College of Engineering

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Final Project - Phase 1 Report

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1 Introduction

Astrobee is a robotic mission designed by NASA to reduce the amount of time astronauts in the International Space Station (ISS) spend on routine duties like documenting experiments, moving cargo, or taking inventory of items [1]. It is meant to be a path forward for robotic technologies in space, especially as the field of space exploration grows larger and larger into the future. Astrobee is designed to have 6 degrees of freedom and be able to fit in a cube with side lengths of one meter. For this project, we have been tasked with developing our own version of Astrobee based on our research, ideas, and discussion as a group. Some design considerations we must address are: how does our version of Astrobee move, both translationally and rotationally, in a zero-g environment, how the robot itself is controlled, the aesthetics of the robot, and other similar factors.

2 Motivation

The motivation and guiding design philosophy behind our idea is maintain simplicity and ease of operation. We desired to use technologies that are currently available today and are not too complicated to fulfill the robot's purpose. We also wanted to take the safety of the robot into consideration, since the robot will be used in close proximity to humans inside the ISS. Many regulations regarding safety of such robotic equipment in a pressurized vessel like the ISS must be taken into serious consideration. Furthermore, we aimed to create a design that would be efficient and practical to use for astronauts inside the ISS. Thus, the design choices we made were born from these principles and below, these choices have been explained.

2.1 Design Requirements

As per the project description, our robot must fulfill the following requirements.

The robot:

- must control its translational and rotational motion in a zero-G environment (6 d.o.f);
- must traverse specific trajectories in a controlled manner;
- must measure roughly $1 \times 1 \times 1$ meters.

2.2 Technology Choices

The use of separate technologies for translational and rotational motion control was selected to better fulfill the design requirements of the robot. In our design stage, we rationalized that separating the translational and rotational motion control systems would aid us in simplifying our design, as combining the two elements together would prove to be more challenging. Additionally, by having this separation, we would be able to more easily prevent a total system failure if the integrated motion system should fail. Thus, in the case of a quasi-system failure, it would still be possible to have some control over the motion of the robot.

For translational motion control, pressurized air thrusters were selected. Six thrusters will be placed on the vehicle, one thruster on each face of the cube. As per our research, these thrusters will offer sufficient thrust to move the robot translationally in all three axes and do not require the robot to rotate to move in a specific direction [2]. Any trajectory that involves specific orientations while moving translationally can thus be achieved, which expands the range of operations the robot can perform. In terms of the practical operation of the robot, the on-board tanks should be periodically refilled with air taken from the ISS, eliminating the need to transport other types of propellants from Earth in order to power the robot.

For rotational motion control, reaction control gyroscopes were selected. These devices consist of a flywheel that is spun up to a constant velocity to hold angular momentum and is then rotated about its other axes of rotation, manipulating the direction of its angular momentum. This change in direction imparts a moment onto the rest of the vehicle due to principle of conservation of angular momentum [3]. The torque output from these devices is superior to that of conventional reaction wheels, and they simultaneously use significantly less energy thanks to the constant speed of their flywheels. They are also tried and true technology, having been used successfully to control missions like that of the ISS [4]. Thus, we felt that this technology was a perfect fit for us because it followed our philosophy of using reliable and tested technologies. The fact that this technology is already used on the ISS is perfect because that means that the astronauts and engineers are already familiar with this design, which will allow them to more easily and quickly understand the vehicle and troubleshoot it should a problem arise.

Because reaction control wheels suffer from saturation, which occurs when the vehicle gains sufficient angular momentum from external forces to overpower its control actuators, an energy-dumping technology is needed to ensure that the reaction control gyroscopes in the robot are not overpowered. Thus, magnetorquers were selected to fulfill this role, as the robot is to operate inside the ISS in low Earth orbit. The Earth's magnetic field can thus be used to return the reaction control wheels back to an operating state in the case of a saturation event. These magnetorquers are located along the edges of the robot inside its body frame.

3 Design

Once the control actuator technologies were selected, an initial model of the robot was created. A CAD model in SOLIDWORKS of the general vehicle configuration was produced. This was done in order to both visualize the proposed design as well as to be able to identify any possible issues with the model that needed to be addressed before continuing with the design. Additionally, using SOLIDWORKS opened the door to being able to calculate the center of mass and the moment of inertia for the vehicle, which would help with data and dynamic analysis.

3.1 Overview

The robot is enclosed in a roughly $1 \times 1 \times 1$ meter aluminum frame, which holds all the actuators the robot needs to move translationally. Pressurized air thrusters are placed at each face center on the frame, providing the vehicle with full translational control. Four reaction control gyroscopes were placed in a grid configuration centered on the aluminum frame. These provide control of the robot's rotational movement.

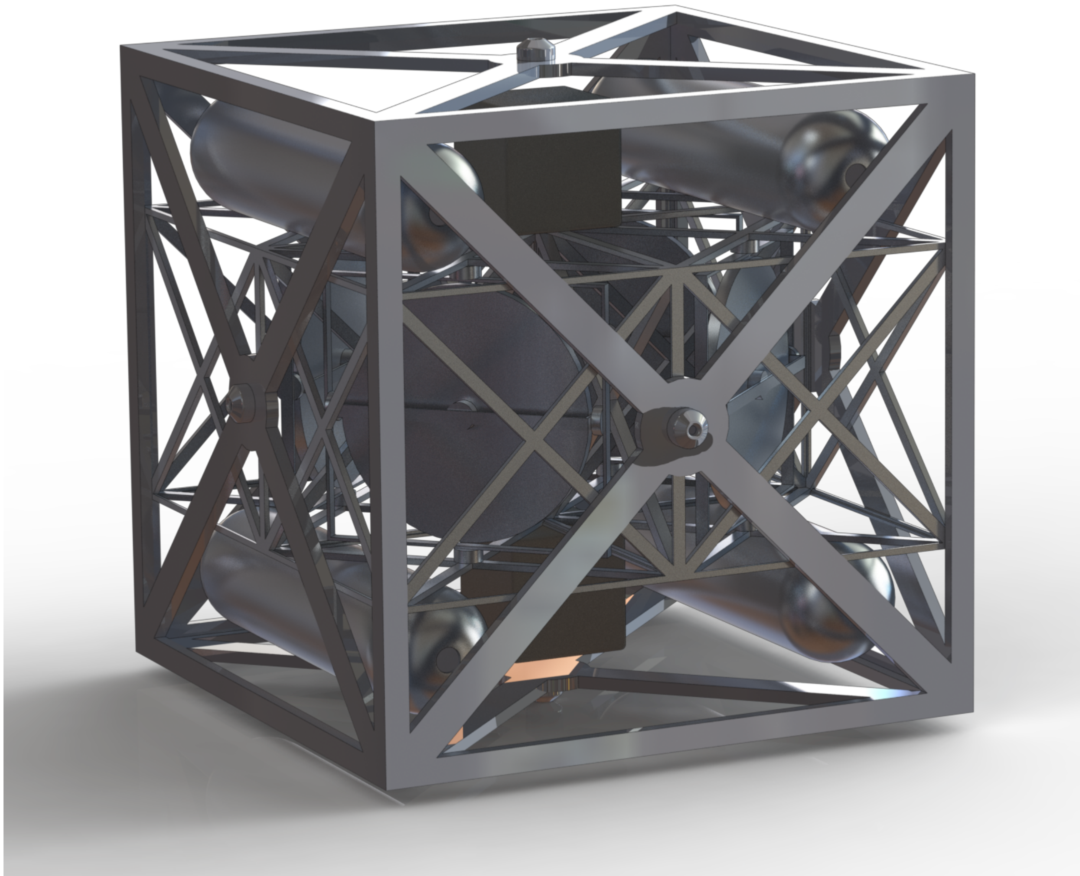

Figure 1: CAD Model Render

3.2 Control Moment Gyroscope Design

Four control moment gyroscope units were placed in a square configuration at the center of the vehicle. This allows full control of rotation in all three axes. Each of these control moment gyroscopes consists of a flywheel supported on an axle, which is then rotated using a motor and a frame around an axis perpendicular to the flywheel's axis of rotation. This frame is subsequently turned around the third perpendicular axis using another motor and frame. The combined movement of these two frames can be used to point the flywheel angular momentum vector in any arbitrary direction.

Each of these control moment gyroscopes is formed by a flywheel rotating around an axis $\overrightarrow{n}_1$ at a constant speed ω. The wheel is kept at an angular momentum ωI_w. This wheel can pivot around perpendicular axes of rotation $\overrightarrow{n}_2$ and $\overrightarrow{n}_3$, changing the direction of this angular momentum. Due to the conservation of angular momentum, the change in the direction of the wheel imparts the opposite change in the angular momentum of the rest of the vehicle. And when used in a four-grid configuration, the rotation of the vehicle along its three principal axes can be controlled easily.

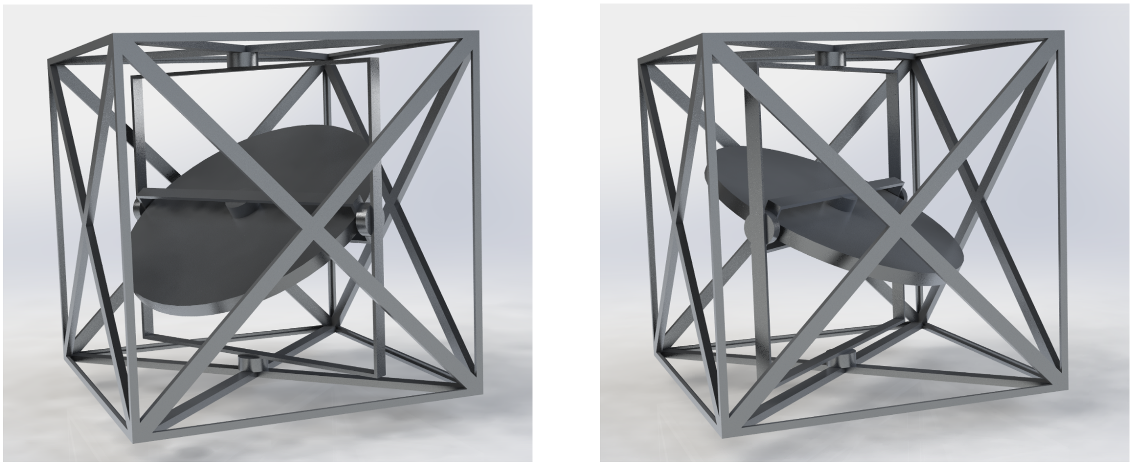

Figure 2: Demonstration of Gyroscope Rotation

4 Control Actuation Data

4.1 Moments of Inertia

Using the rough CAD for the robot design, the experimental moments of inertia at the center of mass were found. These came out to be:

$$\mathbf{I}_p = \begin{bmatrix} 22.66 & 0 & 0 \\ 0 & 22.46 & 0 \\ 0 & 0 & 20.73 \end{bmatrix} kg\ m^2 \tag{1}$$

The total mass of the robot comes out to be 123.66 kg. All masses are symmetrically arranged around the aluminum frame, meaning the center of mass is at the center of the robot. The gas tanks for the side thrusters and the batteries were also modeled, as they add a significant amount of weight to the robot. The avionics of the robot were disregarded as they do not add significant weight to the robot.

4.2 Actuator Data

All data presented in this section was compiled and calculated using MATLAB. A MATLAB LiveScript detailing the calculations used is presented along this report.

For the translational thruster actuators, the following data was determined:

Variable	Value
Thruster nozzle diameter	15.61 mm
Air Pressure	6.895 MPa
Choked mass flow through nozzle	2.35 $kg\ s^{-1}$
Air exit velocity	10 ms^{-1}
Thrust	1323.7 N
Maximum acceleration	10.704 ms^{-2}

The nozzle diameter was chosen for its small size and ease of integration with the rest of the design. Air pressure was chosen to be 6.895 MPa, or 1000 psi, to match the pressure in other pneumatic systems onboard the ISS. The maximum air mass flow through the nozzle was found and used, along with the air exit velocity, to calculate the approximate thrust generated by an individual thruster. Given the mass of the robot, each thrust can impart a maximum acceleration of 10.704 ms^{-2}, which was deemed sufficient for full translational control.

For the the reaction control gyroscope system, the following actuator data was determined:

Variable	Value
Flywheel mass	6.7 kg
Flywheel moment of inertia (Center)	0.1408 kgm^2
Flywheel motor torque	97.2 $mN\ m$
Flywheel angular velocity	6720 rpm
Flywheel angular velocity ramp up time	1019.3 s
Flywheel angular momentum	99.0719 kgm^2s^{-1}
Flywheel angular acceleration about secondary axes	1.3279 s^{-2}

Flywheel mass and moment of inertia were found using CAD. The flywheel motor torque was taken from a Maxon 543631 brushless motor [1] which offered sufficient torque at low profiles and energy consumption. The angular velocity of the flywheel was taken as the maximum attainable speed by the motor. The time needed to accelerate the flywheel to such speeds is significant, but as the angular velocity only needs to be maintained once the flywheel reaches operational angular velocity the motor only needs to apply small amounts of torque to it. Finally, the total angular momentum of the flywheel and the angular acceleration about the secondary axes were deemed acceptable to maintain control of the rotation of the robot.

As the robot incorporates four of these control moment gyroscopes data for the entire rotational control system was determined. The following values were found:

Variable	Value
Total angular momentum	99.0719 kgm^2s^{-1}
Maximum change in angular momentum	396.2875 kgm^2s^{-1}
Maximum angular acceleration on robot about x	17.4884 s^{-2}
Maximum angular acceleration on robot about x	17.6441 s^{-2}
Maximum angular acceleration on robot about x	19.1166 s^{-2}

The maximum change in angular momentum that the system can counteract equals the angular momentum of all flywheels on the robot, assuming the robot is not rotating when the system is first activated. This angular momentum is also the saturation angular momentum: the flywheels will not be able to counteract external torques if the total angular momentum of the robot exceeds this quantity. The maximum torque that the reaction control gyroscopes can exert were used with the robot moments of inertia to find the maximum angular acceleration that the system can exert on the robot. These values were deemed sufficient to control the rotational motion of the robot.

[1] Motor specifications available at: `https://www.maxongroup.com/maxon/view/product/543631`

Finally, the magnetorquers will be used to desaturate the control reaction wheels as the robot picks up external angular momentum. Data regarding the performance of this system was based on the NMTR-X system by NewSpace Systems [2]. The following data was determined for this actuator:

Variable	Value
Magnetorquer dipole moment	300 Am^2
Magnetorquer average torque	0.0075 Nm
Time to desaturate reaction control wheels	14.6773 hours

The average Earth magnetic field strength was taken to be 2000 nT. Although the time to desaturate the reaction control wheels completely is large continued use over time will guarantee that the robot never saturates due to external perturbances. The flywheels will only need to be completely desaturated on rare occassions when a large torque is applied on the vehicle, and even then the robot will be back on operational capability in less than a full day.

5 Conclusion

In conclusion, this preliminary report summarizes our selected Astrobee design concept and our initial dynamics control derivations. These derivations include fundamental assembly properties such as the center of mass and moment of inertia, and some control dynamic equations that we can use to manipulate our design concept. Initial CAD concepts are included, and these show our basic design choices such as the thrusters, the control moment gyros, and the magnetorquers. Finally, our design has successfully fulfilled our design philosophy that revolves around simplicity, efficiency, and practicality.

[2] Magnetorquer specifications available at: https://www.newspacesystems.com/wp-content/uploads/2020/10/NewSpace-Magnetorquer-Rod_2020-10a-1.pdf

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