

University of Colorado  
Department of Aerospace Engineering Sciences  
Senior Projects – ASEN 4018

GHOST  
Conceptual Design Document

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## 1.0 Information

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## 2.0 Project Description

The GHOST satellite seeks to demonstrate a working concept of a heliogyro, which is a spinning satellite with large aspect ratio solar sail “blades” that are held in place by centripetal forces. Heliogyros offer advantages to traditional solar sail designs in that the blades can potentially be several kilometers long without requiring elaborate deployment mechanism and support structures. Additionally, heliogyro satellites have the potential to be steered by pitching these blades and redirecting solar pressure. However, due to the difficulties of testing heliogyros and uncertainties in heliogyro blade dynamics, no heliogyro mission has ever been launched to space. The 2014-2015 GHOST team seeks to design and prototype a pitching and vibration damping controller for the heliogyro blades of the GHOST satellite and validate GHOST as a heliogyro demonstration.

The GHOST heliogyro will have two blades with an aspect ratio of 100:1 that must be able to pitch the solar sail blades  $\pm 90^\circ$  relative to its main body, to within  $\pm 5^\circ$  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 which the controller must damp out. 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, and adequate space must be allocated in this volume for other subsystems of the GHOST satellite.

### Mission Concept of Operation

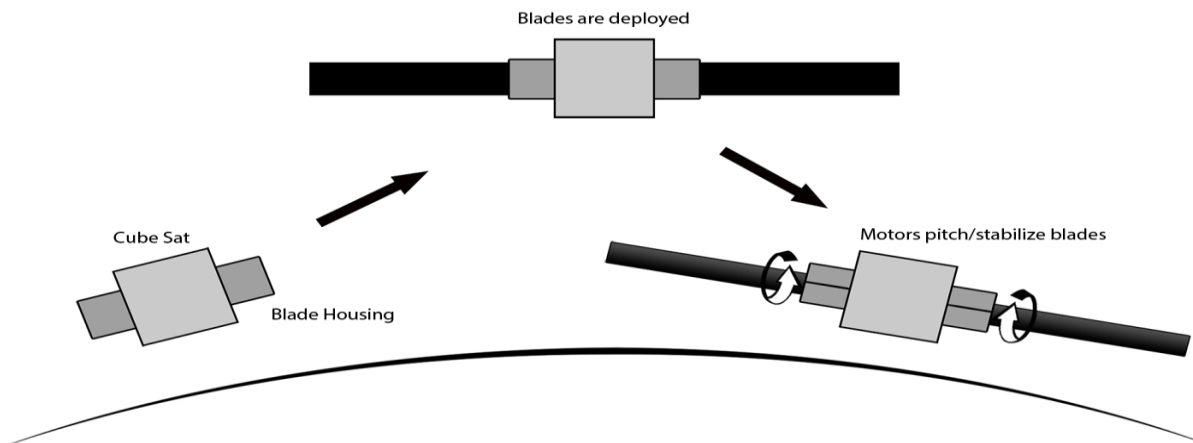
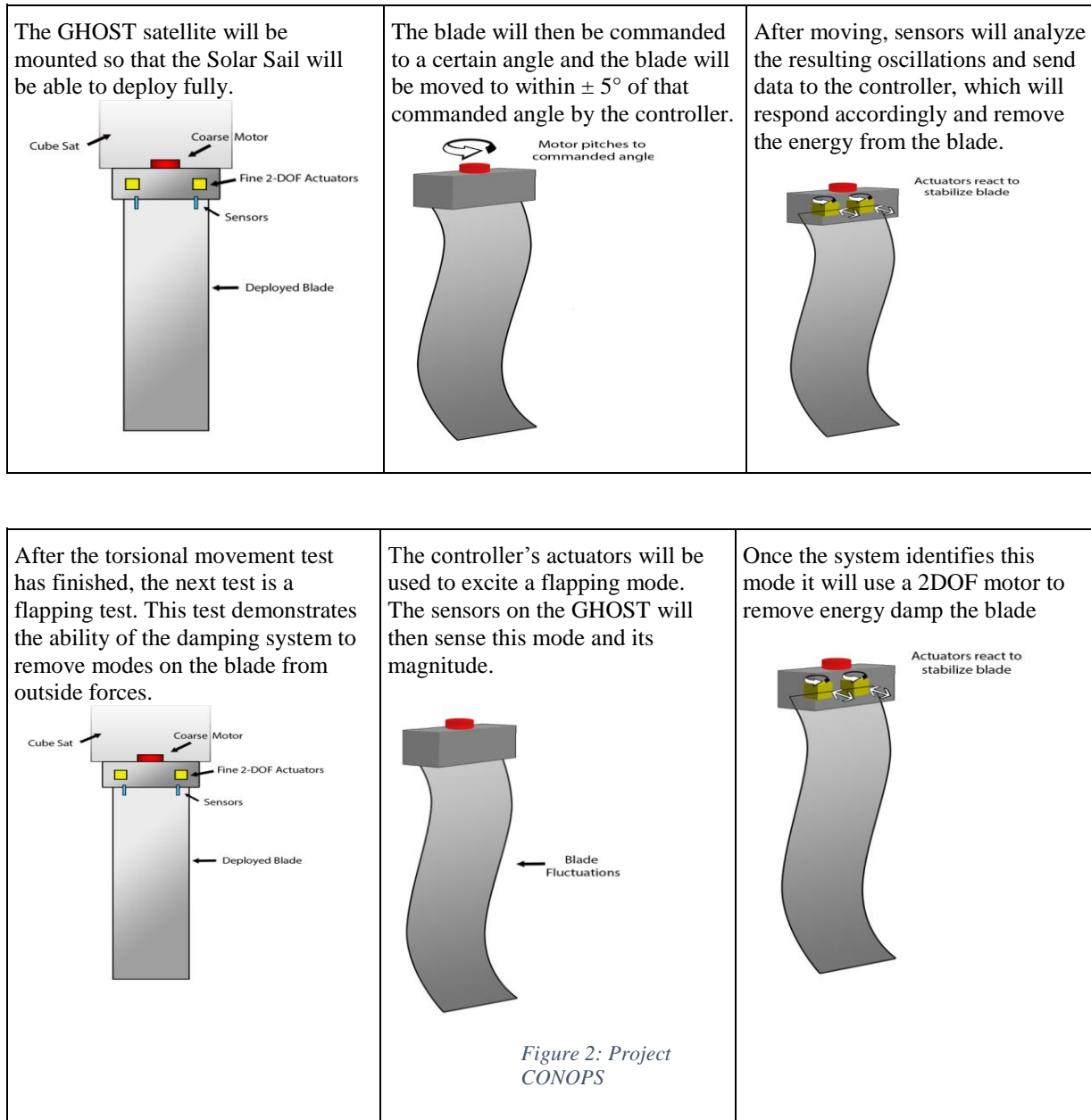


Figure 1: Mission CONOPS

The GHOST satellite will be launched into space on a CubeSat platform. Once in space, the satellite will deploy its blades at a rate between 1 to 10 cm/s. After the solar sail is deployed the satellite uses centripetal force to stiffen the blades and uses the solar sail to accelerate. In order to create the optimal angle for propulsion, the blades must be able to pitch while in space and move to within  $\pm 5^\circ$  of the desired angle. After being pitched, some of the energy that was used to pitch the blades will be transferred to the solar sail material causing the blades to vibrate. The GHOST satellite will use sensors to determine magnitude and frequency of the oscillations and will activate a damping system allowing the blade to return to its original unperturbed state. In addition to the vibrations induced by pitching the blades, GHOST will be subject to out-of-plane or flapping oscillation due to solar pressure interacting with the sail. The GHOST blade damping system will recognize these other modes of the blades and damp them accordingly. The system is expected to experience in plane or pitching oscillations as well as out of plane or flapping oscillations, so the damping system will incorporate actuators capable of moving in both of these degrees of freedom (2DOF).

### Project Concept of Operations

The 2014-2015 GHOST team will demonstrate the functionality of the heliogyro blade controller using a testbed. Damping will be tested on the vibrations resulting from pitching the blade and on the vibrations created by using actuators to excite the modes of the blade directly.



### Functional Block Diagram (FBD)

The FBD below 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.

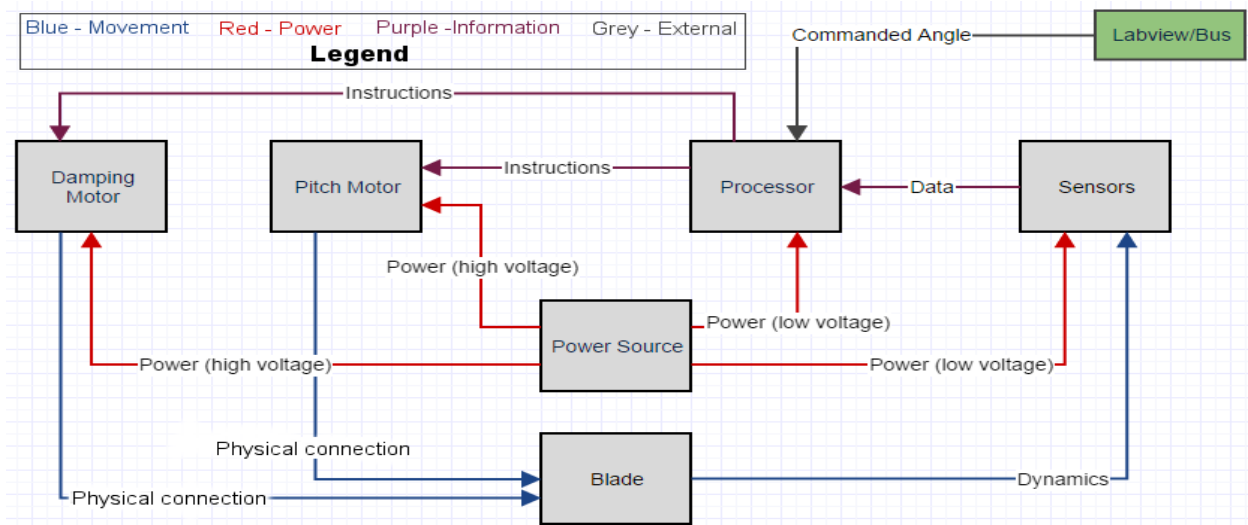


Figure 3: Functional Block Diagram

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.

### 3.0 Design Requirements

The 2014-2015 GHOST team will only be physically manufacturing a control and damping system for one heliogyro solar sail blade, though this design will be used on both blades of the spacecraft. The controller will have two main design components: the actuators that control the pitching and damping of the sail and the sensing system that will be used to measure the solar sail blade dynamics and provide this information to the controller. The functional requirements drive the selection of different actuators and sensing devices, as well as how they are mechanically assembled.

In order to ensure that the design will be able to meet the functional requirements, the project was separated into three different subsystems; actuator/control, dynamic sensing, and electrical/software. As explained above, the actuator/control subsystem will essentially control the pitching movement of the solar sail as well as damping augmentation. The dynamic sensing subsystem will determine the dynamic behavior of the blade and provide feedback measurements to the software subsystem. The electrical/software subsystem will power all other subsystems as well as process feedback data from the sensing subsystem and provide commanded movements to the actuator/control subsystem.

The design requirements for each subsystem were determined based upon what is needed to accomplish each functional requirement. In some cases like weight and space, subsystem design requirements are dependent upon each other.

A table was made for each subsystem as well as for the overall functional requirements. The first column of each table displays the requirement code, FUNCT for functional, ACT for actuator/control, SENS for sensing, ELECT for electrical and SOFT for software. The next column is a description of the specific requirement, the third column displays the parent requirement or the requirement driver, and the final column describes how verification of the requirement will be met.

The Functional Requirements table displays the main requirements that the design must meet in order to be a success. All of these requirements are ultimately driven by the customer.

### Functional Requirements

Requirement	Description	Parent Requirement	Verification
FUNCT.1	The control system design for one blade must fit within a volume of 2U and cannot exceed a weight of 1.3 Kg/U.	Customer	Inspection: Measure the total weight of all subsystems and the volume they will occupy.
FUNCT.2	The operational power of the system is restricted to 5 watts of power.	Customer	Test: Measure the power needed to run the controller.
FUNCT.3	The control system must provide blade rotation of $\pm 90^\circ$ .	Customer	Test: Pitch the blade from $-90^\circ$ to $+90^\circ$
FUNCT.4	The system must be able to damp torsional oscillations with a settling time of less than 45 minutes or half of 1 period of a satellite in low earth orbit.	Customer	Test: Demonstrate that when the control system is turned on it is able to provide noticeable damping effects when compared to nominal case.
FUNCT.5	The system must be able to damp flapping oscillations from solar pressure present at a distance of 1 AU from the sun at $4.523 \times 10^{-6}$ Pa	Customer	Test: Demonstrate that when the control system is turned on it is able to provide faster damping effects when compared to nominal case.

One of the most difficult tasks for the success of this project will be the verification of FUNCT.4 and FUNCT.5. This will require the team to show that the design solution can provide sufficient damping to the solar sail. The team can confirm that the controller provides damping by comparing the behavior of the blade when the control system is turned off to when the control system is turned on. If the magnitude of oscillation decreases faster with the system's controller on, this indicates the controller provides damping in addition to the damping provided by air viscosity. The upper limit for the time to damp requirement of the controller has been established at 45 minutes. This arises from assuming the quickest orbit, which occurs at LEO. Since a LEO is about 90 minutes, 45 minutes is equivalent to half of an orbital period of a satellite in low earth orbit. To accelerate, the satellite would need to pitch its blades at 45 minute intervals to regularly add velocity to its orbit if it were in low earth orbit, and would need to pitch the blades again to avoid decelerating. The goal is to design a controller that will damp oscillations much quicker, but realistic damping expectations are dependent on a blade dynamic analysis that is yet to be performed.

Verifying that FUNCT.4 and FUNCT.5 are met may be difficult if air damping proves to be of a much higher magnitude than the damping of the controller, and it is possible that these tests may need to be performed in a low vacuum environment. Because the solar sail material is so light, the Earth's atmosphere has a significant damping effect on the blade. Due to the damping effects that Earth's atmosphere has on the solar sail material, confirmation of effective damping and control will need to be done in an environment with little to no atmospheric drag to demonstrate that the solar sail damping is a result of the project design and not the Earth's atmosphere.

The table below displays the functional requirements for the Actuator and Control subsystem. The main driver of these requirements is the functional requirements.

### Actuator/Control Requirements

Requirement	Description	Parent Requirement	Verification Requirement
ACT.1	Total mass of actuator subsystem plus other subsystems must not exceed 1.3 kg/U	FUNCT.1	Inspection: Measure mass of actuation design using a scale.
ACT.2	The actuators shall fit within a 30x20x10cm volume	FUNCT.1	Inspection: Measure the dimensions of the actuation design.
ACT.3	The actuators shall not require more than 5 watts of power.	FUNCT.2	Physical Test: Measure the amount of power that is required to run the actuator using lab equipment.
ACT.4	Combination of Actuators must have range of motion of $\pm 90^\circ$	FUNCT.3	Physical test: Measure actuators range of motion when given power and commands
ACT.5	Actuators must provide both rotational motion and vertical motion	FUNCT.4 FUNCT.5	Physical Test: Observe the actuator range of motion when it is functioning.
ACT.6	Torsional damping actuator must have minimum response time of $\pi/90$ rad/second	FUNCT.4	Physical Test: Observe the actuator response time when it is functioning.
ACT.7	Torsional damping actuator must have a resolution less than or equal to the smallest amplitude of oscillation	FUNCT.4	Inspection: Determine resolution of actuator from spec sheet
ACT.8	Combination of actuators must have vertical range of motion sufficient to damp any oscillation within 45 minutes	FUNCT.5	Physical Test: Measure the actuators range of motion in vertical direction.
ACT.9	Vertical damping actuator must have a resolution less than or equal to the smallest amplitude of oscillation	FUNCT.5	Physical Test: Give actuation device a command and measure the difference of the physical result and the desired result

Because all subsystems are restricted to the same space, their weight and volume requirements are dependent on each other. The subsystem weight and volume can be adjusted depending on what is selected for other subsystems. Size and weight constraints are crucial because, if these requirements are not met, the design will not be able to fit within a CubeSat and thus will never make it to space.

The control system must be able to provide damping for both torsional and flapping oscillations. This will require the control system to provide range of motion in two different planes. The actuators must also have an acceptable

level of accuracy so that desired pitch angles can be reached. Resolution of the actuator is important because of the small magnitude of disturbances in the blade.

### Sensor Requirements

Requirement	Description	Parent Requirement	Verification Requirement
SENS.1	Sensor subsystem shall fit within a 2U volume and weight within 1.3 kg/U.	FUNCT.1 ACT.1 ACT.2	Inspection: Measure the dimensions of the sensor subsystem and weigh it on a scale.
SENS.2	Sensor subsystem shall be able to detect with an error on the same order as the actuator error sense at a frequency of $\pi/90$ Hz.	FUNCT.4	Physical Test: Excite a test material to a known amplitude and frequency and compare this to what the sensor subsystem detects.
SENS.3	Sensor shall require less than 5 watts of power	FUNCT.2 ACT.3	Inspection: Measure the amount of power required to run the sensor.

The most important requirement of the sensor subsystem is being able to detect the magnitude and frequency of oscillations in the solar sail. The sensor subsystem must also be able to send data the software subsystem so that the control and actuator system can then implement effective damping responses.

The difficulty in designing the sensing subsystem is that the solar sail is extremely thin and lightweight. Therefore using sensors that must be in contact with the blade can greatly alter the dynamic behavior of the blade. Also sensing rotational and vertical displacement at the blade root will require higher accuracy and resolution since the inertia properties of the solar sail material only allow it to produce a torque on the order of 1 mN-m [11]. One of the greatest challenges of this project is designing an accurate sensing device that is compatible with the size and weight requirements.

### Electrical and Software Requirements

Requirement	Description	Parent Requirement	Requirement Verification
ELECT.1	Electronics subsystem shall be able to power all actuators and sensors using no more than 5 watts of power	FUNCT.3 ACT.3 SENS.3	Physical Test: Measure the amount of power that the electronics subsystem sends out to each individual subsystem.
ELECT.2	Electronics subsystem shall fit within a 6U CubeSat and have a mass no larger than 1.3 kg/U and allow room for the actuation system, bus, and other systems to be added.	FUNCT.1 ACT.1 ACT.2 SENS.2	Inspection: Measure the physical dimensions and weight of electronics subsystem.

SOFT.1	Software must be able to send commands to the actuators.	FUNCT.4 FUNCT.5 ACT.5	Physical Test: Use the software to give a command to the actuators. Measure the physical movement of the actuators compared to the commanded.
SOFT.2	Software must be able to effectively receive and interpret feedback data sent from the sensing subsystem.	FUNCT.4 FUNCT.5 SENS.4	Physical Test: Excite test material to a known frequency and amplitude. Compare this to what the software reads.
SOFT.3	Software must be able to implement effective feedback and damping control.	FUNCT.4 FUNCT.5	Physical Test: Demonstrate that when the software is turned on it provides a noticeable amount of damping when compared to when no damping is given. Test will be run on sail material.

The main requirement of the electrical subsystem is to provide power to all other subsystems. The electrical power is restricted to 5W which is the key driver in designing an effective electrical subsystem.

