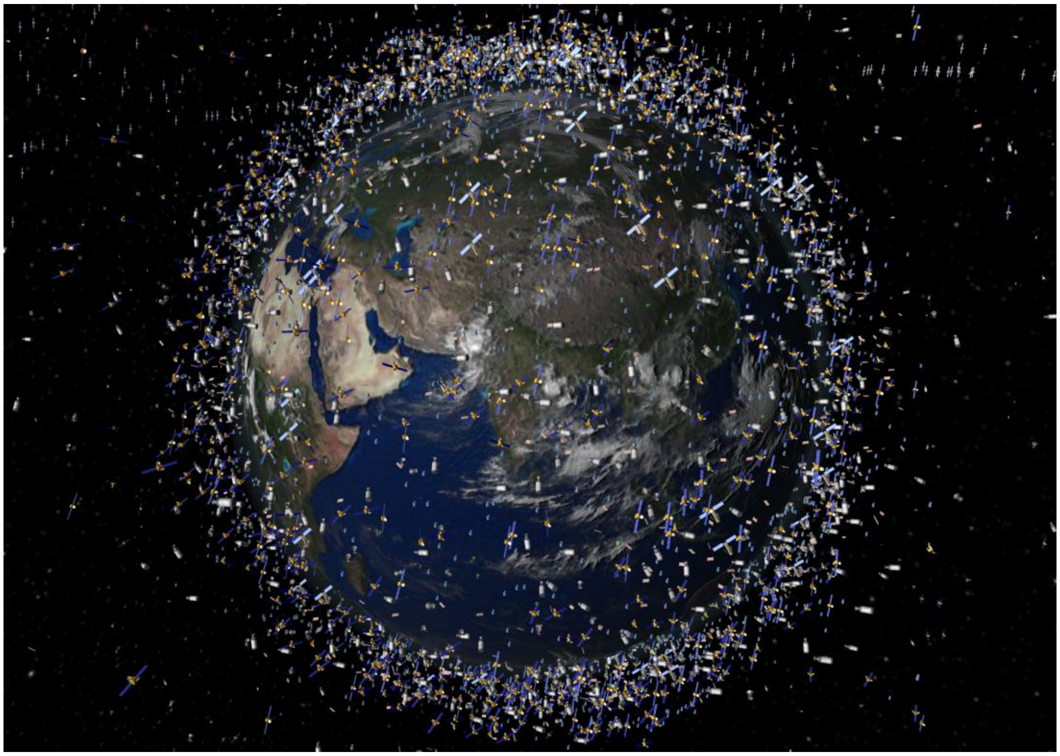
UNIVERSITY OF TORONTO
DIVISION OF ENGINEERING SCIENCE

AER407 Space Systems Design

Rocket-body Re-entry – Deorbit Demonstration (R2-D2) Mission

Command & Control



DeORBs

Jonathan Yam	Zhong Yi Wan	Yasir Malang	Ravindu Lokuwithana	Alexander Hong **LEADER**
(997474308)	(997337831)	(997545198)	(997771905)	(997584706)

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Revision History

Revision	Description	Editors
1.0	Initial creation of document	*Jon* *Jeff* *Yasir* *Ravindu* *Alex*

List of Acronyms

ADC	Analog to Digital Converter
ADCS	Attitude Determination & Control
DAC	Digital to Analog Converter
DC	Direct Current
DP	Deorbiting Pod
EDC	Error Detection and Correction System
EFBD	Electrical Functional Block Diagram
FFBD	Functional Flow Block Diagram
FPGA	Field-Programmable Gate Array
IMU	Inertial Measurement Unit
I/O	Input / Output
LEO	Low Earth Orbit
MDA	MacDonald Dettwiler and Associates
MIPS	Million Instructions per Second
MLBD	Mission-Level Block Diagram
NMR	N-Modular Redundancy
OTS	Off the self
PCS	Process, Control & Storage
PDR	Preliminary Design Review
RAM	Random Access Memory
RFP	Request For Proposals
ROM	Read Only Memory
SBD	System Block Diagram
SHD	System Hierarchy Diagram
TBC	To Be Confirmed
TBD	To Be Determined
TMR	Triple Modular Redundancy
TVC	Thrust Vector Control

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1.0 Command & Control

1.1 Overview

This document describes the command and control aspects of our deorbiting pod (DP) system, including design-related command and data handling requirements and autonomous behaviour requirements. In addition, trade studies are done to analyze possible command and control solutions for our subsystems.

