AP Physics C

Mr. van Bemmel

Prospectus

Rudimentary Spacecraft Guidance System

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1. Introduction

Guidance systems are an integral component in the function of many complex vehicles, including aircraft and spacecraft. They allow for a proper understanding and measurement of various important maneuvering data, such as position and velocity. This enables operators and computers to monitor the movement of the vehicle and, if needed, make correctional changes. For spacecraft, in particular, it is common to employ an Inertial Navigation System (INS) which uses an inertial frame such that tracking the movement of the vehicle is not dependent on external objects or references. To accomplish this, devices such as a computer and Inertial Measurement Units (IMUs) are combined. Typically, IMUs may include components such as gyroscopes and accelerometers which collect different data and sends it to computers that stores and processes it. This processed data can then be used to create a navigation path or make necessary corrections to ensure that the spacecraft is headed to its desired destination.

In the past, IMUs have been an important tool for the Apollo missions, utilizing a six degree-of-freedom system in the three axes of rotation and linear movement. Since the system uses gyroscopes and gimbals, it avoids the wear and tear of a gear system which may have been used instead. For this reason, the IMUs used by the Apollo were a reliable back-up navigation system for when the spacecraft was out of direct contact with the Earth-based control team. The IMUs aboard the missions utilized three gyroscopes and three accelerometers, as well as an optical measurement system. It was found to be an accurate source of orientation and location for the crew. Outside of spacecraft missions, IMUs are a common technology used in everyday devices such as pedometers, enhanced GPS, and drones. Many are readily available in a wide variety of smartphones today in numerous forms.

2. Scope of Project

While a fully-fledged IMU would have many accelerometers and gyroscopes used for linear and angular measurements, this project is focused on the latter. The guidance system will consist of three identical single-axis gyroscopes which inform the user of the roll, pitch, and yaw of the spacecraft in real-time. Results will be displayed on the screen and manifested physically through the manipulation of "flaps" on the spacecraft. The main components that need to be designed are the gyroscopes and the mechanism applied to detect changes. In particular, the gyroscope will be constructed in large part with PVC plastic and the sensing mechanism will use a colour sensor. As well, the budget constraint of $175 CAD (outlined in section (8.)) is an important factor in the design and construction of the spacecraft. Lack of specialized equipment (e.g. metal-working machinery) also limited the materials that could be used. Finally, time constraints also determined what design and construction projects were feasible, as extremely elaborate systems could not be properly devised nor constructed with the limited expertise and time frame of the project. Despite the budget, project, and time constraints put onto the project, the proposed design of a spacecraft navigation system is one that is well within these constraints and also achieves the fundamental purpose of displaying the 3D corrections that need to be made to a spacecraft when it is rotationally moved from its original position.

3. Theory

a. Gyroscope

The basic premise of the project is to find the position of the spacecraft in all rotational axes. Through physical maneuvering and handling, lab technicians would orient the spacecraft in various directions. From this, the rotational information from the spacecraft must be relayed back to the computer which would send the information for autocorrections to be made by the fins attached. The foundation of measuring this rotational motion is done by the three gyroscopes attached within the spacecraft.

Gyroscopes are devices that consist of discs mounted so that a rapidly spinning axis is free to alter its direction. As such, the orientation of the spin axis is not affected by the tilting of the mounting. This is extremely useful for our application as a gyroscope's spin axis can be referenced as the inertial frame. Further discussion on the inertial frame will be conducted in section (4.b).

With regards to the gyroscope, once you spin a gyroscope, the spin axis will want to keep pointing in the same direction. The gyroscope is mounted with two gimbals which supports and allows the rotation of the wheel in one axis. The traditional gyroscope consists of a set of gimbals where they are mounted on one another in orthogonal axes and allow the inner gimbal to remain inert when the orientation is changed. The outer gimbal has one degree of rotational freedom and is used as the gyroscope's frame and is in its own plane. The middle gimbal has one more axis of rotational freedom and is perpendicular to the pivotal axis of the outer gimbal.

In our gyroscope, the outer gimbal will be locked as the stationary housing box. This leaves the gyroscope with one degree of freedom. We will mount two gimbals with their axles at right angles to one another on a platform and place the platform inside a set of gimbals. The platform will remain completely rigid as the gimbals rotate in the desired axis. A rotational motor is attached to the inner gimbal and is also the spin axis, which will be placed perpendicularly to the middle gimbal. The motor will spin around this axis and remain inertial as the gyroscope is moved in different axes. It is free to turn in any direction around the fixed point. Additionally, the additional weight from the motor on one end of the spin axis must be balanced by a counterweight on the other end of the spin axis. This way, no abnormal movements are shown by the gyroscope.

Using the conservation of angular momentum, we see that the net angular momentum at $t = 0\,\text{s}$ must equal the net angular momentum when $t = 120\,\text{s}$. From this, we know that if the net external torque acting on a system is zero, the angular moment of the system will remain constant no matter what changes take place within the system. If we take the spin axis, we see that a change in angle in one axis will affect the rotation speed of another axis. When we have the rapidly spinning gyroscope, changes in the rotation of the inertial frame results in the other gimbals to move, however, we will not see any rotational changes on the spinning axis. This is because one can never put torque on the spinning axis, assuming no frictional losses. As well, the speed that the axis spins at will not decrease due to the constant power-driven motor.

With our colour sensors (discussed in section (4.b)), we can sense this angular change in our outer gimbals. We use the spin angular momentum of our gyroscope as a reference point, which is mounted so no external torque can be imparted on it.

b. Inertial Frame

In its motion, the spacecraft can change its rotational orientation. However, due to the conservation of angular momentum, the spin axis of the gyroscope will always point in the same direction relative to the inertial frame of the Earth. Due to the spacecraft existing in its own inertial frame relative to the Earth, a fiducial point must be set. The reference point will be set as a point inside the box. Its initial angular position for (θ, ψ, Φ) on the x, y, and z axes will be calibrated to (0, 0, 0). Any movements thereafter will be as a rotation relative to the initial orientation on the three principal axes: roll, pitch, and yaw.

For this project, the spacecraft will be situated inside the classroom, which is treated as the inertial reference frame. For an actual application of a gyroscopic inertial navigation system, such as the one in the Apollo space program, the spacecraft would reside in its moving frame relative to the centre of the Earth or the Sun instead. To simulate the realism of this project, the fiducial point is set on the sample end effector. Since this point will be at the origin, any rotation of the spacecraft will not change the end effector's location in three-space. However, angles for roll, pitch, and yaw must be calculated. Also, it must be noted that rotation on the y-axis, for example, is represented by the angle between the initial z-axis and the new z-axis. Pitch is characterized by Φ. Similarly, roll is characterized by the angle ψ between the initial and final y-axes. Lastly, yaw is characterized by the angle θ between the initial and final x-axes. (Fig 1.)

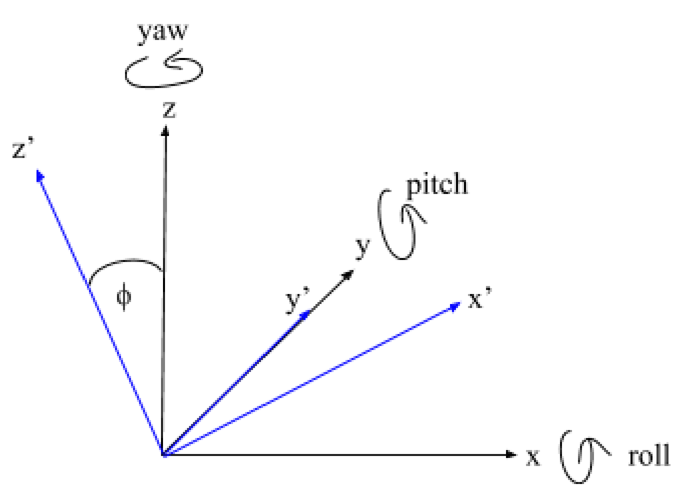

Fig 1. Rotation of Inertial Frame of Spacecraft. A rotation of ϕ degrees around the y-axis would be shown as a pitch of ϕ degrees of the spacecraft. This pitch would be measured as the angle between z and z', as perceived by the spacecraft's angle sensing system. The only rotation is on the y-axis to reduce complexity and improve understanding.

c. Arduino and Raspberry Pi

The spacecraft will have two microcontrollers which help in collecting, processing, and communication of data. An Arduino Mega will connect to each of the motors powering the gyroscopes and will be attached to any additional sensors. The information collected by the Arduino will be processed and sent to the Raspberry Pi (Zero W), which is connected over a USB B cable to USB A. The Raspberry Pi will communicate the data wirelessly over Bluetooth to the software on the controller's computer and display results accordingly.

d. Colour Sensor

The colour sensor on the guidance system comprises of an 8x8 grid of photodiodes (providing a current reading); a quarter of these have no filter on them and the others have a red, green, or blue filter on top, equally distributed among the colours. Doing this separately allows for a colour in RGB format. Each photodiode reads the light in front of it and the current is converted to a frequency (generating a square-wave) that corresponds to a light intensity. On the colour sensor there are 4 LEDs angled inwards which help illuminate the surface so that colours can be accurately taken in the dark and there is consistency in the lighting environment for each reading.

e. Fin Gimballing and Corrections

The success of the final design is determined by the spacecraft's ability to self-correct its flight mid-course when large rotational movements are imparted on it. Through the movements made by group members, the gyroscopes' gimbals will move and its change in angle will be detected by the colour sensor. Then, the servo motors on the fins whill make necessary adjustments.

The information process is as follows: first, the three gyroscopes' spin axis will remain in place as the spacecraft is shifted in all three axes of rotation. Then, the three separate colour sensors will measure the angle of rotation from the three free-spinning gimbals. From there, the information is transferred through wires to the Arduino which would wirelessly send the information to a group member's computer which will display the rotation angles and angular velocity. Then, the computer will send back the angular velocity information to the spacecraft's fins at every timestep of angle collection. Due to the small timestep intervals, the fin's autocorrection movement will be almost instantaneous. The Arduino will process the inforation which is then sent to the fins. The angles will then be flipped in their directional motion. This change is made because as the spacecraft shifts (θ, ψ, Φ), then ($-\theta$, $-\psi$, $-\Phi$) corrections must be made for the fins to stay level to the initial condition. This information will be relayed to the servo motor controlling the fin's angle. Then, the fins will be adjusted accordingly.

The fins and their corrections will be set to the initial starting point when $t = 0$ s. While the housing may be moved by group members during flight time, the fins will remain level to the initial starting point.

4. Build Specifications and Diagrams

a. Exterior of Spacecraft

The spacecraft guidance system will be enclosed in a sample spacecraft, which in this case was chosen to be a space telescope. Not only does this represent the real-world significance and applications of similar navigation systems, but also communicates the importance of such devices in furthering our understanding of outer space. The body of the spacecraft was chosen to be a rectangular box, similar to other telescopes, and three flaps decorated as solar panels will be attached to either of the long sides.

The choice of painting horizontal lines on the flaps to symbolize solar panels as they rotate to show the corrections computed by the guidance system. This is consistent with how space telescopes orient their flaps to receive the most sunlight. Each flap corresponds with a certain axis, and the flaps are attached to a motor to enable them to adjust their position.

Lastly, the approximate dimensions for the rectangular cardboard box enclosure, after taking into account the dimensions of the interior parts, are 55 cm x 20 cm x 20 cm. In addition, the rough dimensions for each 'fin', or cardboard flap would be 50 cm x 15 cm, 10 x 15 cm, and 30 cm x 15 cm, for the x, y, and z-axis fins respectively.

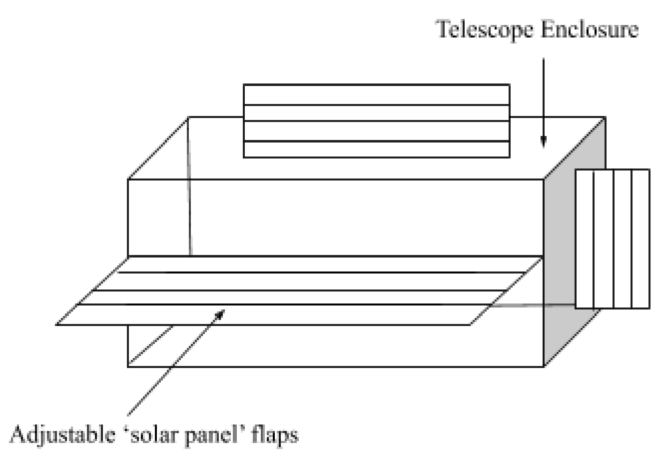

Fig 2. Side View of Exterior. Shows the telescope enclosure in relation to the adjustable flaps, decorated to represent solar panels. The cardboard box houses the other design elements outlined later. This diagram has slightly modified dimensions in order to give a full view of parts.

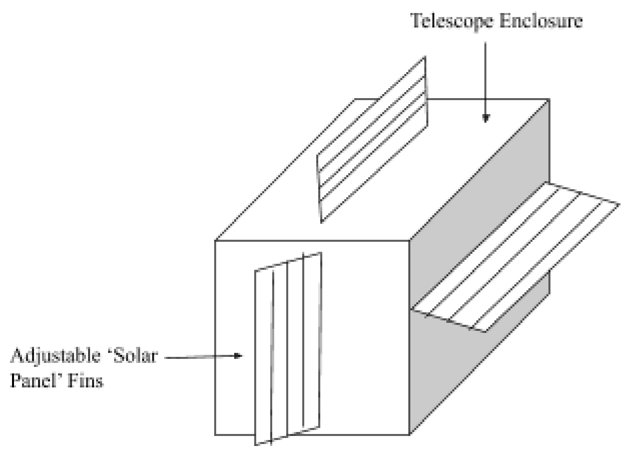

Fig 3. Front View of Exterior. Shows the exterior from a different angle, such that from both diagrams all three flaps can be fully seen.

b. Interior of Spacecraft

The interior of the spacecraft, which houses the guidance control system, consists of three individual square boxes that house the three gyroscope and sensor systems. Each gyroscope system represents one axis of motion, either the x, y, or z axis. Each gyroscope-sensor box would be designed identically, but during assembly would be secured to the bottom of the telescope enclosure in different ways to ensure the gimbals were rotating in their appropriate axis. Thus, a cubic cardboard box of dimensions of 15 cm x 15 cm x 15 cm would be used to house each system. In addition, an Arduino controller would be attached to the back wall of the exterior enclosure, which would allow information from each system to be transmitted through wires at the back of each individual box to the arduino for processing. Three separate systems were used to ensure minimal interference in the colour-sensing system, such that each sensor would only detect the colour from its corresponding gradient system. This would allow information to be collected independent of each other, thus reducing error.

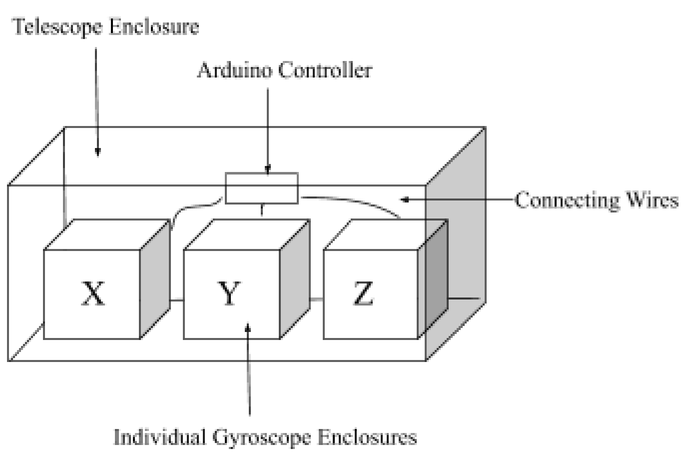

Fig 4. Side View of Interior of Spacecraft. Shows the three individual gyroscope-sensor systems for measuring the rotational change on the x, y, and z-axis, from left to right. In addition, the connections of all three to the Arduino is symbolically shown. The precise wiring diagram will be included later.

c. Gyroscope System

For the interior of the gyroscope enclosure, a gyroscope-like device would be created in order to mechanically show the change in orientation within each axis. This gyroscope would feature a rotating gimbal. A plastic rectangular frame, which would be constructed especially for the guidance system, and would have the dimensions of 10cm x 10cm x 1 cm. The gimbal should be attached to a central strut made from a wooden dowel that would connect the top of the plastic frame to the bottom. An electric motor, which was chosen to be a full rotation servo motor, would power the system. The two wires from the motor would be attached along the gimbal to prevent interference and would exit through a small incision made in the back wall.

In order to counter the effects on rotation the addition of the mass of the motor has, a counterweight constructed from a wooden block with a hole drilled in the middle would be attached on the other side of the rotor. The servo motors will be weighed during the building and testing procedure; the counterweight must also be uniformly distributed in mass and have a similar size to the servo motor to maintain a stable centre of mass. The counterweight would be made of wood or plastic and made to be the same mass as the motor. The dimensions and specifications of the counterweight would be determined during the testing phase. A wooden disk, of approximately 9 cm in diameter, would be cut with a saw from a wooden block. A hole would be drilled in the middle with a diameter of 3.1 mm (1/8") to ensure that the rotor functions properly. The motor, counterweight, and wooden rotor would be attached to the central wooden dowel with strong, adhesive glue.

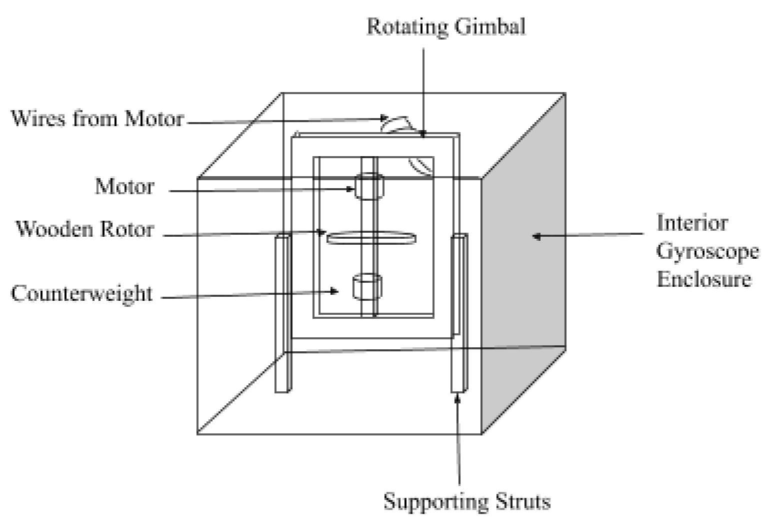

Fig 5. Front View of Gyroscope System in Interior Gyroscope Enclosure. This diagram only displays the parts related to the gyroscope, or mechanical portion of the detection of change in orientation, and omits the sensing parts discussed in the following section. It includes the gimbal, motor, wooden rotor, counterweight, wires, and supporting struts.

d. Sensing System

In order to sense the changes in rotation produced by the gyroscope in response to the change in orientation of the spacecraft, a colour-sensing system was placed inside the enclosing cube. The principles of such a system were explained in the section (3.d). Essentially, a TCS 3200 Colour Sensor with dimensions of 28.4 mm x 28.4 mm (1.12” x 1.12″) would be attached directly above the rotating shell. This would be exactly 7.25 cm from one edge of the cube, ensuring that the sensing can be calibrated correctly. In addition, a ring made of cardstock with dimensions of 4.5 cm in radius would be attached orthogonally to the gimbal along the central wooden dowel.

Pasted directly onto said ring would be a gradient-coloured paper, printed to size, that would cover the entire surface area of the object. The colour gradient would begin from black, with an RGB red value of 0, and gradually transition to a value of 255, which would be pure red. One edge of the paper, the red colour value of 0 would be placed directly below the colour sensor on the shell and the other edge would be secured around the shell.

Thus, when the gyroscope, and thus, cylindrical shell rotates, the sensor would sense the colour value of the portion of the paper directly beneath and relay the new colour value to the Arduino. Based on the change from the initial colour reading to the end colour reading, the angle of rotation and angular velocity can be determined. The sensor chosen is equipped with LED lights, as to ensure accuracy of detection. The wires from the colour sensor would connect to the Arduino controller from wires protruding through the back of the cube.

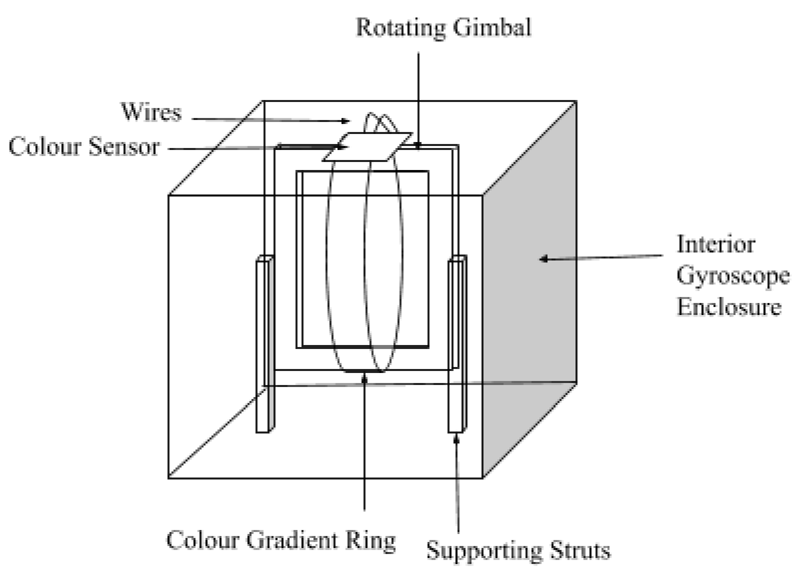

Fig 6. Front View of Colour Sensing System in Individual Gyroscope Enclosure. Shows the colour-sensing, and gradient scale mechanism set up in order to accurately obtain the amount of rotation done on the wheel, and the change in angle. Set up includes a colour sensor, cardstock ring covered with gradient paper, and wires to the Arduino. The sensor is enlarged in the diagram for clarity.

e. Overall Interior of Gyroscope System

Previously, only either the gyroscope or colour sensing systems were fully shown to avoid confusion. However, now that both have been explained, the following diagram shows how they would interact when merged. Both the wires from the colour sensor and the electric motor would exit the interior through a small incision made at the back to reduce potential light interference. In addition, the wires would be attached firmly to surfaces with duct tape in order to avoid damage and to improve the overall efficiency and elegant design.

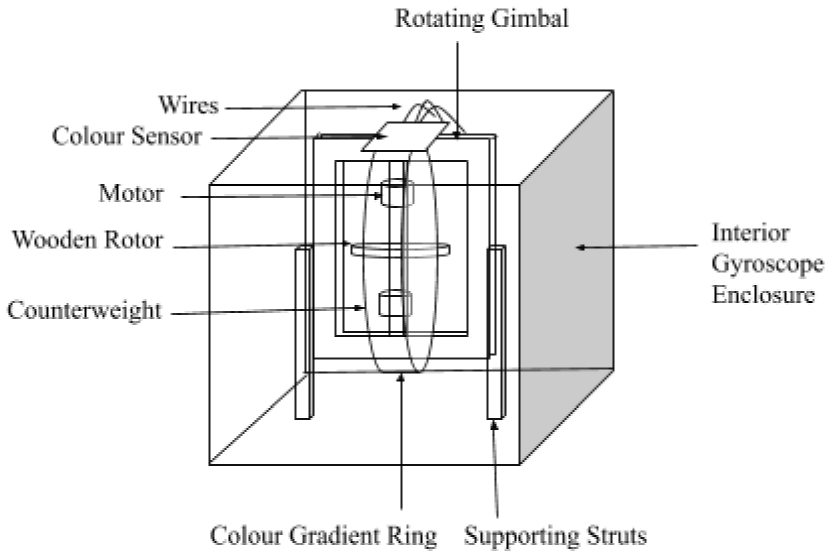

Fig 7. Front View of Entire Interior Gyroscope Enclosure. Displays both the mechanical gyroscope system as well as the unique colour-sensing mechanism devised. It obtains a measurement for the change in orientation on that particular axis and relays it to the external Arduino. The same design is repeated for all three axes.

f. Adjustable Flap System

In order to demonstrate the correction calculated by the gyroscope and colour sensing system, each of the three 'solar panel' flaps would replicate the rotation along each axis, but reversed, in order to 'correct' the orientation of the spacecraft. Thus, a 120-degree servo motor would be attached to the interior of each flap where it connected to the exterior cardboard enclosure which would allow for this to be possible. The dimensions of each flap is outlined in the beginning section, and the servo motor attached is 23 mm x 11 mm x 29 mm. The exact mechanism of a single flap is shown as each flap would be equipped with identical mechanisms.

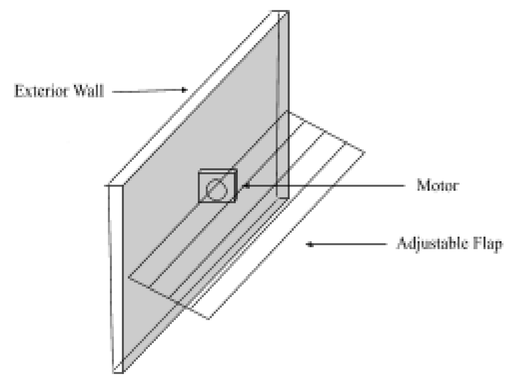

Fig 8. Close-up of Adjustable Flap System. Shows the motor, which would rotate to adjust the flap. Both the motor and flap would be attached to the exterior wall, which an incision made in the flap to allow the motor to pass through. This system would be replicated for all six flaps.

g. Wiring Diagram

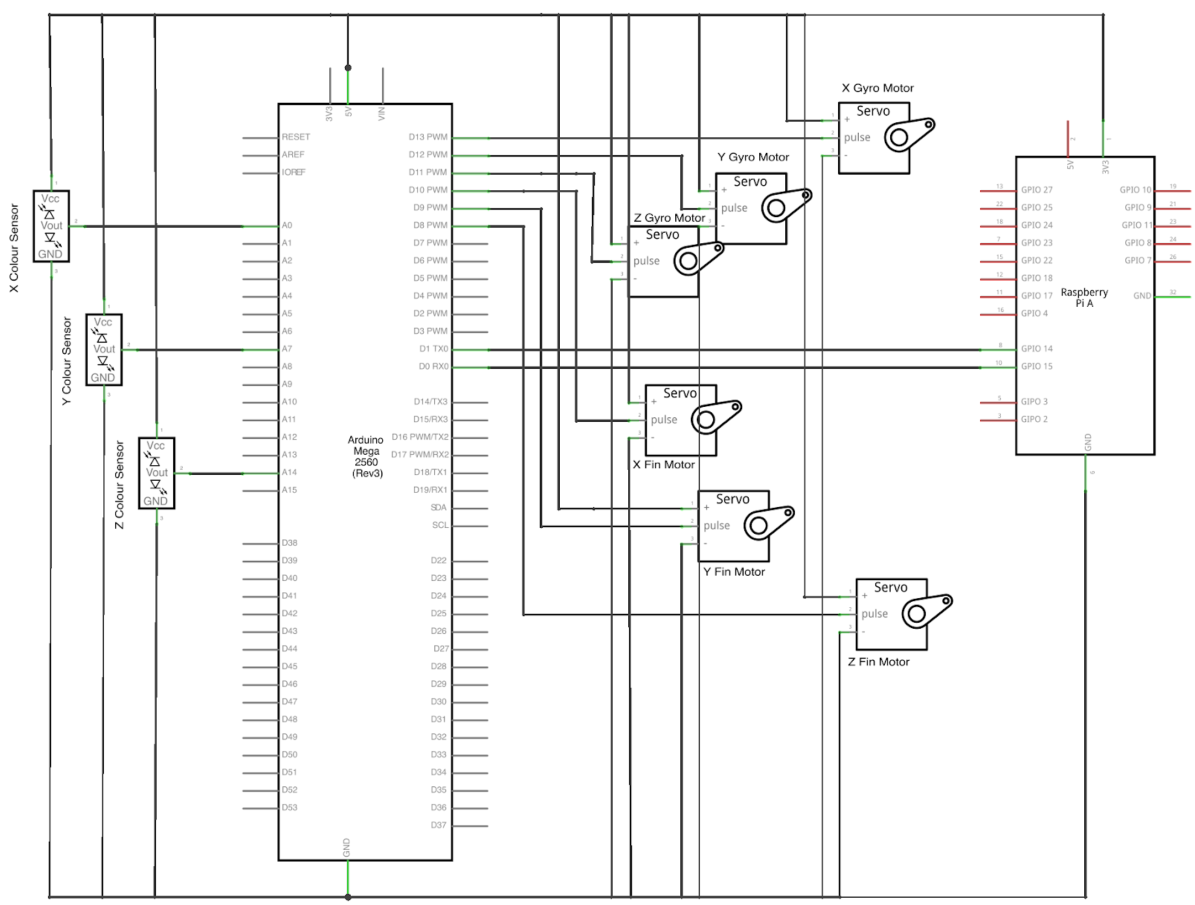

Fig 9. Wiring Diagram. Displays the wiring of each motor and colour sensor from the different gyroscope enclosures to the arduino microcontroller and the Raspberry Pi attached to the computing system. In addition, it also shows the necessary resistors.

5. Program Flowchart

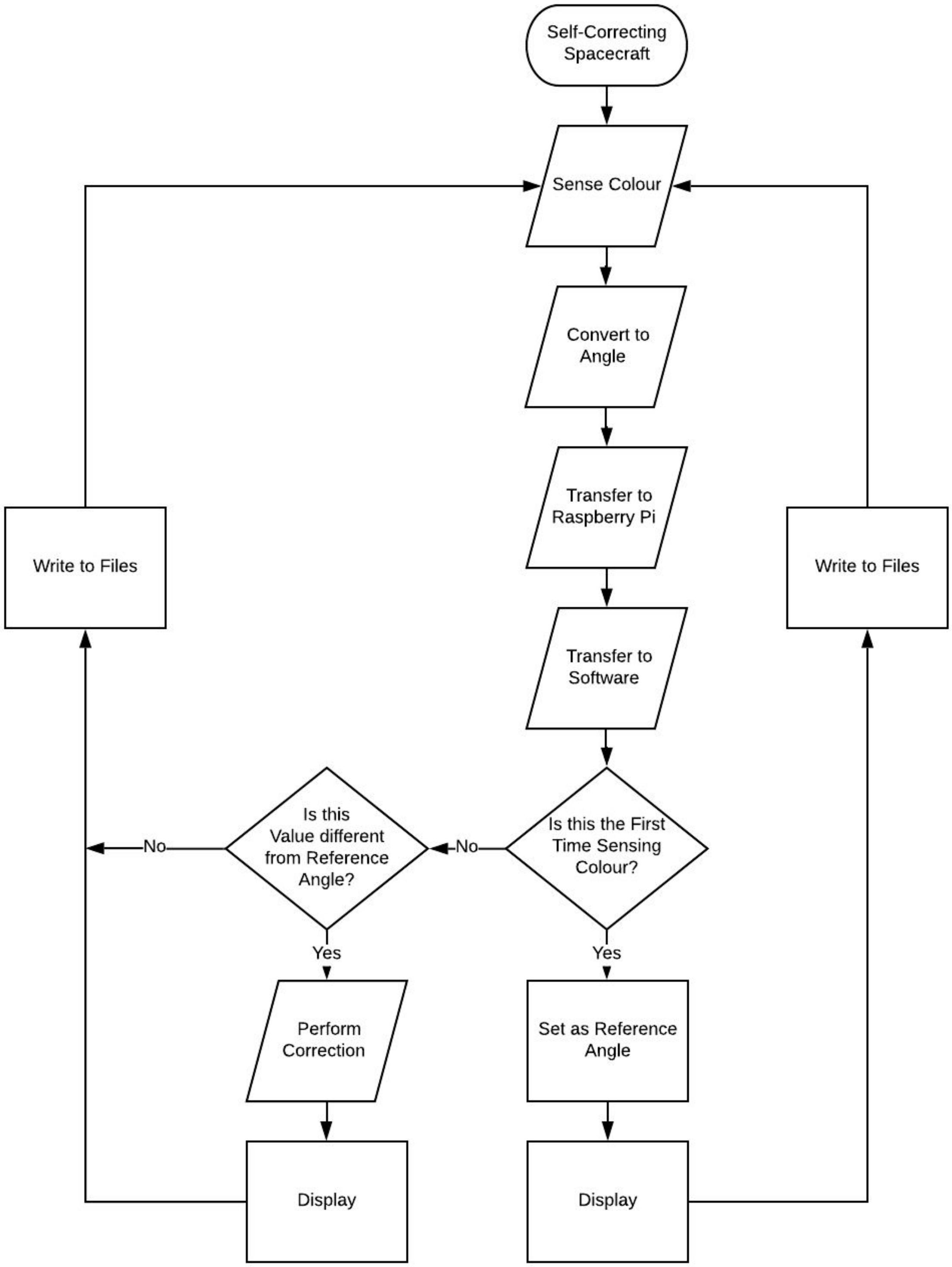

Fig 10. Program Flowchart. Displays the program to be run on the computing system in conjunction with the device described in the above section. Shows the computing process, as well as the output displayed to the user.

6. Testing Procedures

a. Colour Sensor

The three colour sensors will first be tested in well-lit settings, such as a room with normal lighting, to ensure that the differences in colour are sufficient to correspond to an angle that can be read. Next, the same experiment would be tested in a dark room that emulates the conditions of the container it would be in on the spacecraft to ensure that the sensor is still functional in the dark. Additionally, the color gradient should be in a range that is representative of the full 360^{o} range of rotation. Since the colour sensor can only detect 256 different values and a range of 360^{o} is needed, the gradient must be constructed in a certain fashion to account for all necessary angles. This will be tested by seeing if the sensor can accurately detect all the values. The size of the gradient must also be tested when attached to the gyroscope to find the optimal size that maximizes the number of accurate detections from the sensor.

b. Gimbal Ball Bearings

The gimbal ball bearings will be tested by tilting the gyroscope at a known angle and measuring the angle observed. If the residuals are small, then the ball bearing's ability to facilitate movement will be adequate for the project. However, if the ball bearings show under-turning, lubractive substances must be applied to ensure accurate movement and additional fixes must be employed.

c. Motors

The continuous servo motors should be tested for their power to keep the rotor spinning at a rapid rate to maintain gyroscopic properties. If the motor cannot reach high rotational speeds, gears should be used to enhance the rotations per minute to ensure the gyroscope can function. The servo motors used for flaps will first have the flap piece attached and tested in various directions before placed on the entire spacecraft.

d. Arduino and Raspberry Pi

Microcontrollers will be tested for functionality by running rudimentary code through them and observing if the functions of the code are properly executed. This tests the basic functionality of the motors, colour sensors, and wiring along with the microcontroller's ability to function. Another test must also be conducted to verify that the communication between the Arduino, Raspberry Pi, and software is in working order. During the process of writing the code for the spacecraft guidance system, functions of the code must be tested while using the spacecraft as guidance to verify that the calculations are correct.

7. Schedule

December						
Sun	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**
	2 Prospectus	**3**	**4**	**5** -Purchase all materials	**6** -Assemble spin axis and test motors -Attach to mount and gimbal	**7** -Assemble spin axis and test motors -Test gimbals for low friction
8 -Assemble spin axis and test motors -Test gimbals for low friction - Begin code for one axis	**9**	**10**	**11**	**12**	**13** -Finish code for one axis -Test one-axis gyroscope system	**14** -Debug code for one axis -Test one-axis gyroscope system
15 -Debug code for one axis -Test one-axis gyroscope system	**16** -Debug code for one axis -Test one-axis gyroscope system	**17**	**18**	**19** -Finish code for three axes	**20**	**21** -Finish assembly of two more gyroscope units
22	**23** -Test gyroscope units on one axis, then together on three axes	**24** CHRISTMAS EVE -Test and debug code and gyroscope units	**25** CHRISTMAS DAY	**26** BOXING DAY -Test and debug code and gyroscope units	**27**	**28**

29	**30** -Finish testing entire system -Document quasi-working runs	**31** NEW YEAR'S EVE -Paint exterior housing				
January						
			1 NEW YEAR'S DAY	**2** -Paint exterior housing -Fine-tune any issues with system	**3** - Fine-tune any issues with system	**4** - Finish Marketing Brochure and Operating Manual -Finish and document fully working system
5 -Check system's working order	**6** -Check system's working order	**7** -Finish compiling testing data -Finish explanations of deviation from prospectus	**8** -Check system's working order -Format report -Last-minute fixes	**9** -Check system's working order -Last-minute fixes	**10** Presentation Day	

8. Budget Cost

The following table describes the budget for this project. Any shipping costs are included in the cost for each item.

Item	**Quantity**	**Cost per item ($)**	**Costs w/ Shipping ($)**	Notes
Elegoo Mega	1	19.99	19.99	To be purchased
Raspberry Pi	1	15.00	28.25	To be purchased
PVC Pipe (1/2" by 10')	1	8.98	8.98	To be purchased
Ball bearing	10	1.10	11.00	To be purchased
Wood for rotor	1	1.00	1.00	Owned
Wooden dowel (1/8")	1	0.60	0.60	To be purchased
Wd-40	1	0.50	0.50	Owned
Full rotation servo motor	3	6.65	22.60	To be purchased
120 degree servo motor	3	4.75	16.90	To be purchased
TCS 3200 Colour Sensor	3	7.85	26.20	To be purchased
Colour strip (Paper)	1	0.05	0.05	Printed
Cardstock	1	0.50	0.50	Owned
9V Battery	2	1.50	3.00	To be purchased
Battery case	2	0.40	0.80	To be purchased
Resistor	2	0.10	0.20	To be purchased
Copper Wires	1	2.00	2.00	To be purchased
Construction paper	30	0.01	0.30	Owned
Soldering Materials	1	1.00	1.00	Owned
Superglue	1	4.50	4.50	To be purchased
Cardboard	1	0.50	0.50	Owned
Subtotal ($ CAD)			148.88	
Tax ($ CAD)			19.35	
Total ($ CAD)			**168.23**	

9. Rejected Designs

Throughout the three-month planning process for this project, there were numerous versions and designs considered to ensure that there was an efficient way to sense angular rotation and velocity. The spacecraft, however, did not consist of only the measurements of angular rotation, but also physical and budgetary constraints placed by the outline and scope of the project. There were also numerous electrical aspects to be taken into account. As such, different restrictions and objectives had to be taken into consideration.

The first was how to sense angular rotation and velocity. From a basic understanding of gyroscopes from lessons on rolling, torque, and angular momentum and the precession of a gyroscope, there was a strong sense that we were to use gyroscopes to find the spacecraft's rotational movement. Other methods to sense rotational movement such as using gyroscope sensors were dismissed due to limitations placed on internal sensors. However, the gyroscope chip sensors would have helped tremendously in getting an accurate reading of the spacecraft's motion.

Since we had to build a real-life gyroscope, there was a significant discussion on the construction of such a gyroscope. Two major designs that were seriously considered. The first was constructing one gyroscope with three axes of free rotation. The second idea was to have three separate gyroscopes with one free axis of rotation each. The benefits of the first option was that it acted on three axes and can display the movements of the spacecraft with one gyroscope. It takes up less space and can sense rotational motion with fewer sensors. However, the gyroscope would not have the ability to be mounted on a set frame without building another gimbal on the outside. This would mean that the construction of the gyroscope would include one spin axis and four additional gimbals. Since we are using materials such as PVC, it would be extremely difficult to build such a gyroscope. Additionally, the volume that the single three-axis gyroscope would take up would not be significantly smaller than the space taken up by the separate three gyroscopes with one axis of rotation. Also, it would be extremely difficult to measure the rotational movement and velocity with four gimbals. Thus, the three separate gyroscopes, each measuring its own axis of rotation, were used.

We then looked at the different ways to measure the rotational movement and angular velocity. We analyzed four different methods. Some methods analyzed included using mechanical wires, photodiode or resistor, colour detection camera, and infrared or ultrasonic photogate. With the mechanical wires method, we hoped to have a bristled wire on the free axis gimbal poking downwards with a circuit of wires at 2° intervals facing upwards. When the axis spins and closes the circuit, the signal is sent to the Arduino, which is then sent wirelessly to the computer. At the computer, there is an analysis of the peaks of current when the circuit is closed, and the distance between the peaks can be used to calculate the angular velocity. However, this method is rather mechanical and due to the spacing between the wires, there is a significant amount of error and missing measurements in between intervals where nothing is detected. When we look at the photodiode method where a laser is mounted onto the free-spinning axis and firing at cylindrically built walls to the photodiodes attached, it runs into the same issue of having few intervals. The third method, listed in Section (4.c), is consistent and has benefits that outweigh the other options.

We also had to consider budgetary constraints and electrical constraints surrounding the wiring of the spacecraft that were tested numerous times before coming to the most efficient method.

10. Citations

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