December 1, 2017

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John A. Carr
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Dear Mr. John A. Carr,

First off, we would like to thank you for coordinating and sponsoring our senior capstone project. We are continuing to work hard at completing our project and soon we will be starting with the design process. We wholeheartedly plan on completing our project to the best of our ability and assure you that we will have a complete, working prototype at the end of the Spring semester. We chose this project because one, we are both interested in aerospace technologies and the future that it pertains to. Additionally, we felt that this project in particular was achievable based on our skills and current knowledge.

In this report, we will first be elaborating on the problem definition. In this section we will define the problem as well as the needs, constraints, and goals of the project. This section will also feature a description of the system we choose to implement. The next section of the report will encompass the current research we have completed for the project. This section will go into depth on the current technologies available and the possible problems and constraints of our current solution. Then we will go over the engineering requirements of our solution. There will be six categories of requirements we will explain being mechanical, documentation, electrical, software/GUI, environmental, and general. Lastly, we will provide an overview of several different subsystems necessary to our design, and will provide prototyping goals for each subsystem.

Overall, we look forward to your feedback and response pertaining to this report and our project. Thank you again for your endorsement.

Alexander Mueller & Daniel Krollman

Solar Array Deployment System

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II. Problem Definition:

The problem that NASA presented to us was to design and prototype a solar array deployment system for CubeSats. CubeSats are small, light, compact satellites that are mainly used for low earth orbit (LEO) research. Typical rockets can deploy several CubeSats in a single launch, keeping the cost of each satellite relatively low. Our design will be based around the LISA-T 4x Triangular Planar Solar Array Configuration. This configuration unfolds into a flat planar array, which will be easier to articulate than the omnidirectional array option. Both configurations currently lack the ability to be pointed at a light source without adjusting the orientation of the spacecraft itself. Articulating the spacecraft is not always an option, so it is important that the array can articulate itself to maximize power production for the spacecraft.

The deployment system must be capable of pushing a "deployment panel" which holds the stowed solar array up to 1 meter away from the body of the CubeSat. Once the planar array is deployed, the deployment panel can be articulated to point the array towards the sun to produce maximum power for the spacecraft. Ideally, the articulation will happen automatically, with input data from external sources to point the array at the sun. The articulation must also be able to point the deployment plate ±45° in both the X and Y axis directions. The articulation may also be controlled remotely by a control computer. In addition to the deployment and articulation, the deployment mast must be able to retract back into the spacecraft.

Looking forward, this system could be adjusted to work with other foldable CubeSat solar arrays, to allow maximum power production. It could also be scaled up, and used on larger spacecraft solar arrays. Overall, a system like ours will allow solar arrays to maximize power production, so it could theoretically also be implemented on ground-based solar arrays.

The following picture depicts the design of our system.