Command and data handling requirements define functional and performance requirements for compute elements and software. Compute elements include microcontrollers, on-board computers, Field-Programmable Gate Array (FPGAs) for monitoring system health, telemetry, communication message handling, vision processing, power management, data handling, data storing, data retrieving, and commanding the debris manipulation system. On the other hand, autonomous behaviour requirements define functional and performance requirements for control systems, which include system for pointing the DP, guidance, navigation, and feedback. The following table shows the broad command and control categorizations that each subsystem is expected to need. We will use these as framework for generating appropriate requirements and conducting tradeoff analysis.

Table I. Command & Control Subsystem Function Overview

Deorbiting Pod Subsystems	**Command and Data Handling Requirements** *Does something need to send/receive commands/data?*	**Autonomous Behaviour Requirements** *Does something need to behave autonomously / automatically?*
Attitude Determination & Control (ADCS)	✔	✔
Communication	✔	✔
Debris Manipulation	✔	✔
Environmental Control	✔	✔
Power	✔	✔
Processing, Control & Storage (PCS)	✔	✔
Propulsion	✔	✔
Structure	✗	✗

It is expected each subsystem will have these command and control aspects with the following brief justifications.

i) Attitude Determination & Control requires data to be received from the PCS; these are commands to change the DP to the desired orientation. ADCS may also require automatic behaviour with feedback from the attitude sensors to stabilize the DP during debris removal phase.

ii) Communication requires data to be sent and received between the DP and ground control.

iii) Debris Manipulation requires commands to be received from the PCS in order to operate functions on the target rocket body. This function may be autonomous during debris removal phase using feedback from sensors and PCS.

iv) Environmental control requires data to be sent to and received from the PCS. Its function is most likely autonomous to control thermal conditions of the DP.

v) Power requires data to be received from PCS. There may be power management functions that require autonomy. For instance, solar panels may have to face the sun in order to generate power for the DP.

vi) PCS is the brain of the DP and requires constant feedback from other subsystems in order to perform its autonomous functions. Data streams are sent to and received in the PCS.

vii) Propulsion requires data to be received from the PCS in order to apply motion to the DP. Feedback from inertial sensors and PCS may give Propulsion autonomous functions.

viii) The Structure subsystem will not have any data handling capabilities as it comprises of load-bearing members of the DP. Structure will most likely have no autonomous capabilities as the other subsystems cover all other required autonomy. *Note: From the way our structures subsystem was defined in earlier reports, the structure subsystem does not include mechanisms; they are part of other subsystems.*

1.2 Requirements

This section captures the functional and performance requirements considering the command & control aspect of the design.

1.2.0 Command & Control Global Requirements

FUNCTIONAL REQUIREMENTS

CGFR1. The DP system shall allow ground control to override any instruction. *This is to give ground control manual control in cases where any aspect of a subsystem is not functioning as expected. This does not mean that subsystems have to be semi-autonomous (Semi-autonomous means having the ability to influence a control loop during normal operation. This, however, refers to overriding during other unplanned circumstances).*

PERFORMANCE REQUIREMENTS

CGPR1. Each subsystem that has human-in-the-loop commands shall be able to account for a latency of at least 0.4005s (not including time to make human decisions) (TBC) without adversely affecting the mission. *See calculations in Section 3.1.5 for round-trip signal travel time in worst-case scenario. This requirement ensures that if human operators are in the loop, the latency associated with their decision and transmission time is taken into account.*