The main task of the software is to receive and interpret data sent from the sensor subsystem, send it through a feedback controller and then issue appropriate commands to the actuator/control subsystem which will provide damping and control to the solar sail blade. In order to verify that the software works, tests must be done in a low vacuum chamber for the reasons stated earlier concerning the damping effects of earth's atmosphere. This emphasizes the importance of being able to construct or to have access to a low vacuum chamber since it is needed to verify the functionality of many key components of the project.

## Key Design Options Considered

The requirements of the 2015-2014 GHOST team drive the design of a sensor system to measure heliogyro blade vibrations, and an actuator system to remove energy and damp the oscillations present in the blade. 4 actuator designs and 6 sensor system designs are considered in this section, with the pros and cons of each system listed explicitly. Additionally, design solutions to mitigate air damping for the test bed are described including a design for a low vacuum test chamber.



## Actuator Designs

### Series Motors

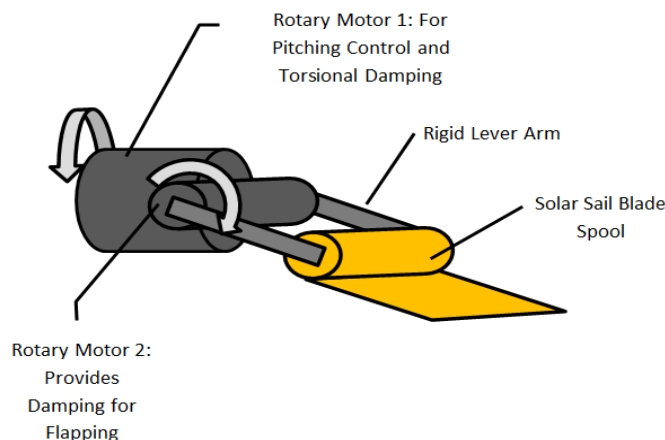


Figure 4: Series Actuator Design

This design consists of two electrical rotary motors that are arranged in-line with each other. The configuration provides pitch control, torsional damping, and damping for blade flapping. Rotary Motor 1 will provide a torque so that it can rotate the deployed solar sail to a desired pitch angle. This motor will also provide torsional damping for the blade. The second rotary motor, Rotary Motor 2, is rigidly attached to the rotational axis of Rotary Motor 1 and is positioned so that its axis of rotation is perpendicular to that of Rotary Motor 1. This way, when Motor 1 torques it is not only rotating the blade, but it is also rotating the second rotary motor. Rotary Motor 2 is then connected to the ends of the spool on which the blade is kept. The mechanical connection from this motor to the spool will be a rigid lever arm, such as bars or rods, so that when the motor actuates it will be directly moving the spool on which the blade is kept. This motion will allow for blade movement in the vertical plane, which

will provide damping to the flapping oscillations in the deployed blade.

Pros	Cons
Rotational actuators are very commonly used so there is a wide variety to choose from. Finding an actuator to fit our desired size, weight, power, and torque specifications should not be difficult.	The lengthwise size of this design may be too large depending on size of motors and need of allocated space for blade sensing package.
One actuator is used to control both rotational control and torsional damping.	Vertical displacement of blade is restricted to the length of the lever arm connecting the second rotary motor and the blade spool.
Simple mechanical design that uses a minimal amount of actuators	Weight and power could become an issue for heliogyro designs with many blades since each blade will require this bulky motor configuration.
Affordable design using electric motors	
High technical readiness level since all team members have had experience with motor control as well as many of our advisors.	

### Flexible Plate

One possible design to acquire a 2 degree of freedom motion for damping is through the use of a flex plate. The flex plate would use piezoelectric actuators. There are two basic designs for this concept. First would be one large piezoelectric attached at the root of the blade with the capability of moving the entire blade system linearly to damp out of plane flapping, and relying on the pitching motor to damp torsional disturbances. Second would be a design that uses two piezoelectric actuators on either side of the blade. These could move independently of each

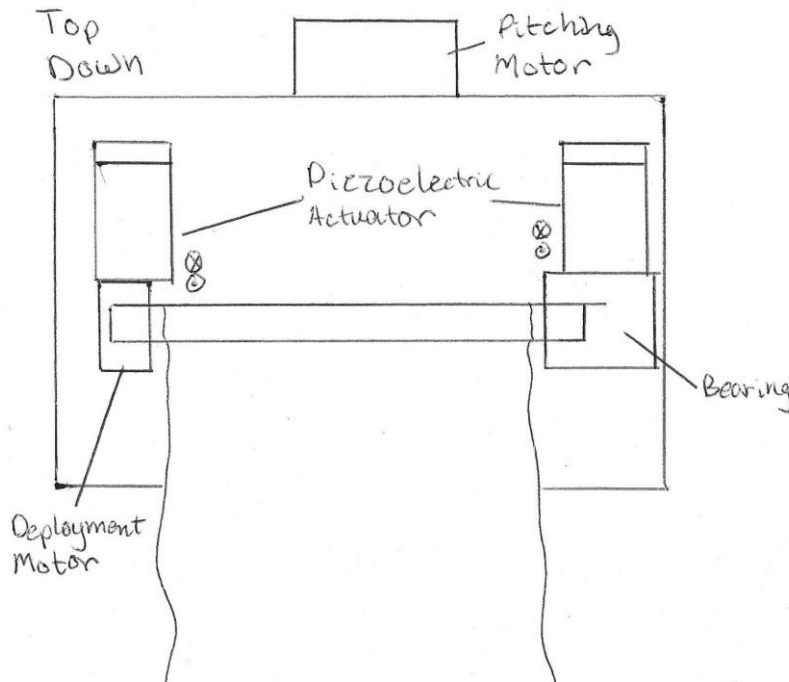


Figure 5: Piezoelectric Actuator Design

the disturbances expected to be seen in the blade are on the same order of magnitude. Piezoelectrics are not as common as standard motors, though several professors and staff have familiarity with them, leading to a moderate technology readiness level.

There are several drawbacks associated with using piezoelectric actuators. First and foremost is the power limitation of 5W. To reach maximum deflection, a typical bending actuator requires around 150V [10]. The power to the actuator would need conditioning to be able to reach these voltage levels. This adds a need for another board or circuit, adding mass and volume to the system. Another issue is that these actuators cannot produce high amounts of force, only a few Newtons. The root of the blade is not very massive however, and although it may slow down the actuator, it should be able to reach its commanded deflection quickly. Piezoelectrics also react to temperature, and common bending actuators will not perform correctly in a vacuum. Space-rated piezoelectric actuators do exist, though they are significantly more expensive. If used for this project, standard piezoelectric actuators will be used in their place.

other, allowing for damping of flap when moving in phase, and torsion when damping in opposite phases. This would remove the need for the pitching motor to be able to command precise motions. Because of the need for small, precise movements, the double actuator system is more likely to be chosen.

This system provides several advantages. Piezoelectric motors are very lightweight, and take up a minimal volume. Larger piezoelectric bending actuators will require less than 1 cm<sup>3</sup>[10]. They also provide deflection proportional to the amount of voltage they are receiving, leading to highly precise capabilities. The resolution of a piezoelectric actuator is dependent on the smallest voltage increment available from its power supply. Similarly, they have a nearly instantaneous response time, and can be commanded at frequencies over 100 Hz, much higher than the modes seen in solar sails. Although they have a small range of motion, between 1 and 3mm[10],

Pros	Cons
Fast response time	High voltage for maximum deflection, ~150V[10]
Frequencies to over 100 Hz, much higher than required	Low force
Low mass and volume	Spaceworthy actuators much more expensive
Precise movements, controlled by voltage down to micrometer	Low deflection
Moderately priced bending actuators (\$80-\$200) [10]	

### Parallel Motors

Another possible design is the use of parallel rotary motors for damping. As before, a single motor is used to command the arm and blade angle with respect to the main body, but damping of torsional and flapping

oscillations comes from two motors attached to the sides of the blade spool. Connections will have to be designed to raise and lower the ends of the blade in a linear fashion when the motors rotate. When the two motors rotate in the same direction, a flapping motion will occur. When they rotate in opposite directions, they will displace the ends of the spool in opposite directions, pitching the blade. The way the damping motors will be installed will make them incapable of satisfying a range of  $\pm 90^\circ$ , so the primary pitching motor is still necessary to achieve the range of  $\pm 90^\circ$  for commanded angles.

While the motors should be fairly reliable, there are complications arising from the necessity of three motors, as well as from the requirement of linearizing the displacement in order to avoid placing too much strain on the blade spool. In addition, this configuration takes up a larger amount of space and adds extra weight to the system.

The advantage of this actuator configuration, compared to the in-line motors, is that it does not intrude too much into the main CubeSat itself. It is also fairly easy to integrate into the original design. Depending on the motor chosen, it can be relatively low-cost, and can have a range of motion that might exceed what is necessary. Rotary motors are also well understood, resulting in a high technical readiness due to both student experience and available on-campus resources.

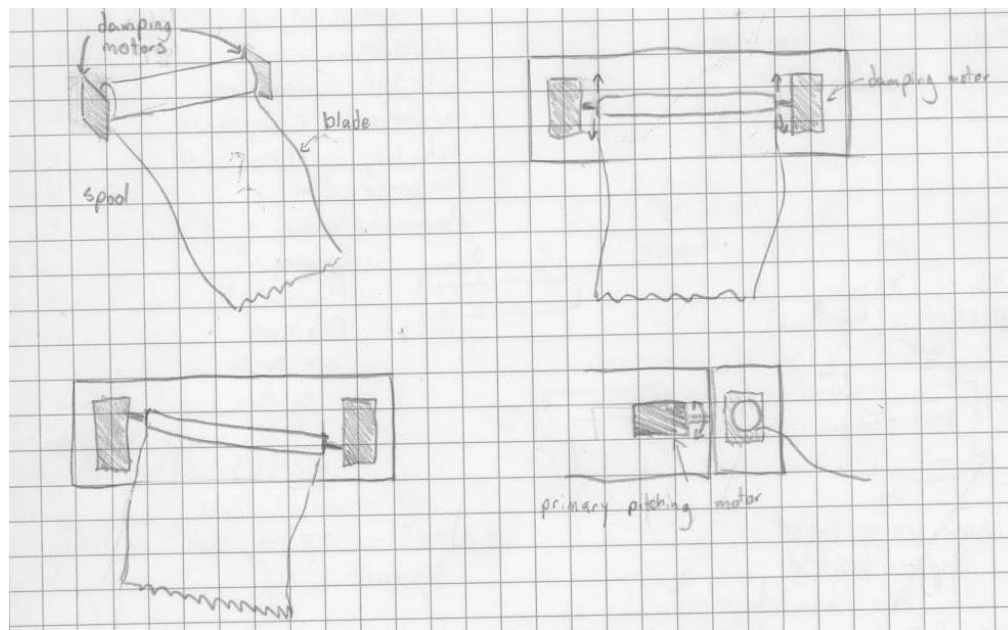


Figure 6: Parallel Motor Actuator Design

Pros	Cons
The commonality of rotational actuators allows for a large variety of choices.	Three motors increase the complexity, as well as weight and size.
Separating the pitching and damping motors allows for fine control.	More expensive than the series motor option
More easily compatible with last year's design	Limited flapping range
Does not extend so far into the primary body of the CubeSat	
Affordable design	
High technical readiness	

### SMA Actuators

Shape Memory Alloy (SMA) actuators are an alternative to standard motors. They would be configured in a similar fashion to the parallel motor option, with one actuator attached on either side of the blade root. They act in a linear fashion rather than rotating. Flapping would be damped through moving the actuators in the same direction, and pitching would be damped by moving them in opposite directions. Using SMA actuators will also necessitate having three actuators, including the pitching motor. Compared to standard motors, however, they are less massive and require less of the restricted volume within the spacecraft. Further advantages include a high displacement, allowing for faster damping and low power requirements.

SMA actuators are small wires that contract when heated. Contraction reduces the length of the wire by 2% to 5% of its total length, depending on the alloy used. This means the maximum deflection is controlled primarily by the

length of the wire. These are the least massive of all available options, having a diameter of less than 0.5 mm.[14] The speed of contraction is directly controlled by the current in the SMA. However, expansion is a result of the ability to release heat from the wire, which could be a cause for concern in vacuum. A heats sink could be used to make up for this. Unlike piezoelectrics, the magnitude of the deflection is not controllable; they are a binary system, either contracted or expanded. These actuators can only decrease from their original size, giving only one direction of motion from their nominal position.

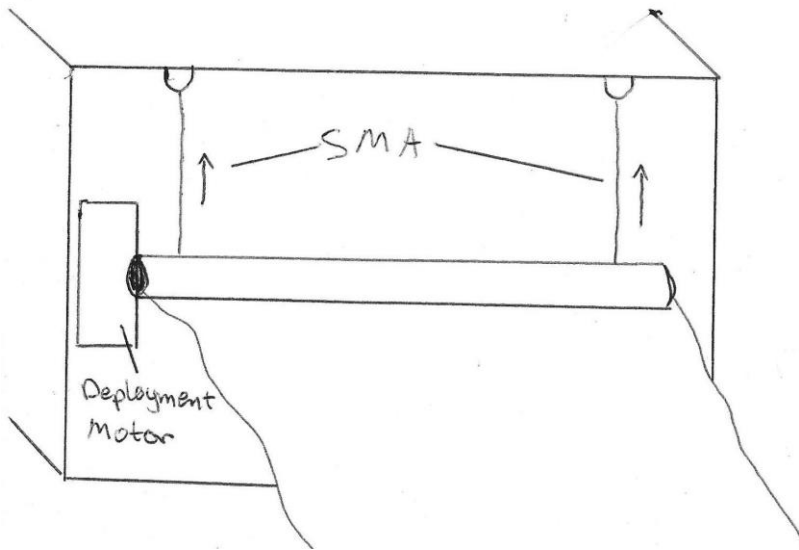


Figure 7 SMA Actuator Design

Pros	Cons
Lowest volume and mass of all actuator options	Contraction takes around 1 second, though it can be decreased with more power[14]
High displacement for size	Expansion requires cooling, difficult in vacuum[14]
Low power requirements (45-400mA)[14]	Low force
Low cost, \$10/m of SMA wire[14]	Heating from solar radiation may cause contraction
	Binary system, no control on magnitude of deflection, only the time to contract

## Sensor Package Designs

### Depth/Distance Sensors

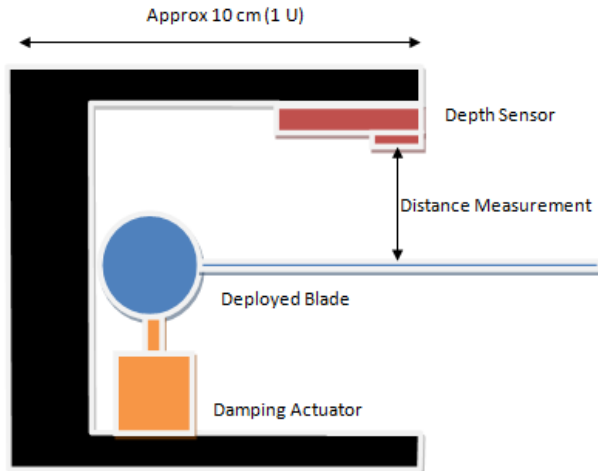


Figure 8: Depth Sensor Configuration

Measuring the oscillations and magnitude of the heliogyro blade can be done by sampling the deflection of the blade over time. Depth sensors capable of measuring these deflections can be positioned above the blade as shown in the figure above. Placing 2 sensors at the edges of the blade would even allow for the recognition of flapping, vs. pitching oscillations. Both sides of the blade deflecting in the same direction would be indicative of a flap, and would be indicative of pitching oscillation if deflecting in opposite directions. Depth sensors also will not need to place any hardware on the blade itself, and despite the An especially useful feature of this design is that the deflection of the blade will be in the direction that the blade needs to be moved by the actuators at the base of the blade in order to remove energy from the blade, meaning this could be a accurate, powerful design option without being complicated

Depth sensors, or time of flight cameras operate by sending out pulses of radiation, usually in the form of a light pulse or laser, and measuring the time it takes for the radiation to reflect back to the sensor. Distance is calculated by multiplying that time by a known speed of light. The resolution of this measurement is dependent on the resolution of the time measurement. Many off the shelf sensors are capable of resolutions of 1 cm. However, as shown in the figure above, the measurement of defection will have to be made by the depth sensor less than 10 cm from the base of the blade. Deflections of the blade at this distance will be small relative to the deflection at the middle of the blade, and the blade itself will be around 100 times longer than this distance. Instead, much larger resolutions, to within millimeters will be needed from this depth sensor to estimate deflections on the order of 10 cm at the peaks of any waveforms in the blade, assuming a sinusoidal interpolation of the blade's deflection.

Sensors that meet these criteria also seem to be affordable for the budget of the project, with some units costing as low as \$100. However, there are 2 other criteria that need to be satisfied. First, some of these models have a minimum distance requirement of around 10 cm. A solution to this requirement, assuming any other sensor without this requirement are unaffordable, would be to reflect the laser off a mirror before hitting the blade perhaps multiple times, but this would undoubtedly induce some level of inaccuracy in the blade that needs to be addressed. Finally, since depth sensors will have to operate in the space environment, with much higher levels of background radiation than on earth, the radiation emitted from the sensors will need to be distinguishable from other sources.

Pros	Cons
Non Contact sensor, does not interfere with blade deployment	Extremely short range measurements required (approx 5 cm)
Direct measurement of the direction in which actuators must move the blade	Measurement must be made close to base of blade. High resolution needed
Capable of measuring period and magnitude of period of oscillations	Depth sensors require power external, in some cases > 5 watts

Relatively low budget solution with some units costing approx \$100	Some depth sensors could be too large for a 6U cubesat platform
Sensor principles should allow for reliability in a vacuum	Radiation in the space environment could be problematic

One application of depth sensors is to measure the angle of deflection close to the root of the blade. This could be achieved using a set of four, short-range depth sensors located above and below the blade. Deflection upward or downward could be measured and translated into an angle and translated into a command for an actuator. Commanding the blade to move with the oscillations will remove energy from the oscillations. To detect flapping oscillations, one sensor under the blade could measure deflection. To compensate for the minimum sensing distance, an additional sensor above the blade would provide data if the sensor below was incapable and vice versa. To detect torsional oscillations, two sensors below the blade, one along each edge of the blade, could provide the blade's 'torsional deflection. As before, to satisfy the minimum sensing distance, additional sensors above the blade could provide data if the sensors below were incapable and vice versa. Additional sensors placed across the width above and below the blade could allow detection of the blade's behavior between its edges.

One major disadvantage of measuring the angle of deflection close to the root is the inability to detect the behavior of the blade some distance away from the root. This is a disadvantage because it does not allow for a full characterization of the blade's behavior, but it is not a fatal flaw. The ability to detect the behavior of the blade close to the root gives a general idea of the motion needed to remove energy from the oscillation; knowing the blade has a deflection and commanding the blade to move in the direction of the deflection will remove energy from the oscillation. Another disadvantage of this application is its inability to fully detect waves moving across the blade. Another disadvantage of this application is the accuracy of the depth sensor. For the depth sensors found, like the VL6180X Proximity Sensor from STMicroelectronics, errors in measurement could be as large as a centimeter. Oscillations with about a centimeter amplitude would go unnoticed or the actuators could be commanded to damp nonexistent motion.

### Proximity Sensor

This sensor type detects if an object is in front of it or not. The output is a voltage, low when no object is in front of the sensor, and the opposite for an object is blocking the sensor. Using an array of these sensors allows a characterization of the blade's behavior. A sketch of the setup for this sensor type is given below.

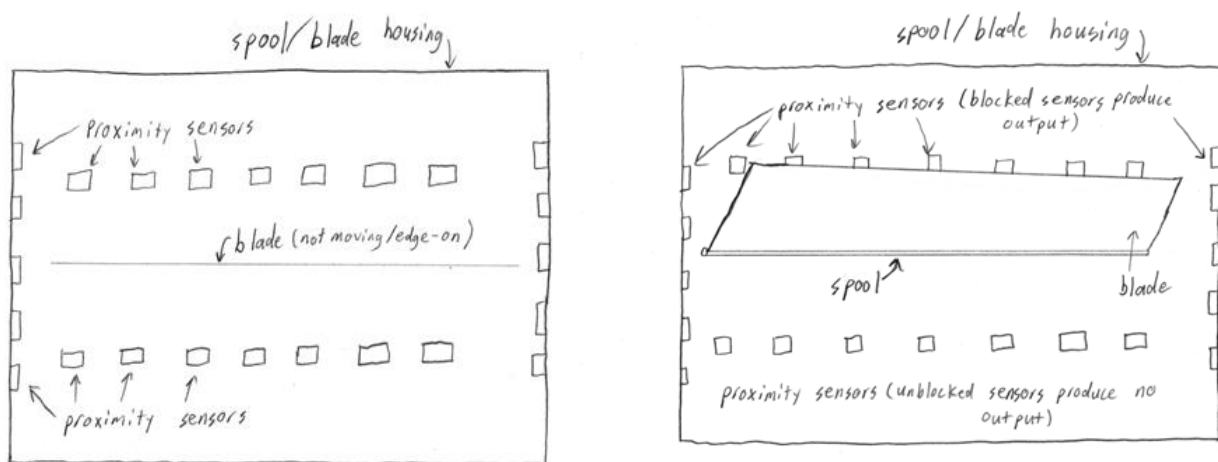


Figure 9: Proximity Sensor Configuration

Shown above is the layout and a general case, in this instance a flapping motion; the lack of a torsional mode in the drawing is not indicative of an inability to detect torsional modes. The sensors on the sides will be used in conjunction with those behind the spool to detect torsional modes.

One advantage of using this type of sensor is the ability to characterize the blade's motion further from the spacecraft than the depth sensors discussed above, which allows a better understanding of the blade's behavior overall. The Sharp IR proximity sensor is low cost, small, lightweight, has a high sampling rate, and seems to be integratable into the current design.

One disadvantage of this sensor type is the maximum sensing distance. The blade is meters long, and the maximum sensing distance for a small Sharp IR proximity sensor is 1.5 meters. Another disadvantage of using this type of sensor, much like for the depth sensor discussed above, is the background IR noise. There are sensors, like the Sharp IR proximity sensor, that are built to be resistant to interference from background IR noise, but they are not insensitive to IR noise. One final disadvantage of using this type of sensor is the need to maintain a temperature between  $-10^{\circ}$  and  $60^{\circ}$  C.

Pros	Cons
Low cost- The Sharp IR proximity sensor is about \$12	Noise from background IR radiation poses a problem for accuracy
Small, Lightweight- The Sharp IR sensor is small, with dimensions of 33 mm x 10.4 mm x 10.2 mm [1], and is lightweight with a mass of 2.5 grams. [1] This would allow a maximum of x sensors based on mass that can be added	Small maximum sensing distance
Low Power- The Sharp IR sensor has a maximum voltage of 5.5 V [1] and a requires a maximum supply current of 50mA [2] for a total power consumption of 0.275 W (neglecting losses due to wires)	Several sensors are needed, which could pose problems for processing, response time
Sampling Rate- The Sharp IR sensor has a sampling rate of 50 to 60 Hz, which is pretty good for sensing low-frequency behavior	Operating temperature $-10^{\circ}$ to $60^{\circ}$ C [2]
Easily integratable into current design	

[1], [2]

### Piezoelectric Sensors

The movement of the blade over time can be measured by the deformation of piezoelectric sensors. This is done by attaching a series of these sensors along the width of the blade as show in the figure above. The movement in the blade will cause the piezoelectric material to deform, which will create a charge on the material. The voltage that is discharged from the sensors can then be measured, and is directly proportional to the amount of deflection in the blade. This voltage would then be relayed to the damping actuator using a small transmitter and receiver. Tracking the strength of the voltages from the different sensors over time will yield the frequency of the mode the blade is undergoing. The amplitude of these oscillations can then be determined by the amount of voltage that is being transmitted.



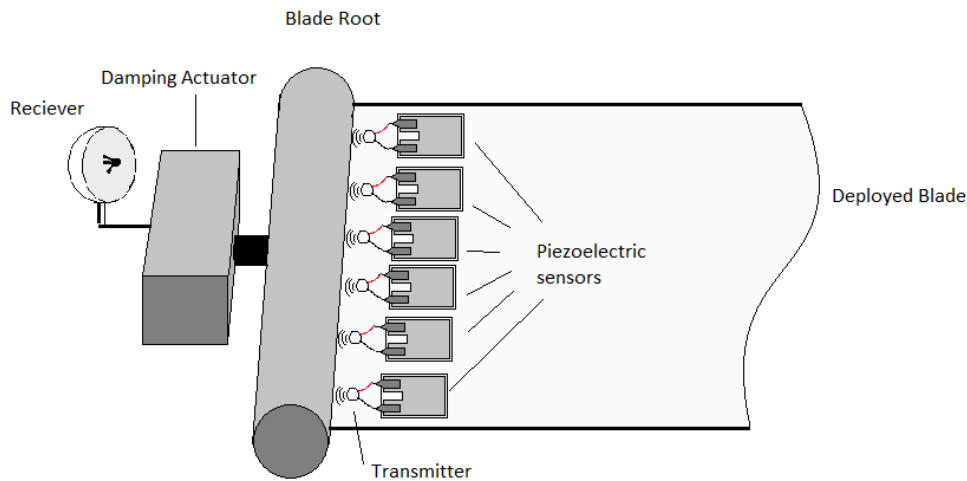


Figure 10: Piezoelectric Sensor Configuration

One advantage of using this model is that the sensors are small and lightweight, which leaves more room for the actuator(s). The type of sensor that was being considered is 2.5 x2.5 cm and only .125 mm thick. These type of sensors are also cheap, starting at \$3 a piece. Another advantage of using piezoelectric sensors is that they are able to power themselves, which leaves more power for other systems.

There are many disadvantages with using this model to determine the mode shape. A series of the piezoelectric sensors would be unable to distinguish a torsional deflection from a in-plane deflection. This is because any deformation of the piezoelectric film causes a charge to be built up. The biggest challenge would be to successfully integrate the sensors into the blade. The accuracy and resolution of these sensors is dependent on the circuit it is linked to. This means that many electronic elements would have to be connected to the sensor and the transmitter. It is unlikely that the blade would be able to support this weight. If the blade was instead connected to an interface between the root that could support the electronics, it would still leave the problem of storing, transporting and deploying the blade in a controlled manner. Assuming that this problem could be overcome, The sensors operating temperatures are between 0 and 85 °C. Sensors are available with a larger operating temperature range but are cables and not thin sheets that can fit on the blade. The piezoelectric sensors are better used to measure vibrations on the kHz scale. The sensitivity of the sensors are about 100 times smaller when measuring small frequencies.[12]

Pros	Cons
Capable of measuring period and amplitude of oscillations.	Contact Sensor, the additional weights will affect the dynamic modes of the blade and will be difficult to integrate into the material.
Low cost, units cost as little as \$3	Low sensitivity at low frequency vibrations (0.01 V/g @10 Hz)[12]
Sensors power themselves from the piezoelectric effect caused by deformation.	Unable to accurately distinguish torsional wave from in-plane due to the voltage produced from any deformation
Units have low mass and volume relative to the Cubesat, which allows more space for other systems.	Operating temperature not ideal for space environment.



### Lateral Effect Photodiodes (LEPDs)

One option for determining the behavior of the solar sails is using lateral effect photodiodes (LEPDs). LEPDs take advantage of photoelectric effects which induce currents in some materials. This effect causes current of varying strength which are related to light of varying intensities. The resistance is proportional to the distance from the output terminals to the point where the light strikes the photosensitive material. [7] The setup for this project uses a light source reflecting off of the solar sail and onto a LEPD. This allows sensing of the position of the blade by measuring the current output and correlating it to both the intensity and position of the reflected light. A sketch of this seen is given below.

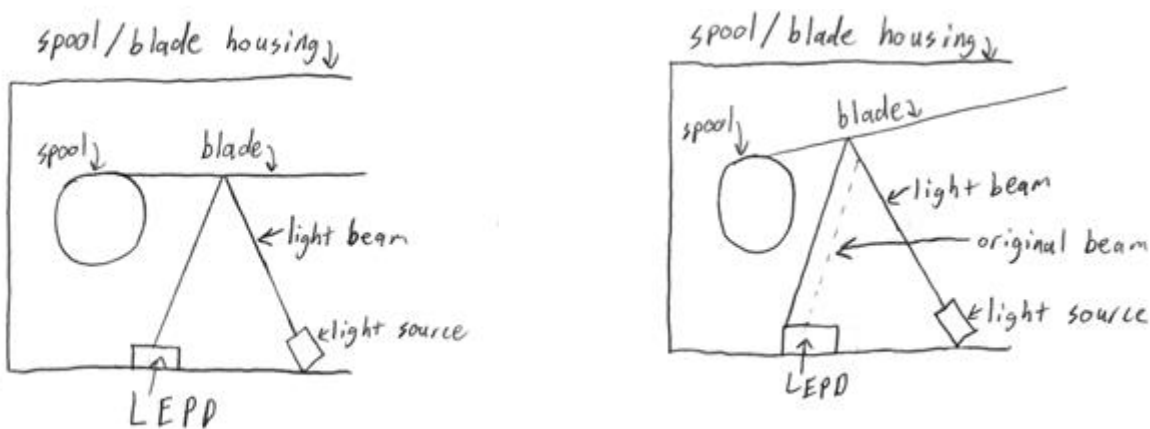


Figure 11: LEPD Sensor Configuration

The sketch above shows the layout and a general case, and again the case of the blade flapping is used to generalize the setup; the lack of a torsional mode in the drawing does not denote an inability to sense torsional modes. Using more than one sensor allows detection of torsional modes.

Advantages of using this setup include a rise time on the order of hundredths of microseconds, error of about 30 micrometers, and its small size. This sensor type is somewhat costly at about \$150 per sensor, but is also cheaper than some other sensor types. LEPDs are available with sensitive areas in a range from 2 mm square to 20 mm square. [9]

A drawback for this setup is that it is limited to sensing at the root. As with all other sensor options for sensing at the root, this allows only a limited characterization of the behavior of the blade. Another disadvantage is that multiple LEPDs would provide a better characterization than just one, which suggests the use of multiple sensors.

Pros	Cons
Lower cost-around \$150 per sensor [9]	Multiple sensors needed
Size-available from 2 mm square to 20 mm square [9]	Sensitivity to temperature
Response time-around 0.025 microseconds [9]	Sensing must take place at the root
Error-30 micrometers [9]	Error increases with the size of the sensor
High sensitivity-0.3 Amps/Watt [9]	Price increases with the size of the sensor
Easily integratable into current design	

[9]

### Image Processing

Image processing is another sensor option. This would involve placing markers along the blade, and a camera near the root, attached to the blade housing. The camera would take consecutive pictures, which would be processed to determine the motion and distance of the markers. By placing markers two separated markers for each location along the length of the blade, we could track both flapping and torsional motion. The advantage of measuring blade displacement further from the spool is the greater range of motion. The need is no longer for millimeter precision, as the further portions of the blade move larger amounts. Unfortunately the computational cost of this would be considerably greater than the other sensor options.

The size and location of the markers (possibly reflective or colored stickers) would be tracked with image processing software, and this would be passed to other coding that could determine how this correlates to the position of the blade. A large amount of calibration would be required. The extra computational power needed for image processing would narrow the range of possible microcontrollers, and the primary cost in this instance would not be the camera, but the board or boards housing the software. The camera also takes up greater space than many of the other options, and weight is a factor as well.

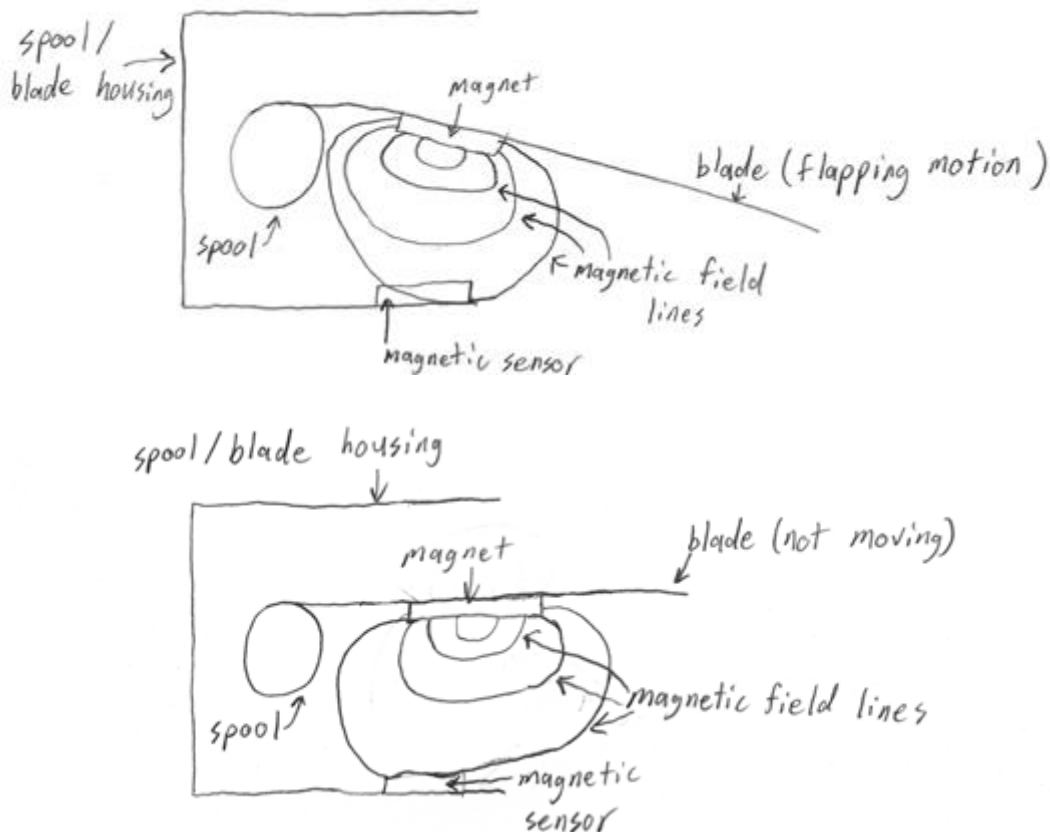


Figure 12: Image Processing Sensor Side Profile and Field of View

Pros	Cons
Lower resolution required	Relatively large weight and size
Variety of choices	Computationally expensive. Increased cost from processor choices.
The actual camera can be relatively inexpensive.	Extensive calibration needed
	Requires putting something on the blade

### Magnetic Sensors

Another option for detecting position is to use a series of magnetic sensors. This configuration uses magnets placed along the blade to detect position. As displacements occur in the blade, the movement of the magnets changes the magnetic field detected by the sensors and the sensors produce a voltage proportional to the motion. [3] This is done by taking advantage of the Hall effect, which is a “separation of charges across a current-carrying wire.” [6, pg 442] The sensor uses a current to determine the Hall potential and by knowing the current, the Hall coefficient, and the thickness of the conductor in the direction of the field, the magnitude of the magnetic field can be determined. [6, pg 442] A schematic of this configuration is given below.



One advantage of using magnetic sensors is that they are small, lightweight, and cheap. Another advantage is the

*Figure 13: Magnetic Sensor Configuration Diagram*

relatively large operating temperature range from  $-40^{\circ}$  to  $150^{\circ}$  C. [3]

One disadvantage of using this type of sensor is that it is a short range sensor. Another disadvantage of using this type of sensor is that magnetism is generally a problem with spacecraft, to the point that Faraday shielding is used on wires to prevent interference in the wires used, and to prevent the wires used from interfering with other instruments. This indicates a two-fold disadvantage: interference from systems on the spacecraft adding noise to measurements and the magnetic fields added to the blade for measurement causing interference with systems on the spacecraft. Another disadvantage is the necessity of adding magnetic strips to the blade or a magnetic coating.

Pros	Cons
Low cost- some cost around \$1, magnetic strips are fairly cheap as well (\$59 for a roll 100 ft long [4], or \$6 for a roll 7 ft long [5])	Noise from spacecraft
Small, Lightweight- the sensor is just a chip, magnetic strips are 5 lbs for every 100 ft [4], or 0.05 lbs per foot	Small maximum sensing distance
Start up time of 5 ms [3]	Required to attach magnets to the blade or a magnetic coating to be applied to the blade
Operating temperature $-40^{\circ}$ to $150^{\circ}$ C [3]	
Easily integratable into current design	
Minimum refresh rate of 281 micro seconds [3]	

[3], [4], [5]

## Test Bed Design

Testing the controller will involve hanging the blade from a ledge equivalent to its length and exciting the modes first by pitching the blade or by using the actuators directly. The presence of air damping will not necessarily mean the controller's ability to damp the blade cannot be modified. Demonstrating that oscillations in the blade decrease faster when the controller is on instead of off, will validate that the controller is working, so it is acceptable to have air present during the test. However, our customer has expressed serious concerns that the air will present too much damping to accurately measure controller performance, so designs have been proposed to eliminate air damping in the event that this is necessary.

## Rope Ladder

Heliogyro blade dynamics have been described as similar to those of a "rope ladder" by several sources [14] [15], especially in the case where the blades are edge loaded, with small amounts of tape being placed along the sides of the blade. Perhaps the simplest method of air mitigation would be to cut square holes in the blade material, essentially creating a rope ladder from the blade. The removing the extremely lightweight blade material will not change the blade dynamics significantly, and having a rope ladder shape will give the air far less surface area to interact with which will reduce air damping significantly.

## Low Vacuum Chamber

Due to the length of these blades, the use of a high vacuum chamber to remove air is impractical. However, it is possible to construct a low vacuum chamber which will remove a majority of the air present during testing. The low vac chamber would be a cylindrical pressure vessel in order to account for the length of the blade. The walls of the chamber will likely be constructed from PVC piping, which is commercially available in diameters up to 0.6 meters. The large diameter 20

meter lengths of large diameter lengths of PVC pipe are expected to cost on the order of \$500 [16], which is compatible with the project's budget. A possible challenge with this design that tests will have to be filmed by cameras inside the chamber and cannot be observed directly, but this should not be a problem using battery powered cameras and light sources. Sealing the PVC and creating a vacuum will require the expertise of Matt Rhodes, but with his experience, construction of a low vacuum chamber should be a practical method of air damping mitigation.

These test bed design solutions are not mutually exclusive, meaning a rope ladder blade can be tested in a low vacuum chamber. Since the rope ladder solution is considerably less expensive and time consuming. This solution will be attempted first if air damping proves too large. Construction of a low vacuum chamber, which offers greater damping mitigation, will follow if necessary. Following this process does not require that we perform a trade study on these options. We already have plenty of solar sail material to experiment with, so we can begin assessing air damping immediately.

## 4.0 Trade Study Process and Results

To compare each of these options, a set of metrics were defined. These characteristics were chosen to describe the overall pros and cons for each choice, allowing us to easily identify the best options via numerical rankings. Each metric was given a weighting between 1 and 5 based on its relative importance to the design as a whole. For the sensor trade study, the following trait, along with their relative weights are described below:

### Cost - 5

Within the Senior Design Project, the allowed budget is not negotiable and therefore it cannot be changed. Because the Budget is hard capped at \$5000, the team must make sure that the price range for the components need to be low enough so all the parts of the project can be built. When looking at different sensors it came to the concern of the team that some sensors could possibly cause the team to go over the \$5000 limit. In this study a 1 is associated with a higher price while a 5 corresponds to a lower price.

### Precision/Resolution - 5

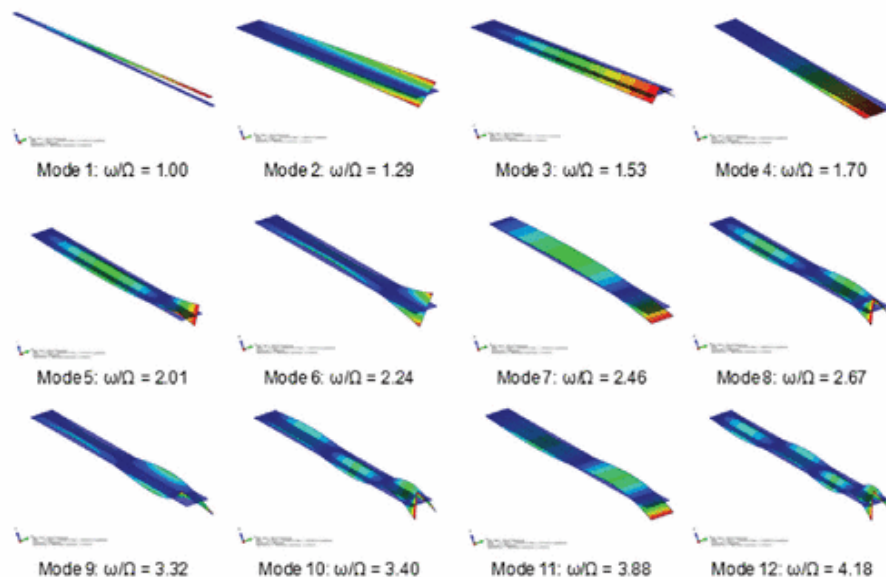


Figure 14: Expected Mode Shapes of Associated with Heliogyro Blades CREDIT [13]

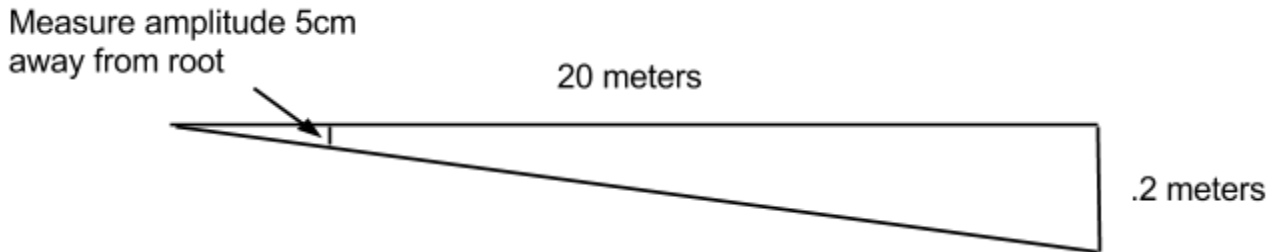


Figure 15: Deflections Estimates near the Root of the Blade

From the known modes of the solar sail it is easy to find that the blade will be encountering very slow oscillations, but at very low amplitudes. The amplitudes are calculated from the known dimensions of essentially what are triangles that are created on the blade. The distance for the tip deflection was found from research done on the HELIOS which show the maximum tip deflection [13]. From this knowledge simple geometry was used to understand that the maximum deflection seen at the measuring station should be around .5mm. In addition, this position was used as the measuring station because the farther from the root the measurement station is, the larger the amplitudes. Therefore from the analysis it can be seen that if the resolution of the blade is larger than .5mm then we cannot damp the blade because the displacement cannot be matched by the system.

#### **GHOST Integration - 4**

The project being developed by this year's senior design project is building on the success of the deployment system developed by the previous GHOST team. For this reason, the sensor cannot interfere with the deployment system and therefore a higher rank was given. In addition, the sensors must be able to fit within the 6U requirements of the entire system therefore a smaller sensor is preferred so that more room can be used for the actuators. In this trade study a 1 is associated with a larger size and/or non-compatibility with the GHOST deployment system.

#### **Noise/Accuracy - 3**

This category looks at the effect of noise on the accuracy of the sensor, which was ranked in the middle because noise can sometimes be removed if it is constant. Within space there are many things such as radiation that may affect the sensor, depending on which sensor is used. If the accuracy is off by a little bit then the vibrations in the blade can be miscalculated, especially when the vibrations seen are barely a millimeter. With this in mind, within this trade study a 1 is associated with a lower accuracy and/or a higher susceptibility to noise.

#### **Power - 3**

The power in the system was ranked in the middle because the main purpose of the system is to show the damping system created can be tested. This means that in an earth setting, the damping should be noticeable and therefore power should not be ranked as high but still in the middle due to it being a customer requirement. Within the trade study a 1 is seen as higher power.

#### **Technology Readiness Level - 2.5**

This category describes the current availability, ease-of-use of the selected products and the knowledge that is out there. Because of the internet and the knowledge of the professors at the University of Colorado at Boulder this metric was ranked lower. The concern with this metric would be if no professor had knowledge on the sensor and would create trouble for any sensor. For this metric a 1 is seen as a design that does not have any knowledge on campus and no knowledge within the group.

#### **Response Time - 2**

The blade's fluctuation modes are expected to have very low frequencies, on the order of minutes per oscillation. Any sensing options will have sufficient response time to accurately detect these modes. However, having a faster response time will allow for better modeling capabilities because it gives better data about the oscillations on the blade. In addition, if the sensor does not measure the peak of the oscillations the period of the entire system could be off. Therefore since most sensors have this metric met, the team has decided that the metric should be placed low to eliminate the sensors that do not meet this metric. In this trade study a 1 is attributed to a low response time from the sensor to the board that will read the data.

For our trade study involving actuators, there are several overlapping categories with corresponding design intentions. These include: **Cost**, **GHOST Integration**, **Power**, and **Technology Readiness Level**.

#### **Cost - 5**

Within the Senior Design Project, the allowed budget is not negotiable and therefore it cannot be changed. Because the Budget is hard capped at \$5000, the team must make sure that the price range for the components need to be low enough so all the parts of the project can be built. In this study a 1 is associated with a higher price while a 5 corresponds to a lower price.

#### **Precision/Accuracy - 5**

For the purpose of actuators, these two categories are combined to express how well the motors will be able to move to the desired position. Like stated in the precision section for the sensor, the amplitude we expect to see from preliminary designs is less than a millimeter. Therefore if the actuator does not meet this qualification it cannot step with the oscillations of the blade and could cause a greater vibration in the blade. Overall, this seems like an important part to the project and therefore a high weight was given to this metric. In this study, a 1 is associated with a motor that does not have the accuracy to go to a commanded displacement and/or great accuracy when moving to a displacement.

#### **Response Time - 4**

This describes the response in the actuator to move to a desired displacement after the onboard computer gives it a command. This is an important metric because if the motor does not move to the desired displacement in time, the blade could have an increased vibration instead of a decay. In addition, within our research it was found that some actuators struggled to achieve movements in a small amount of time. Because of these reasons the response time was given a high rank in the trade study. Finally, in this trade study a 1 is associated with an actuator that takes a long time to execute a desired movement.

#### **GHOST Integration - 4**

The current control system being developed by this years team is building on the success of the deployment system developed by the previous GHOST team. For this reason, the actuator cannot interfere with the deployment system and therefore a higher rank was given. In addition, the actuators must be able to fit within the 6U requirements of the entire system therefore a smaller actuator configuration is preferred. In this trade study a 1 is associated with a larger size and/or non-compatibility with the GHOST deployment system.

#### **Mechanical Complexity - 3**

The mechanical complexity of the actuators is an important consideration, but not a metric that should remove an entire design. The mechanical complexity is a metric that describes how difficult a design would be to be implemented and if it was feasible to place a certain actuator configuration into the system. Within this trade study a 1 is associated with a design that cannot be implemented and has very hard difficulty being placed onto the GHOST system.

#### **Technology Readiness Level - 2.5**

This category describes the current availability, ease-of-use of the selected products and the knowledge that is out there. Because of the internet and the knowledge of the professors at the University of Colorado at Boulder this metric was ranked lower. The concern with this metric would be if no professor had knowledge on the actuators and would create difficulty implementing the system. For this metric a 1 is seen as a design that does not have any knowledge on campus and no knowledge within the group.

Each of the options for sensors and actuators are scored based on these categories, and multiplied by their respective weightings to create a sum total score:

Sensors	Weight	Weight %	Depth		Proximity		Piezo		Magnetic		LEPD		Image Processing	
			Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Cost	5	0.204	3	15	5	25	5	25	5	25	3	15	3	15
Precision/Resolution	5	0.204	3	15	3	15	2	10	3	15	4	20	5	25
Cubesat Integration	4	0.163	4	16	4	16	2	8	3	12	5	20	2	8
Noise/Accuracy	3	0.122	3	9	3	9	4	12	4	12	4	12	4	12
Power	3	0.122	3	9	3	9	5	15	5	15	3	9	2	6
Tech Readiness Level	2.5	0.102	5	12.5	3	7.5	3	7.5	4	10	4	10	3	7.5
Response Time	2	0.082	5	10	5	10	5	10	5	10	5	10	1	2
			86.5		91.5		87.5		99		96		75.5	

Figure 16: Trade Study of Proposed Sensor Designs

The depth sensor configuration received a score of 3 for the cost since high resolution depth sensors cost over \$100. The image processor was also given a score of 3 not because of the cost of a suitable camera, but because a number of extra components would need to be added to the microprocessor, and a more expensive microprocessor would be needed in addition to the camera. The LEPD configuration received a 3 because just one costs around \$150, and multiple sensors are needed. The magnetic sensors, piezoelectric sensors, and proximity sensors all received a score of 5 because each of those sensors cost less than \$20 a piece.

The depth, proximity, and magnetic sensors received a score of 3 for precision/resolution because of their short sensing range or because increasing the number of sensors increases the resolution. The piezoelectric sensor setup received a score of 2 because although it provides information on the magnitude of the blade's displacement, it does not provide information on the direction of the displacement. The LEPD has an error on the order of hundredths of micrometers, but is still limited to sensing at the root of the blade, so it received a score of 4. The image processing setup received a score of 5 because it provides the most information and therefore the highest resolution of any of the sensors.

The depth and proximity sensors received scores of 4 for CubeSat integration because they do not require changes to be made to the blade in order to function, but are larger than other options. The piezoelectric sensor received a score of 2 because, even though it is small, it must be placed on the blade to provide information, and the weight of the blade cannot be altered if at all possible. Similar reasoning gives a score of 3 for magnetic sensors, but since a magnetic coating could potentially be used and would interfere less with the weight of the blade, it is given a higher score than the piezoelectric sensor. The image processing setup is a bit heavier than other options, so it received a score of 2. The LEPD is scored at 5 because it is small and does not require any changes to the solar sail.

The depth and proximity sensors sense light in the IR band, and because of the amount of IR noise in space they received scores of 3 for noise/accuracy. Piezoelectric sensors, magnetic sensors, LEPDs, and the image processing configuration received scores of 4 because each setup has temperature-dependent error or requires temperature maintenance.

The depth sensor, proximity sensor, and magnetic sensors were given a 3 for power because they require power from the spacecraft. The LEPD needs a light source powered by the spacecraft, so it also received a 3 for power. Since the microprocessor and camera both need power from the spacecraft, the image processing configuration received a 2 for power. The piezoelectric sensors do not require power from the spacecraft, so they received a score of 5 for power.

The image processing setup, proximity sensors, and piezoelectric sensors received scores of 3 for technology readiness level because they are the most difficult of the sensor types to configure and/or work with, but should not be beyond the capability of the team. The magnetic sensor and LEPD received scores of 4 because they simply generate current outputs, which are fairly easy to translate into a command for actuators. The depth sensor received a score of 5 because it outputs a voltage, which is the easiest to translate into a command for actuators.

Consideration was given to response time, but given the period of oscillations is expected to be on the order of 1000 seconds, all configurations received scores of 5 except the image processor. The image processor received a score of 1 because it is uncertain how long it will take to process its output and because the other types are relatively much faster.



Actuators	Weight	Weight %	Series Motors		Parallel Motors		Piezo		SMA	
			Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Cost	5	0.196	4	20	4	20	3	15	5	25
Precision/Accuracy	5	0.196	2	10	4	20	5	25	2	10
Response Time	4	0.157	3	12	3	12	5	20	2	8
Power	3	0.118	3	9	3	9	2	6	4	12
Cubesat Integration	3	0.118	2	6	3	9	3	9	4	12
Mechanical Complexity	3	0.118	4	12	2	6	2	6	3	9
Tech Readiness Level	2.5	0.098	5	12.5	5	12.5	3	7.5	2	5
			81.5		88.5		88.5		81	

Figure 17: Trade Study of Proposed Actuator Designs

Of the 4 options considered for actuators that could be used for the GHOST damping system, ultimately the use of piezoelectric actuators, or parallel motors proved to be the most prudent design solution according to our trade study. Both of these options scored close to 90 points overall whereas the SMA and series motor actuator designs scored roughly 10 points lower.

Though each actuator option was affordable based on the project's budget, the piezoelectric actuators were considered to be more expensive than other options and were only scored a 3. Both configuration with motors were relatively more affordable, scoring 4's but SMA material was noticeably cheaper and was scored a full 5 points.

SMAs however, were the one of the worst options for how well they could be commanded to a specific angle/displacement, since the direction of their bending motion can be unpredictable. The series motor option also scored poorly in this category since this configuration would require that motor that pitches the blade also be responsible for damping. Piezoelectric actuators had the highest precision/accuracy score of 5 since some of the options available have resolution on the order of nanometers.

Piezoelectric actuators also have the best response times, since the supply voltage will dictate the deflection of the actuator directly. The series and parallel motor configuration require that magnetic fields be generated before the electric motors begin to torque, meaning they are not quite as responsive. SMAs however, scored the lowest because they have a required cool down period. The difficulties involved in understanding how long is needed for the SMAs to return to a non-contracted state make them a difficult choice.

Most options scored similarly for power, though piezoelectric actuators scored the lowest due to the high voltage differential required to deflect the piezoelectric actuator. Though the piezoelectric actuators can still be used with a 5 watt power supply, choosing piezoelectric actuators would require that the team develops circuits capable of generating voltage potentials of greater than 50 volts.

Most options also scored similarly for CubeSat integration since the designs are expected to occupy the same volume. One exception would be series actuators option, which would likely require a large pitching motor to protrude into the center of the CubeSat which is needed for other satellite subsystems

Finally, for the tech readiness level, the motor actuator solutions were both scored 5 since the team has experience using these motors and these are fairly common hardware components. No one on the team has had experience working with SMAs or piezoelectric actuators, though based on a preliminary survey of the senior design faculty advisors, there are several resources we can use to help implement a piezoelectric system. There appear to be more staff members that are familiar with piezoelectric actuators than SMAs though.

## Selection of Baseline Design

Based on trade study analysis, two options for sensor and actuator designs appear to be the most prudent designs to move forward with.

### Sensors

#### Magnetic Sensor

The magnetic field sensor design proved to be one of the best options from the trade study due to the high resolutions that it is capable of measuring and the relatively low power requirements. The main drawback of the design is that it does require coating a section to GHOST's blade with magnetic material which depending on the amount of magnetic material needed could change the blade dynamics and increase the complexity of any FEM modeling. The thickness of the layer of magnetic material will need to be established concretely in order that a measurable magnetic field can be generated. However, if this modification of the GHOST blade allows for the blade to remain deployable and controllable, then the use of magnetic sensors could prove to be the best design option.

#### Lateral-Effect Photodiodes

This sensor design received the second highest score behind the magnetic sensor. This is a result of the high precision/accuracy of the device and its easy integration with the current GHOST design. These are two heavily weighted metrics in the trade study which gives sufficient reasoning as to why it would be an effective design solution. Another key advantage of the LEPD sensor is that it is a non-contact sensor, meaning no adjustments to the deployment mechanism of GHOST's blades when using this sensor and LEPDs will not complicate models of solar sail blade dynamics. The LEPD also has a virtually continuous sampling rate, and is small and lightweight which should allow for it to be more easily implemented in GHOST's CubeSat platform. With the high precision and accuracy of this device, with error on the order of hundredths of a micrometer, the sensor subsystem will be able to accurately detect blade oscillation and frequencies. This will allow for the software to issue appropriate damping commands to the controller so that blade oscillations can be quickly and efficiently damped.

### Actuators

#### Parallel Motors

The parallel motors actuation configuration tied for the highest trade study score, which implies that it is a design in which the team should continue to move forward with and analyze its advantages and disadvantages more intricately. The key features that separated this design from the others was its precision and accuracy as well as its response time. This design received high scores in both these areas, which were heavily weighted metrics in the trade study. When the parallel motor configuration is compared to the series motor configuration in the trade study table it can be seen that the two designs received very similar scores for all metrics except for the areas of precision and accuracy and mechanical complexity. The series motors were deemed to be much less mechanically complex, however since precision and accuracy is a more heavily weighted metric, the parallel motor design received a higher weighted score. This is essentially what separated the two designs in the study and is why parallel motors would be a better choice for the project.

When compared to SMAs the parallel motor design scored higher in precision and accuracy as well as response time which are two heavily weighted metrics. For this reason the parallel motor design would be a better choice for meeting design requirements.

#### Piezoelectric

Parallel piezoelectric actuators tied with motors for the best actuator configuration. They received high scores in precision as well as response time, two of the more highly weighted trades. They would require less volume within the CubeSat compared to a motor, and would also be less massive. They are more expensive than a motor, but are available in a reasonable price range for this project's budget.

This design would require more signal conditioning to reach the higher voltage requirements of piezoelectric actuators, but it is believed that the appropriate voltages can be reached within the 5 watt limit. Deflection of these actuators is directly proportional to the voltage they are experiencing, making them highly precise. Although they are less common than standard motors, there is enough knowledge and resources within the department to use them.

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