

Mountain Directed Energy Wayfinder (D.E.W.)

A Technical Report submitted to the Department of Electrical & Computer Engineering

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Bachelor of Science, School of Engineering

Errick C. Mah

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Technical Project Team Members

Jeffrey Grow

Kieran Lynch

Anthony Panagides

Daniel Xue

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Adam Barnes, Department of Electrical & Computer Engineering

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I. STATEMENT OF WORK

Jeffrey Grow contributed printed circuit board (PCB) design, manufacturing, and testing. This included the initial schematic capture as well as PCB layout, both of which were completed in the KiCad software. As part of this, he was also responsible for the setup of a repository for the PCB files so all group members would be able to access them from their own computers. He integrated the power supply design from E.M. as well as the pinouts from D.X. into the circuit schematic. Once the PCBs were laid out and ordered, he assisted E.M. with the soldering of the through-hole electrical components. After that, he tested the PCBs to ensure that all functionality was met. Additionally, he worked on the testing environment and found suitable electrical components for the PCBs that met the design requirements.

Kieran Lynch contributed the design and production of all mechanical components of the gimbal. This included the mount for the tripod and all the housing for the electronics. This also included the gimbal itself and the laser holder. The design process included creating a 3D model accounting for the size of various components to allow for press fits where ever possible. The production process consisted of plastic selection and ensuring that the 3D printing process worked without issue. Additionally, he worked on construction of a testing environment with E.M. and soldering with E.M. and J.G.

Erick Mah contributed buck converter design and specifications, including component selection and layout recommendations, according to the associated datasheet and application notes for each chip buck converter. Design of the power supply circuitry was tested alongside in tandem with J.G. and assembly of a testing environment for a final prototype was performed alongside D.X. and K.L. in order to adequately demonstrate the functionality of the project. Also contributed were general administration and logistical management for this project, including scheduling and budgetary concerns; group assignment submissions relevant to the coursework associated with this project, such as reports, presentations, and when within the allotted budget, parts orders; and workspace organization, material acquisition, and itemization. He has also contributed a knowledge of engineering standards and intellectual property to the considerations made for this project.

Anthony Panagides contributed to the design and implementation of the embedded software. This includes the calculations for directing the laser towards targets in the night and attempting to integrate global navigation satellite system (GNSS) signals into the software. Produced visuals and

diagrams for use in presentations and poster session. He also worked with TouchGFX's model-view-presenter framework to test the LCD's operation and create the device's user interface. He also storyboarded, directed, recorded, and edited the group's Final Video, in addition to helping to purchase and organize components for the team.

Daniel Xue contributed the design and implementation of the device's LCD user interface and embedded software for controlling the laser and motors. This includes the generation of a software flowchart matching each screen within TouchGFX's model-view-controller (MVC) framework to appropriate functions of the laser and motors, as well as the creation of software for calculating the azimuth and elevation values for each star given its right-ascension and declination coordinates, the user's latitude and longitude, and the time of day. Also contributed were appropriate documentation of the use of digital input/output pins on the STM32 board for each of the major hardware components, as well as notes on the position and orientation of wires and other connectors between each major component on the final device. He also designed all elements of the input, calibration, and star select menus, including wildcards, tick-based events, and other images. The test chamber's upper supports and its demo targets were also contributed by Daniel, in collaboration with E.M.

II. BACKGROUND

For groups of amateur astronomy enthusiasts, stargazing for the first time can be challenging due to (1) low-light conditions that prevent the easy use of paper guides and (2) lack of wall-power and cell-signals that may limit the use of mobile phones and other smart devices in the remote locations ideal for stargazing. While having a more experienced stargazer present can help resolve these issues, it can often be challenging to direct everyone's attention to the same point in the sky with only one's arm or a flashlight, especially for larger stargazing groups. Because of this, there is a need for automated star-tracking systems for such groups.

Commercial systems that track stars already exist. However, although the systems themselves are only around \$100, these systems only work with telescopes costing upwards of \$1000 [1]. A common budget option is simply to have someone knowledgeable about the locations and positions of stars use a laser pointer to point out stars. This is in fact so common that there is an entire market dedicated to providing lasers for this application [2]. The goal of this project will be to combine these extremes to create an affordable option for those who may not already know someone with stargazing experience.

There are multiple relevant courses to this project, including the ECE Fundamentals series (ECE 2630, ECE 2660, ECE 3750), Electromagnetic Energy Conversion (ECE 3250), Introduction to Embedded Systems (ECE 3430), Optics and Lasers (ECE 5241), Introduction to Control Systems (ECE 6850), and Computer Networks (ECE 4457). The ECE Fundamentals

series helps with the power board design as it was the class where basic circuit analysis, layout, and manufacturing are discussed. ECE 3250 was relevant to the design and implementation of the buck converters. The Introduction to Embedded class assisted with an understanding of the STM32 programming and system design, as microcontrollers were the focus of the class. The Optics and Lasers class was useful for understanding the structure of lasers. Intro to Controls Systems provides a better understanding the motor drivers and their constraints. Initially, it was believed that the Computer Networks course would be useful for parsing and manipulating the data sent to and from the GPS module for calibrating and adjusting the last pointer. However, in the course of the development of the embedded software, it was determined that the GNSS module was not a necessary inclusion in order to satisfy the metric of a minimum viable product.

III. SOCIETAL IMPACT CONSTRAINTS

A. Environmental Impact

Directing lasers to the sky may have an impact on wildlife, particularly migratory birds, as research conducted by the U.S. Department of Agriculture has shown that low-to-moderate power lasers from classes 2 to 3 can disperse bird species under low-light conditions, albeit at no significant harm to the species [3]. This has been leveraged through the creation of laser bird deterrent devices, such as the Agrilaser Autonomic, which uses a higher power laser (Class 3B) for the task of long-range bird deterrence [4]. This effect was not observed for deer using green and blue lasers of a similar level of power [5]; however, suggesting that the laser star finder's environmental impact could be mitigated through systems that detected moving targets in the device's field of view and steered the laser away from targets that were not found to be in the sky.

From a device lifetime standpoint, the materials used to construct the device have an environmental impact, as the process for producing the parts for the device requires some level of electrical power and plastics, both of which contribute to the release of greenhouse gasses in the atmosphere. As the device is intended to function in largely remote areas, it runs on batteries and other electrical components that need to be safely disposed of at the end of their lifetimes. To reduce this impact while testing, less intensive testing techniques have been employed to lower the need to replace specific parts on the device repeatedly, and to always follow the appropriate local regulations when disposing of such items. Since the team has sourced most parts off-the-shelf, however, assembly and testing has a limited impact on the device's lifetime environmental impact.

B. Health and Safety

Lasers can cause eye damage if a laser is directed to an eye, but this mostly applies to high powered lasers that emit beams above 5mW, where the blink reflex is insufficient for protecting the user's eye [6] [7]. Lower powered lasers, like the ones used in this project, in the range of 1mW to 5mW

have a lower risk of causing eye damage if directed towards a person's eye for a period of time. To further mitigate risks to health and safety, the duration of time for which the laser is on can be controlled; for example, only switching the laser on when directed towards the sky should minimize the risk of the laser shining into someone's eye. However, doing so does not eliminate the risk of potential harm, so the system can be entirely powered down if some failure occurs.

C. Public Policy

Public policy surrounding the proper use of lasers is extremely relevant to this project. The Federal Aviation Association (FAA) reports laser incidents in which flying aircraft are a target of a laser, and these incidents can incur a fine and possible legal ramifications. Lasers may distract airplane pilots during takeoff, landing, and other emergency maneuvers or other low-altitude flight, and this is because even low-to-moderate class lasers on the order of milliwatts are still visible well into the sky, even 1 milliwatt lasers are visible 12 miles away in a dense city environment. Higher power lasers may also cause eye injury during flight, although as of February 2019, no documented cases of permanent eye injury in pilots have been recorded due to laser exposure according to the FAA [8]. To prevent possible legal ramifications, it is essential to be aware of the proper regulations and guidelines surrounding the use of lasers in outdoor settings. Because of this, a green laser with a power rating of less than 5 milliwatts was chosen for the project as per the guidelines [9].

D. Ethical Concerns

The major ethical in this project relate to public safety. Under the "FAA Modernization and Reform Act of 2012," the federal government made it a federal crime to direct a laser pointer at an aircraft [10]. As a direct result of this law, regulators keep track of the number of incidents involving laser pointers and aircraft. As responsible engineers, it is important to limit the possibility of the device enabling a user to break the law and being prosecuted for doing so. The risk of Mountain D.E.W. can address this issue by limiting the amount of time the laser points to the night sky.

Additionally, Mountain D.E.W. favors people who live in low light pollution areas. Rural areas, where there is less light pollution when compared to urban environments, have an easier time utilizing the device because the stars have greater contrast in the night sky. The users can look at the laser and immediately view the star the laser is pointing to, but in cities where light pollution occludes stars in the sky, users may not be able to identify the star which Mountain D.E.W. is pointing to.

The initial concept for Mountain D.E.W. utilized GPS to identify stars in the night sky. This could have posed a privacy concern to the users of the product. This concern could have been addressed by assuring users that location data is not stored or transmitted and is only used as part of celestial coordinate calculations for accurate and precise movement of the device.

E. Stakeholder Considerations

Considerations must be made regarding the concerns and interests of individuals involved in scientific research in astronomy, amateur astronomers or stargazers, and the wider astronomy educational community at large. The primary concern with the introduction of an inexpensive alternative to conventional laser-guided telescopes is the increased light pollution resulting from more widespread use: by nature of the device being a beam of artificial light fired into the night sky, should the device be utilized by numerous users centralized in a given region, the visibility of celestial objects is significantly diminished. With a focus on educational and amateur use, the device is designed to be an inexpensive alternative such that accessibility of basic astronomy education is greater, especially for underprivileged or disadvantaged demographics such as those in rural or inner-city areas. The advantage of this device is in its versatility in removing the barrier to access as a result of similar systems being conventionally attached to significantly more expensive telescopes. It is likely that this device will find its most significant usage as either a training aid for individual users or as a device for demonstrations for larger educational groups, such as scouting organizations or amateur stargazing groups. Considerations for the battery life of the system largely depend on the end-user: in conversation with the customer, it was decided that a range of 1-2hrs would suffice for the system, with either replaceable or rechargeable batteries used to prolong or restore power to the device. Similarly, in terms of accessibility, understanding that amateur users likely lack an in-depth understanding of the astronomical locations of celestial bodies, the inclusion of an LCD display is designed such that users will be able to select from a pre-determined list or database of known coordinates. Beyond technical design, if the device were to be placed on the market, a user's manual would likely be necessary for accessibility to general-audience consumers.

IV. PHYSICAL CONSTRAINTS

A. Part Availability and Manufacturability

The materials required to construct this project were a STM32 micro-controller, a gimbal, a laser, a power supply, a screen, and a button and other input system. All components selected had common, off-the-shelf options available to be ordered online or in-person from major vendors, such as DigiKey, Mouser, or McMaster-Carr. If a certain part was not available, reasonable alternatives were purchased or even substituted from past Capstone projects and other self-acquired sources. Additionally, the department had already provided an STM32 Nucleo-64 Development Board and a class-3R laser to begin testing the product, which were incorporated into the final product as needed. All the parts and sensors were relatively inexpensive, and as such, it was initially expected that the project would be able to comfortably remain within the provided budget of \$500. This ultimately was not the case (see section IX). Identifying inexpensive and off-the-shelf parts is key for decreasing the final cost of the device for customers, especially for a hypothetical production version, where every dollar saved may translate in thousands saved at scale.

V. EXTERNAL STANDARDS

The Mountain Directed Energy Wayfinder device is subject to several standards and regulations that govern limitations on both its operations and design. It is constrained by those standards set by the Institute of Electrical and Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), Occupational Safety and Health Administration (OSHA), and American National Standards Institute (ANSI), among others. The following standards are most relevant to the design and operation of the device. Due to the abandonment of a GNSS-based approach, no such standards are considered. The standards relevant to this project are shown in table I. The use of a laser mandates compliance with relevant legal standards regarding laser operation and safety. Likewise, compliance must be met for general electrical safety. Additionally, testing procedures also must adhere to certain standards relevant to each technical area (i.e. motor operation, laser operation, electrical procedure, etc.). [11] [12] [13] [14] [15] [16] [6] [17] [18] [19] [20] [21] [22] [23]

VI. INTELLECTUAL PROPERTY ISSUES

As part of this project, considerations of patentability and potential sources of intellectual property infringement are made. The project is comprised of several systems which may be reconfigured into several claims that would be considered.

A. Claimed Invention

The system apparatus may be described as follows:

- 1) A two-axis motorized gimbal comprising
 - a motor for the purpose of movement along an elevational axis;
 - a motor for the purpose of movement along an azimuthal axis;
 - a counterweight for the azimuthal axis motor;
 - a fixture attached to the rotating axle of the elevational motor for the purpose of attachment to a light-emitting device.
 - an armature onto which the elevational motor and its counterweight are mounted, and is itself mounted onto the rotating axle of the azimuthal motor;
 - a housing onto which the azimuthal motor, a power supply circuitry board, and a display may be mounted, and itself may be situated onto a mount.
- 2) The apparatus of claim 1, wherein the light-emitting device is a laser diode.
- 3) The apparatus of claim 2, wherein the laser diode emits green light.
- 4) The apparatus of claim 1, wherein the motors are bipolar stepper motors.
- 5) The apparatus of claim 1, wherein the housing is configured to mount onto a tripod.
- 6) The apparatus of claim 5, wherein the display is a liquid-crystal display.

TABLE I
STANDARDS AND REGULATIONS

Standard or Regulation	Relevant Area
OSHA STD 01-05-001: Guidelines for Laser Safety and Hazard Assessment II-1 A. Basic Laser Operation III-2 C. Ocular Effects of Laser Radiation III-9 H. Maximum Permissible Exposure Limits V-1 B. Laser Hazard Classes	Laser safety
OSHA 1910 Subpart I: Occupational Safety and Health Standards: Personal Protective Equipment 1910.132, General requirements 1910.133, Eye and face protection	General guidelines
528-2019 - IEEE Standard for Inertial Sensor Terminology	Gimbal testing
647-1995 - IEEE Standard Specification Format Guide and Test Procedure for Single-Axis Laser Gyros	System testing
813-1988 - IEEE Specification Format Guide and Test Procedure for Two-Degree-of-Freedom Dynamically Tuned Gyros	Gimbal testing
IEC 60825: Safety of laser products IEC 60825-1: Part 1: Equipment classification and requirements	Laser safety
IEC 60950-1: Informational technology equipment - Safety - Part 1: General requirements	Electrical equipment
IEC 61747: Liquid crystal display devices - Part 4-1: Matrix colour LCD modules - Essential ratings and characteristics	LCD operation
RoHS 3 Directive 2015/863/EU: Restriction on the use of certain hazardous Substances	Electrical equipment
21 CFR Part 1040: Performance standards for light-emitting products 1040.10 Laser products 1040.11 Specific purpose laser products	Laser safety
ANSI Z136 Series: Guidelines for Implementing a Safe Laser Program Z136.1 - Safe Use of Lasers Z136.5 - Safe Use of Lasers in Educational Institutions Z136.6 - Safe Use of Lasers Outdoors	Laser safety
NEMA SEM S1-2018: Small Electric Motors	Motor safety
ANSI/NEMA MG 1-2021: Motors and Generators	Motor safety

- 7) A method for driving the motors, through open-loop control, of the apparatus of claim 1, to direct the fixture to a pre-determined celestial coordinate.
- 8) The method of claim 7, wherein the celestial coordinate is determined through a calculation of Greenwich-mean sidereal time, incorporating
 - the latitude-longitude; and
 - the right-ascension-declination of a given celestial body.
- 9) An analog electronic circuit configured to step down a DC voltage input, comprising of
 - a subcircuit configured to supply power to a DC motor;
 - a subcircuit configured to supply power to a microcontroller; and
 - a subcircuit configured to supply power to a light-emitting device.
- 10) The apparatus of claim 9, wherein the subcircuit configured to supply power to a DC motor supplies 12 volts.
- 11) The apparatus of claim 10, wherein the subcircuit configured to supply power to a DC motor is configured to supply 12 volts to two bipolar stepper motors.
- 12) The apparatus of claim 9, wherein the subcircuit configured to supply power to a microcontroller supplies 5 volts.
- 13) The apparatus of claim 9, wherein the subcircuit configured to supply power to a light-emitting device supplies 3.3 volts.
- 14) The apparatus of claim 13, wherein the light-emitting device is a green laser diode.

The patentability of the apparatus and its subsystems are evaluated as follows. The robustness of the claims stated here are not comprehensive, and should be considered preliminary.

B. 35 U.S.C 101

The subject matter eligibility of the apparatus and its systems are not under question under 35 U.S.C 101, in regards to inventions patentable. The system and its subsystems are acceptable as a "process, machine, manufacture, or composition of matter", and do not fall under the categories of "abstract ideas, laws of nature and natural phenomena (including products of nature)". Additionally, the invention meets the standard of being "useful" or having "a utility that is specific, substantial and credible", as detailed in regards to the functionality and operation of the invention in section VII. [26]. Under the ruling of *Alice Corporation Pty. Ltd. v. CLS Bank International et al.*, 573 U.S. 208 (2014), any software subject matter must also be applicable to the implementation of unique non-software. subject to the same criteria as an apparatus being considered for eligibility. [27] The embedded software implemented as part of this project controls the precision movement of bipolar stepper motors: this action is not patentable under 35 U.S.C. 103, as detailed in section VI-D. However, the calculation of precise steps to move in order to locate specific star coordinates is a non-obvious solution that may be patentable, as detailed in section VI-E2.