CGPR2. In a given orbit, any human-in-the-loop commands shall be communicated to DP within a 14.3-minute (TBC) window. *See calculations in Section 3.1.6 for total ground satellite visibility time in worst-case scenario (at 200km where orbital period is fastest). This requirement means that some solutions will be less feasible because they may require long continuous periods of human-in-the-loop operation.*

1.2.1 Attitude Determination & Control Command & Control Requirements

FUNCTIONAL REQUIREMENTS

AC-CFR1. The subsystem shall be capable of controlling attitude in accordance with the Propulsion subsystem. *This is to ensure the DP's attitude can be controlled in conjunction with thruster operation during orbit transfers.*

AC-CFR2. The subsystem shall be capable of controlling attitude in accordance with the Debris Manipulation subsystem. *This is to ensure the DP's attitude can be controlled to accommodate the de-orbiting process.*

AC-CFR3. The subsystem shall measure the orientation of the system relative to inertial space. *This allows the subsystem to have autonomous capabilities as it provides feedback in the attitude control loop.*

AC-CFR4. The subsystem shall be able to stabilize the rotational motion of the DP.

AC-CFR5. The subsystem shall control attitude based on commands received from the PCS.

AC-CFR6. The subsystem shall be capable of being controlled by ground control. *This allows for human-in-loop controls for rocket body rendezvous and emergency modes.*

PERFORMANCE REQUIREMENTS

AC-CPR1. The subsystem shall be able to control the DP with 3 independent rotational degrees of freedom. *This is to provide the entire system with the ability to orient itself in any direction.*

AC-CPR2. The subsystem shall have a pointing accuracy of 0.25 degrees (TBC) taken with respect to an inertial or Earth-fixed reference when orienting the DP. *This is to ensure accuracy in controlling the DP's attitude with respect to a commanded direction* [1].

AC-CPR3. The subsystem shall measure the attitude with an accuracy of 0.25 degrees (TBC) with respect to inertial space about all three axes [1]. *This is to ensure the correct orientation of the DP is used for calculations and DP maneuvers.*

AC-CPR4. The subsystem shall have range of angular motion in all attitudes, within 50 degrees from nadir and within 20 degrees of Sun (TBC). *This is to ensure the DP has the control performance to freely orient itself for deorbiting rocket body, pointing for communication, thrusting and power generation* [1].

AC-CPR5. The subsystem shall have less than 1 degree/hour (TBC) of drift. *This is important when the system drifts off target set point with infrequent resets* [1].

AC-CPR6. The subsystem shall have a maximum overshoot of 2 degrees/s (TBC) in rotational motion after settling time. *This is used to limit overshoot and increase pointing accuracy* [1].

1.2.2 Communication Command & Control Requirements

FUNCTIONAL REQUIREMENTS

CM-CFR1. The subsystem shall be able to point antenna in a direction that allows the ground station satellite to receive (and send) transmissions. *Pointing can be done with actuators on the actual antenna, or via the entire DP re-orientation using attitude control system.*

CM-CFR2. The subsystem shall be able to receive command data from ground control. This includes all of the following types of human-in-the loop commands: orientation of DP, activation of debris manipulation subsystem, activation of environmental control subsystem, switching of power supply (stored power versus solar cell), deployment of solar cells, emergency shutdown. *These will be routed to PCS.*

CM-CFR3. The subsystem shall be able to transmit data and commands to ground control. This includes: sensor readings, orientation information, and status of all subsystems (operating versus having points of failure). *These are taken from PCS.*

Performance Requirements

CM-CPR1. Shall be able to point antenna with steady state tracking error of no more than 1.5 degrees (TBC) away from the specified position. *The specified position can be from ground control, or in the case of closed loop control, the set-point. Taking parabolic reflectors as the critical case with which has one of the narrowest beam widths of approximately 15 degrees, having a 10% deviation from the true value is deemed acceptable.*