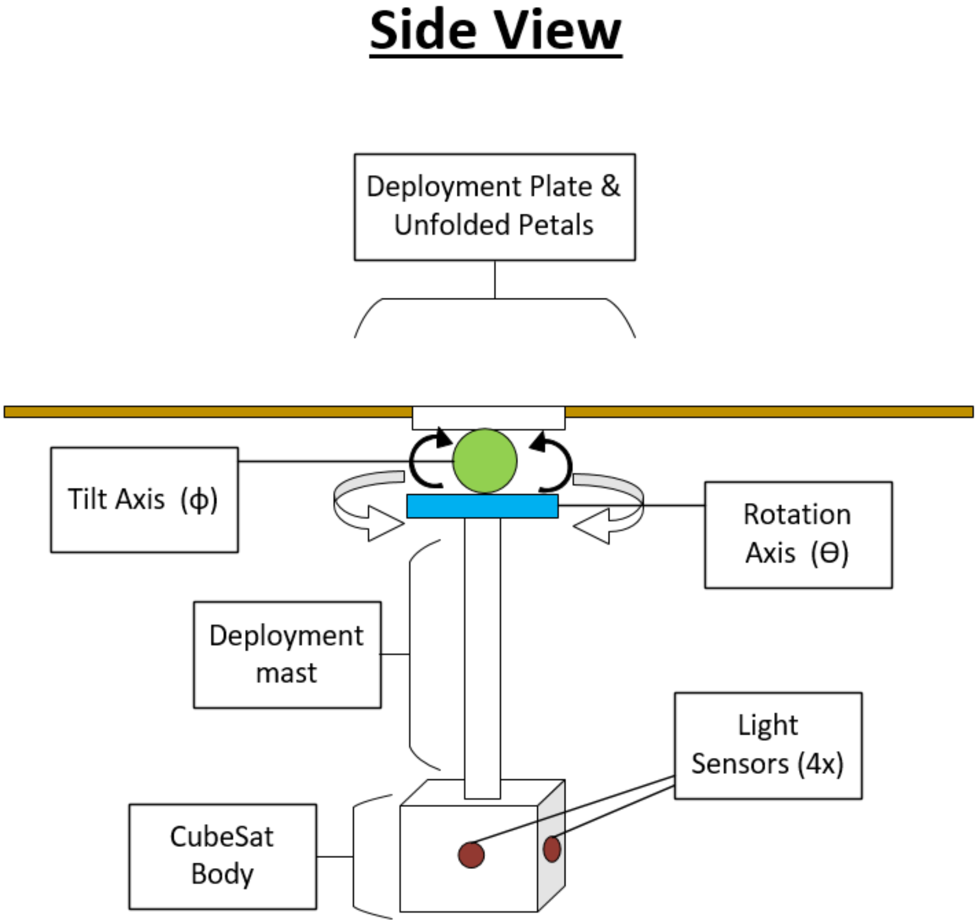

Fig.1. Side view of deployed array, illustrating articulation system & light sensor configuration

III. Research Survey Results

In this section, we will discuss the preliminary research we have done while considering our project definition. There are two separate sections, one is Dan's research, and the other is Alex's research. We each looked into different topics.

Existing Design

The existing design of the deployment system consists of a kinetic energy deployment boom, and a rigid deployment plate that holds the folded array. The deployment is triggered by a single burn wire, and once the mast is deployed, it cannot be retracted. The current design does not have means of articulating the array or auto-articulation. This requires the spacecraft to re-orient itself in order to point the array at the sun to maximize power production. By re-designing the array to articulate itself, re-orienting the cubesat will become unnecessary.

Components

Arduino Microcontroller

In order to re-design the deployment system, we will use an Arduino microcontroller to prototype the system controls. Arduino is an ideal platform to prototype this project on because of the vast libraries available to the public, as well as compatibility with most consumer-end electronic components [1]. The code is a modification of C, and could be easily ported to other systems if the prototype is successful. Arduino also makes it easy to work with both digital and analog components, as well as offering various bluetooth or wireless modules so we can complete one of the stretch goals of having a remotely controlled system.

Linear Actuators

In addition to a few simple servos and stepper motors that we will need for the articulation of the array, the main challenge of this project will be re-designing the deployment mast to retract. In order to solve this problem, I have been looking into various types of telescoping linear actuators. A linear actuator seems ideal for this project because the deployment mast must be able to retract, which means cycling linear motion. The linear actuators must be Telescopic in order to limit size and weight on the spacecraft. In addition, most linear actuators can be controlled by a microcontroller in one way or another, so that grants us control with the Arduino.

Throughout my research, I have found two telescopic linear actuation methods that seem like possible solutions to the deployment mast issue. The "SpiralLift" uses two bands of coiled stainless steel to intertwine and create a rigid column [2]. This solution is compact, and allows for a longer deployment range in a smaller package than any other linear actuators I have been able to find. However, there are drawbacks for the SpiralLift. The only commercially available components seem to be for heavy-lift purposes (ie. >200 Kg). Because they're engineered for high-lift capacity, they are also made out of heavy materials. The smallest SpiralLift, IL75, while small enough to potentially fit on a CubeSat, would be a significant mass addition to a spacecraft. Overall, I think the SpiralLift is a promising solution to the deployment mast retraction issue, and if it could be re-engineered to be more lightweight, I think it would be an ideal solution to this project.

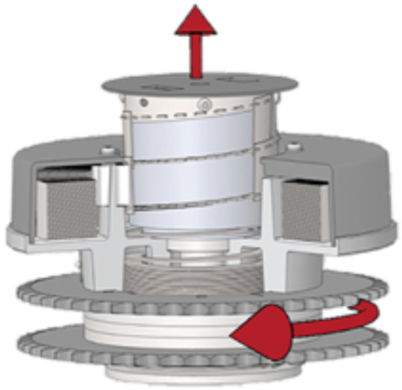

Fig 2: SpiralLift Linear Actuator

The second telescopic linear actuator method that seemed like a possible solution to this project is the Rigid Chain Actuator Method. This method consists of a single or two coiled chains, that when deployed, lock into themselves to create a rigid column [3]. This solution still has the benefits of retractability and telescopic actuation, the actuation range is more limited than the SpiralLift, and these actuators are typically less compact than the SpiralLift. The rigid chain actuation method also suffers similar drawbacks to the SpiralLift in the sense that it has a lift capacity much greater than the mass of the deployment plate, and it will show in the weight of the component. Again this can be solved down the line by re-engineering the actuator with lighter weight materials.

Electrical Motors

There are many electrical motors available for electrical applications on the market. To name a few: Brushless DC, Brushed DC, Multiple phase, servo, and stepper motors. In our project we are choosing to focus on two types: stepper and servo motors. Stepper motors are motors that contain a rotor and a stator. The rotor is the moving part and the stator is stationary. The stator of of these motors typically have multiple coils which are sent current. Once the current is sent to one set of coils, say coil set A, the southern pole of the rotor adjusts to the new north magnetic pole of coil set A. If the coils are sent a current in succession, the rotor will rotate. The rotor and the stator both have small teeth which account for the amount of degrees the rotor will turn with each successive pulse. The rotor itself is magnetically charged to have a north and a south pole, the north being the shaft and the south being the bottom side of the rotor [4]. Figure 5 illustrates the operation of this motor and is located below.

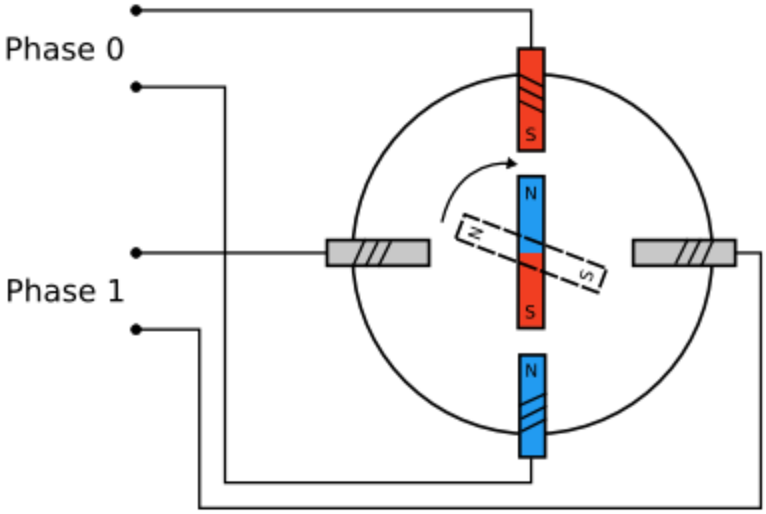

Fig. 3. Two Phase Stepper Motor [5]

Servo motors work differently than stepper motors in that they can generally only rotate +-90 degrees from their initial state. These motors take in a pulse width modulation (PWM) signal and rotate depending on the length of the signal. These motors are generally used for their precision and accuracy[6].

In order to integrate these two types of motors for our project, we need to make sure the motors we choose can be driven with an arduino and/or a transistor circuit. If the motors should be driven with an arduino, the two motors must be able to be driven with 5V and at most 1000 mA. Otherwise, these motors need to be driven using an external power supply and a transistor circuit. A stepper motor I found that could potentially be used is the NEMA17. This motor is rated to be used with a voltage of 5-12V and needs to be supplied at least 400 mA[7]. A servo motor that could potentially work for our project, although a bigger one may need to be selected, is the Parallax 900-00005. This motor needs a voltage supply of 4-6V and has no current specifications that I can find[8].

Electrical Power Supplies

Electrical power supplies work by limiting the amount of voltage from the wall, 230V AC, to a lower voltage DC to be used in a specific device[9]. Selecting the correct power supply for our purposes is crucial to the success of our project. In order to pick the correct power supply, we need to know how much current each part of our system will draw and how much voltage each component will need. Ideally, the components that need more current or voltage than the arduino is able to supply, should be selected to have the same operating voltage and similar current draw.

The common voltage for a large number of compact linear actuators describe in Dan's research are 12V devices. In this case, we will need to select a 12V power supply. As long as the power supply can provide the minimum needed current, the selected 12V supply can be used. Mouser has a large amount of 12V wall adapters with variable voltages and currents[10] so finding the correct wall adapter is not the problem we need to solve. The problem is we need to first select the motors and linear actuation device before we can select the proper power supply.

Solar Articulation Methods

Currently, once the solar array is deployed and unfolded, it is in a fixed position. This is a problem if the array isn't pointed towards the sun, and it's not always possible to reorient the entire spacecraft just to make the array face the light. Power production is a critical aspect of the spacecraft, so if the array isn't operating at peak efficiency due to a few degrees of tilt, articulation could remedy that issue. In order to articulate the array towards the sun, we intend to use a stepper motor and a servo axis to control the rotation and tilt of the planar array. This will essentially give us "dome" coverage around the end of the spacecraft the array is mounted to. Through my research I found a paper by Vijayan Sumathi et al., that details various solar tracking methods developed through the past decade [11]. Some of those systems include multi-axis control, and light sensors, which will most likely be the direction we take this project in. We plan on prototyping several different articulation methods to try out various sensor configurations. Ultimately, we need to strike a balance between accuracy, and wasted mass due to excess sensors & wiring.

Android Application Development

One of our goals for this project is to control our deployment system remotely. In order to perform this function, we think creating a mobile application will create a user-friendly solution. Creating a mobile application will require the knowledge of developing Android applications.

Currently, Android applications are created using Java, C++, or Kotlin. Kotlin was more recently endorsed as the platform's third language[12]. Knowledge in one of these three languages is needed in order to create an application. Personally, I have experience with both java and C++ but we will use java since that is what I am most familiar with. In addition to knowledge of one of these three languages, we need an Integrated Development Environment (IDE). The most used platform for android development is the official IDE for android called Android Studio. Android Studio features the standard unit testing as well as an emulator for testing the user interface on a digital smart phone so-to-speak. Along with android studio itself we will also need to download and install the Java Development Kit (JDK) and ensure that the JDK is up to date.

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IV. Project Requirements & Specifications

General:

In general, the deployment system must reliably deploy and articulate itself in a space environment. However, our budget of $2,000 will not be enough to build a prototype that will be space-ready so we are constrained by cost. In addition to cost, we have some performance requirements that need to be met. The prototype needs to be self-adjusting in order to produce the maximum amount of power possible from the solar array. Also, the prototype must deploy 1 meter away from the spacecraft in order to gain enough space for the articulation to have a maximum effect. The customer also wants the telescoping structure to be able to retract back into the spacecraft.

OBJECTIVE	NEEDS	WANTS	CONSTRAINTS
Articulation	Articulate array +-45 degrees in direction of sun	Automatic, better than +-45 degrees of range of motion	none
Deployment	Deployment	Deployment/ Retraction	Lightweight and Compact
Cost	NA	NA	$2000.00

Electrical:

The electrical system will consist of components which will provide power for the mast and motors. The motors and boom also need to be controlled by a microcontroller. Furthermore, in order for the electrical system to function properly, the proper motors must be selected along with a compatible power supply and microcontroller. The system must automatically articulate the solar array toward the sun so this articulation needs sensors in order to gather data from the environment. Additionally, the control of the deployment system needs to be done wirelessly, in order to simulate the communication from the control room to the CubeSat.

COMPONENT	NEEDS	WANTS	CONSTRAINTS
Power Supply	Able to power motors, mast, and arduino	NA	Needs to supply 12V (working value)
Tilt motor	Able to rotate +-90 degrees	NA	Needs to work with power supply
Rotation motor	Able to rotate +-360 degrees	NA	Needs to work with power supply
Sensor	Able to sense light	Tell sun's direction	NA
Microcontroller	Control articulation of array	Bluetooth/wifi controlled	Control system remotely

Mechanical:

The mechanical system is required to lift a stowed mass of 550 grams away from the spacecraft greater than or equal to one meter in length. The mast is also wanted to be able to retract back into the spacecraft. Although this is a stretch goal, we will do our best to make this a reality. In addition, the array articulation should have a range of movement ±45° in the X and Y axis, although for our purposes, we will be using a spherical coordinate system, so it will be ±45° on the ϴ (theta) and ϕ (phi) axis.

OBJECTIVE	NEEDS	WANTS	CONSTRAINTS
Force	Lift 550 g of mass	NA	Lift 550 g of mass

Software/GUI:

At this point in time, the customer has not requested any software requirements. However, we decided to work with the Arduino microcontroller system because of it's ease-of-use and potential to be controlled wirelessly. The solar articulation will be done automatically, so the only controls we will need on the remote GUI are deployment and retraction control, and a toggle for having the array auto-track. The remote control aspect of our design will be integrated using bluetooth with an android application interface. This will allow for ease of use when the prototype is to be tested.

OBJECTIVE	NEEDS	WANTS	CONSTRAINTS
Programming	Able to program Arduino	Easy to use	NA
GUI	GUI to control the system	Mobile application	NA

Documentation:

In order for the client/consumer to understand how to use our system their needs to be a user's manual. The manual would entail how to use the application as well as how the system operates in different environments. The manual should also include any limitations the system has as well as any alternative functions the system could potentially be used for. There is also a need for the schematic of the electrical system. In order to troubleshoot any hardware failures, this schematic should included in the documentation.

OBJECTIVE	NEEDS	WANTS	CONSTRAINTS
User Manual	A cohesive manual of the system for the user	Easy to understand with multiple explanations for different applications	NA
Electrical Schematic	Schematic of the electrical system for troubleshooting	Possible troubleshooting scenarios	NA

Environmental:

Since our project will not actually be deployed in space, we do not have any real constraints, needs, or wants for the prototype. Although in section of our final report we will be elaborating on how the prototype could be implemented in a space environment. In that aspect, our final design must be able to function in space. The system needs to work in extremely low temperatures. Additionally, our system needs to be protected from space radiation using components that can work in this harsh environment. Also, the final design needs to take into account the vibration and shock in the initial launch of the CubeSat.

OBJECTIVE	NEEDS	WANTS	CONSTRAINTS
Functionality in harsh environments	Functions in space	NA	Functions in space
Components	Components need to be resistant to harsh environmental variables	NA	Components need to function in harsh environment

V. Project Breakdown & Prototyping Goals

Our solar array deployment system has five tentative subsystems that need to be designed and implemented. The five subsystems are motor control, light sensing, control feedback, CubeSat chassis/component housing, and deployment/retraction. The motor control for our system consists a network containing two servo motors and one stepper motor. The two servos will control the tilt in the z plane and the one stepper motor will control the rotation in the x-y plane. This network is needed in order to articulate the solar array such that it can generate the maximum amount of power from the sun. Additionally, in order to find this point of maximum power generation, there needs to be an additional subsystem which senses the location of the sun. A light sensing system will be used in order to find this point of maximum power generation. Also, our deployment system needs to showcase its location at all times to the user. For this reason, we need to implement a feedback subsystem that tracks the location of the sun as well as providing feedback to the user about the coordinates in which our array is pointed. Another subsystem we need to complete our project is the CubeSat chassis, deployment plate, and component housing. Creating these components will allow for our system to have a permanent housing and a complete, finished product to showcase. The last subsystem we must implement is the deployment of our system. Deployment is our primary objective and retraction is a stretch goal. Although only deployment is necessary, we feel we will be able to design a subsystem that performs both functions.

All five subsystems integrate together to complete our solar array deployment system. Each system serves a different purpose necessary to the completion of this project. In the following section of this report, each subsystem will be analyzed as to what the subsystem is, why it is needed, and how it will be implemented. Each subsystem has unique design parameters that need to fit the project requirements designated in the section prior.

Project Subsystems:

Light Sensing Technology and Techniques

4-Sensor Array

i. Our design will feature 4 photoresistors to track the position of the sun as the spacecraft orbits earth. The photoresistors will be located on the 4 faces of the CubeSat Adjacent to the face that holds the deployment mast. This will give us a full 360° sensing array around the body of the CubeSat. This sensing profile will be parallel to the axis of rotation (ϴ). We will read voltage values from the 4 photoresistors, and using those values, we will be able to calculate the approximate position of the sun with respect to the CubeSat orientation. In addition to the use of 4 photoresistors to track the position of the sun, we can also monitor the power produced by the solar array itself, and treat it as a 5th sensor to assist with finding the optimal point to position the array. Pseudocode for the articulation and light sensing can be seen in figure 4 below.

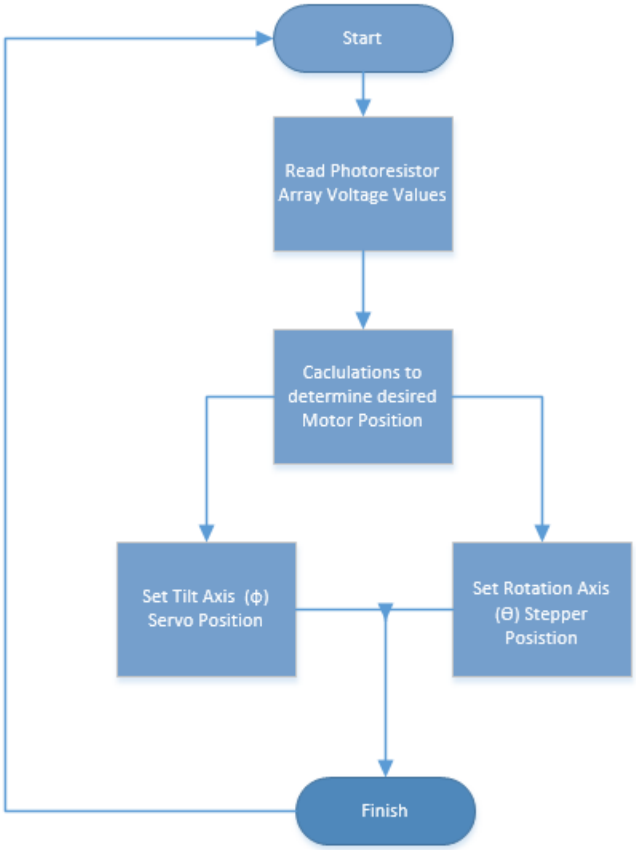

Fig. 4. Initial pseudocode flowchart for sun tracking & articulation system

ii. **Prototyping Goal:** Connect an array of photoresistors to the Arduino Microcontroller and be able to accurately and reliably read voltage values for each photoresistor

Motor Control

Stepper Motor

iii. A single stepper motor will be used for the rotation (ϴ) of the articulation axis and deployment plate. We decided to work with a stepper for this axis of rotation because of the potential small step size and reliability of stepper motors. Stepper motors are also typically weaker than other types of motors (DC, servo), so we were worried we wouldn't be able to apply it to the tilt (ɸ) axis due to the required torque to move the deployed petals of the array.

Servo Motors

iv. A single or dual servos will be used to control the tilt (ɸ) axis of the articulation system. We decided to work with a servo for the tilt axis because of their higher load capabilities, considering that the tilt axis is the primary load-shifting axis.
Prototyping Goal: Prove that we can control rotation of the motors (simulating two rotational axis') by using the Arduino microcontroller.

Control Feedback

In addition to motor control, we want to be able to accurately track the position of each motor. As the motors adjust themselves to track the sun, they may become misaligned with the actual position values that we will be using in the code. It is important to have some type of feedback from the motors so that we can track the actual position of the motors against the positions that we're sending to the servos and stepper through the Arduino. To achieve this, we will attempt to modify a servo to have its internal potentiometer provide position data back to the arduino. If we are unable to achieve this, we will include a manual override system in the code so that the position of the articulation servos can be controlled manually, and we will use the power output from the solar array to position the motors in the optimal position.
Prototyping Goal: Modify servos to provide position feedback so we can accurately track and position the servos for maximum power production. If this fails, we will implement a manual control option to control the articulation, and we will use power data from the solar array to find the optimal position of the array.

Physical Axis and CubeSat Chassis

Articulation Axis

v. We plan on designing and modeling using CAD an articulation axis that we can mount the motors to. This will be a key prototyping element for the articulation system early next semester. Overall, we will have a base that fits with the stepper motor, and it also has a rounded axis perpendicular to the stepper where the servos will control the tilt of the axis. See figure 5 for an illustration of our idea of the 3D printed articulation axis.

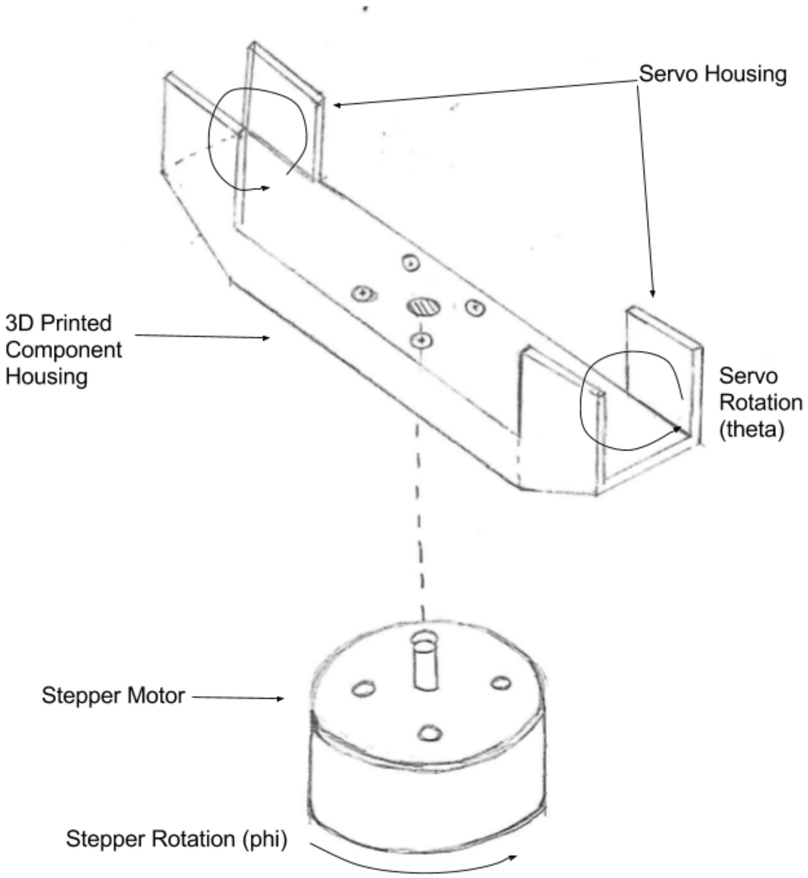

Fig. 5. Component Housing and Motor Placement

CubeSat Chassis

vi. We plan on 3D printing a model CubeSat for our project as well. The printed model will house our components and will be the size of a 1U CubeSat. We decided we wanted a realistic model and this is the closest model we are able to obtain that is within our budget. We have been provided a CAD design file of a CubeSat chassi by our customer at NASA to further improve our physical prototype so that it could be easily fitted to an actual CubeSat.

<u>Prototyping Goals</u>: 3D print both a CubeSat Body, and an initial articulation axis by the end of winter break.

Deployment/Retraction

For the end of this semester, we will be focusing primarily on designing and prototyping the subsystems necessary for the articulation aspect of our design. We will focus on designing a retractable deployment mast next semester, because the retraction requirement was a stretch goal from our sponsor at NASA. In addition, we would like to have a functioning prototype of the articulation and sun tracking system before we start working on the deployment mast.

VI. Conclusion

After conversations with our customer at NASA, we have decided that the primary problem we plan on solving with our design is the articulation of the array to track the sun, the secondary problem will be re-designing the deployment mast to be capable of retraction. In order to accomplish the primary goal, we plan to create a rotational tilt plate for the deployment plate to attach to. By using two axis of rotation on the fixed plane of LISA-T solar array, we will be able to articulate the face of the array at least ±45° in the ϴ (theta) and ф (phi) axis', achieving one of our primary goals. We will also be researching and testing various techniques for solar tracking to determine which system would be ideal for spacecraft implementation. The secondary goal of this project will be improving the deployment mast to be capable of retraction. We will continue researching new telescopic linear actuation methods, and possibly contact the companies associated with SpiralLift and rigid chain actuators to inquire about lighter-weight and more compact components. Overall, we will focus on the perfecting and troubleshooting the articulation of the array for the remainder of the fall semester. We will reserve the spring semester in order to potentially design a custom deployment mast. For the end of this semester, we will be prototyping initial concepts for the light sensing subsystem, the motor control system, and the motor feedback/manual control system. We also hope to have an articulation axis, and sample CubeSat body 3D printed by the end of winter break.