PROSPECTUS FOR

POLARIS

Precision **O**ptical **L**aser-Based **A**eronautical **R**otation **I**nformation **S**ystem

Received: 2 December 2019

S. Chourasia
R. Li
A. Lin
J. Ye
E. Zhao

Table of Contents

1.0 Introduction

Astronomers and cosmologists today are living in the golden age of astronomy: they have access to far superior mirrors and lenses, imaging processes, and technology than the generations before them. Amongst these many advantages is the placement of satellites in orbit, such as the Hubble Space Telescope, Fermi Gamma-ray Space Telescope, and the Chandra X-Ray Observatory. These remote satellites are critical to the development of both macro- and micro-scale understandings of the Universe, as they allow for significantly improved imaging of interstellar bodies as they are not restricted by the visual interference created by the atmosphere. However, these satellites all depend on stable, well-controlled, and precise spacecraft to be placed into orbit.

The aim of this project is to develop a rudimentary spacecraft guidance system that is able to detect the orientation state of a spacecraft model, and to use collected data to perform the necessary adjustments.

Pursuant to van Bemmel (2019), the following basic requirements for the operations of the device were defined. The guidance system is expected to detect any positional changes in one axis for a duration of at least 120 seconds. During this time, the system should be able to analyze the collected positional data, then compute and perform any changes required to stabilize the flight by controlling fins on the rocket plume. Furthermore, the device is expected to relay engineering and flight performance data to an operator. This information may include battery voltage, sample end effector location, and system status, as well as a log for the inputs and deflections to the model's fins. This information is then expected to be numerically and graphically displayed on a separate monitor. If this is accomplished, further steps shall be taken to make the device functional in all three axes of rotation in three-space.

A system was designed to conform to these necessary criteria. The following document contains schematics, technical design information essential to the design of the guidance system. Furthermore, testing procedures, timeline, and budget information is shown as well.

2.0 General Structure

The rudimentary guidance system will be housed in a model designed to replicate a spacecraft. The model will be encased in a box approximately 29 cm wide, 30 cm high, and 73 cm in length. The interior will house three gyroscope devices which will be connected to the central processing Arduino unit. The entire system will be powered by a number of 1.5V D cell batteries.

The guidance system will rely on three gyroscopes as the most essential source of positional and velocity data. Fundamentally, gyroscopes are discs that rotate about a spin axis. As a result of this angular momentum, the disc tends to maintain its orientation in space; when a force is applied to the spin axis, gyroscopic discs apply a perpendicular force opposing the motion. Gyroscopes can be placed in gimbals to maintain their spin axis direction. External forces acting upon the gyroscope can then be measured utilizing a sensor while being applied to the gimbal rather than affecting the disc itself, thus creating a stable measurement of position. For this system, three gyroscopes were selected such that each would be oriented to rotate in one of three planes, thereby allowing for one plane measurement per gyroscope. This necessitates the single-gimbal design, where each gyroscope only has one degree of freedom in the desired plane of rotation. The Design Optimization section will detail the justification for the design choices. These three gyroscopes will be ordered within the model spacecraft with respect to the position of the relevant fins that they control.

Given the dimensions of the model casing, each gyroscope will be able to have its own cubic apparatus with side lengths of 22 cm. This will encase not only the single-gimbal gyroscope but the laser detection scheme that relays the angular displacement of the spacecraft in the respective plane, which involves 2 lasers stationed at one end of the apparatus stationary relative to the gyroscope, pointing horizontally at the other end at a photoresistor. Between the photoresistor and the lasers, a plastic transparent film will be attached to the rotating gimbal axis and rotate with the gyroscope; on the film will be a printed greyscale gradient that will correspond to angle measures, such that the photoresistor will receive a varied brightness which it can interpret as an angle relative to the initial reading before flight. The remaining space above the gyroscopes will be for the breadboard and the electrical components which are wirelessly connected to a computer.

2.1 Materials

Many materials are required in the construction of the said model spacecraft. Primarily, wood will be used to form the frame of the spacecraft. Wood was selected as a relatively lightweight material which is both easy to work with and to fix into place using metal tools. Furthermore, wood is a durable substance, allowing for ease of transportation of the model. Small metal screws will then be used to connect the panels of wood. Wood was decided to be used since it is an insulator of heat and electricity, and thus the rest of the parts should not interact with each other significantly in terms of heat transfer, especially due to the motors and lasers.

In addition, the use of wood, an electric insulator, ensured that insulation was not required at the junctions of wiring. Wood glue and screws will be used to connect the outer frame of the gyroscopes to the sides of the smaller boxes. Tin wiring will be required to connect the various components to the controlling device and 1.5V D cell batteries will be used to power the system; tin wiring also allows for greater ease in soldering. Data from the gyroscopes and voltmeter will be analyzed and processed by an Arduino unit; this information will then be sent to a computer to be displayed.

2.2 Gyroscopes

Three separate single-gimbal gyroscopes will be constructed and oriented such that each is responsible for the measurements of rotation around one principal axis in three-dimensional space. These gyroscopes will be made of a purchased wooden disc, and each will be placed in a wooden gimbal and accompanied by appropriate support for a motor. Each gyroscope will be placed in a square wooden frame such that it may be housed in the larger spacecraft model. A wood disc will be used. Additionally, to minimize the wood friction from these components, they will be lubricated with paraffin wax, Vaseline, or specialized Rubik’s Cube lubricant as needed.

Furthermore, each gyroscope disc will have a DC motor within the spin axle to maintain constant torque and rotation. To motorize the gyroscope, the spin axle will be selected as a hollow tube through which the motor shaft can be placed. To do so, discs attached by epoxy glue will be combined. This same adhesive will then be used to connect the motor to the gyroscope itself. When attached to the processing unit, the data from all the gyroscopes can be consolidated.

2.3 Detection and Telemetry

The gyroscope readings will be made with two fixed lasers attached to the housing, which are aimed at two corresponding photoresistors. These pairs of lasers and photoresistors will be separated by an angle of 45°. The internal gimbal of the gyroscope, which is allowed to rotate freely, will have a circular film with a greyscale gradient attached to it. This film will allow different amounts of light through depending on the angle that the gimbal is set at; these values will be calibrated beforehand (each level of brightness will correspond to an angle) and output the corresponding angle to the gimbal orientation in the gyroscope unit's axis.

When the gimbal is blocking neither laser beam's path to its corresponding photoresistor, two measurements will be attained, one from each laser-photoresistor combination, and these values can be averaged to find a more accurate value for the angle. When the gimbal is blocking one of the lasers, however, data from one of the laser-photoresistor combinations is still available, and so the angle resulting from this will be used. When the gimbal is blocking neither laser beam's path to its corresponding photoresistor, two measurements will be attained, one from each laser-photoresistor combination, and these values can be averaged to find a more accurate value for the angle. When the gimbal is blocking one of the lasers, however, data from one of the laser-photoresistor combinations is still available. The resulting angle will be sent to the secondary Arduino board. A Bluetooth Shield module connected to the communications board will then send the gyroscope telemetry to the paired computer.

2.4 Central Processing

Information from the gyroscopes will be sent to the central Arduino unit, which uses angular position data from the gyroscopes and the Arduino internal timer in order to calculate the angular velocity, orientation, and velocity of the spacecraft. Additional information, namely battery voltage and end effector location, are also sent from sensors to the central unit, where it is then processed. The central Arduino unit itself will be an Arduino Mega, which will be placed within the confines of a wooden frame at the centre of the spacecraft model in order to minimize the lengths of wire junctions between components, and thus, minimize potential error or short-circuiting. The motion of this component must be restricted; thus, the frame will be made to snugly surround the perimeter of the unit and to keep it in place while the spacecraft is moved.

Information from the central Arduino unit about the gyroscopes, battery voltage, and end effector location will then be sent to an Arduino Uno unit through a wired connection. In order to maintain this connection, the secondary Arduino will be placed in a similar frame to the first, and fastened in a similar manner. This unit will also be placed near the centre of the model, for ease of connection to the first computer. Then, this Arduino unit will relay information to an external device through the use of an Arduino Bluetooth Shield.

2.5 Fins

The fins on the spacecraft are for display purposes only, and do not affect the readings for the positional and velocity data of the guidance system. These fins will give our spacecraft a more realistic look and simulate the movements of fins on a real spacecraft. They will move depending on the orientation data received from the gyroscopes and will position in a way that would correct the spacecraft back to its original path of motion.

A small DC servo motor on each side of the model spacecraft will be used to control the movement of the fins. These are selected due to their ability to move to precise angles based on an Arduino input. To optimize the mobility of the fins with low power motors, a light material is selected for their construction: cardboard. Sheets of cardboard with dimensions 20x10 cm will be shaped and fixed to the servo disc with tape such that it may orient in tandem with the motor itself.

Since the construction for the gyroscopes is segmented, construction of subsequent gyroscopes cannot be achieved until the first gyroscope is tested and proofed such that it reliably functions. Likewise, the fins cannot all be constructed at the same time; rather, the construction of fins will be delegated to members to manage while other members construct the remaining gyroscopes. Since different fin/aileron systems correct different areas of spacecraft flight, only the set of fins pertaining to the first gyroscope's measured axis will be initially constructed and tested, whether it be for pitch, roll, or yaw, in aircraft terms. Additional sets of fins will be constructed upon the completion of the other gyroscopes' testing. Fins will include wing ailerons to roll the plane, a body flap near the tail to correct pitch, and a rudder to adjust yaw as permitted by the construction of the other components.

2.6 Voltmeter

The voltages across the batteries used in the device will be measured with a specialized Arduino Voltage Sensor Module. This is connected in parallel to the batteries, and the other end with the signal is connected to the central Arduino. The signal will then be measured to find the potential difference across the battery in real time, so that it can be displayed. The module functions by converting the analog value to a digital value, sending the received value as a signal to the central processing Arduino.

2.7 Computer Interface

The live telemetry from the central Arduino unit will be sent via Bluetooth to be displayed on a computer screen. The computer interface will be broken down into two parts that can be accessed with a mouse click: flight data and data logger. The flight data screen will be split into three graphs with numerical fields accompanying them to display the telemetry live. The data logger will display tables that will be updated after every second of run time.

The computer interface will consist of two panels which can be toggled for a viewer. The first will be a flight logger, which will contain three gyroscope readings will be displayed within three text fields as three angles indicating the spacecraft's deviations from its original position during flight, with each corresponding to one axis of rotation. Below, a graphical plot with three lines indicating the spacecraft's rotation about the three axes will be generated accordingly to show the deviations in each axis from the expected path. A similar format will be used for the fin orientation. The second panel will display all relevant engineering data of the ship. This will include information regarding battery voltages as a function of time as a broken line graph. Fin positions will also be displayed.

Selecting any of the displays will bring up the logger for that particular dataset. The logger will be in the form of tables that will display data for the last five seconds of flight, providing numerical values to the graph. The logger data can be downloaded as a CSV file with additional data points after the run has completed.

2.8 Design Optimization

Throughout the designing process, extensive consideration was taken to encompass possible inefficiencies or difficulties that required optimization to improve the device construction and function. The design process is essential as an iterative process for problem solving and optimization. In this manner, prototyping and testing various possibilities will always result in a more complete product. This is ideal as emphasis can also be placed on the constraints of the device as a whole as well as its exact functional goals in reverse engineering many of its aspects.

The first step of this process was to identify the needs of the system pursuant to van Bemmel (2019). To apply this to designing the guidance system required subtask division and integration. Such subtasks were considered both by function and by composition of the system in order to ensure a comprehensive and segmented approach to the design. Figure 18 in Software Design demonstrates the functional aspect of the system. Through understanding these functional requirements, it becomes more apparent where constraints and criteria can be established. This process is also vital because it identifies crucial elements of success: constraints are fixed requirements where a product not within constraints does not qualify as a solution, and criteria are metrics that evaluate how a solution can improve on itself. All solutions must resolve constraints, but optimal solutions tend to appeal to more criteria.

Considering the components' needs for their design, the gyroscope is constrained to ideally detect in all three dimensions. Typical mechanical gyroscope designs are given at least two degrees of freedom and can be stabilized in space, so that they are double-gimbal or more (NASA uses a four-gimbal gyroscope to negate gimbal lock). This would allow for a single gyroscope to relay a specific angular position based on, perhaps, detecting a colour on a spherical gradient that would correspond with coordinates. However, a basic constraint is the feasibility of construction, which in this case is very difficult and all produced at once; if the gyroscope were to fail, the entire project would as well. With this in mind, a single-gimbal gyroscope was selected for its comparative ease of construction as well as the freedom to now separate the measurement of each axis and compartmentalize the building.

The gimbal is rectangular and compact, such that the size of the DC motor can rest on a support protruding from the gimbal, and the spin axle matches the researched diameter of the DC motor shaft. The axle was initially planned to be metal due to higher resulting moment of inertia and Given the need for a compact and lightweight system, wood was chosen and the size of the apparatus confined to within 75 cm in length to ease the manual carrying and testing. However, the wheel still had to be large enough to produce a sufficient torque to maintain its orientation when in motion. The constant torque of the DC motor allows for the wheel to resist the torque imposed when it attempts to veer in axes that are not free, such that precession and systemic error are minimized; any unforeseen error will likely be a measurable function that can be tested for and considered when the first gyroscope is constructed. The imbalanced torque from the motor's weight on the spin axle will not be significant, firstly because the starting orientation of the axle will have the heaviest side down, and secondly because the torque applied on the axle is perpendicular to its degree of freedom when the motor sufficiently powers the rotation. Thus, the gyroscope should not precess as a result of its structure.

Likewise, other components were designed to be compact and centralized efficiently for integration as well as individual testing. The organization of gyroscopes within the model allowed for the shortest wire distance to fins to minimize errors, and the fins were designed to be a rigid and light material, i.e. cardboard, so that the servo motors could still reliably move them and they could maintain their form. The segmented design of the fins further enabled the ability to segment and delegate tasks by order of priority. Safety and efficiency constraints for the telemetry and computer interface also called for two microcontrollers, again to lower the responsibility of each and to separate functions according to the functional flowchart. Great concern was given to the wiring of the circuit so that electrical components could be externally shut off.

The angular position detection method was the most difficult due to the basic constraint that it should function for 120 seconds and the criteria to maximize its precision. Initially, multiple ideas were proposed, including the usage of polarizing filters in conjunction with a laser, so that the intensity of a polarized laser beam after passing through the filter could be measured with a photoresistor. The laser and photoresistor would be attached to the gyroscope housing, and the filter would be attached to the rotating gimbal. The square of the cosine of the angle that the filter was set at could then be determined using Malus's law. However, this design was decided not to be used due to the ambiguities involved in having the value of $\cos^2\theta$, which could not be resolved in a simple manner; such a method would require three or more lasers, which would also be prohibitively expensive.

As a result, a similar method was instead chosen, where the polarizing filter would be replaced with a film annulus with a greyscale gradient ranging from light gray to dark gray, allowing different amounts of light through depending on the part of the film the laser shines through. This ensures that only one measurement is required, except for the edge cases where a laser is blocked by a gimbal. In these edge cases, the corresponding photoresistor would read the value as completely dark due to the laser not passing through the gimbal, and so there is ambiguity involved, as the gimbal may be in one of two positions. For these cases, a second laser is required to resolve the ambiguity; this second laser can also add to the accuracy of measurement when the gimbal does not block either laser, as the average of the two measurements can then be taken. This method also requires a lower amount of precision in mounting the film onto the gimbal, and only requires two lasers per gyroscope unit.

2.9 CAD Designs

The following diagrams depict the general structure and scale of the system.

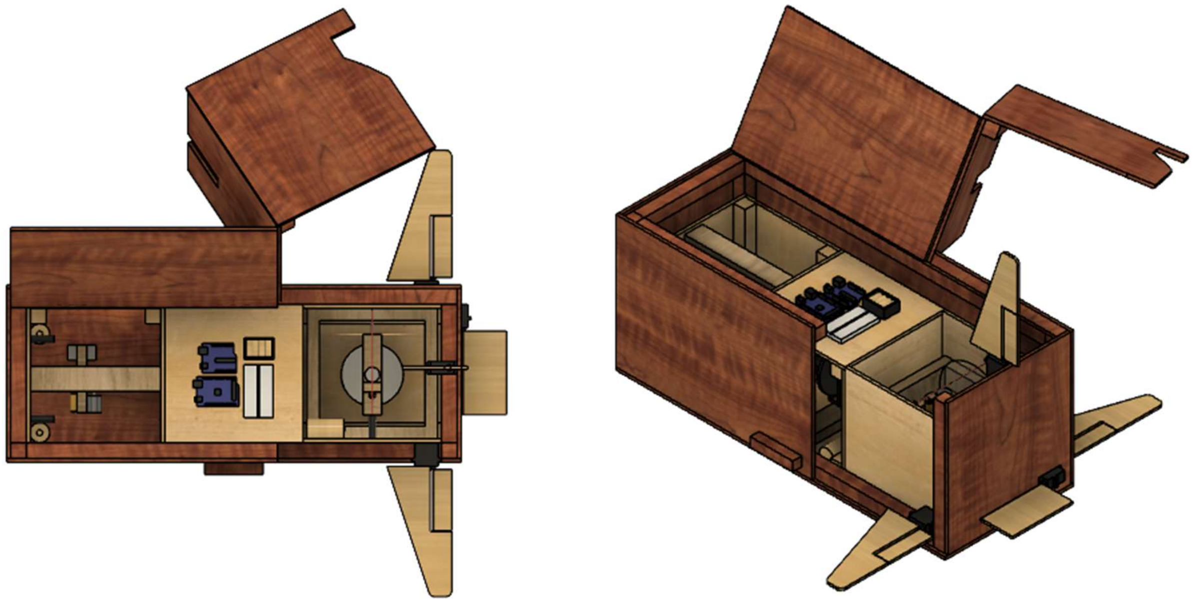


Fig 1. Overall Design of the Apparatus from Above (left) and Side (right). The apparatus houses the three gyroscopes in line, with space for the breadboard and electrical circuit components above them. The fins are also attached to the outside of the housing, and connected to the circuit board through wiring holes. The housing is closed with a latch door, to allow easy access to the interior of the spacecraft, while also creating a spacecraft shape when it is shut.

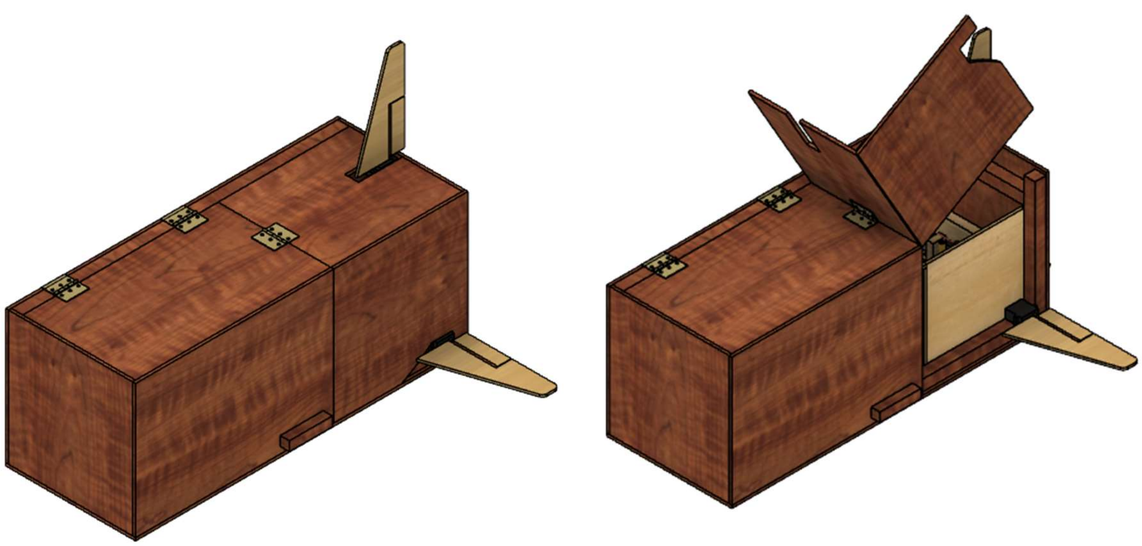


Fig 2. Exterior Design of the Apparatus Closed (left) and Open (right). From the outside, the apparatus is a closed system which can be internally accessed with hinged panels on the top. The front compartments open and close outwards, and the back compartment opens upwards as to allow access to the fin/wing systems.

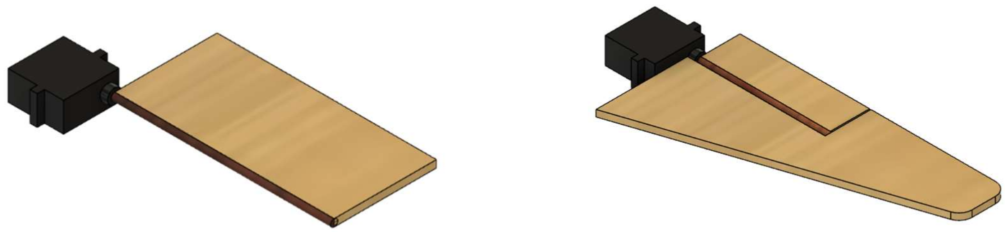


Fig 3. Elevator (left) and Aileron/Rudder (right) Design. Each cardboard fin is controlled using a servo motor that receives positional commands. Each is a rectangular flap, which is then integrated into a wing-shaped design to be placed on the exterior of the model. When the motors are in motion, only the outlined flap will rotate to model the motion of an aileron, elevator, or other.

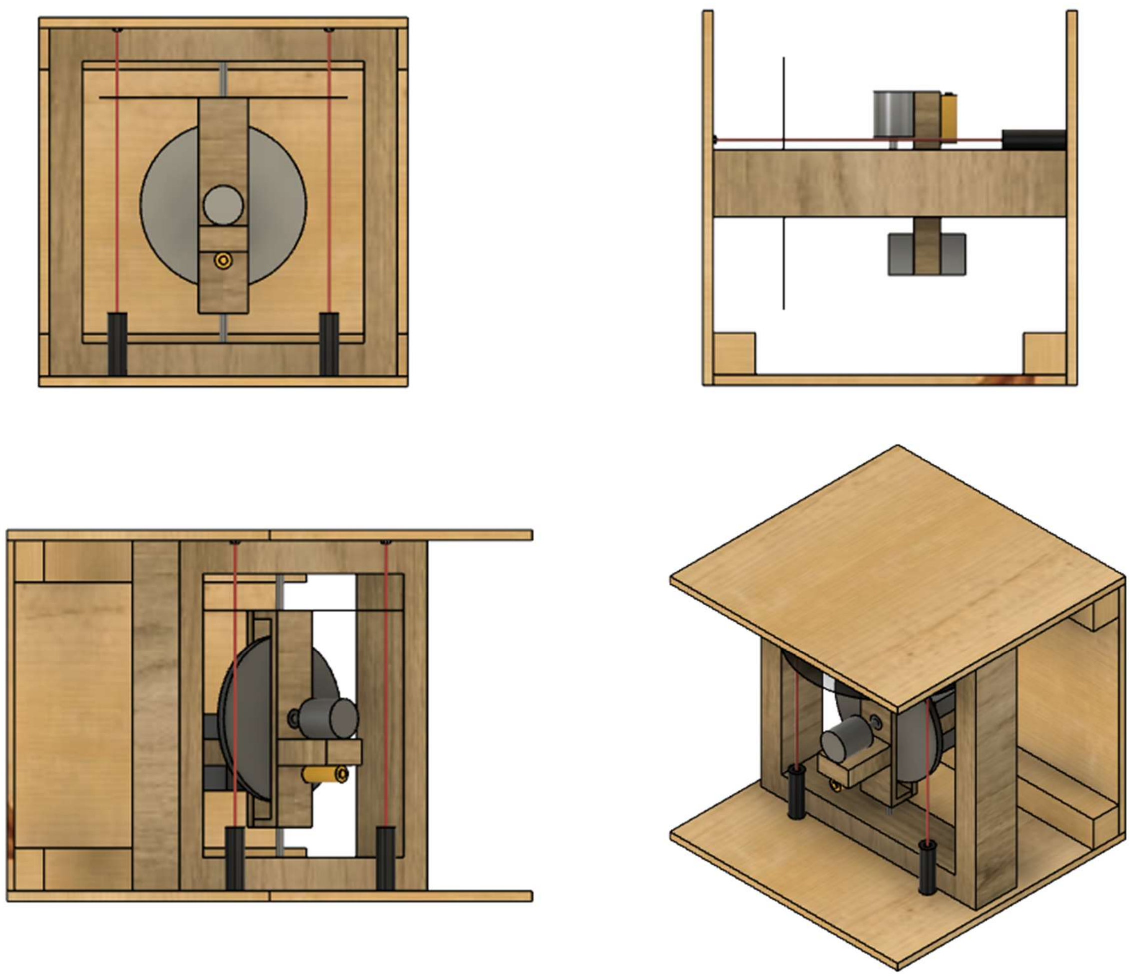


Fig 4. Design of a Single-Gimbal Gyroscope. Three gyroscope units are used for the device, each oriented to take measurements in a different axis of the spacecraft device. The gyroscope consists of a spinning motorized disc attached to a free-moving gimbal; a plastic gradient film is attached to the gimbal and allows differing amounts of laser light through to hit the photoresistor on the opposite wall. Two lasers are required for each gyroscope unit. The gyroscope unit is fixed in a wooden frame to remove unwanted motion. Four angles are shown of the gyroscope unit.

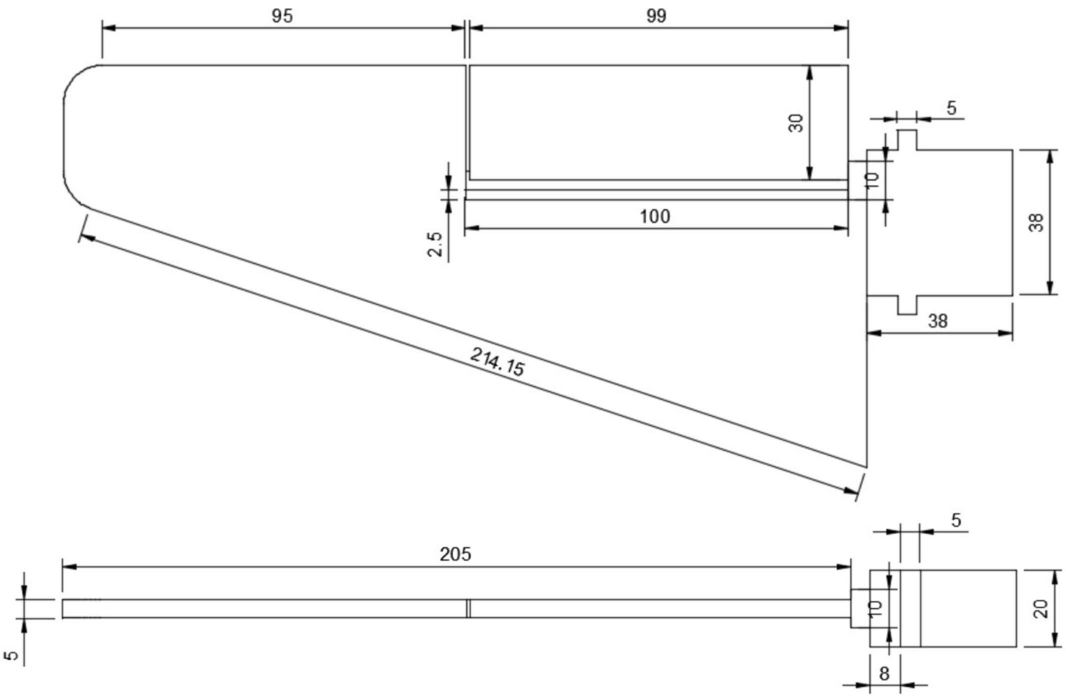
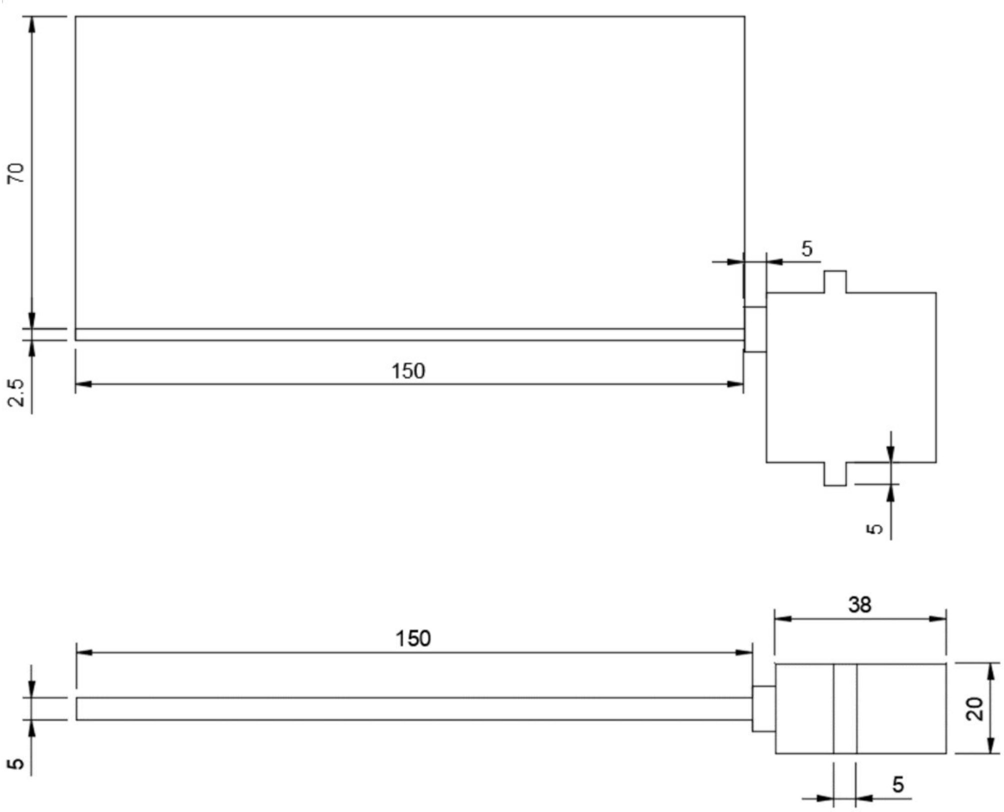


Fig 5. Aileron/Rudder Scale Diagram from Above (top) and Front (bottom). Dimensions of the aileron and rudder designs are given in millimetres, including the adjusting flap (centre) and the motor (right). It is shown where the ailerons are connected to the rest of the wing.



ss

Fig 6. Elevator Scale Diagram from Above (top) and Front (bottom). Dimensions of the elevator design are given in millimetres, including the motor (right). The motor shaft is connected at one end, allowing rotation along the bottom edge.

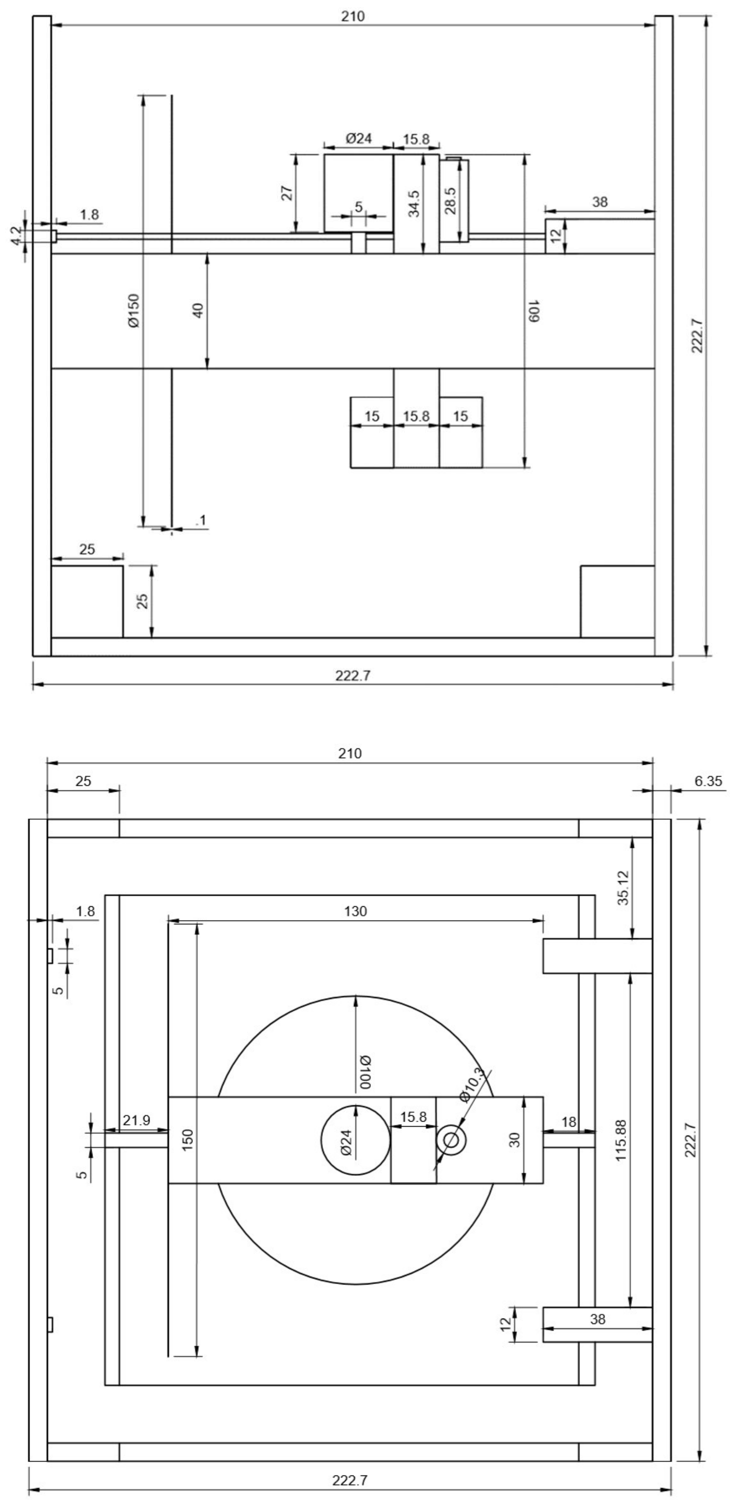


Fig 7. Gyroscope Box Scale Diagram from Side (top) and Front (bottom). Dimensions of the design are given in millimetres. From the front, the wheel is motorized and the gimbal rotates with the thin film on the left. The two lasers on the right shine across the film toward the small photoresistors noticeable from the front view.

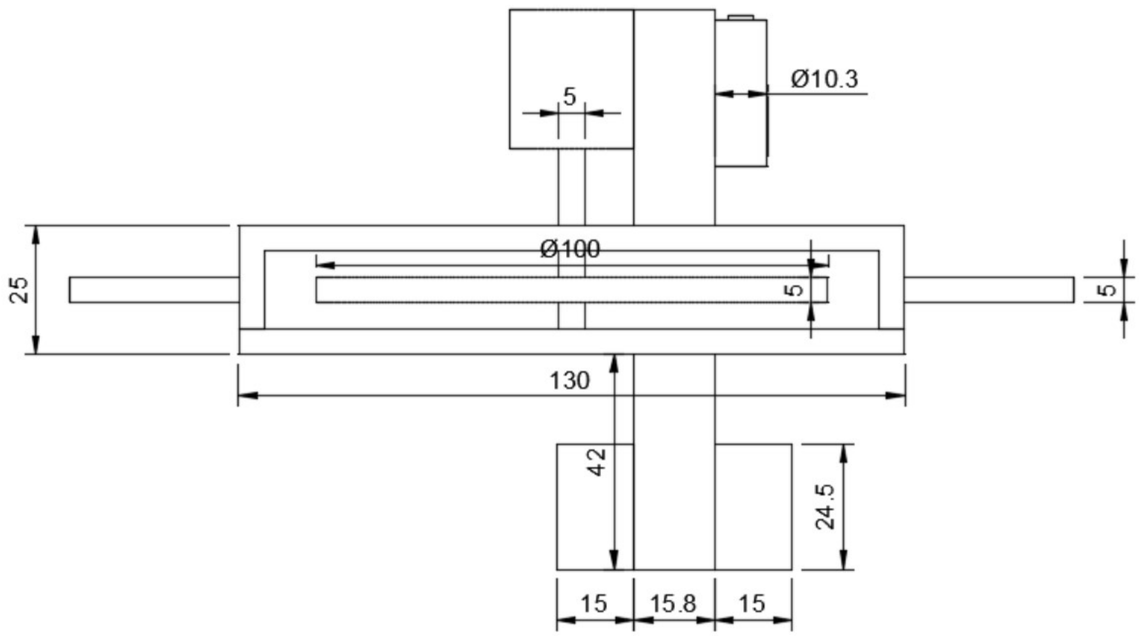


Fig 8. Gyroscope Disc and Gimbal Scale Diagram. Dimensions of the design are given in millimetres. A horizontal spinning disc is enclosed in the rectangular gimbal (centre) which is connected at its two ends to the casing. The motor and battery are seen above with a possible counterweight design on the bottom.

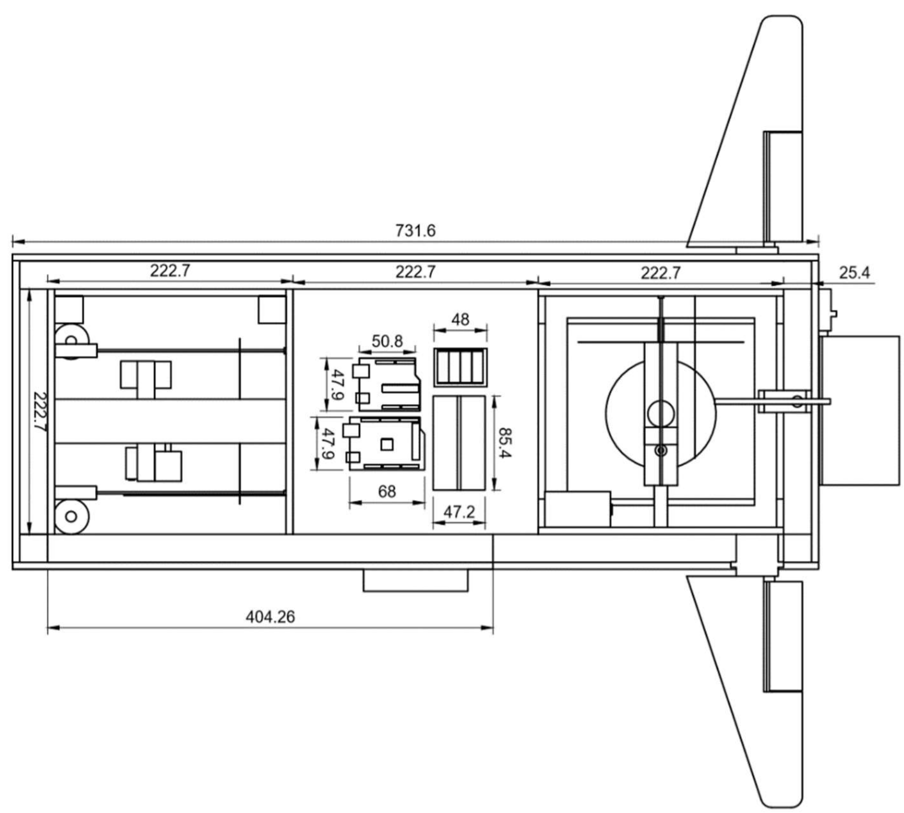


Fig 9. Spacecraft Model Interior Diagram. Dimensions of the design are given in millimetres. The three gyroscopes are oriented orthogonal to each other, and the electrical circuitry can be seen above the middle gyroscope. The fins will be wired to the circuit through openings in the box.

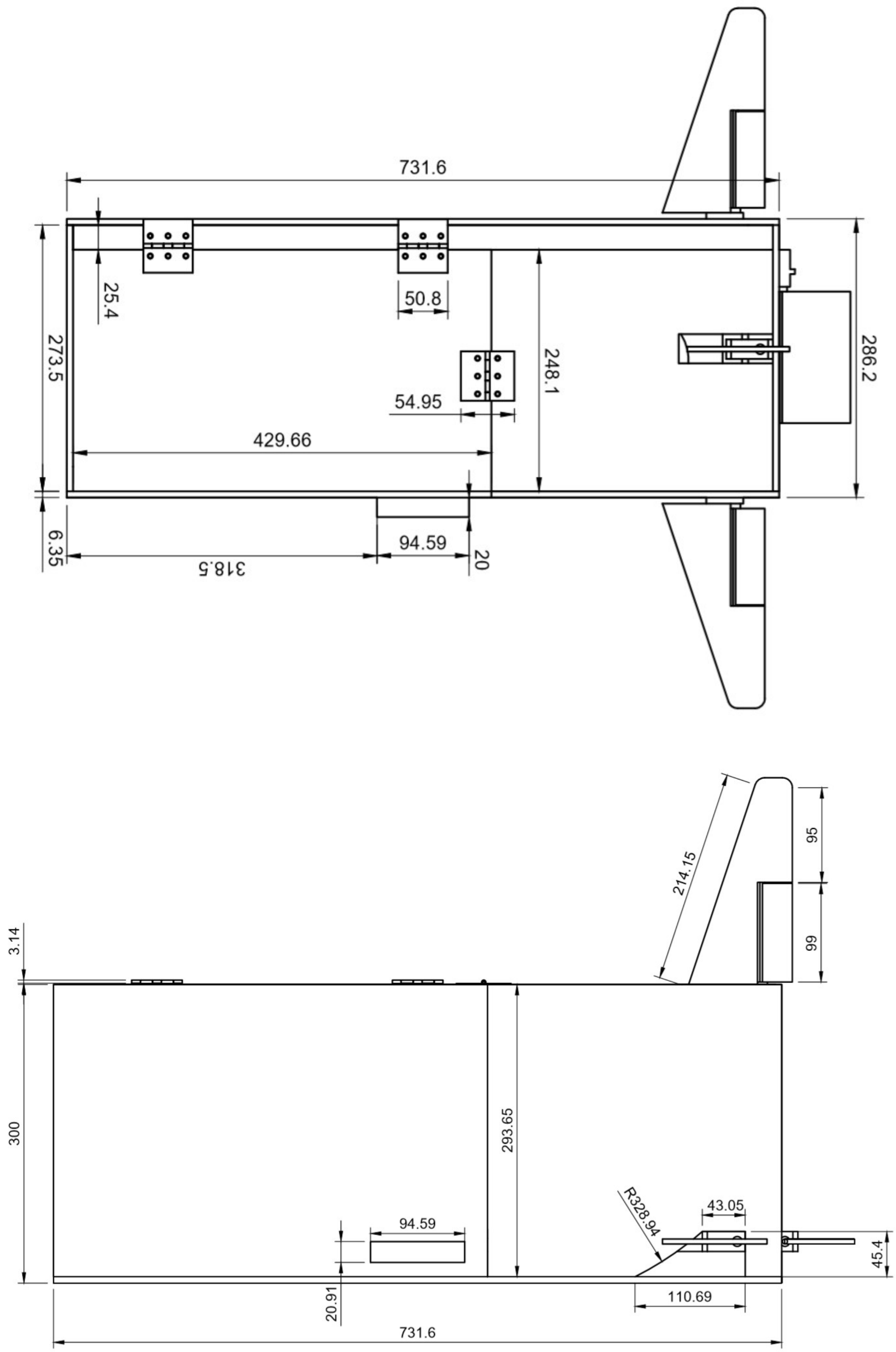


Fig 10. Spacecraft Model Exterior Scale Diagram. Dimensions of the design are given in millimetres. The exterior can be seen from above (top) and the side (bottom), depicting the relative size of the structures and the placement of latches.

3.0 Wiring Diagram

In this section, the detailed blueprints and wiring diagrams for the circuit components are laid out. Provided is also justification for design and wiring choices, to ensure that the system was optimally designed and adhered to the constraints in van Bemmel (2019).

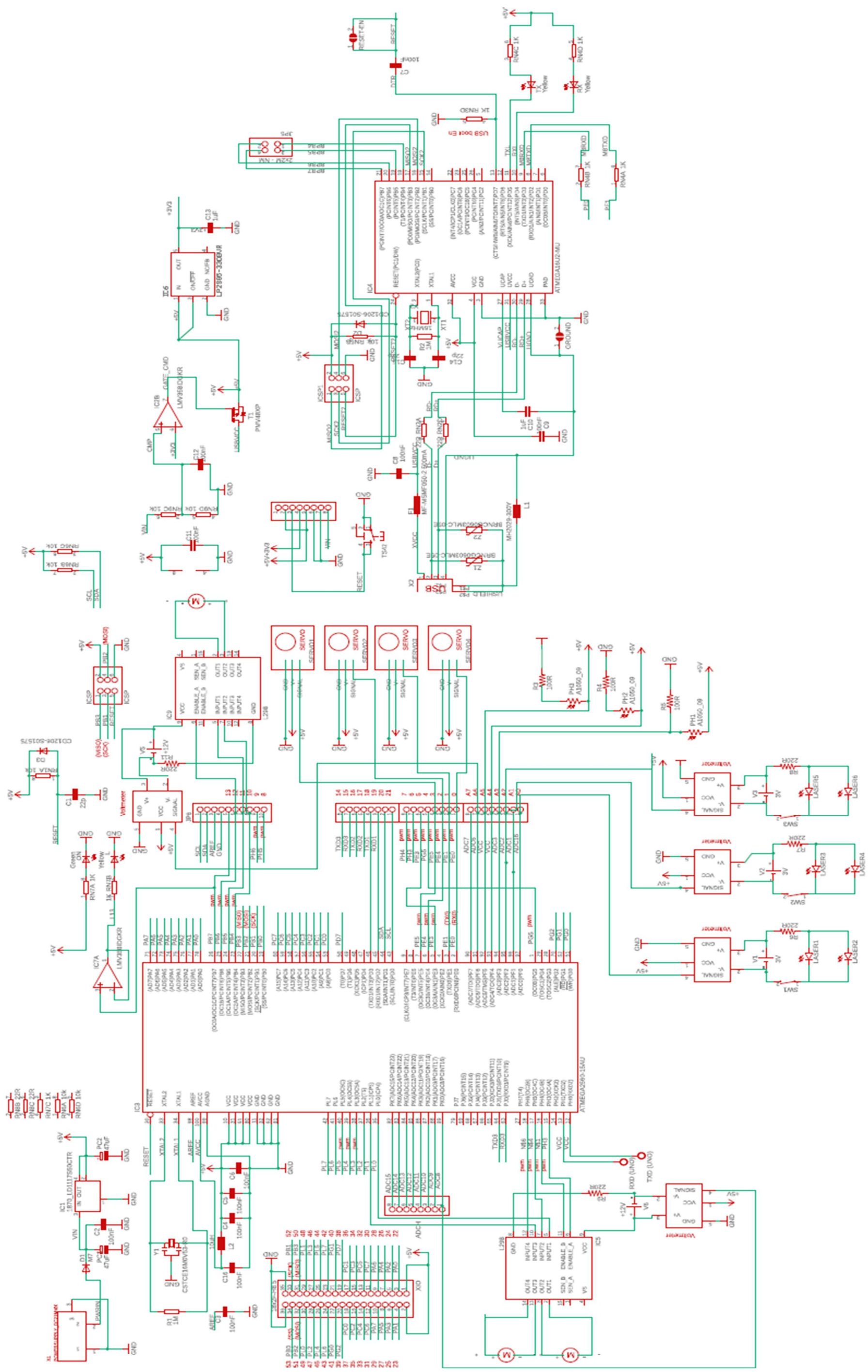


Fig 11. Overall Schematic of Arduino Mega. It is comprised of 54 digital input/output pins that make it an appropriate microcontroller unit given the numerous components that must be attached. This board acts as the central processing Arduino, handling all data collection and processing, before sending data to the secondary Arduino board.

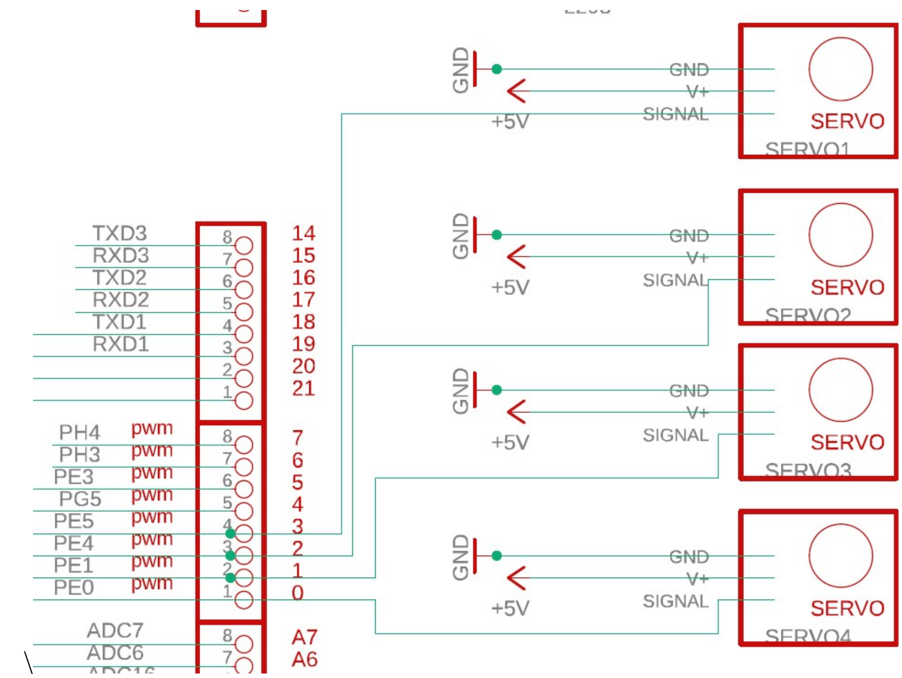


Fig 12. Schematic of Servos Motors. The motors are each connected separately to a PWM pin as well as to ground and a power source located on the breadboard. These servos will be responsible for the movement of the fins.

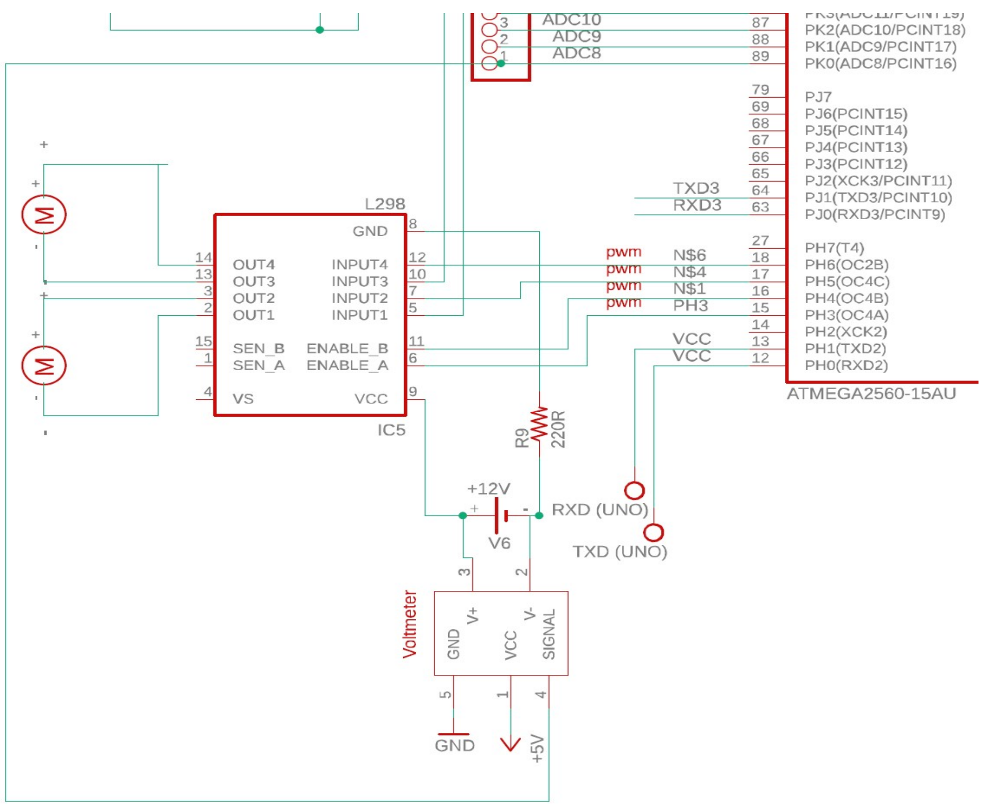


Fig 13. Schematic of DC Motors. These motors will be used to power the rotations of the gyroscopes. DC motors were selected due to a combination of their consistent torque and their size, which is large enough to fit a gyroscope but small enough to be contained in a closed system.

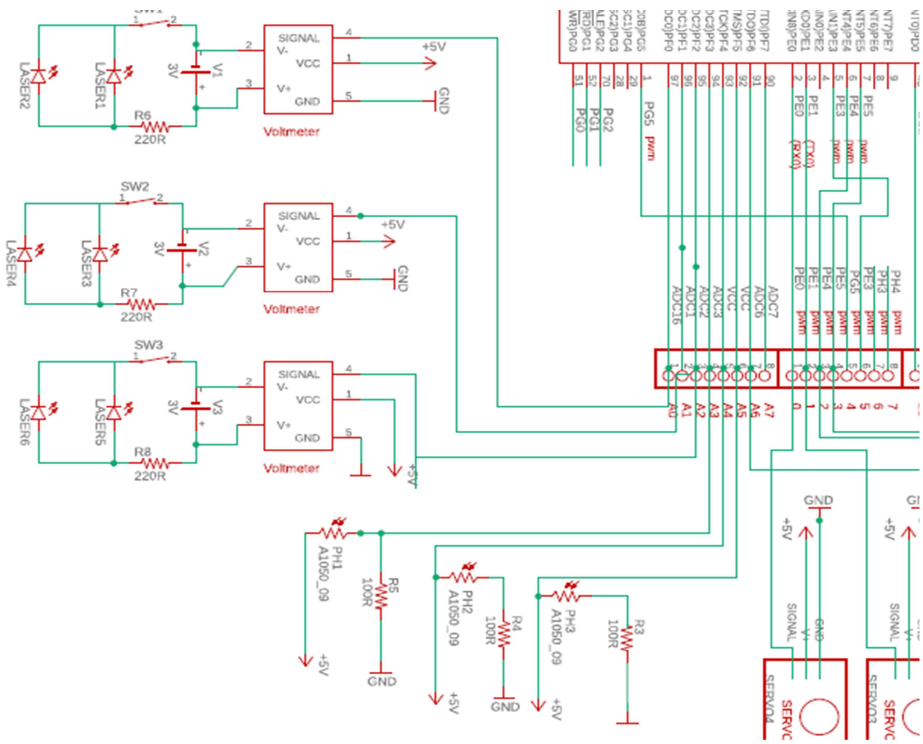


Fig 14. Schematic of Lasers and Photoresistors. Three modules of laser are connected to a voltmeter and powered by one battery each. The voltmeter signals are then sent to the central processing Arduino board. Below them, photoresistors are connected to the main Arduino board, which reads in light intensity data to map a function for gyroscope position.

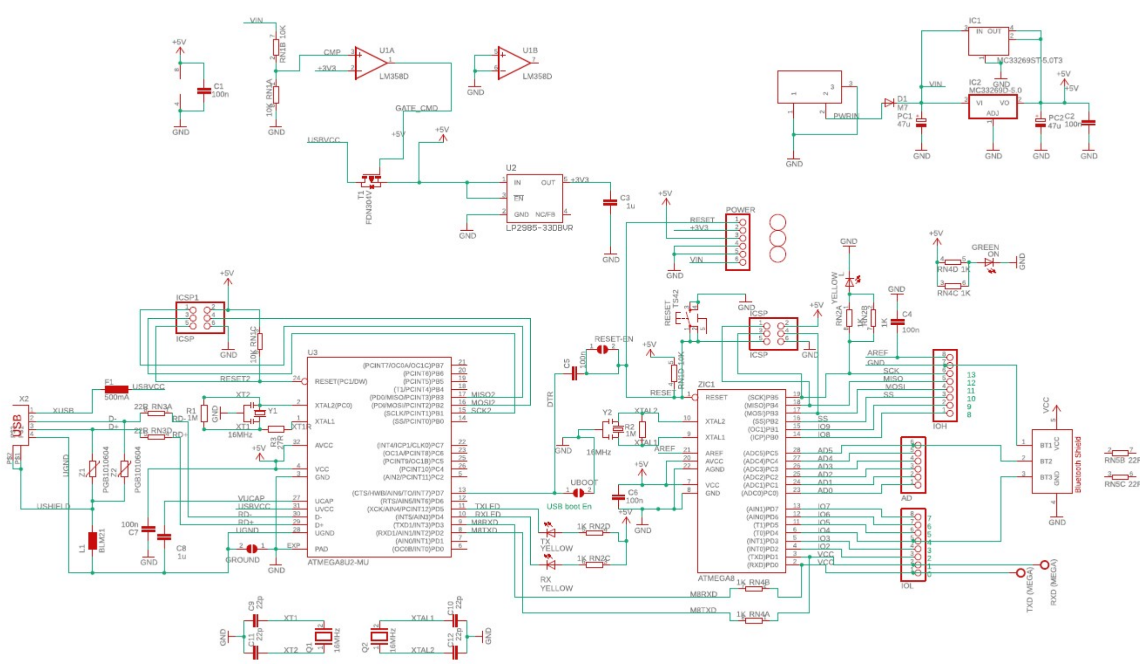


Fig 15. Schematic of Arduino UNO. The Arduino UNO board is used solely for communications purposes. It acts as a communicator between the main processing unit and an external device, such as a laptop computer.

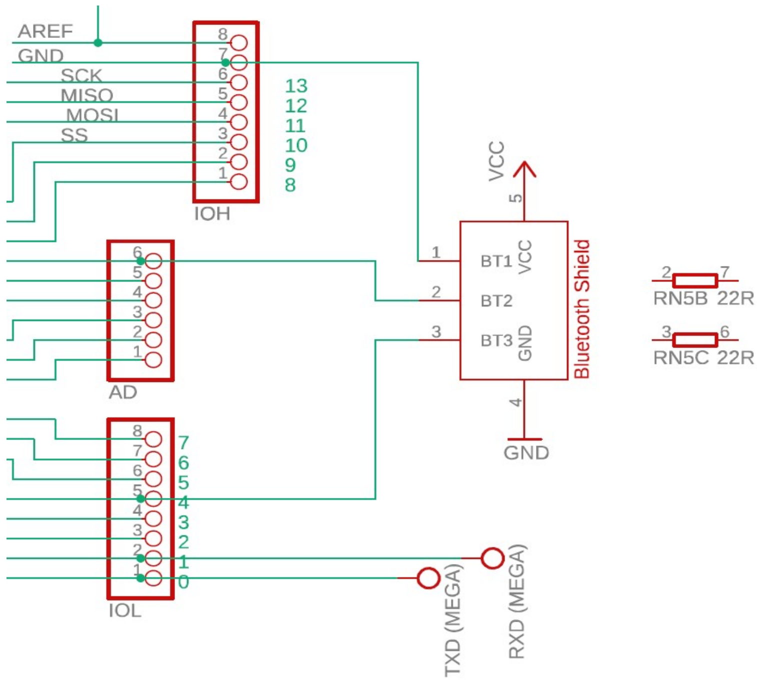


Fig 16. Schematic of communications and Bluetooth Wiring. This schematic outlines the wiring required for the secondary communications Arduino board and the attached Bluetooth Shield. Signals from the central processing Arduino board are sent to the secondary board, where the Shield is then able to send signals to the paired computer through Bluetooth connection.

4.0 Procedures

4.1 Construction

The following will detail the construction of the system in chronological order. First, the gyroscopes will be constructed. Each will be composed of a metal disc with a hole drilled through the center, through which the shaft of a DC motor is placed. The gimbals will be made of wooden rings, which have holes drilled through them. Each will be connected to each other and the rod containing the gyroscopic disc. These gimbals will, in turn, be connected with lubricated bearings to ensure freedom of movement. The outer gimbals will be attached to the housing, and shall be fixed relative to the casing, such that only the inner gimbal is allowed to move.

To detect the movement of the gyroscope, an annulus of film, with a greyscale gradient from light gray to dark gray, will be attached to the interior of the gimbal, and two lasers on opposing sides of the gimbal housing will be attached to the housing. The lasers will be positioned in such a manner that the beams will go through the film and reach the photoresistor on the other side; the photoresistor is attached to the housing and kept stationary relative to the lasers. The photoresistor will be connected to the Arduino in order to provide measurements of the laser intensity, and the lasers will be connected in parallel with their respective battery. The first gyroscope will be constructed and fully tested, requiring that it must be satisfactory for the time constraints of the project, before the other two gyroscopes are constructed with the same procedure as the first. The aim is for three such gyroscopes to be made, and the systems oriented such that each gyroscope allows measurement of one axis.

To read battery potentials, an Arduino Voltage Sensor Module will be attached to the housing and wired in parallel with the battery used to power the device. It will be connected to the central processing Arduino to provide information about the battery voltage in real time. The data will be processed and sent to the computer to read the potential difference across the battery.

The fins will then be made of rigid cardboard, and small servo motors will be connected to each allow motion in one axis of rotation. Two fins will be attached as ailerons, one shall be placed as a body flap, and one will be placed as a rudder. The servo motors shall be connected to the central processing Arduino, which will send signals to the motors to allow the fins to move in a manner suiting their orientation.

Finally, the housing of the spacecraft will be constructed with wood planks. It is designed to be a box with dimensions 29 cm × 30 cm × 73 cm, and held together with screws. However, this step is the last in the construction process in order to maintain flexibility regarding dimensions, as there is a possibility that the device will require more or less space than expected. Five of the faces of the box will be constructed, allowing the other parts to be inserted into the housing. Then, a top face will be attached using a hinge that can be opened and closed. This housing will be designed to snugly surround the various components of the gyroscope systems in order to reduce the effects of Newton's Third Law. In doing so, at any point where a force is applied by an object that is meant to be stationary, the counteraction will not result in unwanted motion within the contraption.

The Bluetooth part of the device involves a Bluetooth shield and a secondary Arduino. Pursuant to the constraints set in van Bemmel (2019), the secondary Arduino board will only be used for communications purposes. The Bluetooth Shield transmit and receive pins are connected to the secondary Arduino using serial port jumpers to the D digital pins. The Bluetooth Shield is then paired to the computer the device software is run on.

4.2 Testing

Throughout the design process, testing plays a key role in ensuring the parts of the device work as they should, performing troubleshooting, and identifying possible areas for improvement. Prior to any construction, every component shall be tested to ensure their functionality. First, basic Arduino programs will be run on both control units, and then both will be connected to ensure that data can be transmitted through wiring between the two. Then, individual components such as the photoresistor, lasers, the Bluetooth module, and voltage sensors will be run with the Arduino Mega. This will be done using sample code from online resources, such that each test of a component will have a standard comparison provided. Once it is ensured that every component is functional, construction will begin.

Following the construction of the gyroscope and gimbal, its stability will be tested before it is secured with lasers. This will be done my manually manipulating the gimbal around the gyroscope and by manipulating the frame of the gyroscope in the appropriate axis of rotation. In both cases, the axis of the gyroscope should move minimally; rather, the gimbal should rotate freely around it. For the purposes of this testing, observations will be done largely subjectively, with the objective of typical axis deviations of under 10 degrees.

As the gyroscope is by nature a precision device, great care will be required to ensure that it is properly calibrated and able to find results in all cases. Particular care must be taken for the edge cases, where it is possible that the gimbal ring blocks the laser beam, causing a null reading for the laser beam. For this reason, it was decided that there should be two laser devices, such that there is always a reading even in the edge cases where one of the beams is blocked due to certain gimbal positioning, and so that there is redundancy in the data for cases where multiple laser data is available. Extensive calibration will be required for the laser-photoresistor combinations, to ensure that the readings are correct, especially in the edge cases where one laser is blocked.

The effects of movement on the gyroscope devices must also be subjected to extensive testing. Rapid motion of the device may lead to disturbances in the gyroscope units, which would impact the measurements taken. In addition, movement may affect wiring if it is not sufficiently robust. For this reason, following the calibration of the lasers in the gyroscopic frame, the device will be subject to a variety of motions, including sharp rotations, large rotations exceeding 180 degrees, and gentle shaking. Through this, the structural integrity of the parts will be evaluated; this information will then be used to determine which areas of the device require fixing or structural reevaluation. It is ultimately expected that the gyroscope will be able to maintain stable rotation with a free-moving gimbal under all of the conditions listed above, at which point it will be placed into the spacecraft model and fastened in place.

Following this, testing of telemetry will be conducted in accordance to the software flowchart in 6.1. Each step will be processed with the gyroscope running and within the spacecraft model and displayed to a serial port to ensure the validity of the data. At this point, basic visual displays of data will also be tested: plots will be generated from the data and compared to serial displays to ensure their accuracy. Ideally, the objective for the S/N ratio of the collected data will be around 10 to ensure its precision. Also, the effective ranges and delay on the communications will also tested. After being connected to the central processing Arduino and the computer, orientation data will be sent through the Bluetooth at a rate of 30Hz, and voltmeter data will be sent once every second. The fidelity of the connections will be tested, by testing for periods of disconnections, and ensuring that there is not a significant lag between changes in the device's orientation and the telemetry readings.

Furthermore, testing is also required for the fin movement. Even though the fins are designed primarily to show that the system responds to the orientation of the spacecraft, they are also required to be somewhat sturdy, and orient themselves in a manner in accordance with how a spacecraft should respond in order to accommodate the new attitude. As a result, the fins will be tested to ensure that they produce the correct results and that the motors controlling the fins prevent the fins from falling due directly to gravitational force. Basic testing includes the general relaying of gyroscopic motion to the motors powering the fins, which can be performed independent of the spacecraft apparatus. Edge cases will also be needed, considering extreme orientations for each axis. Upon the construction of the apparatus and putting all the components together, protoflight testing will complete the testing to ensure that the contraption functions in flight conditions.

Finally, a last round of testing will be conducted for the final project to assure its functionality in its entirety. This will include gyroscopic precision, data display accuracy, appropriate fin responses, and adequate power supplies to maintain the system for two minutes.

5.0 Production Schedule

Task	Subtask	Start Date	End Date	Performed?
Planning				
	General Design Outline	10/05/19	11/01/19	Yes
	Gyroscope Construction Planning	11/01/19	11/20/19	Yes
	Determine Required Materials	11/10/19	11/20/19	Yes
	Determine Subtasks	11/10/19	11/10/19	Yes
	Order Materials	12/03/19	12/03/19	In Progress
Prospectus				
	Introduction	11/20/19	11/22/19	Yes
	General Structure	11/21/19	11/25/19	Yes
	Gyroscope Structure	11/21/19	11/25/19	Yes
	Computing Structure	11/21/19	11/25/19	Yes
	Voltmeter	11/21/19	11/25/19	Yes
	Wiring Schematics	11/25/19	11/30/19	Yes
	Software Flowcharts	11/25/19	11/30/19	Yes
	Testing Procedures	11/25/19	11/30/19	Yes
	Production Schedule	11/10/19	11/15/19	Yes
	Budget	11/30/19	12/01/19	Yes
	Sources	11/25/19	12/01/19	Yes
Gyroscope Construction				
	Design Creation	11/01/19	11/20/19	Yes
	Single Gimbal Construction	12/07/19	12/10/19	No
	Single Gyroscope Construction	12/07/19	12/12/19	No
	Motor Implementation	12/12/19	12/15/19	No
	Range of Motion Testing	12/10/19	12/13/19	No
	Laser Implementation for Single Gyroscope	12/08/19	12/13/19	No
	Telemetry Testing for Single Gyroscope	12/15/19	12/20/19	No
	Construction of 2nd, 3rd gyroscopes	12/13/19	12/18/19	No
	Testing of 2nd, 3rd gyroscopes	12/19/20	12/21/19	No
Central Unit Construction				
	Arduino Setup	12/15/19	12/21/19	No
	Bluetooth Shield Interfacing	12/18/19	12/21/19	No
	Gyroscope Connection	12/13/19	12/15/19	No
	Voltmeter Connection	12/14/19	12/14/19	No
	Testing of Central Unit Processes	12/20/19	01/05/20	No
Body Construction				
	Design and Materials	11/21/19	11/25/19	Yes
	Body Construction	12/08/19	12/10/19	No
	Stability Testing	12/10/19	01/03/20	No

Voltmeter Construction				
	Design Creation	11/21/19	11/25/19	Yes
	Voltmeter Construction	12/14/19	12/14/19	No
	Meter Testing	12/14/19	12/15/19	No
Fins Construction				
	Fin Development	11/21/19	11/27/19	Yes
	Motor Connection	12/21/19	12/21/19	No
	Fin Attachment	12/21/19	12/21/19	No
	Fin Testing	12/21/19	12/24/19	No
Software Construction				
	Telemetry Readings	11/21/19	12/29/19	In Progress
	Voltmeter Readings	12/10/19	12/30/19	No
	Data Visualizations	12/20/19	01/03/19	No
Integration of Components				
	Integration of Body, Central Unit, and Single Gyroscope	12/23/19	12/24/19	No
	Testing of Single Axis Gyroscope in Body	12/23/19	12/25/19	No
	Integration of Remaining Gyroscopes	12/26/19	12/28/19	No
	Testing of Remaining Gyroscopes in Body	12/26/19	12/28/19	No
	Integration of Fins and Body	12/29/19	12/29/19	No
	Testing of Fins and Body	12/29/19	12/30/19	No
	Integration of Voltmeter, Software and Body	01/02/20	01/04/20	No
	Testing of Final Project	01/03/20	01/09/20	No
Overall				
	Prospectus		**12/02/19**	
	Final Project and Demonstration		**01/10/20**	

Fig 17. Production Schedule. A number of broad tasks were agreed upon, which were further split up into subtasks. The tasks were not decided to be constrained by time, but the subtasks are heavily time-based, as many depend on other subtasks. A status was added for each subtask, marking the progress as of December 2nd, 2019.

5.1 Schedule Monitoring System

In order to maintain this schedule, a system to ensure productivity was developed. Each subtask and its respective end date will be written on a sticky note and placed on a large scheduling board. These notes shall be categorized into four columns: tasks that have not yet been started, tasks that have been started, tasks that are overdue and not yet completed, and tasks that have been completed. Furthermore, the first three columns will be arranged such that they are listed in order of priority, with tasks placed at the top being the most crucial aspects that must be completed. In doing so, this system will provide a visualization of every task that must be completed and ensure that the project team remains diligent and conforms to the production schedule.

To meet the scheduling demands, the project group aims to meet, at minimum, three times a week while conforming to each individual schedule. Each work session will be opened with a brief orientation, during which subtasks on the schedule board will be delegated to each member.

Furthermore, end goals and an end time will be set prior to each session, in order to impose a sense of deadlines for the group at each meeting, thus maximizing productivity during each period.

6.0 Software Design

In order for the gyroscope data to be assimilated and function as flight control data, as well as to transmit data, adequate software must be designed. As specified by van Bemmel (2019), the software must be able to obtain information from the communications part of the spacecraft device about gyroscopes, fin position, and battery voltage. In addition, the software must provide a visualization of the spacecraft's orientation and fins as they are in the moment, with relatively trivial delays. It was decided that the software would be created with the programming language C++, due to the simple interfacing with the Arduino language, and the ability to create visualizations and graphic user interfaces.

6.1 Software Flowchart

The basic function of the software processing is summarized below:

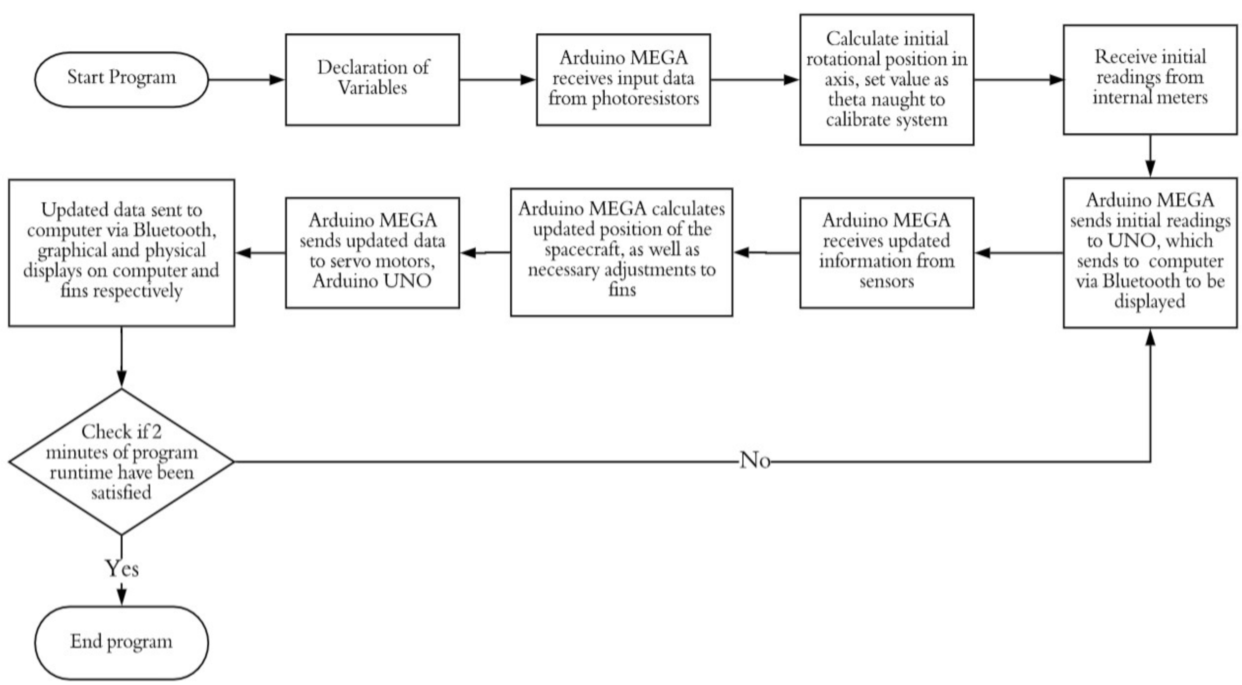


Fig 18. Software Flowchart. The general structure of the software utilized to collect data from the gyroscopes, voltmeters, and fin motors are shown. This software does not cover the GUI or visualizations shown on the computer.

First, the input data from the photoresistors is sent to the central processing Arduino unit. This data is then used to calculate the initial position of the gimbals and set this as the initial value. The initial reading from the voltmeter is also found. Afterwards, the program enters a loop, where it will, for a constant timestep, check the current data from the photoresistors and use that to find the gimbal position, allowing for calculation of the spacecraft's orientation.

6.2 Positional Computation

Through the use of a plastic film with a greyscale gradient, the orientation of the gimbal for each gyroscope assembly can be found by measuring the intensity of light rays received by the photoresistor. In particular, the angle that the gimbal is at is measured by corresponding the photoresistor output signal; this correspondence is found by calibrating the gimbals beforehand. Calibration will be performed by allowing the gyroscope to undergo one revolution, and finding the curve relating the gyroscope angle to the light intensity encountered by the photoresistor, allowing a correspondence to be found.

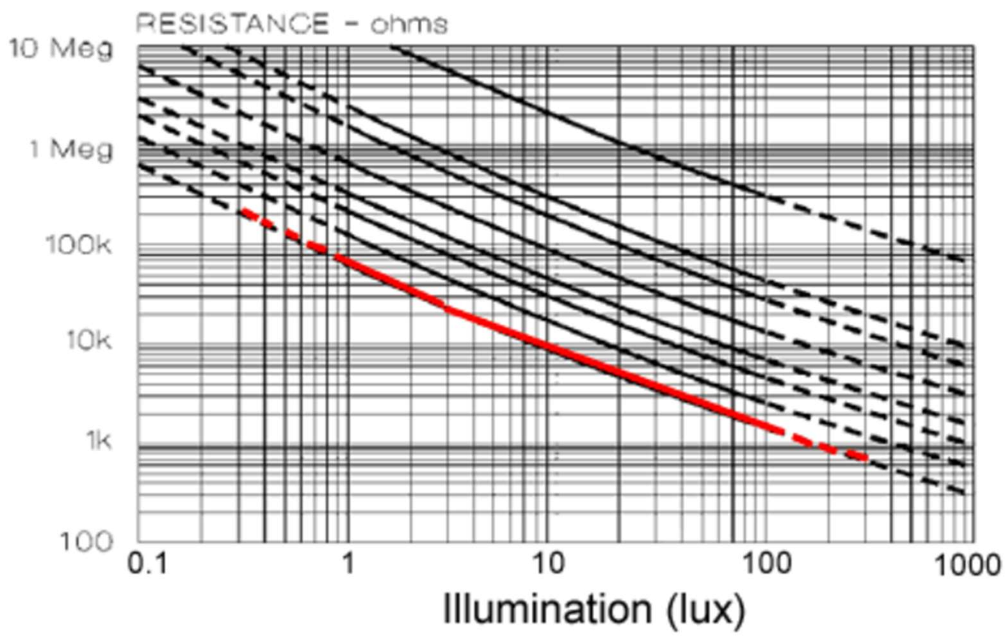


Fig 19. Illumination vs. Resistance for an A9950 Photocell. The logarithmically scaled graph describes the photocell's output resistance for a given light source. Notice that the darker the light exposure, the higher the resistance. This log-log relationship can be represented as an approximate function on the computer program to output the correlating angle measure.

However, in some cases, one of the lasers may be blocked by the gimbal. When this occurs, the gimbal may be in one of two positions; there is ambiguity in these cases. For this reason, a second laser is implemented. When one of the lasers is blocked, only one photoresistor is receiving light, and it is the only measurement used. When the gimbal is positioned in a manner such that none of the lasers are blocked, both measurements can be averaged, and the average can be used as the angle value. This redundancy allows for accurate measurement of gimbal position in all cases, with slight concessions for when the gimbal blocks a laser.

The position of the fins is required to produce the optimal form for stabilization, for the orientation of the spacecraft at any given moment. It was decided to simply move the fins at the angle given by: $\theta_F = \arctan(\tan\theta_G))$, where, θ_F is the angle the fins are set at by their corresponding motors, and θ_G is the angle the corresponding gyroscope is at. Although it is very unlikely that the testing motions will include full loops and edge case motions, the fins will have a maximum rotation of 90°. In ambiguous cases (e.g. 180 degrees pitch, roll, and yaw together just resolve to the original orientation), this will have to be differentiated via the program itself, which will resolve the angles for each axis of rotation to determine the most efficient fin motion to return to the original orientation, updating the reference positions of the gyroscopes as well.

7.0 Budget and Cost Breakdown

Purpose	Component	Cost per Unit ($)	Number of Units	Subtotal ($)
Gyroscopes				
	Ball Bearings	1.16	12	13.91
	Metal Rod	3.25	6	19.47
	Plastic Film	3.99	1	3.99
	Paraffin Wax	4.97	1	4.97
	775 DC 12V Motor	2.86	3	8.58
	12V Battery	1.99	3	5.97
	Breadboard	0.88	1	0.88
	L298N Arduino DC Motor Shield	1.91	2	3.82
Central Processing				
	Arduino MEGA 2560	7.34	1	7.34
	Arduino UNO R3	14.29	1	14.29
	HC-06 Arduino Bluetooth Shield	3.00	1	3.00
	Wires	1.49	1	1.49
	Arduino Voltage Sensor	1.74	5	8.70
Lasers				
	5mW 650nm Red Laser Diode Module	3.80	7	26.60
	5528 Photoresistors	0.037	10	0.26
	Duracell 1.5V AA Batteries	1.12	6	6.74
Housing				
	0.25” X 2’ X 2’ Hardboard Panel	3.98	2	7.96
	2” X 4” X 8’ Lumber	3.02	3	9.06
	Wood Screw	0.06	27	1.44
	Wood Glue	4.97	1	4.97
	Door Hinge	2.69	1	8.07
Fins				
	SG90 9G Servo Motor	1.80	4	7.20
	Cardboard	0.00	4	0.00
			TOTAL ($):	169.00

Fig 20. Budget and Cost Breakdown. To ensure that the purchases for this endeavor were planned out and pursuant to financial constraints, a budget was created to outline every purchase involved in the project. The total cost was $169.00, which fell under the $175 restriction on all materials used in the project.

8.0 Sources

http://www.hmvb.org/apc1920lm.pdf
https://www.britannica.com/technology/inertial-guidance-system
https://hackaday.io/project/2744-1-d-laser-ring-gyroscope
https://science.howstuffworks.com/gyroscope1.htm
https://howthingsfly.si.edu/flight-dynamics/roll-pitch-and-yaw
https://www.youtube.com/watch?v=jADvSItPxxk
https://youtu.be/XPUuF_dECVI?t=2628
https://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts-gnnc.html#sts-imu
http://www.cleonis.nl/physics/phys256/gyroscope_physics.php
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19890006569.pdf
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19960035752.pdf
https://courses.lumenlearning.com/physics/chapter/27-8-polarization/
http://linksprite.com/wiki/index.php?title=Photo_Cell_Sensor