1.2.3 Debris Manipulation Command & Control Requirements

Functional Requirements

DM-CFR1. The subsystem shall determine the relative position of the rocket body with respect to the DP. *This information will be used to derive control signals for rendezvous and manipulation operations (for maintaining operational distance, if applicable).*

DM-CFR2. The subsystem shall determine orientation of the rocket body, including angular position and angular velocity. *This requirement may mean optical sensors will be needed.*

DM-CFR3. The subsystem shall control manipulation mechanism to exert force at specified location on rocket body. *PCS processes location of centre of mass of the debris into a set of coordinates for the subsystem to act on.*

DM-CFR4. The subsystem shall be able to control force exerted by manipulator. *Based on the previous trade studies, the manipulator could be either a robotic arm or an ion thruster. We have chosen to keep the requirements general.*

DM-CFR5. The subsystem shall be able to receive commands from PCS to manipulate the debris.

DM-CFR6. The subsystem shall be capable of being controlled by ground control. *This allows for human-in-loop controls for rocket body rendezvous and emergency modes.*

Performance Requirements

DM-CPR1. The subsystem shall be able to point the manipulator with a minimum speed of at least 2 degree/s (TBC). *This is an estimated figure, determined to be reasonable because the maximum angular velocity of the rocket body will be no more than 1 degree/s, so it is expected that through the course of firing an ion beam or moving a robotic arm, its potential rotation of 2 degree/s should be sufficient.*

DM-CPR2. The subsystem shall be able to point the force generating mechanism with a steady state tracking error of no more than 0.01 metres (TBC). *Any force that is not directed at the centre of mass will generate torque on the rocket body, and that will result in angular velocity changes, which will make the motion of the debris more complicated to accommodate.*

DM-CPR3. The subsystem shall be able to change force application magnitude at a minimum speed of 0.1 N/s (TBC). *At this minimum rate, it will take approximately 1s to reach the necessary nominal 0.1N for deorbiting. This is a reasonable period of time.*

1.2.4 Environmental Control Command & Control Requirements

FUNCTIONAL REQUIREMENTS

EC-CFR1. The subsystem shall be capable of measuring the temperature of each subsystem.
EC-CFR2. The subsystem shall be capable of controlling and maintaining the desired temperature of each subsystem through commands received by PCS.
EC-CFR3. The subsystem shall communicate its operational status with the PCS.

PERFORMANCE REQUIREMENTS

EC-CPR1. The subsystem shall maintain the operational temperature of the PCS subsystem in the range between 5 °C – 65 °C (TBC) [9].
EC-CPR2. The subsystem shall maintain the operational temperature of the power source in the range between 0 °C – 70 °C (TBC) [10]. *This is to ensure batteries (if used) are functional throughout the mission.*
EC-CPR3. The subsystem shall control the temperature of other subsystems with a maximum error of 5 °C (TBC).

1.2.5 Power Command & Control Requirements

FUNCTIONAL REQUIREMENTS

PW-CFR1. The subsystem shall be capable of enabling charging of the power source when extra power is available from solar arrays. *This capability allows charged batteries to be used when solar power is not available.*
PW-CFR2. The subsystem shall be capable of controlling which power source is used for each subsystem. *Power source can be stored energy, such as a battery, or solar arrays.*
PW-CFR3. The subsystem shall be capable of distributing sufficient power to each subsystem.
PW-CFR4. The subsystem shall regulate the voltage distributed to the subsystems.
PW-CFR5. The subsystem shall be capable of orienting solar arrays for maximum exposure to the sun at a given position and an orientation of the DP.
PW-CFR6. The subsystem shall be capable of determining whether lighting is sufficient for use of energy directly from solar panels.

PERFORMANCE REQUIREMENTS

PW-CPR1. The subsystem shall control voltage to other subsystems with an accuracy of 1% (TBC).

PW-CPR2. The subsystem shall cut off power to other subsystems in case of a high current consumption within 2 milliseconds (TBC). *This ensures that the subsystem has enough time to cut off power to its own faulty equipment and achieve the correct current levels. This will prevent the subsystem from getting shut down.*

1.2.6 Processing, Control, and Storage Command & Control Requirements

FUNCTIONAL REQUIREMENTS

PCS-CFR1. The subsystem shall be capable of receiving commands from other subsystems.

PCS-CFR2. The subsystem shall be capable of validating commands from other subsystems. *Validation consists of receiving synchronization code, checking command message length (correct number of bits), and detecting no errors in polynomial code.*

PCS-CFR3. The subsystem shall be capable of processing data sent from other subsystems. *The data is processed by an onboard computer and includes calculating control dynamics of the spacecraft. This also includes acquiring spacecraft housekeeping data (health and status), feedback for onboard control of spacecraft functions, and routing payload or subsystem data to and from receivers and transmitters, storage or system controllers.*

PCS-CFR4. The subsystem shall be capable of detecting data faults and correcting them. *This ensures the system will have measures to deal with potential failures.*

PCS-CFR5. The subsystem shall be capable of decoding data from other subsystems. *The decoder executes commands that pass the validation of commands by the PCS.*

PCS-CFR6. The subsystem shall provide operational feedback for commands being executed. *Feedback can be in the form system status. This is used for autonomous capabilities of the PCS.*

PCS-CFR7. The subsystem shall be capable of distributing commands to other subsystems.

PERFORMANCE REQUIREMENTS

PCS-CPR1. The subsystem shall have a maximum processing time of 30 sec for all individual functions (TBC).

PCS-CPR2. The subsystem shall have a double precision floating point accuracy (TBC). *This provides the necessary accuracy in determining control dynamics of the spacecraft.*

PCS-CPR3. The subsystem shall communicate with other subsystems at a total bandwidth of 4096 kbps (TBC). *This is needed to successfully rendezvous with the rocket body and perform other maneuvers.*

PCS-CPR4. The subsystem shall be capable of storing 2 gigabytes (TBC) of data onboard [1]. *This ensures that the system will have enough available memory for onboard calculations and storage.*

1.2.7 Propulsion Command & Control Requirements

FUNCTIONAL REQUIREMENTS

PP-CFR1. The subsystem shall be able to measure the inertial position of the DP. *The position of the DP is needed so that the appropriate maneuvers can be performed to move the DP.*

PP-CFR2. The subsystem shall open or close thruster valve according to commands from PCS.

PP-CFR3. The subsystem shall be able to move the DP (translational movement).

PP-CFR4. The subsystem shall be able to operate in conjunction with the Attitude Determination and Control Subsystem to position the DP anywhere in inertial space.

PERFORMANCE REQUIREMENTS

PP-CPR1. The subsystem shall measure translational speed of DP within 0.07 m/s. *See calculations in Appendix Section 3.1.2.*

PP-CPR2. The subsystem shall open or close thruster valve in at most 1 s (TBC). *This is needed to successfully rendezvous with the rocket body. See Propulsion Subsystem Calculations in Appendix Section 3.1.3.*

PP-CPR3. The subsystem shall be capable of providing a thrust vector through the center of mass of the DP with an error of 2 degrees (TBC). *This is to minimize use of Attitude Control subsystem when the DP is commanded to move in purely translational motion.*

1.3 Trade Studies

For each subsystem, trade studies have been conducted for the main command & control design choices at this stage of our design. Weights are assigned to each category and the design choices are ranked from 1 to 5, with 1 representing a poor design and 5 representing an excellent design choice with respect to each category. The weighted table is then used to determine a winning design, which is boldfaced and highlighted in each table.