C. 35 U.S.C. 102

Under 35 U.S.C. 102(a), post-America Invents Act (AIA), an invention may be eligible for patentability unless the "claimed invention was patented, described in a printed publication, or in public use, on sale, or otherwise available to the public before the effective filing date of the claimed invention". [28] In a sense, 35 U.S.C. 102 considers "anticipation" of a claimed invention based on previously-published or otherwise disclosed prior art.

Claims 1-2 would likely be rejected as being anticipated by Blackburn '458 (US 8982458 B2). [29] Blackburn teaches in independent claim 1 a "beam director, comprising: a beam director elevation motor elevation motor that rotates the beam director about an elevation axis; a beam director azimuth motor that rotates the beam director about an azimuth axis, the azimuth axis intersecting and being substantially perpendicular to the elevation axis". This is directly comparable to the two-motor gimballed system with a laser as specified in the assembly of the claimed invention.

Claims 9, 13, and 14 would likely be rejected as being anticipated by Khalili '404 (US 2005/0185404 A1). [30] Khalili teaches in independent claim 2 a "voltage conversion circuit to provide power to the laser diode with fixed intensity of light...wherein a highly efficient DC to DC converter circuit made from discrete components or integrated circuits...mounted on a PCB or similar assembly". Therefore, the power circuitry included as part of the assembly of the claimed invention would be unpatentable, due to anticipation by Khalili.

D. 35 U.S.C. 103

As previously mentioned, the system is not disclosed by any one specific element of prior art. However, according to 35 U.S.C. 103, post-AIA, an invention may not receive a patent if "the differences between the subject matter sought to be patented and the prior art are such that the subject matter as a whole would have been obvious at the time the invention was made to a person having ordinary skill in the art to which said subject matter pertains." [31] The criterion therefore indicates a greater flexibility: the question is asked of if it would be obvious for a person having ordinary skill in the art – in this case, assumed to be a career electrical engineer who does not have astronomical experience – to examine two pieces of prior art, and combine them such that the claimed invention is not patentable.

Claim 5 would be rejected as being unpatentable over Blackburn '458, in view of Davidson '881 (US 4196881) [32]. Davidson teaches in independent claim 1 "a tripod, comprising mounting means for removable mounting of a camera or the like, three legs having independently articulating connection", which succinctly defines the structure of the tripod structure that would likely be used for the mount for the housing mentioned.

Claim 7 would be rejected as being unpatentable over Blackburn '458, in view of Chandhoke '310 (US 2009/0051310 A1) [33]. As previously stated, Blackburn materially teaches claim 1. Chandhoke teaches in independent claim 1 "a method for controlling a stepper motor...generating a new position value to drive the stepper motor; providing an output position value to the stepper motor to drive the stepper motor". While Chandhoke specifies a closed-loop method of motor control, the obviousness criterion is also supported in terms of common knowledge in the art: "the rationale may be expressly or impliedly contained in the prior art or it may

be reasoned from knowledge generally available to one of ordinary skill in the art, established scientific principles, or legal precedent established by prior case law". [34] Based on this additional criteria, claim 7 would further be rejected: it would be obvious for a person having ordinary skill in the art to control stepper motors using an open-loop system, due to it being common knowledge. As such, it would be obvious to a person having ordinary skill in the art to combine the apparatus of Blackburn with the motor control method of Chandhoke, such that the motors in the apparatus of Blackburn may be driven with the method of Chandhoke.

The rationale found in Section 2144 of the Manual for Patent Examining Procedure [34] would likely also be used to reject claims 3, 4, and 10.

E. Allowable Subject Matter

Due to the rejection of what would be independent claims 1, 7, and 9 it is likely that claims 6, 8, 11, and 12, as dependent claims, would be objected to as being dependent upon a rejected base claim; would be allowable if rewritten in independent form including all of the limitations of the base claim and any intervening claims.

1) *Hardware Subject Matter:* As to claim 6, at time of writing, no such gimballed motor system incorporates an LCD display with associated display control was found. If specified as such, it is possible that the overall apparatus, incorporating the unique addition of the LCD display, may potentially be patentable.

As to claims 11 and 12, the powering of a microcontroller is not disclosed by a known prior art as of time of writing.

2) *Software Subject Matter:* As to claim 8, the most likely allowable subject matter present as part of the invention is the embedded software program for the control of the motor systems. As previously mentioned in section VI-D, the act of stepping motors itself may be considered obvious to a person having ordinary skill in the art. As briefly introduced in section VI-B, the calculation of the precise steps to move in order to locate specific star coordinates is a non-obvious solution given a person having ordinary skill in the art, assumed to have the layperson's knowledge of astronomy. The complexity of the calculation is found in its incorporation of an understanding of three factors:

- 1) Greenwich-mean sidereal time, as derived from the Julian date, as derived from the Gregorian date and current clock time.
- 2) Latitudinal and longitudinal coordinate systems, such that they may be applied to calculate the azimuthal and elevational position of a given star.
- 3) Right-ascension and declination celestial coordinates, such that they may also be applied to calculate the azimuthal and elevational position of a given star.

As such, with express application towards a material, unique result, the embedded software applicable to the movement of the motors, for the purpose of directing the laser towards a specific star coordinate, may be considered potentially allowable subject matter.

F. Software License Agreements

The software libraries used for this project, including the TouchGFX library, is licensed under the STMicroelectronics SLA0048 software license agreement. [35] The PEPCISco design team acknowledges and accepts, in using STM-sourced libraries, the software package license agreement, and has maintained compliance with the details of the agreement, in using the relevant provided software for strictly educational purposes as opposed to commercial applications.

VII. PROJECT DESCRIPTION

A. Objectives

Mountain D.E.W. (Directed Energy Wayfinder) is an educational tool designed to assist novice astronomers and stargazers in identifying and seeking stars in the night sky. To accomplish this, the device was initially designed to incorporate a GNSS module that receives spatial coordinates and time data and then references an on-board database of existing celestial bodies to orient the device. This aspect has since been abandoned. Users are then able to select a desired star for viewing, upon which the device parses through the sky, moving a laser, mounted to a two-axis gimbal, to point at the star in question. The device incorporates the STM32 Nucleo-G071RB microcontroller, along with a X-NUCLEO-GFX01M2 LCD expansion board, as the primary processing unit, due to the robustness and flexibility of the microcontroller [36]. The STM32 Nucleo is responsible for the operation of laser power, input processing, user interface display, and the pulse-width modulation signals that drive the stepper motors. The microcontroller and associated circuitry is located underneath the main gimbal platform. A diagram of both power and data flow is shown in figure 1.

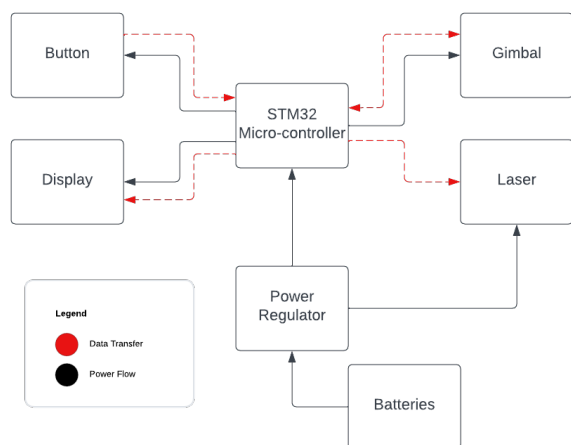


Fig. 1. Block Diagram - Power Flow, Data Transfer

B. Functionality

The first step is for the user to place the device in an area where the night sky is present. Stars should be visible to the naked eye in this area. When the device is powered, the user will input their current latitude and longitude using the joystick button located on the LCD display. Next, the user

will enter the current date and time. After that, the user will confirm their selection and then use the joystick to maneuver the laser to point at Polaris, the north star. Then, the user will select a given star from a list on the LCD, and the device will determine the star's azimuth and elevation with respect to the user. Mountain D.E.W. seeks out stars by parsing GPS data to find the device's location and time and then directs the laser to the star via controlling the stepper motor drivers that move the gimbal. The user will be able to select a new star, then the process is repeated as many times as the user wants it to or until the machine is powered off.

To correctly align the system and point the laser at the correct star, the device will need to be able to interpret the celestial coordinate system. There are five different systems to choose from, each with a different fundamental plane that they base the system off. One option that may be used is the equatorial system [37]. This system is used by many professional and amateur astronomers and uses the Earth's center as its relative origin. Coordinates are based off the locations of stars relative to the Earth's equator. This coordinate system uses two values: declination and right ascension. Declination is the measure of where an object is between the north celestial pole and the south celestial pole and can have a value from -90° to 90° . Right ascension (RA) is the measure of where an object is along the equator and is measured relative to the Vernal Equinox Point. RA is dependent on time since the Earth spins, and thus sidereal time to find the RA must also be calculated [38]. Sidereal time can easily be calculated on-board the device, by using a GPS module and by inputting time manually. To perform the initial orientation of the device, the laser can be pointed at the north star, Polaris, which is located at the north celestial pole. Next, the combination of GPS data and time will be used to calculate the initial RA. After this, the device will know exactly where it is and where it is pointing, allowing it to calculate how to point at any other start in the night sky.

C. Technical Considerations

Mountain D.E.W. is comprised of six design blocks, incorporating (1) a laser mounted onto (2) a two-axis gimbal, controlled by (3) an STM32 G071RB microcontroller, powered by (4) a standalone power supply, with (5) a GPS chip for calibration and geolocation, and (6) a user interface comprised of a button and LCD display. The technical feasibility of such a design has been proven by amateur inventors utilizing an Arduino-based system [39]. Scaled down to what is technically feasible within the scope of a 2.5-month project, the versatility of the STM32 microcontroller [40] and the extensive documentation available for applications of the STM32 [41] allows for a more-streamlined application of the microcontroller to the purposes of this project. Health and safety concerns restrict the operation of a green laser to 5 milliwatt, which has been demonstrated to be sufficient for amateur astronomical usage [42]. In terms of the operation of the gimbal, use of a two-axis gimbal requires considerations of pitch (rotation relative to a transverse axis) and yaw (rotation relative to a vertical axis), as shown in figure 2.

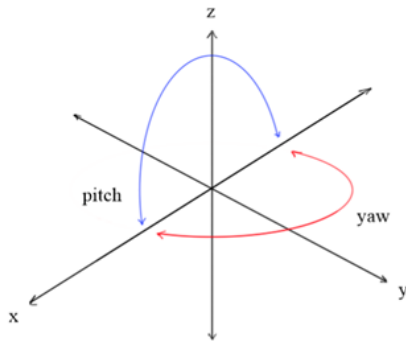


Fig. 2. Pitch and Yaw Definition

For the purposes of the operation of Mountain D.E.W., the device requires, for its two degrees of freedom, the ability to move 360[Equation] in yaw, and 90[Equation] in pitch, for both vertical operation and near-horizontal operation. Considerations for stability of motion for when the device is oriented are available and will be made a primary priority, such that smooth movement and orientation of the gimbal-mounted laser are made possible [43]. It is expected that the device will be able to operate independent of a wall power supply: this restricts the operation of the device to battery operation. A 12V lead-acid battery was chosen due to the large capacity and sufficient voltage output [44].

To supply power to the entire system, a series of buck regulators was implemented on the PCBs. As the system was originally designed to be supplied by 18V from two 9V batteries, the power is initially fed into an AP63300 buck regulator which steps the voltage down from 18V to 12V [49]. Using the equations found on the regulator's datasheet, resistors, capacitors, and inductors that would output 12V and supply the necessary current were selected. The 12V output from the AP63300 is then used to power the STM32 as well as the stepper motors via the motor drivers. It also goes into an AP62150 buck regulator that steps the 12V down to 5V [50]. Again, the AP62150 datasheet was consulted to select the support circuit elements. The 5V from the output of the AP62150 is used as an alternate power source for the STM32 and power for the laser. A final buck regulator converts the 5V to 3.3V. An AP61100 buck regulator was chosen and its datasheet was used to select the required component values [51]. The 3.3V output from the buck regulator was used to provide power to the original motor drivers before another motor driver was found [52]. It was also used to provide an input to a 3.3V low-voltage dropout (LDO) regulator since the Adafruit GNSS module required a smooth voltage supply which a buck regulator cannot provide [53].

The STM32 has a wide variety of modules and expansion boards that allow for easy integration of the different sub-systems this project requires. Initially, the GY-NEO6MV2 GPS module was chosen, however, the required pins it uses for data transmission conflicted with pins that were used by the LCD display module. This forced the team to use the

Adafruit PA1616S GPS breakout board which was able to communicate using the UART serial data communication protocol on different STM32 pins. The LCD module chosen, the X-NUCLEO-GFX01M2 interfaces directly with the STM32 microcontroller. The LCD module also features a 64-Mbit NOR Flash memory which stores the images and typography that is displayed on the LCD. Both the LCD and NOR Flash communicate with the STM32 using the SPI (Serial Peripheral Interface) communication protocol. The LCD module also features a joystick which can be pressed in the center, up, down, left, and right directions. This joystick and the board's on-board user button is the primary method that users will use to interact with the system and is used to set the latitude and longitude, move the laser during initial orientation, and select which star to point at. Another feature of the LCD module is its usage of the TouchGFX graphical user interface (GUI) framework. TouchGFX was used to generate all of the screen images that the user interacts with on the LCD.

To calculate the azimuth and elevation of a celestial body with respect to some observer on the Earth's surface, the user's latitude and longitude, the body's right ascension and declination, and the Greenwich mean sidereal time (GMST) must be known. Sidereal time is a measure of how much the Earth has rotated with respect to distant celestial objects, with sidereal time relative to the Prime Meridian in Greenwich as the standard used by astronomers for converting right ascension and declination to pitch and yaw code. [55] GMST can be calculated from the current time of day and the user's timezone, which are first converted to the Julian Date using the following equations: [56]

$$\begin{aligned} A &= \text{INT} \left(\frac{M - 14}{12} \right) \\ B &= 1461(Y + 4800 + A) \\ C &= 367(M - 2 - 12A) \\ E &= \text{INT} \left(\frac{Y + 4900 + A}{100} \right) \end{aligned} \quad (1)$$

$$\text{JDN} = \text{INT} \left(\frac{B}{4} \right) + \text{INT} \left(\frac{C}{12} \right) - \text{INT} \left(\frac{3E}{4} \right) + D - 32075 \quad (2)$$

The Julian date and time can be used to find the Greenwich mean sidereal time using the following equation: [57]

$$\begin{aligned} \text{GMST}_{\text{P03}}(\text{UT1}, t) &= \theta(\text{UT1}) + 0''.014506 \\ &\quad + 4612''.156534t + 1''.3915817t^2 \\ &\quad - 0''.00000044t^3 - 0''.000029956t^4 \\ &\quad - 0''.0000000368t^5. \end{aligned}$$

where the hour angle can be found using the following formula: [58]

$$\theta(T_u) = 2\pi(\text{UT1 Julian day number elapsed since } 2451545.0 + 0.7790572732640 + 0.00273781191135448T_u),$$

The Greenwich mean sidereal time is used instead of the Greenwich apparent sidereal time to reduce the complexity of the calculation, as an error of 1 second (or 0.0003 degrees) is not detectable to the naked eye. [55] The GMST, observer latitude and longitude, and right ascension and declination can then be used to find the azimuth and elevation of a given celestial body using the following formulas to calculate its hour angle (or position relative to the Prime Meridian), and then finding the azimuth elevation coordinates: [59]

$$H = GMST + lon - RA$$

$$az = \arctan 2(\sin(H), \cos(H) \sin(lat) - \tan(Dec) \cos(lat))$$

$$alt = \arcsin(\sin(lat) \sin(Dec) + \cos(lat) \cos(Dec) \cos(H))$$

D. Design Challenges

The major challenge that this project faced was the determination of the initial orientation of the device and how to use available databases of celestial objects to point the laser at the correct star or planet. Multiple techniques to determine the initial orientation of the device have been considered during the preliminary planning phase. For the purposes of this proposal, a decision was made between two orientation techniques: the use of a camera to map the visible stars and determine the initial orientation, or pointing the laser at the north star, Polaris, and using a GPS module. Using a camera to orient the device poses many technical challenges. First is ensuring there is enough resolution in the camera to be able to identify individual stars in the sky. If the camera quality is poor, the image will be too blurry to determine what stars the device is looking at. Second is making sure that the STM32 Nucleo board and its accessories have enough processing power to quickly perform the calculations necessary to process the image, which depend on the amount of data and the algorithm chosen for the task. Orienting the system using Polaris also poses challenges since it will need to be manually pointed at the star, introducing a degree of error from the manual inputs. Additionally, this limits the functionality of the system to the northern hemisphere since Polaris is only visible from there. The device could be made to orient to Sigma Octantis, the pole star of the southern hemisphere, but further research will have to be done [54]. On the other hand, using a GPS module would only require that the device's initial orientation will be relatively level with respect to the ground, as the latitude, longitude, and type of day can be parsed from GPS data at a much lower power and computational cost than the orientation based on image processing alone. While this does introduce the challenge of initial orientation, this may also be addressed through manual calibration via the user or the use of additional sensors or header boards, such as an inclinometer for the laser's initial position.

Another major challenge that was faced was choosing the best method to power the system. Initially, two 9V batteries in series were chosen to power the system. This would provide 18V which would then be stepped down to 11.1V, then 5V, and ultimately 3.3V. After switching gimbal systems, the

11.1V level had to be re-designed to output 12V instead. Upon testing, it was discovered that the 18V to 12V switching regulator did not function on any of the PCBs that had been soldered and as such were forced to abandon it. This meant that the power source had to be switched from the two 9V batteries to a single 12V lead-acid battery which would then be connected directly to the input of the 12V to 5V regulator. This battery is very bulky and heavy which means it is hard to transport.

From the standpoint of human factors engineering, it is necessary to ensure that the system is both safe and easy to use, which poses a challenge if the device primarily initialized and used in dark environments. From a safety standpoint, the laser specified is low power at less than 5mW: common-sense precautions are intended to be designed into the device, such as only allowing the laser to turn on when the device has finished gimbaling to decrease the chance that it may cause injury to user vision. The laser may instead be configured to only circle around the area of interest a certain number of times instead of pointing directly at the area of interest. Proceeding with this methodology, the smoother the system runs with minimal user input, the less the user will need to mess with the device and risk having the laser point into their eye. Having LEDs or some other method of signaling to the user that the board is powering on, calibrating, or adjusting itself, may help increase the amount of feedback that the user gets to prevent them from spending too much time around the device. These features will be iterated for additions and improvements, for the purpose of improving safety and ease of use.

E. Test Plan

Once each component of Mountain D.E.W. has been acquired, the PCBs were assembled and soldered. Next, the power supply circuitry on the PCB was tested to ensure that each electrical component was getting the correct voltage and power. Then, each piece of hardware was tested by sending the corresponding control signals for each basic function, or state of the device, and verified that the correct output was measured and/or observed for each set of inputs. For the laser, for example, a check was made for the laser to turn on when it receives the right set of control signals. The display's output would verify that the data sent to the board is visible and correctly oriented for the user. For the input system, this test also required verification that the data being fed in meets specifications for each subsystem. Next, the software that controls the gimbal was tested to verify that it points where it is instructed to within the testing program. Lastly, the gimbals were verified to have the capability to correctly move the laser, or a dummy payload representing the laser, from one star to another once the system is correctly calibrated.

After testing each component manually, the system was assembled in stages with basic tests for connectivity occurring when each module was attached. The microcontroller and laser were the first to be assembled, such that their joint functionality may be verified for each relevant state, proceeded

by integration of the gimbal, displays, and input system until complete integration was achieved and tested.

F. Resources & Equipment

To complete this project, access to soldering equipment, a 3D printer, multimeter, and other standard electrical test equipment was required. The soldering equipment was needed to solder electrical components like resistors and voltage converters as well as make any other connections to the laser and gimbaling system that were required. The 3D printer was needed to manufacture the housing for the device. The PCB and gimbaling system need a structure to support them, and designing a casing using software like Autodesk Fusion 360 provided the most freedom. To make sure the PCB is functioning properly, electrical test equipment like multimeters, oscilloscopes, and a power supply were necessary so that the power supplied to the system could be controlled, and any possible damage that would otherwise result could be prevented.

G. Software

The software tools that used for this project include tools that were used to develop both the hardware components, software components, and case design. The tool used for board development was KiCad. It was used for the initial circuit schematic capture and for PCB layout. Software tools used for this project include the STM32 CubeIDE, STM32CubeMX, and TouchGFX for embedded system coding and VSCode for other coding related activities. The group used a Git repository hosted on Github for version control for development of the device's code base. Lastly, the casing for the project was designed in Autodesk Fusion 360, which is computer aided design (CAD) software.

VIII. TIMELINE

From a high-level perspective, the Gantt chart from the proposal sufficiently estimated the amount of time that was needed to complete the initial project proposal, initial design, and the first rounds of parts orders. Where the Gantt chart failed was usually in two places: 1) no time was allotted on the original Gantt chart for the completion of the Poster Session material and Midterm Design Review, as well as the Final Video, and 2) insufficient time was budgeted for not only the assembly of each subsystem and their integration, but also the time needed to properly improve and iterate upon each subsystem. Additionally, the original Gantt Chart does not reflect the additional time the group built into the final report due to delays in shipping for various products, such as the original planned gimbal from CopterLabs, which increased the time needed to assemble each subsystem and integrate it into the whole device. For group assignments like the Project Proposal, the initial approach was to divvy up the work by subsection, and then having each member read over the whole product at the end. This approach quickly broke down when the Project Description section, given its length and subject material, needed the input of multiple

members for completion. Thus, Errick was switched in to help with the Project Description in addition to the External Considerations, while Jeffrey was assigned to take over the Test Plan. Additionally, due to a miscommunication, Anthony also completed a large portion of the External Considerations section, so Jeffrey also helped take over the budget outline. Given all the role-swapping with the Project Proposal, when deciding roles for the next report assignments, the team felt that a less rigid division of responsibilities would give each member more flexibility in giving input to others' sections. Doing so would also clutter the Gantt Chart less, since each member still had to address their responsibilities for designs and ordering during that same period of time. This approach was successful enough that the team chose to go with the same approach for creating the Final Video and Report, where material created for past reports could be recycled and updated with input from other team members as necessary. To save space on the figure above, this more flexible arrangement has simply been noted as a full 'Team' responsibility on the final Gantt Chart, keeping in mind that the responsibilities for each section carry over from the Project Proposal but with the need for each member to collaborate with each other to complete the entire deliverable. Shifting to more technical logistics, the initial design and orders section of the Gantt Chart had to be modified as the group made decisions and changes about the exact materials needed for the project. This included: 1) splitting the line for laser acquisition into laser source and laser mount, 2) adding GNSS and LCD expansion board acquisition tasks, 3) condensing the gimbal chassis, motor, and sensor acquisition tasks into a single task to reflect the initial plan to use an off-shelf gimbal and motor assembly. The programming tasks associated with this period were also augmented with a laser control FSM task, since the team felt that a clearer idea of the device's UI was necessary for designing the algorithms for adjusting and calibrating the motors. Finally, the gimbal and the first iteration of the PCB had to be extended an additional week due to delays in shipping, with the calibration code design also extended due to uncertainty regarding the gimbal.

With regards to the initial stage of assembly and testing, the initial Gantt chart failed to take into account what would happen if the design for a subsystem failed subsystem testing and required further iterations before it could even begin system integration. Case in point: when the Copter Labs chassis arrived, it was quickly realized that the subsystem did not meet the specifications given by the client. Thus, the Gantt chart had to be updated to reflect that assembly and testing for the laser, backup gimbal motors, and the LCD was completed, but also to show that chassis assembly required more time. Extra lines for software testing with the FSM, GNSS, and LCD were also added to this part of the project. As the project progressed, the team realized that certain components could not be used in conjunction with the LCD due to overlapping digital pin requirements. This affected the order in which components could be integrated into the entire system, as certain parts needed to be re-designed and re-ordered based on what pins the team could use from

	A	B	C	D	E	F	G	H	I	J	K
1	Week	1	2	3	4	5	6	7	8	9	10
2	Date	08/28-09/03	09/04-09/10	09/11-09/17	09/18-09/24	09/25-10/01	10/02-10/08	10/09-10/15	10/16-10/22	10/23-10/29	10/30-11/05
3	Event	Initial Presentation	Swap Date		Project Proposal	Fall Break	Poster Session	Midterm Design, PCB 1	Withdraw Date	PCB 2	Family Weekend
12	Project Proposal										
13	Background		Kieran								
14	Project Description		Jeffrey								
15	Test Plan		Errick								
16	External Considerations		Anthony								
17	Deliverables		Anthony								
18	Budget Outline		Jeffrey								
19	Timeline		Daniel								
20	Expectations		Daniel								
21	Abstract, Formatting			Kieran							
23	Design/Orders										
24	Power Source & Distribution										
25	Laser Source										
26	Microcontroller & Mount		Anthony	Daniel							
27	Gimbal Chassis										
28	Gimbal Motors										
29	Gimbal Sensors										
30	Input System										
31	Printed Circuit Board										
32	Calibration Code										
33	Adjustment Code										
34	Test Plan										
35	Assembly/Testing										
36	Chassis Fabrication										
37	PCB Assembly										

Fig. 3. Initial timeline for project proposal, design, and component orders.

	A	B	C	D	E	F	G
1	Week	0	1	2	3	4	5
2	Date	08/28-09/03	09/04-09/10	09/11-09/17	09/18-09/24	09/25-10/01	10/02-10/08
3	Event	Initial Presentation	Swap Date		Project Proposal	Fall Break	Poster Session
4	Initial Presentation						
5	Title Slide, Formatting	Errick					
6	Project Outline	Kieran					
7	Technical Considerations	Jeffrey					
8	Team Roles	Daniel					
9	Team Roles	Anthony					
10	Team Roles	Team					
11	Project Proposal						
12	Background		Kieran				
13	Project Description		Jeffrey				
14	Test Plan		Errick				
15	External Considerations		Jeffrey				
16	Deliverables		Anthony				
17	Budget Outline		Anthony				
18	Timeline		Daniel				
19	Expectations		Daniel				
20	Abstract, Formatting			Kieran			
21	Poster Session						
22	Information					Errick	
23	Block Diagram					Anthony	
24	Finite State Machine						Daniel
25	Presentation						Team

Fig. 4. Final timeline for initial presentation, project proposal, poster session.

the STM board. Thus, the order of integration became: LCD, GNSS, Power PCB, Gimbal, Laser, and then DC Power Supply. The GNSS board had to be re-ordered with a different model from Adafruit, while the PCB had to be split into STM and Power PCBs to better fit the planned casing.

