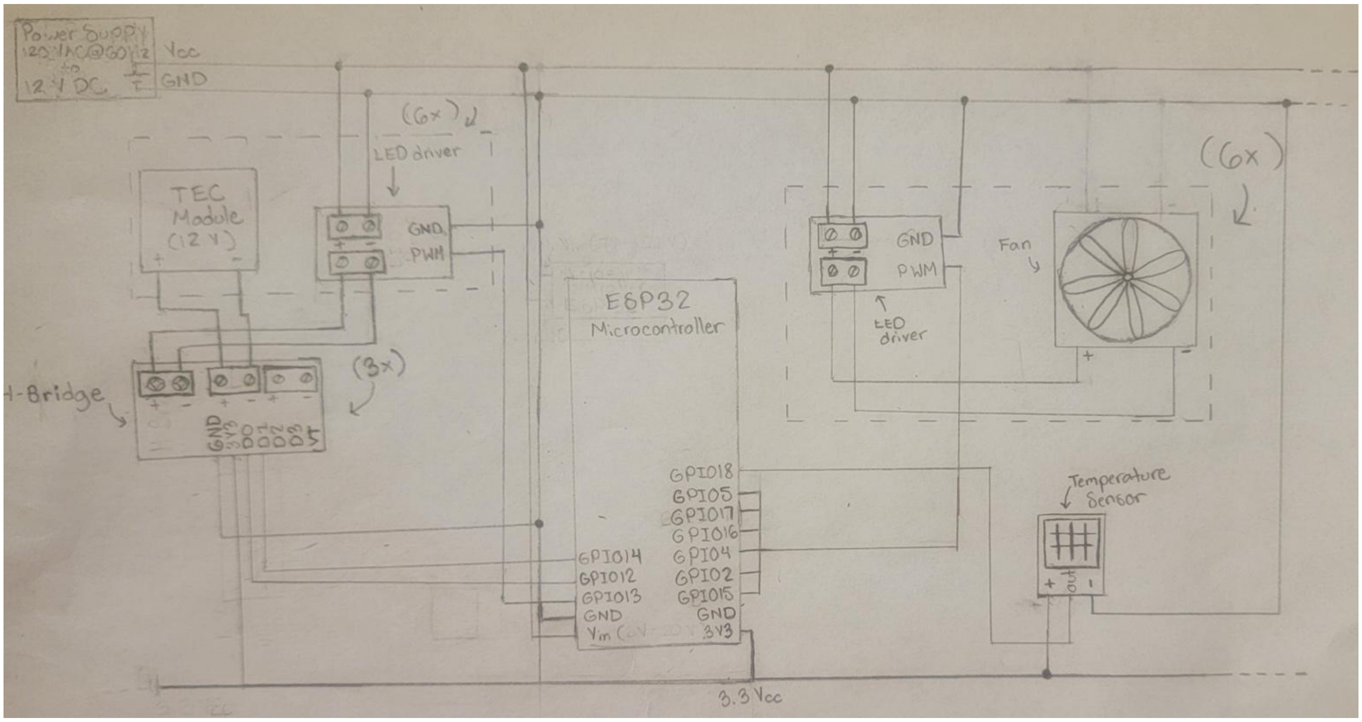


Figure 24: Original Electrical Design of the Bed

Challenges and Redesigns

Significant changes were made to the electrical system when undergoing prototyping. Firstly, the original proposed system would have demanded a very large current to be regulated from the main power block. With 12V DC, to power the TEC modules alone in parallel would require 5A * 6 TEC Modules = 30A to be expended on the main line, requiring a very durable distribution block to be used. This not only created safety concerns, but also requires high-grade, typically expensive equipment to meet this high demand. Therefore, the system was redesigned to operate using 36V DC and the TEC modules were wired in series to reduce the current threshold on the main line from 30A down to 10A, maximum. Unfortunately, no matter the setup used, power consumption would remain the same, since 12V * 30A = 36V * 5A * 2 = 360W, where the right-side expression calculates the power consumed by 2 TEC subsystems total when 3 TECs are wired in series. In response to this, the switch power supply whose specifications were outlined earlier was selected.

The 36V to 5V buck converter (mounted onto the leg of the bed) was selected when it was understood that the ESP32 was not capable of handling an input current greater than 5V safely, which was a misunderstood assumption in the original design. Additionally, the temperature sensors needed to be powered (ideally) using a 5V source. Finally, the TEC fans were originally going to be powered using 12V, but because of the unknown specifications previously mentioned, it was wise to use the down-converted voltage to power them instead of 12V. The 36V to 12V buck converter (suspended via tension in wiring connections) was selected simply to power the bed fans, ensuring that its maximum output current and adjustable range was compatible with the fan's specifications.

Abandoned Features and Adjustments

The 3D printed electronics box was quickly abandoned due to its insufficient size to fit every component, as well as due to it being a hassle to prototype with, since it was necessary to continue to plug and unplug certain components that would have been contained in it. This particularly includes the USB cable necessary to upload code to the ESP32 microcontroller, which had to be mounted via two separate breadboards due to its ill-fitting pin arrangement for a single breadboard. Additionally, it needed to be mounted onto the bed via drill, and continuing to rerun through the procedure of uninstalling and reinstalling the electronics box would have killed a lot of testing time.

An intermediate version of the electrical design appeared when we attempted to wire every fan on one side of the bed in series. For instance, all TEC fans wired in series on the left side of the bed, and all bed fans wired in series on the left side of the bed, resulting in an ideal 36V voltage drop across each line. Then, each fan subsystem would be connected directly to the terminal distribution block module which contains 36V from the switch power supply. However, a major hiccup prevented this that seemed to be quite nuanced: fans are not supposed to be wired in series due to voltage potentially not being shared equally between all of them, which might damage them. Once this was realized, the circuit was reconstructed to resemble the final design of the circuit illustrated in Figure 12, where each fan is now powered in parallel. However, it was discovered that the fan guards were screwed on too tightly, causing the fans not to power in either configuration (12V or 36V). Once they were loosened, the fans began to operate as intended. This means that we do not know if the original design of wiring the fans in parallel would have operated or not.

Soldering and Operational Precautions

Many connections had to be soldered together. This includes the wires which allow the ESP32 controller to adjust the output current via the LED Drivers (PWM and GND wires). Connecting the TECs in series required a solder operation since there were no available wires which had a securable female-to-female connection. The 36V to 12V buck converter's input and output set of wires had to be soldered onto the component for a secure connection, since it's not directly mounted to the chassis of the bed. Additionally, wires which simply didn't have enough reach to extend to the breadboard had to be soldered.

It’s necessary to physically plug in a micro-USB cable into the ESP32 microcontroller which is connected to a computer to change the code written on the device. Afterwards, the switch power supply is hooked into an outlet to fully power the system, since the USB power cable doesn’t provide sufficient power for each peripheral device on the bed electrical system. However, precautions should be taken when unplugging the switch power supply, since the system still contains residual current for about 1 to 2 minutes before it’s able to fully discharge. Unfortunately, this was briefly ignored while swiftly attempting to test components and both the H-Bridge module we planned to use (Figure 25) and the ESP32 microcontroller were both short-circuited, rendering them completely inoperable and no longer safe to prototype with. Resultingly, the power supply would emit a high-pitch whine and not operate when attempting to power the H-Bridge (which was mounted to the inner wall of the bed frame via 4 metal screws) after this incident, and it was determined through thorough trial-and-error testing, that the H-Bridge was responsible for possibly overdriving the power supply.

This was foreseen, but not prioritized to prevent from happening, since it didn’t delay testing time too much. A simple circuit breaker with manual push-to-trip reset wired between the power supply and distribution module could have prevented this, but none were conveniently available. While the ESP32 was simply replaced and no other damage to the system could be detected, this caused us to readjust the circuit from using the H-Bridge to simply using an LED Driver, albeit these modules aren’t capable of polarity reversal. We found this ideal to do given our time constraints, allowing us to focus purely on attempting to cool each air chamber instead of both heating and cooling. The H-Bridge component was rejected completely in the final design altogether as a result.

Figure 25: Dual DC Motor Driver Module Board 3~36V 10A Peak 30A Speed Control PWM Module

Sensor Installation

The temperature sensors were easy to install, although one was defective and had to be replaced when undergoing testing. Conveniently, since the temperature sensors needed only needed 5V to operate, it was possible to test them without utilizing the power supply on each testing iteration while uploading new versions of code to the ESP32.

Software Challenges

For this project, the best overall function for the ESP32 to facilitate user interaction between the app interface and the bed's subsystems was for it act as an access point with its own Wi-Fi network. This means that the user would simply have to connect to the ESP32 Wi-Fi displayed on their cellular device, connect, and then utilize their browser to control the bed. While prototyping the app's skeleton was relatively straightforward, there were a few challenges that were quite difficult to overcome.

The first being that plotting chart data collected via the temperature sensors required a library (with a specific format) that needed to be retrieved from the internet. Unfortunately, the ESP32 is unable to connect to the internet when it acts as an access point. Therefore, it was necessary to download the entire library onto the ESP32, despite its limited flash memory which took a significant amount of time to do. Once this was accomplished, although total system memory never exceeded 80% (approximately 73% of memory was being uploaded to the ESP32), it did dramatically increase code upload time, increasing testing time.

The second hurdle that needed to be addressed was making sure that webpages serviced from the ESP32 to the client are done so in a particular order. More specifically, what took quite a while to diagnose was the temperature sensor data not outputting to the website to be displayed on the client due to a very nuanced issue. As a webserver, the ESP32 processes incoming HTTP requests sequentially, checking each route handler in the order they are defined. When a request is received, the ESP32 web server will match it against pre-registered routes already defined in the code (*server.on()* function calls). And if no explicit route matches, a function called *serverStatic()* will be called to act as a "catch-all" for any remaining requests. Rearranging the order of these methods is what addressed the issue and allowed data to be displayed on the website.

Cable Management

To reduce clutter and ensure safe operation, all wires within the system were taped down securely. This not only minimized the risk of accidental disconnections during testing but also helped prevent wires from obstructing airflow around the TECs and fans. Proper cable management also made it easier to identify and address specific components during troubleshooting.

Results

The completed electronic setup (Figure 26) allowed for easy manipulation of the TEC modules through the app. Its features included the ability to manipulate the fan speed, temperature, and exhaust fan speed of either side of the bed to meet the user's needs the best. This accomplished one of the main objectives of the project while also including the additional feature of having split control of either side of the bed. During the expo, it was shown that even with a bedsheet on top of the mattress, the airflow was powerful enough to be felt through the fabric, albeit adjustments to the comfort layer must be made to improve the airflow through that medium. The prototype also included a hatch that enabled the frame to open and expose the inner electronics. This made the prototype extremely modular and easy to work on, while also being interesting to show during the expo. If this product goes forward to a fully functioning mattress instead of a proof of concept, that feature would need to be removed in order to increase safety and efficiency of the system as a whole.

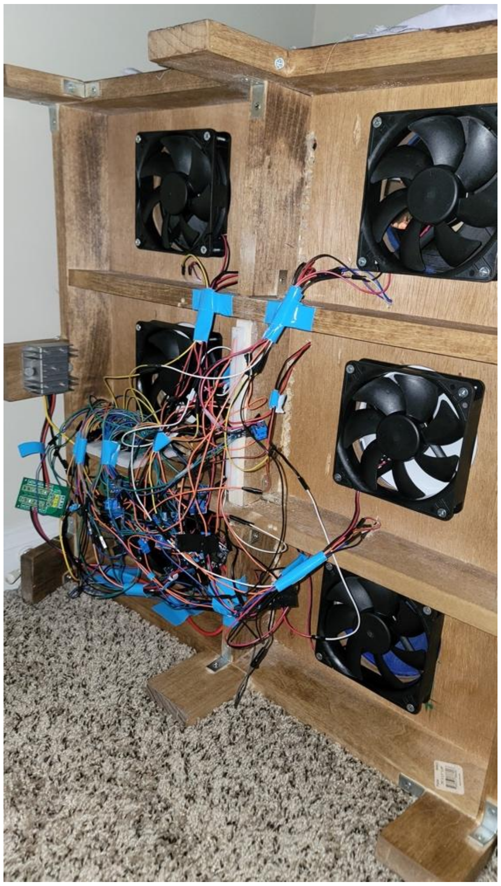


Figure 26: Finalized Electronic Assembly

Heat Management and Ventilation Adjustments

During testing, the TEC modules presented significant thermal challenges. While they were intended to cool the air chamber, the substantial heat generated on the opposite side of the TECs caused the aluminum fins of the heat sinks to become extremely hot. This heat, instead of being fully dissipated by the TEC fans, began to escape into the bed fan chamber. As a result, the heated air inadvertently flowed into the air chamber intended for cooling, negating the cooling effect and, in some instances, actively raising the air chamber temperature. We addressed this issue by drilling ventilation holes at the bottom of the bed frame directly below the TEC fans to allow excess heat to escape more efficiently. This ensured that the hot air produced by the TECs could exit the system rather than circulating within the bed structure.

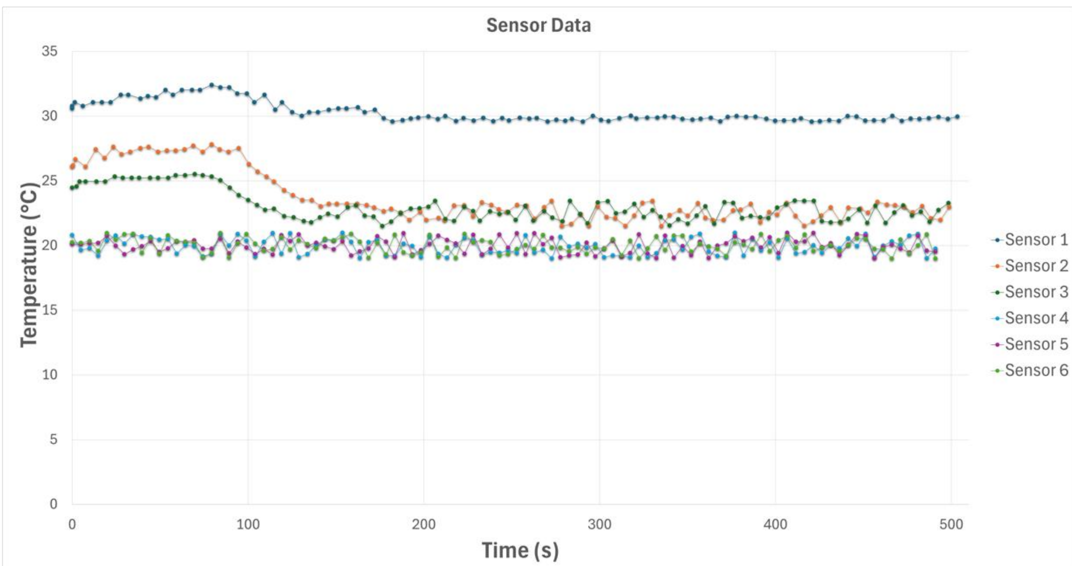


Figure 26: Sensor Data

Conclusions & Future Work

Our team chose a design of a heating, cooling, and airflow unit built into the bedframe itself, spanning the full area of the 2ft square mattress. This design was superior to alternate designs involving water for temperature regulation because it saved the headache of routing the water and the purchasing of condensers. We decided against housing the temperature control module in one dense container because we were concerned that the airflow and temperature would not be even throughout the mattress. By spreading the system out, we ensured a better temperature distribution. For this prototype, 6 fans and 6 TEC modules were employed. TEC modules were chosen over other methods for heating and cooling because they could cool air by only using current run through a wire, avoiding the headache of fluids. By using a controller with built-in Wi-Fi and Bluetooth pairing, the product was made easy and convenient to use, while also saving costs on the construction of a control panel. After assembling the prototype and resolving all the bugs, we stress tested the system and observed that it was effective at most of its intended tasks. With sufficient data being collected to quantify a successful heating cycle and proper ventilation, the only area in which this prototype lacked was the cooling cycle. The heat energy produced by the TEC modules was too much for the ventilation system we had in place, and, therefore, a reasonable temperature difference could not be maintained across the modules. In response to this information, further insulation and ventilation for the exhaust boxes was added. Due to lack of time, more data could not be collected after the modifications, but these modifications are believed to be the proper solution to the energy buildup.

Using all the information we have gathered and all the lessons we have learned, a full-scale product can be visualized. Firstly, producing our own mattress with a custom network of holes and tubes would be unreasonable to achieve in a product for sale. The reasonable alternative would be to make a bed frame with all the ventilation and TEC modules we know but apply it to an existing mattress. There are companies that produce mattresses with high porosity and breathable designs, so the added manufacturing of our own mattress would not be necessary. Instead, the focus would be on improving the efficiency of the TEC modules and producing even more airflow throughout the mattress. With the efficiency of both the TEC modules and fans increasing with size, perhaps a design with fewer, larger fans and TEC modules would be the correct design choice. With full sized units produced, clinical trials can be conducted to prove its effectiveness in preventing bed sores and helping athletes in recovery.

To conclude, we produced a prototype which could easily be converted into a full-scale product to be used in the mass market. With some modifications to the scope of the design, a reasonable and effective unit can be produced. With further development and testing, this prototype can evolve into a product that provides a true benefit to those with medical issues.

Team Contributions

Jake Boudreau: CAD design, Prototyping, Patents, Results, Editing for Cohesion

Zachary Mathews: Conclusion and Future Work, Morphological Chart, Prototyping, Patents

Vishnu Murthy: CAD design, Design Overview, Function Tree, Introduction, Prototyping

Cordell Palmer: Electrical Schematic, Design Overview (Electrical), Design Analysis – Electrical, Electrical Design, Programming, HoQ

Reanna Rafiq: BOM, Design Analysis (Chassis), Societal and Environmental Considerations, Hand Calc

Tejas Raman: Concept ideation, Morphological Chart, BOM, Editing and Formatting

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