	Poor				Excellent
Weighting:	**1**	**2**	**3**	**4**	**5**

1.3.1 Attitude Determination & Control Subsystem

Attitude Controllers

Table II. Attitude controllers weighted matrix

		Methods				
Attitude Controllers	**Weight**	**Zero Momentum (3 wheels)**	**Zero Momentum (Control Moment Gyroscope)**	**Cold Gas Thruster**	**Magnet-orquer**	**Hybrid System (Reaction Wheels with Thrusters)**
Meet Subsystem requirements						
Pointing Options (AC-CPR4)		5	5	3	2	5
Controllability (Stabilizing & Orientating) (AC-CFR4)		5	5	3	2	5
The subsystem shall satisfy the PRECISION REQUIREMENT		5	5	2	2	5
The subsystem shall satisfy the ACCURACY REQUIREMENT		5	5	4	2	5
Score	0.4	1	1	0.6	0.4	1
Control & Command Complexity						
Design complexity		4	3	3	4	3
Implementation complexity		3	2	3	4	3
Score	0.3	0.7	0.5	0.6	0.8	0.6
Risk						
Control Risk (risk of software, hardware, autonomy failure) Will it last 1 year? Can redundancy be built?		4	4	3	5	3
Technological Risk (New Tech vs Ground tested vs. Used in Space)		4	4	5	5	2
Score	0.3	0.8	0.8	0.8	1	0.5
Total Score		**85**	79	66	70	73

Zero momentum (3 wheels) work by having reaction wheels of each of the DP's axis. They control attitude without using fuel and are particularly useful when the spacecraft must be rotated by very small amounts. They apply torque simple by changing the rotor spin speed. Zero momentum (control moment gyroscope) is similar to 3 reaction (momentum) wheels, but tilts the rotor's spin axis without necessarily changing its spin speed. This allows for high speed attitude changes. Cold gas thrusters release gas from a nozzle as reaction mass to control attitude. Magnetorquer use electromagnetic coils to develop magnetic field which interferes with the Earth's magnetic field. Thus, counter-forces provide torque. A particular hybrid system, using reaction wheels and thruster is also a viable solution for attitude control as it has the same functions as reaction wheels but allows orientation changes at a higher rate.

From our trade study, zero momentum (3 wheels) prevail as our top choice for attitude control due to its simplicity and high accuracy. Cold gas thruster and magnetorquer options do not have high accuracy and flexibility in spacecraft pointing as the other options. This is important for our DP to orient in the correct position in order to perform debris deorbiting and rendezvous maneuvers. Control moment gyroscopes and hybrid systems provide the capabilities, but their solutions have higher control complexity. For instance, hybrid systems rely on two systems to act together in harmony to provide attitude control. High rates of attitude change are also not necessities for this mission.

Autonomy

A trade study was done for autonomous capabilities of the ADCS subsystem in **Table III**. Ground-based (teleoperated) and open-loop controls for ADCS is not feasible for the mission. According to requirement CGPR2, there is only a 14.3 minute window time frame for teleoperators to command the DP. A closed loop control for ADCS would make the most sense. Autonomous control is preferred over semi-autonomous in most cases of the mission. However, the complexity of rendezvous with the debris is high and may require supervision from ground control. Thus, semi-autonomous control wins over autonomous control in our trade study and allows for less risk in the mission.

Table III. Attitude control autonomy weighted matrix

Attitude Control Autonomy	Weight	Methods			
		Autonomous	Human-in-loop (Semi-Autonomous)	Ground-Based (Teleoperation)	Open Loop
Meet Global system requirements					
Latency Requirement (CGPR1)		5	5	5	5
Operate under time constraint (CGPR2)		5	4	2	1
Score	0.15	1	0.9	0.7	0.6
Meet Subsystem requirements					
Rendezvous Difficulty (**Error! Reference source not found.**)		2	4	3	1
Controllability (Stabilizing & Orientating) (AC-CPR4)		4	4	2	2
The subsystem shall satisfy the PRECISION REQUIREMENT		4	4	2	1
The subsystem shall satisfy the ACCURACY REQUIREMENT		4	4	2	1
Score	0.4	0.7	0.8	0.45	0.25
Control & Command Complexity					
Design complexity		3	3	4	4
Mission Execution complexity		4	3	3	1
Score	0.15	0.7	0.6	0.7	0.5
Risk					
Control Risk (risk of software, hardware, autonomy failure) Will it last 1 year? