Payload for Remote In-Space Maintenance Mission

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The Payload for Remote In-Space Maintenance (PRISM) mission aims to develop an in-space servicing capability by adding an auxiliary battery to the Neil Gehrels Swift Observatory to extend its operational lifespan. This proof-of-concept mission addresses the issue of battery failure in satellites, as approximately 13% of satellite failures are linked to battery degradation. PRISM demonstrates how satellites not originally designed for servicing can be maintained through autonomous operations. The mission architecture includes three primary phases: rendezvous with Swift, installation of the auxiliary battery, and departure from Swift. PRISM will utilize the Venus Class X-Sat Bus to autonomously navigate to Swift's orbit and position itself for payload operations. The payload will then mount to Swift using the grabbing arm. The payload will then use the designated battery arm to mount and seal the auxiliary battery autonomously onto Swift's umbilical port. After verifying the successful attachment, PRISM will detach and deorbit. The development of the PRISM mission involved multiple trade studies and research into various subsystems. The path to Preliminary Design Review consists of conducting in-depth FEA analysis of the payload and fielding resources to construct a functional prototype to test on Earth.

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I. Introduction

The PRISM mission (Payload for Remote In-Space Maintenance) is a hypothetical mission to attach an external auxiliary battery to the Neil Gehrels Swift Observatory (Swift) in a scenario where Swift has a complete battery failure. This mission was created to complete an ISAM (In-Space Servicing, Assembly, and Manufacturing) capability per the request for proposal given by the 2025 COSMIC Capstone Challenge. ISAM capabilities include in-space additive manufacturing, active debris removal, satellite system repair, and in-space inspection. The request for proposal states that the proposed design is required to demonstrate three or more operations to provide an ISAM capability. Swift was not developed with the intention of future servicing in mind, so PRISM developed a method to add an auxiliary battery to supplement Swift's existing systems. PRISM's top-level objectives are to autonomously rendezvous to Swift, autonomously dock and connect the battery to Swift, and autonomously confirm the successful installation of the battery.

According to a University of Maryland study, roughly 13% of satellite failures are linked to battery failure [1]. On top of this, existing satellites were never developed with the intention of future servicing in mind, so most battery failures cannot be corrected. Satellites with battery failure become space debris and pose a risk to future operations. Increasing the satellite's lifespan allows satellite operators to continue their use of the satellite for a longer operational lifespan. This reduces the costs of developing, building, and sending a new satellite of similar capability to space.

A) **Mission Overview**

The PRISM mission will begin with an arrival phase, followed by the payload operations, and conclude with a departure phase. After matching the attitude, the payload will autonomously grab and orient the external battery with the designated battery arm. Once PRISM verifies that the attachment of the auxiliary battery is successful, the designated grabbing arm will mount onto Swift. Verifying the attachment is important to reduce the risk of damage or disruption of Swift and its orbit. Once the Maintenance payload is securely attached to Swift, the battery arm will plug into Swift's umbilical port. Once the battery has been mounted and secured with epoxy, PRISM can test to see if the auxiliary battery is working. The testing of the battery will be done by checking the vital systems onboard the satellite to ensure they are functioning and in good condition before dismounting from the satellite. Once PRISM confirms the battery connection, PRISM will then detach from the satellite and adjust itself to transfer into a safe disposal orbit. By being able to accomplish these tasks, PRISM will be able to sustain older satellites that are susceptible to battery failure. The overview is shown in Figure 1.

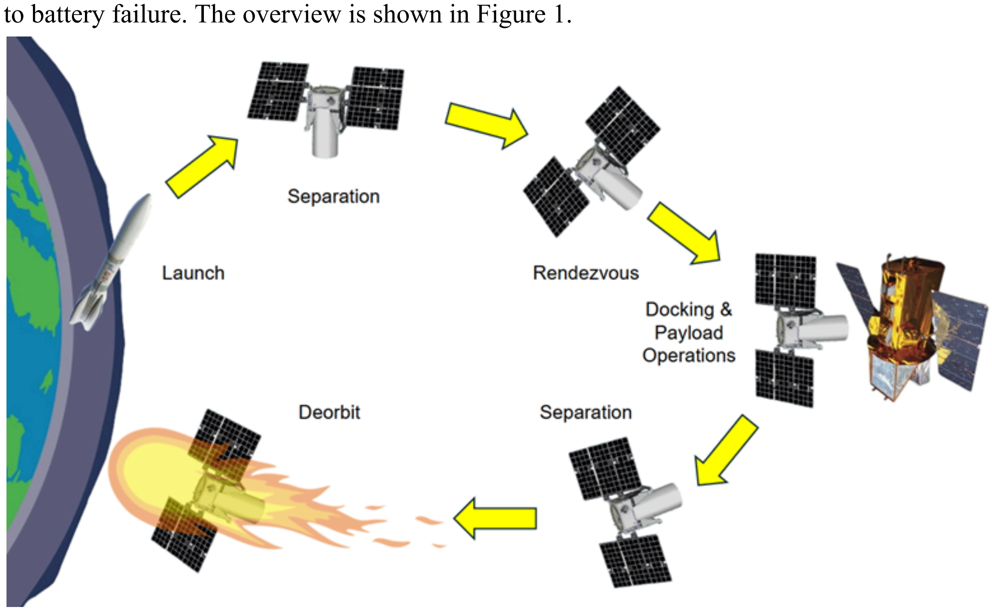

Figure 1. Storyboard of PRISM's macro operations

The payload itself primarily consists of two robotic arms and an auxiliary battery. The arms and auxiliary battery are attached to a truss structure. The truss structure mounts to the X-Sat Venus Class bus. The payload operation starts after a successful rendezvous with Swift. First, PRISM will extract the battery arm. The battery arm will wrap around and grab the external battery pack. The second step will be to pull the external battery pack from its initial spot on the structure. The battery arm will orient the battery to prepare for attachment. The third step is for the payload to grab onto Swift. This is done by the second arm, called the grabbing arm. The grabbing arm will reach out and grab onto Swift. The fourth step is attaching the battery. The battery arm will plug the external battery pack into Swift's umbilical port. This operation is stabilized with the grabbing arm. Once the battery is plugged in, PRISM will verify the installation. Afterward, the fifth step is to retract the grabbing arm. The final step of the payload operations is to retract the battery arm. This is shown in Figure 2. A complete layout is shown in figure 3.

