University of Colorado
Department of Aerospace Engineering Sciences
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Project Definition Document (PDD)

Geocentric Heliogyro Operation Solar-Sail Technology (GHOST)

Approvals

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1.0 Problem

This phase of the Geocentric Heliogyro Operation Solar-Sail Technology (GHOST) project will design and prototype a pitching and blade damping control system for a heliogyro propulsion system for a 6U cubesat. The GHOST heliogyro will have two blades with an aspect ratio of 100:1 that must be able to pitch ± 90°, to within ±5° of a commanded angle. The blades will experience in-plane and out-of-plane low frequency oscillations due to the lack of structure inherent in a heliogyro system. The blade controller will be capable of damping oscillations typical of a heliogyro to reasonable levels within 3 minutes, or 1 full rotation of the spacecraft. The exact performance criteria of the controller will be established by the team as the project progresses. Finally, all the hardware involved in the controller including all sensors, actuators, and micro-controllers, must be compatible with an existing blade deployment system and must be capable of fitting within a 6U CubeSat, or 60 cm^3, while allowing 2U of empty space, or 20 cm^3, to be used for other CubeSat bus systems.

2.0 Previous Work

In 1967, the concept of the heliogyro solar sail was first introduced by Richard MacNeal. The initial design consisted of two 5700 meter-long blades, supported by the centrifugal force of the spinning spacecraft. Though he was able to experimentally demonstrate the successful pitching of two-meter blades, little else was done with the concept until 1977, when Jet Propulsion Laboratories (JPL) conducted a design study. A heliogyro solar sail was considered for a rendezvous with Halley's comet, but was sacrificed for a less risky means of propulsion. Their design consisted of 12 blades in two levels rotating opposite each other. Each blade was 8 by 7500 meters, an aspect ratio slightly less than our parameter of 100:1.

An MIT team proposed an eight-bladed heliogyro design in 1989, which was also never built. Aside from occasional dynamics studies, the concept of the heliogyro sail was left alone for many years. [1] After the JAXA IKAROS, a square-shaped solar sail, was successfully launched and proven in 2010, interest in solar sails and particularly the weight-saving heliogyro design, re-emerged. NASA proposed HELIOS, a reference design for heliogyro technology. [3]

The project being designed by the current Senior Projects team for senior design is a continuation of the work done by the 2013-14 GHOST team. From the information gathered about last years team, it is known that the GHOST team successfully created a deployment system that was tested in a 1G environment. Within the 1G environment the blade was able to deploy the blade at a controlled rate between 1 and 10 cm/s. In addition, the GHOST team was able to maintain a power level of less than 5W per blade. Finally, the final design incorporated a motor that could be used for blade pitching. This blade did not correctly move the blade into the angle, but this motor may be incorporated for future use.

3.0 Specific Objectives

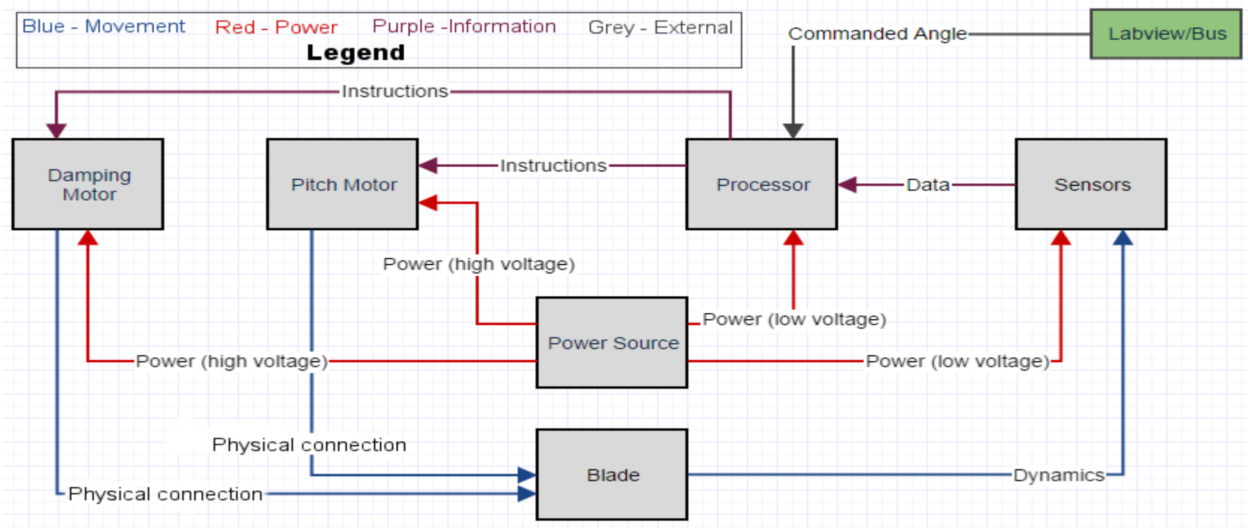
The objective of this phase of the GHOST project is to design a control and actuation system for one blade of a two blade heliogyro. This system will be capable of rotating a blade with an aspect ratio of 100:1 in the range of ± 90° to a tolerance of ± 5° of the commanded angle. In addition, the system must dampen any oscillations arising from commanding the blade to rotate as well as any unforeseen external perturbations in the range of TBD to TBD Hz with a settling time of TBD. The size of the system must satisfy the CubeSat requirements of a mass of 1.3 kg/U and a volume of 4U, giving a total mass of 4 kg and a total volume of 40 cm^3. The budget is limited to $5,000. The purpose of this project is to demonstrate the feasibility of developing and implementing a solar sail control system that is also compatible with a CubeSat platform.

Success Level 1 will be the ability to pitch a solar sail blade to a commanded angle with a tolerance of ± 5° of the commanded angle within a range of +90° to -90°. This will be tested by hanging the blade and commanding an angle with the control system designed. The test will include a measurement of the actual pitch angle and a comparison will be made between the commanded angle and the actual angle.

Success Level 2 will be the ability to dampen all oscillations, torsional and out-of-plane, arising from commanding the desired angle. Success will be the ability to dampen one characteristic mode of oscillation at a frequency of TBD Hz with a settling time of TBD. This will be tested by first commanding an angle with the feedback control law deactivated, then commanding the same angle with the feedback control law activated. Success will be showing a faster damping of oscillations in the blade with the feedback control law activated than with the feedback control law deactivated. Success Level 2 will satisfy Success Level 1.

Success Level 3 will be to dampen oscillations described by level 2 as well as perturbations from out-of-plane blade flapping. Success will be the ability to dampen one characteristic mode of oscillation at a frequency of TBD Hz arising from an external perturbation with a settling time of TBD. This will be tested by exciting the blade using the TBD external method (at this time, this method will be a motor controlled with LabVIEW). Success Level 3 will also satisfy Success Levels 1 and 2.

4.0 Functional Requirements

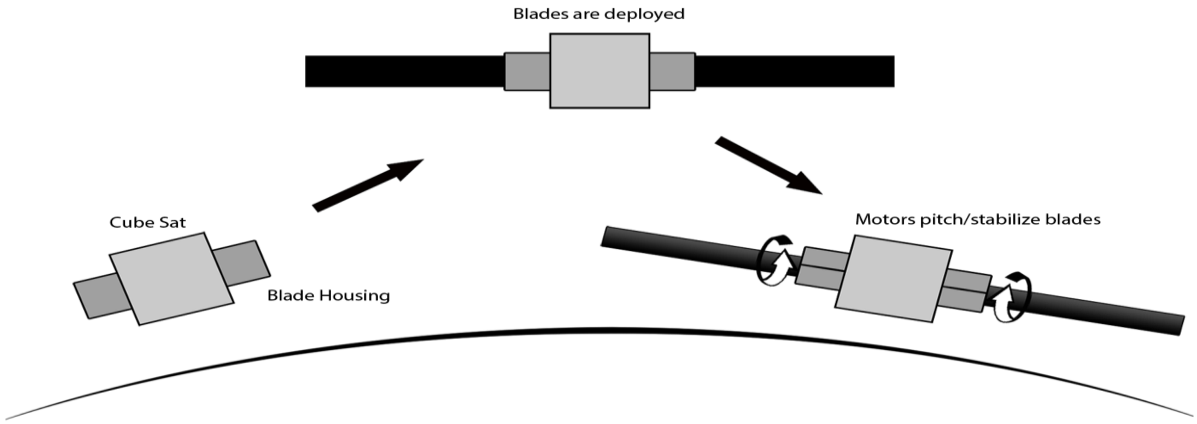


The FBD above shows the individual components of the system the team will be working on. While the GHOST project also consists of a deployment mechanism, deployment is not a focus of this year's team. In addition, while the blade control system must respond to commands from the main satellite, populating the CubeSat and programming the mission is not within our parameters. The bus will be considered an external system, and commands from the spacecraft's core processor will be simulated with LabView.

The motors, sensors, and power source will all be purchased. The pitching motor is already in place from last year, though the team may choose to change it if necessary. The solar sail blade is a part of last year's hardware, and extra material has been provided by the customer. We will be designing the processor, the electrical and physical connections between all of the elements in the diagram, and the programming necessary to dampen blade oscillations.

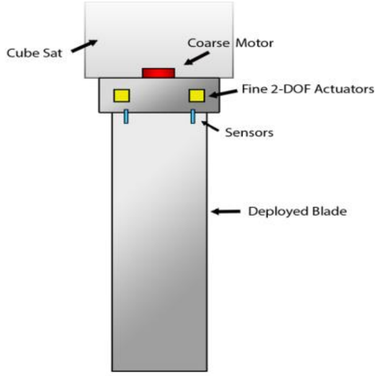
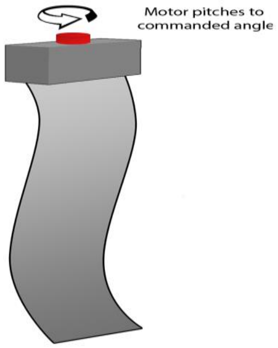
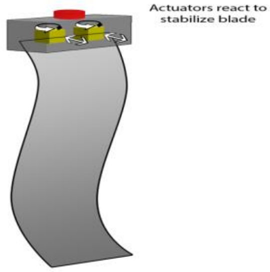
The bus, or LabView, will send a command to the processor to attain a desired pitch angle in the blade. This will be translated into a command that will be sent to the pitch motor, which will rotate the blade at the root. Since the blade is not a rigid body, the movement of the root will excite oscillations in the material, which will be picked up by the sensors. The sensors will send this information to the processor, which will use the location of the blade and the desired pitch angle to determine what to send to the damping and pitching motor, and the process repeats. A power source must provide an adequate supply for both the motors, which will require greater power, and for the sensors and processor, which will presumably need only a small amount for functionality. The sensors will be used to determine the displacement of the blade from the commanded position. How this data is acquired is yet to be determined.

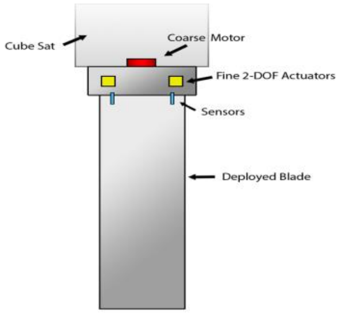
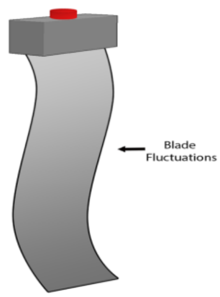
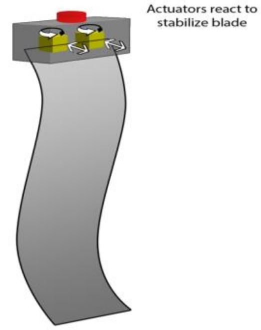
4.1 Mission Concept of Operation



The GHOST satellite is a project that fits into the bigger picture of the ongoing missions with CubeSats. The Cubesats are launched from earth into space and need a way to stay in their orbit with the limited power that is available to them. The GHOST satellite is there to be mounted onto the CubeSat and be launched as a combined payload. Once in space, the Ghost satellite will then deploy the blades at a rate between 1 to 10 cm/s which is controlled by a motor on GHOST. Once the solar sail is deployed the satellite uses centripetal force to stiffen the blades and uses the solar sail to generate propulsion. In order to create the optimal angle for propulsion, the blades must be able to pitch while in space and move to within ± 5° of the desired angle. After being pitched, the non-rigid solar sails will have vibration associated with them. Therefore the GHOST satellite will use TBD sensors to determine which mode is being induced and will act to correct it. This will allow the blade to be in its original state with minimal vibrations. In addition to vibrations caused by the pitching angle, there are other modes that the solar sail may see from external interactions with the sail. When this occurs there will likely be out of plane motions in the blade, or flapping. The GHOST system will recognize these vibrations with TBD sensors and will then use a 2 degree of freedom (2DOF) motor to add damping to the sail and will remove the flapping energy in the sail.

4.2 Project Concept of Operations

The GHOST satellite will be mounted so that the Solar Sail will be able to deploy TBD meters so the test can initiate. 	The GHOST will then be commanded to a certain angle in which the system will be within ± 5° of that commanded angle 	Due to torsional movements when moving to the commanded angle, the GHOST will need to damp the system. TBD sensors will allow the system to understand which mode is being excited and allow damping to take place by removing energy from the system. 

After the torsional movement test has finished, the next test is a flapping test. This test demonstrates the ability of the damping system to remove modes on the blade from outside forces.  	A TBD system will be used to excite a mode from TBD to TBD frequencies onto to the solar sail material. The sensors on the GHOST will then sense with TBD sensors the flapping of the solar sail.  	Once the system knows the mode that the blade is in, the system will use a 2DOF motor to remove the energy from the system and dampen  the blade

5.0 Critical Project Elements

The aspects of this project that are anticipated to carry the most risk and consume the majority of the project's resources are listed below. They are arranged roughly in the chronological order in which they are expected to be encountered.

5.1 Space Worthiness

GHOST is designed to fly onboard a 6U Cubesat system. Integration with the Cubesat platform is not the focus of this project, but all design solutions must be considered in the context of the space environment

5.1.1 Cubesat Compatibility: The heliogyro system will occupy no more that 4U of the 6U satellite with sufficient volume left for the Cubesat's other systems. Additionally, GHOST must conform to the Cubesat weight requirement of 1.3 Kg/U as well as all other Cubesat Design Specifications [6].

5.1.2 Power: The blade control and actuation system developed shall not use more than 5 Watts per blade. Demonstrating blade damping in an earth environment will likely require more power, so any design solutions will have to justify how a smaller amount of power would be required in space.

5.2 Blade Dynamics

Before any kind of manufacturing or electronic elements are produced, the team must understand how the solar sails will react in most situations, especially considering the blade cannot be treated as a rigid body.

5.2.1: Research existing blade dynamics models: There is already considerable research into the dynamics of heliogyro blades including several papers authored by Professor Dale Lawrence and his graduate students. Obtaining and understanding the results of these studies is essential for project success.

5.2.2: Predict and model the magnitude and frequency of oscillations for GHOST's blades: The dynamics of the blades of GHOST need to be modelled through FEM analysis and or testing. All members of the team are familiar with FEM analysis tools and 2 members are taking higher level classes in FEM analysis. Physical validation of this modeling is possible in professor Frew's motion tracking lab.

5.3 Measuring Blade Perturbations and Response

In order for the controller to function, sensors will be needed to measure the oscillations and pitch angle of the blades. The best type of sensors to fulfill this requirement is not yet known.

5.2.3: Blade measurement sensors: The exact method of measuring vibrations in the blade depends on the magnitude of the oscillations. It is likely magnitudes will be very small [7], so it may be impractical to measure the torque in the blade directly; other methods such as measuring deflections and estimating torques may be necessary.

5.4 Implementing Two Degree of Freedom Motor Control

To effectively provide damping augmentation for torsional twist and out of plane flapping a motor controller with two degrees of freedom must be implemented into our design.

5.4.1: Pitching mobility: The blade must pitch to $\pm 90°$, which is likely larger than the requirements of a damping system. Separate motors may be needed for pitching and damping.

5.4.2: Flap damping: Separate actuators will be needed to control flapping oscillations, which are expected to be perpendicular to pitching oscillations.

5.5 Validate System by Testing

This project will need to show that the blade controller will work in the space environment without being able to perform any testing in a space environment, since the size of these blades will limit the possibility of using high vacuum chambers.

5.5.1: Controller Validation

In an earth environment with air viscosity, demonstrating that damping is faster with the controller on rather than off will be necessary to validate that the controller provides damping.

5.5.2: Air damping mitigation

If air damping proves to be too large for measuring controller performance, a low vacuum testing chamber may need to be constructed or holes cut in the blade material to create a “rope ladder”.

6.0 Team Skills and Interests

Name	Skills and Interests
Michael Andrews	Software, electronics, control
Brendon Barela	Dynamic modeling, mechanical
Austin Cerny	Dynamic modeling, mechanical
Corinne Desroches	Software, electronics, control
Kyle Edson	Structural/mechanical integration
Conrad Gabel	Mechanical/electrical integration
Chris Riesco	Software, electronics, control
Justin Yong	Dynamic modeling, vibrations

7.0 Resources

Critical Project Element	Team Resources
2 DOF Motor Control	Matt Rhode and Trudy Schwartz can be valuable resources in selecting appropriate motors and in integrating software and motor control.
Measuring blade dynamics	Trudy Schwartz, Matt Rhode and Dale Lawrence all have insight into methods of measuring low magnitude, low frequency oscillation. James Mack’s resolution camera systems will also be helpful.
Validate system by testing	Potential tests may require a low vacuum chamber; Matt Rhode and Dale Lawrence will be helpful resources in the construction of such a device.
Space Worthiness	Professor Lawrence will be a valuable resource in determining which proposed design solutions are practical for cubesat integration
Blade Dynamics	Professor Lawrence, his graduate students, and Professor Felippa will be able to help model our blades with FEM tools, as well as Professor Frew’s motion tracking lab.

8.0 References

[1] "Heliogyro Concept- History." The Field Robotics Center. The Robotics Institute, n.d. Web.

[2] Wilkie, W. K., J. E. Warren, M. W. Thomson, P. D. Lisman, P. E. Walkemeyer, D. V. Guerrant, and D. A. Lawrence. *THE HELIOGYRO RELOADED*(n.d.): n. pag. *NASA*. Web. <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110023680.pdf>

[3] Wilkie, W. K., J. E. Warren, M. W. Thomson, P. D. Lisman, P. E. Walkemeyer, D. V. Guerrant, and D. A. Lawrence. *RECENT PROGRESS IN HELIOGYRO SOLAR SAIL STRUCTURAL DYNAMICS*(n.d.):n. pag. *NASA*. Web. <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140003899.pdf>

[4] Wilkie, Keats, Jerry Warren, Jer-Nan Juang, Lucas Horta, Justin Littell, Robert Bryant, and Karen Lyle. *Heliogyro Solar Sail Research at NASA*(n.d.): n. pag. *NASA Technical Report Server*. NASA. <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20130014933.pdf>.

[5] Macdonald, Malcom, Advances in Solar Sailing, Springer Praxis Books, Chichester, UK, 2014.

[6] Nason, I., M. Creedon, and J. Puig-Suari. "CubeSat Design Specifications Document." Revision V (2001): 1-6.

[7] Guerrant, Daniel, Dale Lawrence, and W. Keats Wilkie. "Performance of a Heliogyro Blade Twist Controller with Finite Bandwidth." AIAA/AAS Astrodynamics Specialist Conference. 2012.