The motorized gimbal had to also be completely reworked into a 3D printer armature design. While every component was eventually integrated into the system powered by a DC power supply for field testing at the residence of Mr. Dudley White, generously offered, this still resulted in three weeks of

	A	C	D	E	F	G	H	I
1	Week	1	2	3	4	5	6	7
2	Date	09/04-09/10	09/11-09/17	09/18-09/24	09/25-10/01	10/02-10/08	10/09-10/15	10/16-10/22
3	Event	Swap Date		Project Proposal	Fall Break	Poster Session	Midterm Design, PCB 1	Withdraw Date
27	Midterm Design Review							
28	Synopsis					Kieran		
29	Block Diagram						Anthony	
30	PCB Schematic						Jeffrey	
31	Software Flowchart						Daniel	
32	Test Plan						Errick	
33	Gantt Chart						Daniel	
34	Formatting						Errick	
35							Team	
36	Design/Orders							
37	Power Source & Distribution			Jeffrey				
38	Laser Source			Daniel				
39	Laser Mount				Kieran			
40	Microcontroller & Case	Anthony	Daniel					
41	Laser Control				Daniel			
42	GNSS Expansion Board			Anthony				
43	Gimbal			Kieran				
44	Input System			Errick				
45	Display System			Errick				
46	Printed Circuit Board			Jeffrey				
47	Adjustment Code				Anthony			
48	Calibration Code						Anthony	
49	Test Plan					Daniel		
50						Errick		

Fig. 5. Final timeline for midterm design review, design, and component orders.

	A	G	H	I	J	K	L	M	N	O	P
1	Week	6	7	8	9	10	11	12	13	14	15
2	Date	10/02-10/08	10/09-10/15	10/16-10/22	10/23-10/29	10/30-11/05	11/06-11/12	11/13-11/19	11/20-11/26	11/27-12/03	12/04-12/10
3	Event	Poster Session	Midterm Design, PCB 1	Withdraw Date	PCB 2	Family Weekend	PCB 3		Thanksgiving		Final Project Report, Demo
37	Assembly/Testing										
38	Chassis Fabrication										
39	PCB Assembly										
40	Subsystem Testing										
41	System Assembly										
42	System Testing										
43	System Evaluation										
44											
45	Design/Orders 2										
46	Subsystem maintenance										
47	Subsystem improvement										
48	Additional Feature(s)										
49	Power Source & Distribution										
50	Printed Circuit Board										
51	Code Optimization										
52	Test Plan										
53											
54	Assembly/Testing 2										
55	PCB Assembly										
56	Subsystem Testing										
57	System Assembly										
58	System Testing										
59	System Evaluation										
60											
61	Final Project Report										
62											
63	Final Project Demo										
64											

Fig. 6. Initial timeline for assembly, testing, second design iteration, final report, and demo.

delay from the original Gantt Chart. Thus, the team pivoted towards improving certain aspects of the project from the rubric to increase score, instead of completing another full design cycle on the device.

For the last three weeks, instead of going through a second design cycle, the team split into groups to focus on getting the GNSS board integrated into the system, improving the

Power Supply PCB, and 3D printing a tripod mount for the entire system. While the latter two objectives were achieved by the end of November, the GNSS board could not be integrated due to difficulties with the TouchGFX library. Thus, additional screens had to be added for the user to manually input their latitude, longitude, and time of day.

All in all, while the group was unable to complete its orig-

	A	I	J	K	L	M	N
1	Week	7	8	9	10	11	12
2	Date	10/16-10/22	10/23-10/29	10/30-11/05	11/06-11/12	11/13-11/19	11/20-11/26
3	Event	Withdraw Date	PCB 2	Family Weekend	PCB 3		Thanksgiving
52	Assembly / Testing I						
53	Chassis Assembly	Kieran					
54	PCB Assembly	Jeffrey					
55	Laser Testing	Errick					
56	Power PCB Testing		Jeffrey				
57			Errick				
58	Gimbal Motor Testing		Daniel				
59	FSM Testing	Daniel					
60	GNSS Testing	Anthony					
61	LCD Testing		Anthony				
62			Daniel				
63							
64	Assembly / Testing II						
65	FSM + LCD (SYS-I)		Daniel				
66			Anthony				
67	SYS-I + GNSS (SYS-II)		Anthony				
68	SYS-II + PCB (SYS-III)		Jeffrey				
69			Errick				
70	SYS-III + Gimbal (SYS-IV)			Kieran			
71				Daniel			
72	SYS-IV + Laser (SYS-V)			Errick			
73	SYS-V, DC Power Supply				Team		
74	SYS-V Evaluation				Team		

Fig. 7. Final timeline for assembly, subsystem testing, and integration.

	A	J	K	L	M	N	O	P
1	Week	8	9	10	11	12	13	14
2	Date	10/23-10/29	10/30-11/05	11/06-11/12	11/13-11/19	11/20-11/26	11/27-12/03	12/04-12/10
3	Event	PCB 2	Family Weekend	PCB 3		Thanksgiving		Final Project Report, Demo
77	Testing III							
78	SYS-V Maintenance			Team				
79	SYS-V + Battery Power (SYS-VI)			Jeffrey				
80				Errick				
81	SYS-V + 3D Case (SYS-VI)			Kieran				
82	SYS-VI, Crude Targets			Daniel				
83				Daniel				
84	SYS-VI, Low Visibility			Anthony				
85	SYS-VI + Stronger Laser (SYS-VII)			Team			Team	
86	SYS-VII Evaluation						Team	
87								
88								
89	Final Project Report							
90							Team	
91	Final Project Demo							
92								Team
93	Final Project Video							
94								Team

Fig. 8. Final timeline for system testing, field testing, and demo.

inal intended schedule of design with two cycles of assembly and testing, the team was still able to achieve a functional device prototype even when presented with delays in shipping, issues with pin configuration, and challenges with printed circuit board design. While certain aspects of scheduling and the chart could be improved in the future to better reflect the parallel nature of subsystem development and iterative design, this Gantt chart served its purpose well in guiding the team in its efforts creating its final demo, report, and video.

IX. COSTS

The cost of the project development can be seen in Appendix-A and Appendix-B. A full outline of the cost of both a single unit and mass production of 10,000 units can be seen in Table II.

TABLE II
COSTS SUMMARIZED

Subsystem	1 unit (\$)	10000 units (\$)
PBB	1.96	0.75
Components	29.47	12.04
STM	11.21	10.21
LCD	35	35
Stepper Motors	28	28
Laser	105	105
Mechanical Components	8.33	0.50
Motor Drivers	9.30	9.30
Tripod	15	15
Battery	20	Not Included
Total	263.27	215.80

A. Single Unit

The total cost of the device of \$263.27 as can be broken down into 6 major components: Custom Electronics, Embedded Electronics, the Motors, the laser, the battery, and Mechanical Setup. The custom electronics consists of a Power PCB with components soldered onto it and a breakout PCB for the embedded electronics. The PCBs cost \$9.80 for 5 boards so \$1.96 per board and the components that were soldered onto the PCBs cost a total of \$29.47 per board, an itemized version of which can be seen in the appendix. The embedded electronics consists of an Nucleo G0B1RE with the LCD header board, the X-NUCLEO-GFX01M2. This cost \$11.21 for the STM32 and \$35.00 for the LCD Header. Two motors, 32 Adafruit Industries LLC Stepper Motors, which cost \$14 each for a total of \$28 were purchased. The laser, the VLM-520-52 LPB, cost \$105. To power the setup, a lead acid battery for \$20 was used. Finally the mechanical setup consists of custom 3D printed parts in PETG plastic. Each roll of 1Kg of plastic costs \$24.99 and each mount is approximately 1/3 of a kilogram of plastic of which approximately 0.3Kg is the tripod and electrons mount and the mount is approximately 0.05Kg. This least to a total 3D printed cost of \$8.33. The tripod, Targus TG-5060TR, costs approximately \$15. The motor drivers in the final project, the SparkFun Quadstepper Motor Driver Board, is no longer made or sold so Allegro A4988 were used to estimate the cost. These drivers are \$4.65 a piece and 2 drivers are needed for a total of \$9.30.

B. Mass Production

If this device were purchased on a large scale of, for example, 10,000 units the cost of each device would fall to \$215.80 battery not included. The laser, motors, motor drivers, tripod, and the embedded electronics do not decrease in price with scale from any current suppliers. However, with the STM it may be possible to create a board with the micro controller and power electronics directly connected potentially saving approximately \$1. The components that were soldered on the board do greatly scale with unit costs. The chips and larger components such as MOSFETs and jumper pins reduce in price by approximately 60%. Smaller component such as capacitors are approximately 80% lower in cost. This leads to an overall drop in cost for the electronic components to about \$12.04 per unit. The PCBs drop to \$0.75 on an order of 10,000. Additionally, the 3D printed components could be converted

to injection molded which would likely reduce unit costs to approximately \$0.50. The battery would not be included in a production outfitting.

X. FINAL RESULTS

The rubric by which the project is scored is detailed in Table III. The performance metrics shown dictate how the project demonstrates a sufficient degree of operation.

A. Power

Score: 2

- Stepper Motor Control Board: 1A @12V (12W)
- STM32 + LCD: 300mA @12V with 92% efficiency (3.9W)
- Laser: 380mA @ 5V with 92% efficiency (2.1W)
- Battery capacity: 12V 7Ah (84Wh)
- Maximum time on: 4.5h

Even at maximum output, the device can operator for more than hour on a single charge.

B. Laser

Score: 2

Laser tick-based events implemented circling implemented to a limited extent, however, after field testing, it was realized that circling the laser increased the risk of hitting nearby aircraft and decided to shift back to just single pointing.

C. PCB

Score: 2

A single PCB design is split into two to allow for more compact, modular design. All components are successfully soldered on with a fabricated case/mount.

D. Gimbal

Score: 2

The gimbal is fully assembled with laser. All components are well mounted and set on a tripod raised above the ground which allows user to stand instead of having to crouch down avoids dirt and other material on the ground that could affect device operation heat sinks placed also help regulate the gimbal's internal temperature.

E. User Interface

Score: 2

The system features 23 stars. More stars can be added so long as the star's RA and Declination coordinates are known. The system stores star ID on the microcontroller, and has options for manually inputting the time of day, latitude, and longitude and displaying the corresponding azimuth and elevation for each star.

TABLE III
MOUNTAIN DEW FINAL PROTOTYPE POINT ALLOTMENT

Subsystem	Great (2)	Sufficient (1)	Insufficient (0)
Power	Device operates for one hour or more on a single charge	Device operates for at least 15 minutes on a single charge	Device fails to deliver power to one or more subsystems
Laser	Laser turns on and off at each specified time and circles around objects of interest instead of pointing directly	Laser turns on and off at each specified time	Laser fails to turn on or off at each specified time
PCB	PCB is well laid-out with all components soldered on with a fabricated case	PCB is well laid-out with all components soldered on	PCB is poorly laid-out and/or missing components
Gimbal	Gimbal is fully assembled with laser and all components are well-mounted with other protection measures for outdoor use	Gimbal is fully assembled with laser and all components are well-mounted	Gimbal is not fully assembled and/or one or more components are poorly mounted
User Interface	User interface well-laid out with five or more options for stargazing and sends appropriate data to microcontroller	User interface is well-laid out and sends appropriate data to microcontroller	User interface is poorly laid-out and/or sends incorrect data to microcontroller
GPS	STM32 receives timely and correct GPS communications and works in poor GPS environments works in poor GPS environments	STM32 receives timely and correct GPS communications	STM32 receives incorrect and/or untimely GPS communications
Calibration	Calibration to the North Star occurs on startup, with additional recalibration upon changes in time, position, or orientation	Calibration to the North Star reliably occurs on startup	Calibration to the North Star fails to occur on startup
Pointing	Device reliably points to other user-inputted stars present in the night sky	Device sometimes points to other user-inputted stars present in the night sky	Device fails to point to other user-inputted stars present in the night sky
System	Device is fully assembled and tested as a system with additional features to streamline use	Device is fully assembled and tested as a system	Device is not fully assembled and/or tested as a system

F. GPS

Score: 0

The GNSS module had difficulty achieving a timely fix in the room. Even outside, the module also integrated poorly with TouchGFX, likely due to overlap with the LCD's DMA pins. Thus, GNSS communications were untimely and often garbled leading to a transition to the manual input of coordinates.

G. Calibration

Score: 2

Calibration to the North Star occurs at startup, assuming that the laser is level, pointed north, and parallel to the earth's surface. The user can easily recalibrate the device back to the north star after multiple iterations of star finding. The device can also be reset to change coordinates and time of day (this can also be made an additional options menu if the UI is redesigned)

H. Pointing

Score: 2

The motors can reliably and accurately point within 1.8 degrees of each star (as represented by the sticker demo targets placed in the testing chamber) by keeping the stepper motors always enabled. Heatsinks were added to the motors and motors driver to keep the system cool. This pointing works for all stars included in the demo version.

I. System

Score: 1

The system is fully assembled but due to lack of time no other accessibility features were implemented.

J. Total

Score: 15

Using the rubric in Table IV the project satisfies the criteria for an A+.

TABLE IV
MOUNTAIN DEW FINAL PROTOTYPE GRADING SCALE

Points	Grade
13+	A+
9-12	A
5-8	B
1-4	C
0	D

XI. FUTURE WORK

Given more time to work on this project, there are several elements that could be improved.

A. Portability

First, the system should be condensed to make it more portable. When the project started, the goal was to make it as portable as possible. This was done to make it as easy for the user as possible to transport the system and set it up. As the project progressed, the functionality of the system was prioritized over its portability. For example, the battery used to power the system is a bulky 12V lead-acid battery which is cumbersome to carry. This was done since other battery solutions could not be researched in time. Future work can be done to research the implementation of rechargeable lithium batteries like the Spektrum Smart 14.8V battery. [60] This battery was chosen due to its high voltage and capacity. The system would need to regulate the discharge of the LiPo battery to ensure the battery does not enter a dangerous state.

B. GNSS Functionality

Another aspect of the project that requires future work is the GNSS module. The GNSS module could not integrate into the system on time and subsequently, it was left out of the final design. The module took too much time to connect to the navigation satellites. This meant that calibration would take too long for it to be beneficial to the user. Another problem that was encountered was that the module would not work well with the framework used by the STM32 to communicate with the LCD display module. The GNSS and LCD modules shared a common interrupt pin which made it impossible to enable communication to both at the same time. [61] Since the GPS coordinates are a critical part for orienting the system, another method was able to be implemented for the user to manually input their latitude and longitude using the buttons on the STM32 microcontroller. This solution is not optimal since it would require the user to have a way to know their exact, or rough, coordinates and as such, should be fixed in future work.

C. Gearing System

Another part of the project that could be worked on is a gearing system for the motors. The NEMA17 stepper motors that are currently used on the system do not have the precision to move the laser when whole-stepping. This means that the motors must micro-step to ensure the laser is pointed precisely. The problem with micro-stepping is that the motor will move to the nearest whole-step when it is turned off which means that the stepper motors can never be turned off while the system is on, otherwise the laser will not point at the correct position in the sky. Having the motors always enabled draws a lot of current which both drains energy from the batteries and heats up the motors. Because of this, heat sinks were added to the motors to dissipate the heat. Using a gearing system would let the motors move in whole-steps since the coarse movement would be reduced to a much finer and precise movement. [62] The motors could then be disabled when not in use, decreasing power consumption and minimizing the heat generated.

D. Improved System Calibration

Finally, the current calibration process to set the initial orientation of the system does not factor in the angle of the system relative to the ground. It treats the system on an incline the same as if it were on level ground. This means that the system would not function properly if it were set up on a hill, something that would be problematic if users wanted to place the system on a hillside when stargazing. Future work needs to be done to work on a solution to this problem. One possible method would be to use an accelerometer to measure the tilt of the system. [63] This data could be integrated with the existing calibration algorithm to provide a more accurate system.

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B. Additional Budget Used

Item	Budget Used	Price Per Unit	Units Needed	Total Price	Link	Reimbursed?	In Final Product?	Add. Budget Used	Add. Budget Remaining
VLM-520-52LPB-ND	Errick	\$ 105.000	1	\$ 105.00	https://www.quarton.com/uploa	<input type="checkbox"/>	<input checked="" type="checkbox"/>	\$ 562.15	\$ 560.09
Ball Bearings	Errick	\$ 8.570	1	\$ 8.57	https://www.amazon.com/623-2/	<input type="checkbox"/>	<input type="checkbox"/>	Add. Expenses Breakdown	
RTC Module, Arduino RPI	Errick	\$ 9.990	1	\$ 9.99	https://www.amazon.com/AITRIP	<input type="checkbox"/>	<input type="checkbox"/>	Errick	\$ 318.25
Accelerometer, Arduino	Errick	\$ 11.980	1	\$ 11.98	https://www.amazon.com/Steme	<input type="checkbox"/>	<input type="checkbox"/>	Kieran	\$ 121.66
Nano Board	Errick	\$ 19.990	1	\$ 19.99	https://www.amazon.com/LAFVH	<input type="checkbox"/>	<input type="checkbox"/>	Anthony	\$ 61.24
More Ball Bearings	Errick	\$ 9.990	1	\$ 9.99	https://www.amazon.com/uxcell	<input type="checkbox"/>	<input type="checkbox"/>	Jeffrey	\$ 61.00
Electric Lime PETG	Kieran	\$ 24.990	1	\$ 24.99	https://www.amazon.com/gp/prc	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Sum Check	\$ 562.15
Solder Paste	Errick	\$ 15.950	1	\$ 15.95	https://www.chipquik.com/datas	<input type="checkbox"/>	<input type="checkbox"/>		
Isopropyl Alcohol	Errick	\$ 12.730	1	\$ 12.73	https://www.techspray.com/cont	<input type="checkbox"/>	<input type="checkbox"/>		
Wire, 18AWG, Green	Errick	\$ 0.430	4	\$ 1.72	https://www.cnctech.us/pdfs/10	<input type="checkbox"/>	<input checked="" type="checkbox"/>		
Wire, 18AWG, Black	Errick	\$ 0.430	4	\$ 1.72		<input type="checkbox"/>	<input checked="" type="checkbox"/>		
Wire, 18AWG, Red	Errick	\$ 0.430	4	\$ 1.72		<input type="checkbox"/>	<input checked="" type="checkbox"/>		
Wire, 18AWG, White	Errick	\$ 0.430	4	\$ 1.72		<input type="checkbox"/>	<input checked="" type="checkbox"/>		
4-pos Header	Errick	\$ 0.470	4	\$ 1.88	https://mm.digikey.com/VolumeC	<input type="checkbox"/>	<input type="checkbox"/>		
4-pos Header	Errick	\$ 0.450	4	\$ 1.80	https://mm.digikey.com/VolumeC	<input type="checkbox"/>	<input type="checkbox"/>		
Nucleo G0B1RE	Errick	\$ 11.210	1	\$ 11.21	https://www.st.com/resource/en	<input type="checkbox"/>	<input type="checkbox"/>		
LCD GFX01M2	Errick	\$ 35.000	2	\$ 70.00	https://www.mouser.com/datash	<input type="checkbox"/>	<input type="checkbox"/>		
White Circular Labels	Errick	\$ 9.690	1	\$ 9.69	https://www.staples.com/avery-l	<input type="checkbox"/>	<input type="checkbox"/>		
Black Paper Roll	Errick	\$ 22.590	1	\$ 22.59	https://www.staples.com/fadeles	<input type="checkbox"/>	<input type="checkbox"/>		
S7004-ND	Kieran	\$ 0.520	2	\$ 1.04	https://mm.digikey.com/VolumeC	<input type="checkbox"/>	<input type="checkbox"/>		
S7006-ND	Kieran	\$ 0.570	10	\$ 5.70	https://mm.digikey.com/VolumeC	<input type="checkbox"/>	<input type="checkbox"/>		
S7122-ND	Kieran	\$ 2.290	4	\$ 9.16	https://mm.digikey.com/VolumeC	<input type="checkbox"/>	<input type="checkbox"/>		
23-0393570008-ND	Kieran	\$ 3.950	4	\$ 15.80		<input type="checkbox"/>	<input type="checkbox"/>		
RMCF0805JT10K0CT-ND	Kieran	\$ 0.016	10	\$ 0.16		<input type="checkbox"/>	<input type="checkbox"/>		
31-AP63300WU-7CT-ND	Kieran	\$ 0.920	5	\$ 4.60		<input type="checkbox"/>	<input checked="" type="checkbox"/>		
31-AP62150WU-7CT-ND	Kieran	\$ 0.410	5	\$ 2.05		<input type="checkbox"/>	<input checked="" type="checkbox"/>		
31-AP61100Z6-7CT-ND	Kieran	\$ 0.510	5	\$ 2.55		<input type="checkbox"/>	<input checked="" type="checkbox"/>		
490-6473-1-ND	Kieran	\$ 0.106	10	\$ 1.06		<input type="checkbox"/>	<input type="checkbox"/>		
311-1136-1-ND	Kieran	\$ 0.058	10	\$ 0.58		<input type="checkbox"/>	<input type="checkbox"/>		
1284-1019-1-ND	Kieran	\$ 0.509	10	\$ 5.09		<input type="checkbox"/>	<input type="checkbox"/>		
1276-6687-1-ND	Kieran	\$ 0.102	10	\$ 1.02		<input type="checkbox"/>	<input type="checkbox"/>		
1276-2478-1-ND	Kieran	\$ 0.047	10	\$ 0.47		<input type="checkbox"/>	<input type="checkbox"/>		
490-3044-1-ND	Kieran	\$ 0.128	10	\$ 1.28		<input type="checkbox"/>	<input type="checkbox"/>		
1276-1066-1-ND	Kieran	\$ 0.062	10	\$ 0.62		<input type="checkbox"/>	<input type="checkbox"/>		
732-10955-ND	Kieran	\$ 0.363	10	\$ 3.63		<input type="checkbox"/>	<input type="checkbox"/>		
399-20795-ND	Kieran	\$ 1.736	10	\$ 17.36		<input type="checkbox"/>	<input type="checkbox"/>		
5900-560-RC-ND	Kieran	\$ 4.000	2	\$ 9.96		<input type="checkbox"/>	<input type="checkbox"/>		
IRLB8721PBF-ND	Kieran	\$ 1.070	3	\$ 3.21		<input type="checkbox"/>	<input type="checkbox"/>		
RMCF0805FT44K2CT-ND	Kieran	\$ 0.019	10	\$ 0.19		<input type="checkbox"/>	<input type="checkbox"/>		
RMCF0805FT52K3CT-ND	Kieran	\$ 0.019	10	\$ 0.19		<input type="checkbox"/>	<input type="checkbox"/>		

311-422KCRCT-ND	Kieran	\$ 0.024	10	\$ 0.24		<input type="checkbox"/>	<input type="checkbox"/>		
A103671CT-ND	Kieran	\$ 0.881	10	\$ 8.81		<input type="checkbox"/>	<input type="checkbox"/>		
AP2120N-3.3TRG1DICT-ND	Kieran	\$ 0.380	5	\$ 1.90		<input type="checkbox"/>	<input type="checkbox"/>		
JLPCB order 1	Anthony	\$ 35.700	1	\$ 35.70		<input type="checkbox"/>	<input type="checkbox"/>		
JLPCB order 2	Anthony	\$ 25.540	1	\$ 25.54		<input type="checkbox"/>	<input type="checkbox"/>		
RLB0914-330KL-ND	Jeffrey	\$ 0.360	10	\$ 3.60		<input type="checkbox"/>	<input type="checkbox"/>		
RLB9012-560KL-ND	Jeffrey	\$ 0.720	4	\$ 2.88		<input type="checkbox"/>	<input type="checkbox"/>		
S7008-ND	Jeffrey	\$ 0.660	4	\$ 2.64		<input type="checkbox"/>	<input type="checkbox"/>		
RMCF0805FT44K2CT-ND	Jeffrey	\$ 0.020	10	\$ 0.20		<input type="checkbox"/>	<input checked="" type="checkbox"/>		
RMCF0805FT52K3CT-ND	Jeffrey	\$ 0.020	10	\$ 0.20		<input type="checkbox"/>	<input checked="" type="checkbox"/>		
311-422KCRCT-ND	Jeffrey	\$ 0.025	10	\$ 0.25		<input type="checkbox"/>	<input type="checkbox"/>		
490-3044-1-ND	Jeffrey	\$ 0.145	10	\$ 1.45		<input type="checkbox"/>	<input type="checkbox"/>		
1276-6687-1-ND	Jeffrey	\$ 0.102	10	\$ 1.02		<input type="checkbox"/>	<input type="checkbox"/>		
A103671CT-ND	Jeffrey	\$ 0.881	10	\$ 8.81		<input type="checkbox"/>	<input type="checkbox"/>		
1276-2478-1-ND	Jeffrey	\$ 0.047	10	\$ 0.47		<input type="checkbox"/>	<input type="checkbox"/>		
1284-1019-1-ND	Jeffrey	\$ 0.546	10	\$ 5.46		<input type="checkbox"/>	<input type="checkbox"/>		
1276-1066-1-ND	Jeffrey	\$ 0.062	10	\$ 0.62		<input type="checkbox"/>	<input type="checkbox"/>		
23-0393570008-ND	Jeffrey	\$ 3.950	1	\$ 3.95		<input type="checkbox"/>	<input type="checkbox"/>		
S7004-ND	Jeffrey	\$ 0.520	2	\$ 1.04		<input type="checkbox"/>	<input type="checkbox"/>		
S7006-ND	Jeffrey	\$ 0.660	4	\$ 2.64		<input type="checkbox"/>	<input type="checkbox"/>		
S7122-ND	Jeffrey	\$ 2.290	2	\$ 4.58		<input type="checkbox"/>	<input type="checkbox"/>		
311-1136-1-ND	Jeffrey	\$ 0.058	10	\$ 0.58		<input type="checkbox"/>	<input type="checkbox"/>		
RMCF0805JT10K0CT-ND	Jeffrey	\$ 0.017	10	\$ 0.17		<input type="checkbox"/>	<input type="checkbox"/>		
490-6473-1-ND	Jeffrey	\$ 0.119	10	\$ 1.19		<input type="checkbox"/>	<input type="checkbox"/>		
RG20P200KBCT-ND	Jeffrey	\$ 0.330	10	\$ 3.30		<input type="checkbox"/>	<input type="checkbox"/>		
TS391AX-ND	Jeffrey	\$ 15.950	1	\$ 15.95		<input type="checkbox"/>	<input type="checkbox"/>		