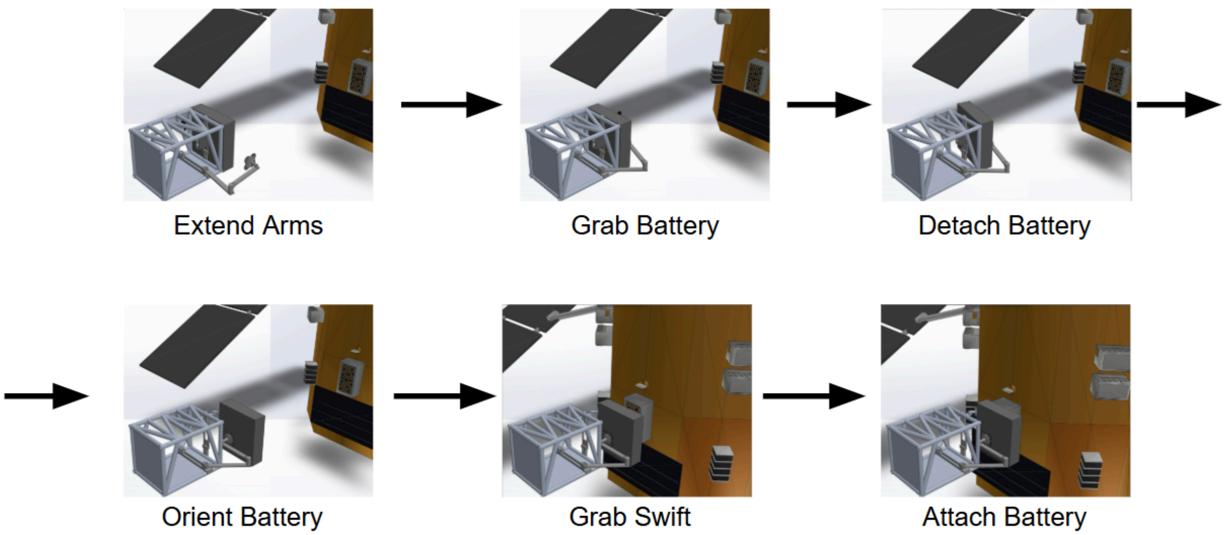

Figure 2. Storyboard of PRISM's micro operations

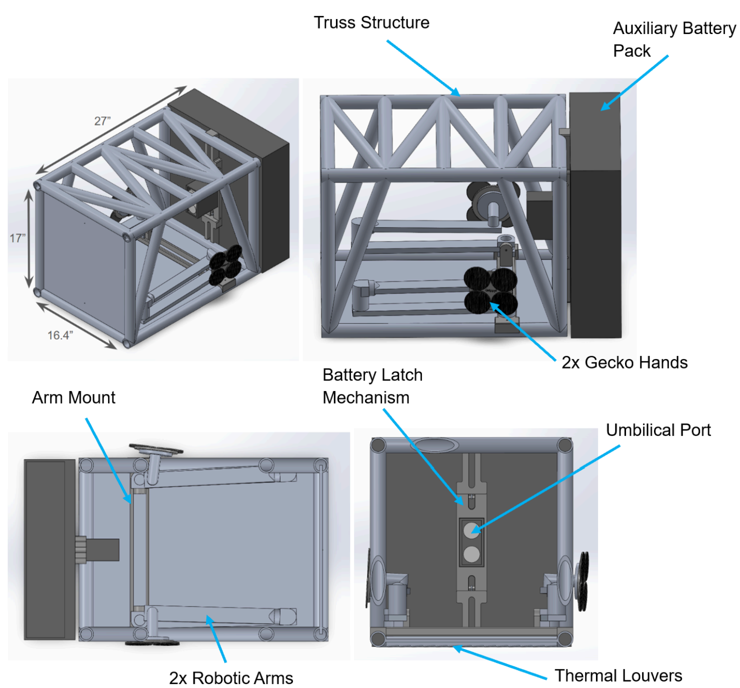

Figure 3. Isometric and 3-View of the payload for PRISM

II. Payload Design

The PRISM Maintenance Payload is divided into multiple systems. The Robotics and External Battery / Battery Bracket subsystems are all encompassed in the Maintenance payload.

A) Auxiliary Battery

The Auxiliary Battery Subsystem is responsible for providing power to the Swift satellite to restore its operational capability via accessing the umbilical port halfway up Swift's midsection. The auxiliary battery can store a sufficient amount of energy to power the target satellite, ensuring it can be brought back into operation. This process requires a battery with a high energy storage capacity, and the requirement is sourced from PWR-1 with verification involving ground testing to demonstrate that the auxiliary battery can provide enough power. Additionally, the auxiliary battery must be at 80% capacity during launch since it will not be charged by the payload. Ensuring that it holds 75-80% charge throughout the mission will be verified through testing.
Based on documentation from NASA, "Swift Gamma-Ray Burst Explorer: Mission Design for Rapid, Accurate Location of Gamma-ray Bursts," it is known that Swift uses an 80 A-Hr Nickel-Hydrogen (NiH2) battery [2]. From a trade study conducted on multiple batteries, it was determined that the 55 Ah Lithium-Ion cell batteries from Eagle Picher would be the best option for the mission.

Table 1. Auxiliary battery Selection trade study

Lith-Ion Battery							
Criteria	**Explanation**	**Grade**	**Weight**	**30 Ah Space Cell**	**43 Ah Space Cell**	**60 Ah Space Cell**	**55 Ah Lithium-Ion Cell**
Energy Density	Maximizes stored energy while keeping mass low, ensuring efficient power use without exceeding payload constraints.	10 = Best 1 = Worst	30%	7	9	10	8
Mass	Lower mass reduces launch costs and improves maneuverability, making the spacecraft more efficient.	10 = Best 1 = Worst	30%	9	8	7	7
Power Storage	Ensures enough energy for operations during eclipse periods when solar panels aren't generating power.	10 = Best 1 = Worst	25%	5	6	7	10
Volume	Space is limited; a high energy density per unit volume ensures more power storage while leaving room for other components.	10 = Best 1 = Worst	15%	9	8	6	6
		TOTALS:	**100%**	74.00%	78.00%	77.50%	79.00%

Each battery has a mass of 1.68 kg with dimensions of 138 x 141 x 34 mm. The battery has a capacity of 55 Ah, with a nominal voltage of 3.6 V. The cycle life is 2000 cycles at 100% Depth of Discharge (DOD). It has an energy density of 343 Wh/L, a specific energy of 134 Wh/kg and can operate within a temperature range of -20 to 60°C [3]. To supply sufficient power to Swift, only two batteries are required. However, for redundancy, four batteries will be used. In addition, the auxiliary battery pack is designed to be future-ready. The design allows multiple additional cells to be stacked on top of the previously existing cells. This allows for better manufacturability and more flexible design for future customers.

However crucial, the cells that make up the battery's power storage are not the only crucial aspects of its design. The first of which being the shielding and structure material for the pack. To elaborate on the latter, beryllium was chosen to be the best candidate. This decision was made in tandem with the structure subsystem lead, as he determined that the material would be perfect for the truss system that makes up PRISM's skeleton, a concept to be discussed further in this section. In short, beryllium was chosen due to its lightweight, good behavior under thermal cycling, and high conductivity to contribute to heat radiation. The case was given a thickness of .005 meters; the philosophy behind this choice was mainly the conservation of mass as a thick thermal and radiation shielding would be located just beneath the shell.

PRISM will be using a layer of polyethylene for the top and sides of the pack to shield it from solar radiation, and PRISM's decision to use polyethylene is supported by and was made on the basis that NASA uses the material on the ISS. To determine the required thickness, the battery pack subsystem referred to previously conducted research, and this study found the optimal thickness to be 4.8 g/cm^2 [4]. Their conclusion would put the thickness for PRISM's shielding at 5 centimeters. This will provide adequate shielding for the cells within the battery, the BCM, and the epoxy reservoir housing the required material to hold the pack in place.

PRISM will also use epoxy to ensure proper adherence of the pack within Swift's umbilical port. Loctite Ea 9690 aero was chosen to be the best choice for PRISM's mission, a choice made by a quick search on Loctite's products [5]. This compound cures extremely well in low-pressure environments such as LEO and has a low tendency to flow, and the latter will allow for PRISM to easily modulate the extrusion of the epoxy at the corner of the umbilical connection and the body of the pack. In addition, the zero-outgassing design makes this epoxy the best material to adhere the pack to Swift.

PRISM will be curing this epoxy by way of 2 heating coils directly at the surface, but still internal, of the bottom of the battery pack. The epoxy will be extruded at 2 points, each 180 degrees from one another on the sides of the umbilical connection, and it is at these points where the coils will be wrapped around the extrusion port. Extruding the epoxy itself will be done with a solenoid plunger at the rear of its reservoir, located internally along with the cells themselves. Maintaining a proper barrier between the environment and the ports is crucial as the epoxy will seek the lower pressure in LEO rather than remaining in the reservoir, and a solenoid-controlled ball valve makes for a great seal between these pressure differentials. To properly control the rate of extrusion, ball valve percentages, coil heating, and battery discharge rates, the pack will also need a proper PCB with inbuilt capabilities for battery modulation and charge monitoring.

A low wattage processor would be required to put on the battery bracket's PCB. A radiation-hardened Arduino-like system would be best for PRISM's battery bracket. The power draw will occur from the batteries within the battery bracket itself and then will be used until the confirmation of attachment to Swift. As a result, the commands will be managed within the Arduino system itself and then be turned off once the epoxy curing method is completed. The Arduino components will have to be radiation hardened, so an Atmel Space Rad-Hard processor would be ideal for this system. Arduino systems have been used in spacecraft missions successfully, so no new testing will be required. The PCB board will also have temperature sensors, which can be routed through and analyzed within the Arduino system itself. The purpose of the temperature sensors is to analyze the respective temperatures of each of the heating coils for curing the epoxy, and they will be regulated such that each coil is maintained at the same temperature until the epoxy has cured.

B) C&DH:

The payload will require the use of 2 cameras for each arm. One camera will be located in the "hand" of the arm mechanism, and the other will be attached to the wrist of the mechanism. The cameras used will need to be low power and small to fit within the arm dimensions. Upon researching small cameras with space applications, it was found that CrystalSpace has nanosatellite cameras that are ideal for the PRISM mission, fulfilling the necessary criteria. The CrystalSpace micro camera is radiation-hardened and uses a peak of 900 mW of power, which would be drawn from the battery bracket [6]. A total of four of these cameras will be used on the payload and will be routed through the host spacecraft's centralized processing architecture, discussed in the host spacecraft section of this report. The payload will utilize the ASC GSFL-16KS Flash LIDAR system [7]. This was found through a review of LIDAR flight experiments done by NASA, where the company ASC's DragonEye flash LIDAR was used on the SpaceX Dragon and was extremely successful [8]. The GSFL-16KS system was chosen through a trade study between different Flash LIDAR systems.

C) Structure

The structure of PRISM is important as it will hold all the equipment and resources required to complete the payload's operation. Two trade studies were conducted: one to determine the type of structural layout and one to determine the material of the structure. The truss structure ended up being the best choice due to it being the most mass-efficient, having the best launch survival ability, and risk/reliability. The truss structure achieved high rankage compared to tower, compression, and tension structures due to being made out of links, which provide strong structural support and have low mass as it takes up less volume. The material trade study was conducted afterwards, in which the team determined the material that will safely hold together the payload and ensure its reliability as well as safety. To select a material, a launch force of 7560 kN was assumed along with a surface area of $2.3323m^2$, and a pressure of 3.24 MPa. Each material was then ranked based on the mass density, thermal conductivity, elastic modulus, yield tensile strength, yield factor of safety, and specific strength.

Table 2A. Table of the trade study conducted for the payload structure layout

Payload Structure Layout Trade Study							
Criteria	Explanation	Grade	Weight	Tower Structure	Compression Structure	Truss Structure	Tension Structure
Mass Efficency	Minimize the amount of mass allocated to structure to fit the mass budget.	10 = Best 1 = Worst	25%	8	6	10	9
Launch Survival Ability	Structure needs to be high strength and resistant to the forces from launch, protecting hardward onboard payload.	10 = Best 1 = Worst	25%	10	6	10	8
Risk/Reliability	Since the structure is holding the entire payload together, the structure needs to be reliable at handling heavy stresses and risk free.	10 = Best 1 = Worst	20%	10	6	10	6
Payload Compability	Structure needs to be able to be comptabile with the payload and its systems.	10 = Best 1 = Worst	15%	10	6	8	6
Thermal Performance	The structure needs to be able handle the varying temperatures from the space enviorment while working with the thermal system. Structure needs to be able to uniformly distribute the temperature.	10 = Best 1 = Worst	10%	6	6	8	6
Volume Efficency	Space is limited so the structure needs to be compact enough while leaving room for other components.	10 = Best 1 = Worst	5%	6	6	8	8
		TOTALS:	**100%**	89.00%	60.00%	94.00%	73.50%

Table 2B. Table of the trade study conducted for the material of the structure of the payload

Material Trade Study for Structure of Payload							
Criteria	Explanation	Grade	Weight	Magnesium Alloy	Aluminum 6061 Alloy	Beryllium	Stainless Steel
Mass Density	Minimize the amount of mass allocated to structure to fit mass budget.	10 = Best 1 = Worst	20%	10	7	9	3
Thermal Conductivity	Material needs to have efficent thermal conductivity to handle the varying temperatures of the space enviorment.	10 = Best 1 = Worst	10%	6	7	5	10
Stiffness	Material needs to have high stiffness so that plastic deformation and failure of the structure is prevented.	10 = Best 1 = Worst	20%	4	5	9	7
Strength to Weigth Ratio	Weight needs to mimimized while strength is maxmimzed to prevent failure of the structure.	10 = Best 1 = Worst	25%	6	8	10	4
Factor of Safety	Factor of safety needs to be high but not to high as the material will be too heavy. Too low of a factor of safety means the structure has a great chance of fracturing	10 = Best 1 = Worst	25%	5	7	6	8
		TOTALS:	**100%**	61.50%	68.50%	81.00%	60.00%

Beryllium ended up being the best-rated material for use due to having excellent strength-to-weight ratio and very good stiffness. This allows for it to not only withstand the forces of launch but also minimize the amount of mass it takes from the mass budget. A report was also found on the prediction of failure of thin beryllium sheets in use on spacecraft structures. The results of this report showed that beryllium can withstand the forces of launch and has a durability for in space operations [11]. This further solidifies that beryllium is an excellent choice for the structure of the payload. From the layout and material trade studies, a design was produced to ensure there were enough links to provide high strength and integrity throughout the whole payload. The structure has a length of 22.68 inches, a height of 17 inches, and a width of 16.4 inches. There are a total of 11 links in the structure, with 7 on the top and 2 on the left and right side of the structure. Each link has a 1-inch diameter of thickness, and most of them are at a 45-degree angle besides 3 on the top, which are vertical. The battery pack will be connected to the back of the structure, with the front end being connected to the bus through the base plate on the front face. There is also a base plate that will be attached to the bottom of the structure that will be for mounting the arms on the top face and holding thermal louvers on the bottom face.

D) Robotic Arms

Due to PRISM's unique mission architecture, careful consideration was required when choosing the grabbing mechanisms, joints, sizing, and material. To elaborate on sizing and joints, the team used existing dimensions and models of Swift to determine the proper sizing for PRISM's arms. There are a select number of locations the payload will be able to attach to, and as such, it will need to reach from this point to the point of interest, that being the Swift's umbilical port. The image and diagram used can be seen below in Figures 4 and 5.

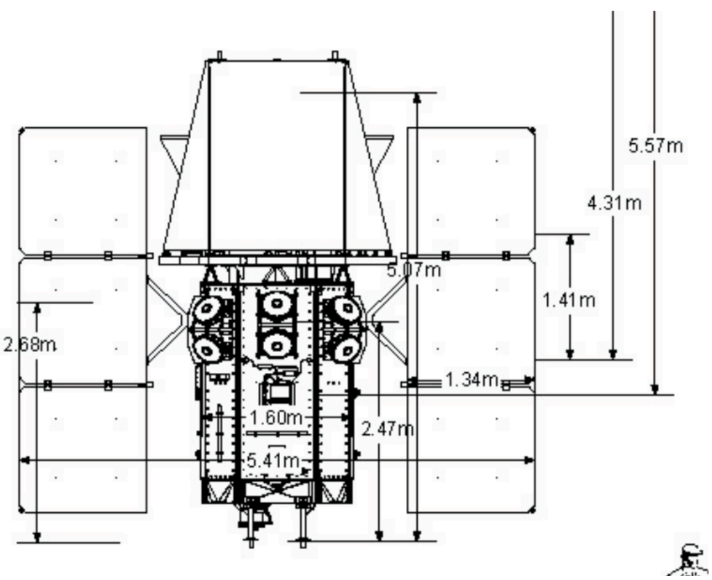

Figure 4 (Left): reference photo used to verify geometry and location of Swift umbilical port.[9]
Figure 5 (Right): Dimensions provided by Swift presskit as given by assigned liaison. [10]

Leveraging the dimensions given by the presskit schematics, the robotics subsystem lead was able to approximate the size of the umbilical and the distance from the radiator to the port. The aforementioned sizing was determined to be at least 1.07 meters (~3.5 feet) between the two arms. A 1:5 scale prototype of PRISM and a model of Swift were created to affirm the arn's dimensions. The design would allow PRISM to attach to the X-ray's radiator and also reach the umbilical port after the battery pack has been removed from its hull.

Kollmorgen AKM1 series brushless DC motors were chosen for the robotic arms. AKM1 motors have a power draw of 300 watts under max load, but with proper gearing, the same torque can be achieved with a much lower power draw. Analysis of the arms and the auxiliary battery pack shows that less than 2 N of force is required to move the auxiliary battery pack.

Lightweight, rigid, and resistant to thermal cycling were the most important criteria when choosing the material to craft the arms from. As such, Aluminum 6061-T6 with carbon fiber reinforcement was chosen due to being lightweight and easy to manufacture. The carbon fiber reinforcement helps with the thermal expansions that arise with Aluminum.

Both robotic arms use a 'gecko gripper'(setae) to attach to Swift and the auxiliary battery. NASA has experimented with this material and has shown its strength on reduced-gravity flights, using 2 pieces about 2 inches by 4 inches in area to manipulate a 50-kilogram object. Applying a shear force is the best way to detach these grippers from whatever surface they are attached to, and in this case, there will be 4 pads on each arm, with each rotating counter to the adjacent pad. When PRISM needs to release, it can do so easily by simply rotating these pads while remaining idle. A CAD model of the robotic arms can be seen in Figure 6.

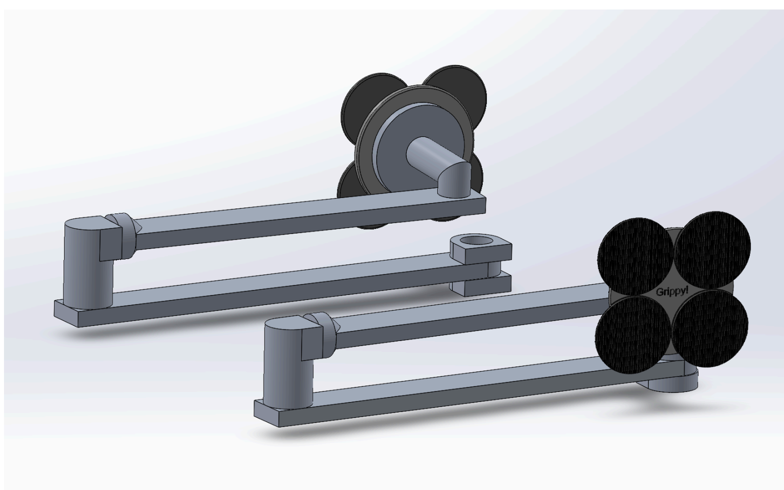

Figure 6. A CAD model of the robotics arm

The final estimated mass of the payload is shown in table 3. A 15% margin was included as a safety buffer to account for any unexpected increases in the mass of other components during manufacturing.

Table 3. A table of the mass budget for the payload

System	Item	Mass (kg)
Ext. Battery	55 Ah Lithium-Ion Cell	6.72
Battery Bracket	Bracket (Case)	11.70
	Epoxy	0.25
	Heating Coils	0.75
	Extruders	1.00
Thermal	Louver System	0.57
Structure	Truss + Mounts	11.50
	Bracket Mount Servos	0.99
Robotics	"Gecko" Arm Beams	6.44
	"Gecko" Arm Motors	4.50
	Ext. Bat Arm Beams	6.44
	Ext. Bat Arm Motors	4.50
Misc.	Margin (15%)	10.50
Payload Total:		**65.86**

III. Host Spacecraft Bus and Mission Element Design & Verification

The Venus Class X-Sat Bus encompasses the GNC, Communication, Propulsion, Power, and Thermal subsystems. The bus will handle these subsystems on behalf of the payload.

A) Guidance, Navigation, and Control Subsystem:

PRISM's Guidance, Navigation, and Control Subsystem (GNC) will have primarily two main components: Attitude Sensors and Attitude Controllers. Attitude Sensors will provide important information about the attitude of the Venus Class X-Sat Bus and PRISM as it approaches the target satellite, Swift, to attach to it and begin installing the auxiliary battery. The Attitude Controllers, on the other hand, will be actuators that are used to match the attitude of Swift. The actuators and sensors will be on the Venus Class X-Sat Bus, and they will relay data using the command and data handling system, then communicate it with the ground station. For the host spacecraft attitude information, a trade study revealed that a combination of gyroscopes and star trackers would be the best choice for the information. To control the attitude of the spacecraft, the results of a trade study, shown in Table 4 and 5, determined that the reaction wheels are the most applicable method to control the attitude of the host spacecraft for this mission. The reaction wheels chosen were the RWP050 reaction wheels, and there will be 3 of these wheels to manage the stability of all three axes of the host spacecraft. The star tracker chosen from Blue Canyon was the Mid Extension NST star tracker to have proper determination of the initial attitude. The gyroscope decided upon through research was the NewSpace Systems' NSGY-001 Stellar Gyro [12]. This gyroscope has an active pixel CMOS detector, small size, low mass, low power consumption, and a simple interface for integration into the host spacecraft [12].

Table 4. Trade Study of Attitude Sensor Combinations

Rank	Characteristics	Gyroscopes + Star Tracker	Gyroscopes + Sun Sensor	Magnetometers + Star Tracker	Magnetometers + Sun Sensor
60%	Accuracy	3	1.5	3	1
15%	Complexity	3	2	1	3
5%	Drift/Inaccuracy	2	3	2	1.5
20%	Practicality	2	2	3	2
100%		**2.5**	**2.125**	**2.25**	**1.875**

Table 5. A qualitative and quantitative description of the rankings for the attitude sensor trade study

Characteristics	Rank 1	Rank 2	Rank 3
Accuracy	0.5 degrees or greater	0.0003 to 0.01 degrees	less than 0.0003 degrees
Complexity	This sensor combination will require a system to be built that has high complexity and requires a large amount of volume, mass, and power.	This sensor combination will require a system to be built that has medium complexity, and will require a significant amount of volume, mass, and power.	This sensor combination requires a minimally complex system, if even a system at all, which requires little amount of volume, mass, and power.
Drift/Inaccuracy	The drift rate of this sensor combination is large and must be consistently calibrated to ensure accuracy.	The drift rate/inaccuracy of this sensor combination is significant, and calibration may be needed during the mission to ensure accuracy.	The drift rate/inaccuracy of this sensor combination is small and the system will not need calibration during the timespan of the mission.
Practicality	This sensor combination is likely to work for only a small part of the mission, will require consistent calibration, and not be able to provide consistent attitude data during the mission time.	This sensor combination will work for most of the mission, and will require some calibration, and be able to mostly provide attitude data during the mission time.	This sensor combination will work for almost the entire mission, and will require little to no calibration. This sensor will be able to provide consistent attitude throughout the mission time.

B) Command and Data Handling Subsystem:

Given that the Venus Class X-Sat Bus is the host spacecraft, the PRISM payload will be using the command and data handling system of the Venus Class X-Sat Bus. As a result, the design of the command and data handling system will be done to the host spacecraft. There are different types of processor architectures, such as centralized architecture, federated or "bus" architecture, and other architectures, including multiprocessor architectures [13]. For the PRISM mission, multiple processors will not be needed, and it was decided on a centralized architecture for the host spacecraft. The reason for this is that a federated architecture requires a bus where everything must be connected, and this bus will need to contain all sensors and propagate the flow of data. Rather than that, the mission would best align with a centralized system where the data flows into the central processing unit directly, and the wiring can be managed throughout the system directly into the central processing unit. The host spacecraft will also need a radiation-hardened CPU and components. An example of a low wattage, radiation-hardened processor used in space that would be ideal for this mission is the RAD6000, which was used on the 2004 Spirit and Opportunity Rovers [14]. This processor was not used for intensive computations and will suffice for the data transfer that will occur at the downlink discussed in the Communications subsystem section of this report. A flowchart of the command and data handling subsystem is shown in Figure 7 below.

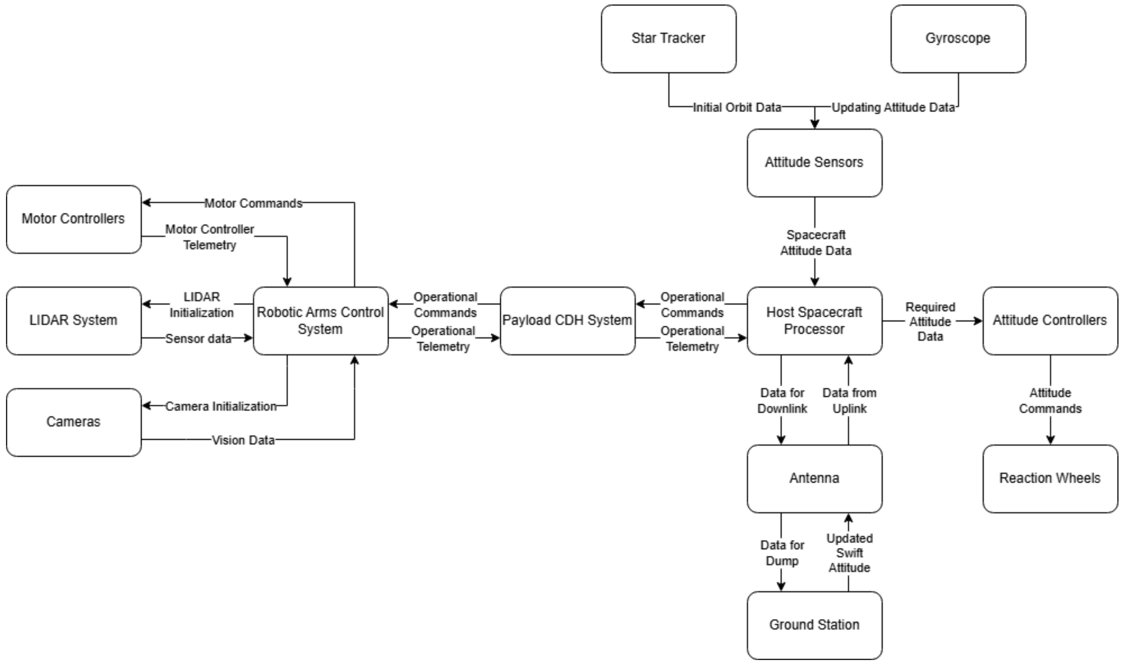

Figure 7. A Flowchart of Data Handling and Communication on PRISM

C) Propulsion Subsystem

Using the data collected from the orbital analysis, the propulsion subsystem was researched to find the ideal thruster type to achieve the total velocity change required for rendezvous. The ideal thruster would be able to maximize specific impulse (I_{sp}) to minimize the mass of the propellant (m_p) while providing sufficient thrust to perform the required drift and vBar hop over 36000 seconds.

Since power is a limiting factor for the Venus Class X-Sat Bus, at a peak draw of 444W, it was decided that electric propulsion would not be ideal for the PRISM mission. However, since the propulsion system will be utilized in times when the payload is idle, the propulsion system will be able to pull more power during maneuvers, such as RPO. Since the total Δv required for the PRISM mission is relatively small at 220 m/s, cold gas thrusters would suffice to make the maneuver while minimizing power draw. Liquid monopropellant would achieve the orbit change faster but would require adding more fuel mass and allocating more power to the propulsion subsystem. Thus, nitrogen cold gas thrusters were chosen as the optimal propulsion system for the PRISM mission since nitrogen cold gas thrusters have an ideal I_{sp} around 60s, which is higher than other cold gas propellants [15] [16]. Using the rocket equation, it is estimated that the mass of the nitrogen fuel will be 35kg, including a 10% reserve to reduce the risk of error.

D) Thermal

From analysing all the parts and sensors on the payload, it was determined that the most temperature-sensitive component on our payload is the motor, with an operating range of 5-40C°. Table 6 shows the equilibrium temperatures of the payload when both arms are using a combined 72 W.

Table 6. Equilibrium temperatures of the payload

Day Time Closed			Eclipse Time Closed		
Q_sun	3315311148	W/m^2	Q_sun	0	W/m^2
Q_motor	7525280838	W/m^2	Q_motor	7525280838	W/m^2
Temp	322.6734628	K°	Temp	294.5307736	K°
	121.142233	F°	Temp	**70.4853924**	F°
	46.54346276	C°		18.40077356	C°

Day Time OPEN			Eclipse Time OPEN		
Q_sun	3315311148	W/m^2	Q_sun	0	W/m^2
Q_motor	6549439678	W/m^2	Q_motor	6549439678	W/m^2
Temp	315.1530612	K°	Temp	284.4795397	K°
	107.6055102	F°		**52.39317153**	F°
	39.02306122	C°		8.349539737	C°

E) Power Subsystem

The payload relies on the bus to supply the necessary power for operation. To ensure the Venus Class X-Sat Bus power subsystem can provide sufficient power to the payload, a power budget is created for both the bus and the payload. Given that robotic arms are used, the team chose the dual-array setup capable of generating 444 W. A power budget can be generated using Table 6.3 as a starting point from the Elements of Spacecraft Design. Additionally, the time spent in eclipse and daylight, determined using STK, is 8.5 hours and 15.5 hours, respectively. Based on this information, along with the knowledge that the payload primarily relies on the bus subsystems to function, a power budget is generated, as shown in table 7.

Table 7. Bus and Payload Power Budget During Day and Night

Day Time			Eclipse Time		
Subsystem	**% Allocated**	**Watts Allocated**	**Subsystem**	**% Allocated**	**Watts Allocated**
Thermal Control	12%	28.57	Thermal Control	24%	38.17
Attitude Control	8%	18.75	Attitude Control	5%	7.95
Power	2%	3.75	Power	2%	3.18
CDS	10%	24.37	CDS	5%	7.95
Comms	20%	48.75	Comms	5%	7.95
Propulsion	2%	3.75	Propulsion	0%	0
Mechanisms	2%	3.75	Mechanisms	0%	0
Battery Charging	1%	1.87	Battery Charging	0%	0
Payload	28%	65.62	Payload	0%	0
Power used During day (W)		199	Power used During Eclipse (W)		65
Power used w/ 25% Margin (W)		249	Power used w/ 25% Margin (W)		82
	Xi	0.9		Xe	0.75
	Ti (Sec)	55467		Te (Sec)	30933
Power Solar Array	337	Watts	Allowed Bus array	444	W
Array Area	0.83	m^2	Array Area	1.09	m^2

According to Elements of Spacecraft Design, a spacecraft nearly doubles its power usage for the thermal system. To ensure adequate power during eclipse periods, most of the spacecraft's subsystems will operate at minimal power. With this info, we can estimate the power needed during eclipse and lighting; a 25% factor of safety is incorporated to ensure sufficient power is available for unexpected cases. Next, using equation 21-6 from the New SMAD, it was determined that the power needed to be generated by a solar array is 337 W, as shown in table 7. This means that there will be an excess of 107 Watts that will end up being stored in the buses' batteries.

Using the equation $P = \eta AG$, where: η is the array efficiency (30%), A is the array area, G is the solar irradiance, the necessary array area can be calculated [17]. All generated power will be stored in the bus batteries.

Some other information known about the spacecraft bus is that it consists of three 1P8S 28V batteries, each weighing 650g, a capacity of 3.4 Ah, Energy of 99 Wh [18]. The Bus also comes with 2 Solar Array Drive Assemblies (SADA), which point the arrays at the sun to maximize power generation.

F) Communication and Ground System:

The communications system of a spacecraft is essential in a mission to ensure proper data transfer to Earth or to receive commands from Earth. The PRISM mission utilizes a radio frequency (RF) system on the S and X bands. The PRISM mission will use the Malindi Ground Station in Kenya as the primary ground station since Malindi is the ground station for Swift. Malindi already contains all the proper equipment to communicate with the spacecraft bus.

The PRISM mission shall utilize the communications system on the Venus Class X-Sat Bus, which was chosen to be the Space Inventor S-Band 2x2 antenna array due to its low mass and power usage. The frequency of this antenna is 2025-2100 MHz for uplink and 2200-2900 MHz for downlink, validating that it is an S-band antenna. The bandwidth of the antenna is listed as >85 MHz for uplink and >90 MHz for downlink, and it is under 170 grams in weight [19].

G) Communication Links:

The PRISM mission will have two primary communication links for uplink and downlink. These links will occur at the primary ground station, which is the Malindi ground station. The reasoning behind using two links is so that updated attitude data can be uploaded to the host spacecraft and the data from the system can be downlinked to the ground station. The data regarding the target satellite Swift's orbit and attitude data will be loaded before launch and will be updated if needed at the uplink from the ground station. The attitude quaternions shall be known by the GNC subsystem. The Command and Data Handling system will need to downlink the data of success validation once in the range of the Malindi ground station so that the success can be verified. The CDH system will also downlink data from the sensors and systems of the host spacecraft and payload to the ground station. Once the downlink occurs, the Venus Class X-Sat Bus will then detach and move away from Swift.

H) Link Budget:

When calculating the Link Budget for PRISM, it was determined that more information about the Malindi ground station and general requirements for the mission was needed. Since PRISM must match the orbit of Swift, the altitude of Swift's orbit is going to be the propagation path length for the communication system. Swift's orbit has a perigee height of 463 km and an apogee height of 472 km [20]. The communication system will be designed around the maximum altitude of the orbit, so the apogee height was used as the propagation path length for communication. This will ensure that the system will work at any altitude, rather than only in a certain lower range of heights. The first link budget determined was the uplink for updated attitude data, which is shown below in Table 8a, using the SMAD spreadsheet. The link margin yielded is 34.30 dB, which is around ≈33 dB for commands. This is sufficient for the commands with updated attitude at the uplink. The second link for the mission is the downlink of data. Entering the values into a link budget spreadsheet to calculate the link margin yielded a link margin of 34.58 dB, shown in Table 8b. This is well above the requirement of ≈3 dB for data. This means that the communications system is overdesigned and does not need to be as robust as it is, but it still fits the requirements. The communications system has also been accounted for in the mass and power budgets.

Table 8a. Link Budget for the PRISM mission uplink (Left).
Table 8b. Link Budget for the PRISM mission downlink (Right).

Freq.	f	Ghz	input	**2.03**
Xmtr Pwr	P	W.	input	**0.2500**
Xmtr Pwr	P	dbW	10 log(P)	-6.02
Xmtr line loss	L_l	dB	input	**-1.00**
Xmtr Ant. Beamwidth	θ_t	deg	Eq. (13-19)	79.772
Peak Xmt. Ant. Gain	G_{pt}	dB	Eq. (13-20)	6.26
Xmt. Ant. Diam.	D_t	m	input	**0.13**
Xmt. Ant. Pointing Error	e_t	deg	input	**1.00**
Xmt. Ant. Pointing Loss	L_{pt}	dB	Eq. (13-21)	0.00
Xmt Ant. Gain	G_t	dB	$G_{pt}+L_{pt}$	6.26
EIRP	EIRP	dB	$P+L_l+G_t$	-0.76
Prop. Path Length	S	km	input	**4.720E+02**
Space Loss	L_s	dB	Eq. (13-23a)	-152.05
Prop. & Polariz. Loss	L_a	dB	Fig. 13-10	**-0.10**
Rcv. Ant. Diam.	D_r	m	input	**10.00**
Peak Rcv. Ant. Gain	G_{rp}	dB	Eq. (13-18a)	43.94
Rcv. Ant. Beamwidth	θ_r	deg	Eq. (13-19)	1.04
Rcv. Ant. Pointing Error	e_r	deg	input	**0.12**
Rcv. Ant. Pointing Loss	L_{pr}	dB	Eq. (13-21)	-0.16
Rcv. Ant. Gain	G_r	dB	$G_{rp}+L_{pr}$	43.78
System Noise Temp.	T_s	K	input (using Tab	**614.00**
Data Rate	R	bps	input	**120000.00**
Est. E_b/N_o (1)	E_b/N_o	dB	Eq. (13-13)	40.80
Bit Error Rate	BER	--	input	**1.0E-05**
Rqd. E_b/N_o (2)		dB	Fig. 13-9 (BPSK,	**4.50**
Implementation Loss (3)		dB	input (standard	**-2.00**
Margin		***dB***	***(1)-(2)+(3)***	***34.30***

Freq.	f	Ghz	input	**2.20**
Xmtr Pwr	P	W.	input	**0.0500**
Xmtr Pwr	P	dbW	10 log(P)	-13.01
Xmtr line loss	L_l	dB	input	**-1.00**
Xmtr Ant. Beamwidth	θ_t	deg	Eq. (13-19)	73.427
Peak Xmt. Ant. Gain	G_{pt}	dB	Eq. (13-20)	6.98
Xmt. Ant. Diam.	D_t	m	input	**0.13**
Xmt. Ant. Pointing Error	e_t	deg	input	**1.00**
Xmt. Ant. Pointing Loss	L_{pt}	dB	Eq. (13-21)	0.00
Xmt Ant. Gain	G_t	dB	$G_{pt}+L_{pt}$	6.98
EIRP	EIRP	dB	$P+L_l+G_t$	-7.03
Prop. Path Length	S	km	input	**4.720E+02**
Space Loss	L_s	dB	Eq. (13-23a)	-152.77
Prop. & Polariz. Loss	L_a	dB	Fig. 13-10	**-0.10**
Rcv. Ant. Diam.	D_r	m	input	**10.00**
Peak Rcv. Ant. Gain	G_{rp}	dB	Eq. (13-18a)	44.66
Rcv. Ant. Beamwidth	θ_r	deg	Eq. (13-19)	0.95
Rcv. Ant. Pointing Error	e_r	deg	input	**0.12**
Rcv. Ant. Pointing Loss	L_{pr}	dB	Eq. (13-21)	-0.19
Rcv. Ant. Gain	G_r	dB	$G_{rp}+L_{pr}$	44.47
System Noise Temp.	T_s	K	input (using Tab	**135.00**
Data Rate	R	bps	input	**120000.00**
Est. E_b/N_o (1)	E_b/N_o	dB	Eq. (13-13)	41.08
Bit Error Rate	BER	--	input	**1.0E-05**
Rqd. E_b/N_o (2)		dB	Fig. 13-9 (BPSK,	**4.50**
Implementation Loss (3)		dB	input (standard	**-2.00**
Margin		***dB***	***(1)-(2)+(3)***	***34.58***

I) Launch Vehicle, Launch Site, and Mission Orbital Analysis

The launch vehicle is an important selection for the mission. It must meet the requirements of the payload mass and volume, launch window availability, cost, and possible orbit injections. The team weighted the inclination of the launch site as the most important factor for a launch vehicle, making the Ariane 6 the best choice for the mission compared to other options. The inclination of the launch site heavily affects the payload design and orbit trajectory, as launching from an inclination greater than the desired one requires us to do an expensive velocity change (Δv) maneuver. The desired orbit for this specific mission is 20 degrees, but the Ariane 6 launching from the Guiana Space Centre gives the team the flexibility to reach other orbits for future missions.

The orbital mechanics of the PRISM mission revolve entirely around minimizing error since PRISM is designed to perform Rendezvous Proximity Operations (RPO). Therefore, hand calculations would be insufficient for determining the total velocity change (Δv) to rendezvous with the Neil Gehrels Swift Observatory. To minimize error, the Ansys Satellite Tool Kit was used to model in-orbit maneuvers. Since PRISM is performing rendezvous proximity operations on Swift, the orbits must have negligible error between their orbital elements; PRISM's orbit will be designed as identical to Swift's current orbit.

Table 9. A table of Swift's orbital elements (Epoch time of 2 March 2024 10:48:31 UTC)

Keplerian Orbital Element	Value
Perigee Height (km)	469.2
Apogee Height (km)	477.9
Eccentricity	0.0006376
Inclination (°)	20.5561
Right Ascension of the Ascending Node (°)	23.3093
Argument of Periapsis (°)	218.5510
Mean Anomaly at Epoch (°)	141.4475
Orbital Period (min)	93.9

Swift lies within a very circular Low Earth Orbit but has a miniscule eccentricity that allows for the definition of an eccentricity vector. Since the eccentricity vector exists – albeit with a small magnitude – true anomaly, argument of periapsis, and RAAN are defined for Swift's orbit. This information makes it easier to locate Swift (and PRISM) at any given moment using Kepler's Equation. Because the launch site chosen (Guiana Space Centre) is at a lower latitude than the orbital inclination, it will be possible to insert PRISM directly into Swift's orbit. However, PRISM will be at a slightly higher altitude, with a semimajor axis of about 6950 km compared to Swift's 6844 km. This was chosen to allow PRISM to minimize the gap between the two satellites before RPO since PRISM will be moving slightly slower to maintain a higher orbit. The launch vehicle chosen, the Ariane 6, will provide sufficient thrust to deliver PRISM to this orbit.

Once PRISM has been inserted into Swift's orbit, it will need to perform rendezvous proximity operations to interact with Swift. This will require PRISM to perform a drift maneuver and a vBar hop. After both maneuvers are performed, very fine adjustments may need to be made moving toward Swift to completely latch onto it. The total velocity change (Δv_{total}) required for both maneuvers was calculated by AGI STK and was 220.11 m/s (0.22011 km/s). This is the total change in velocity required for the minuscule shape change and hop needed by PRISM to rendezvous with Swift. The total time for the RPO actions to take place is 10 hours, or 36000 seconds.

IV. Risk and Fault Recovery

As is standard for all space missions, a risk and fault recovery plan was developed to mitigate potential issues that may occur during operation. The team looked at each subsystem and part to determine critical items and modes of failure. After identifying possible failures, the team had to determine how the failure would be detected by PRISM. Failures will be detected from multiple redundant sensors throughout PRISM. From these sensors and feedback, the team can start recovery processes either manually from mission control or from PRISM itself. The major risks the team identified are shown in table 10, along with their causes and mitigation plan. An accompanying ABS risk matrix is included as well.

Table 10. A table of common risks, their causes, and a mitigation plan for them

ID	Subsystem	Risk Statement	Cause	Mitigation Plan
1	GNC	One Actuator Stops Working	Momentum Wheel Oversaturation or Failure	- Use the other two momentum wheels in the GNC system of the spacecraft to stabilize and change the attitude.
2	CDH	Camera Failure	Exposure to Radiation, Unforeseen damage from launch/space environment	- Backup cameras are included on the "wrist" of the arm in case of failure of the cameras in the hand of the arms. - Since the cameras are radiation-hardened, only one should fail at a time, if at all.
3	COMMS	Improper Data Dump at Link	Data from CDH Subsystem is over the Communication Limit	- The Link Budget for data has a high margin of ~33 dB, which means that there is a lot of room for error regarding data transfer at the downlink. With a data rate of 120,000 bps, there is room for error with the data transfer. This can be monitored. - The data can be attempted to be sent at the next downlink transfer with the ground station.
4	THERMAL	Bi-metal spring stops working	Vibrational forces from launch	- Add multiple springs
5	Aux Bat	The battery has a puncture	Damage to Aux Battery	- Include redundant battery units in series
6	Aux Bat	BCM Failure	Bitflip or computational errors arise due to radiation interference	- Redundant BCM on battery

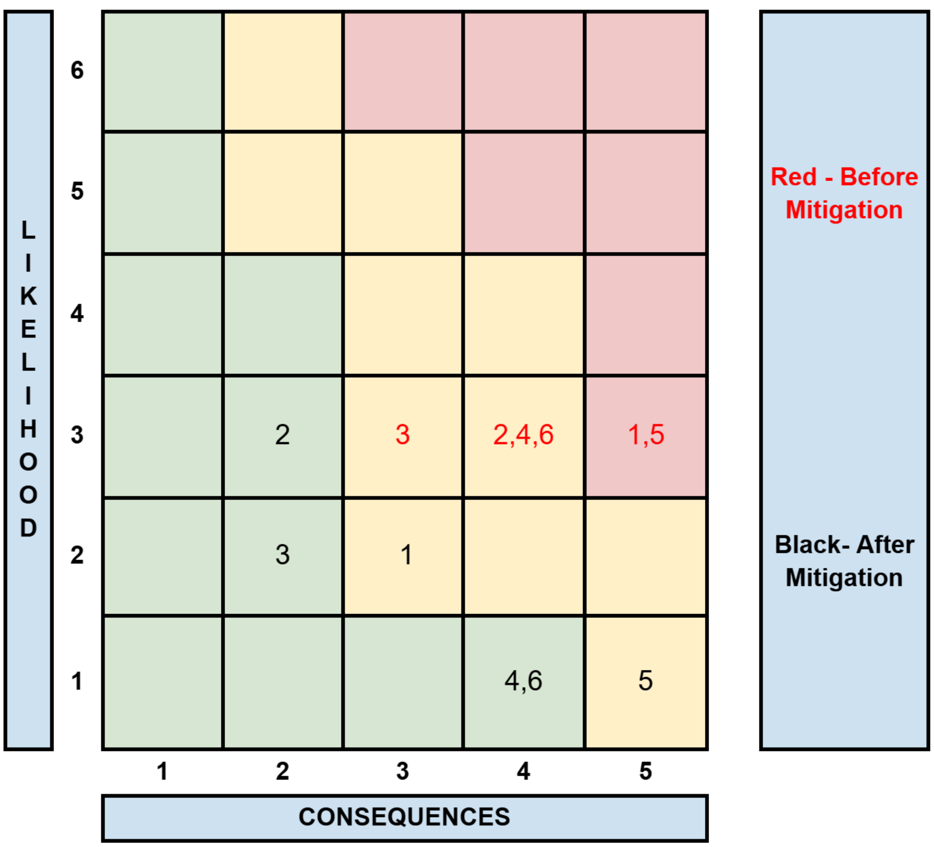

Figure 8. The risk matrix for risks that could occur for PRISM

Additionally, a safety plan was derived in case of payload errors. Due to the amount of redundant sensors and systems on PRISM, there are multiple points of access to monitor for issues. Furthermore, each autonomous operation has multiple checks for errors. If an error is detected, the system will first attempt to autonomously restart the operation from the most recent step. If a complete failure of the payload occurs, the spacecraft bus can deorbit itself to prevent itself from becoming space debris. This will be decided manually from mission control.

V. Conclusion

The PRISM mission addresses the issue of battery failure in satellites through the attachment of an external, auxiliary battery pack. In the hypothetical scenario of a battery failure in the Neil Gehrels Swift Observatory, the PRISM mission would be able to restore operations to Swift. PRISM can accomplish this while meeting all requirements stated in the COSMIC Capstone Challenge Request for Proposal. While the current design is developed for Swift, the payload was also designed to be easily modifiable to serve other satellites.

The next steps of this project would be to complete a finite element analysis of the stresses the payload as a whole would receive during operation. After making changes to counter areas of high stress, the next step will be to develop a full-scale prototype to run tests on Earth. The development of a full-scale prototype would require special production of the truss, along with the custom robotic arms. The prototype would go under stress and environmental testing. These tests will produce information that will allow us to refine the design.

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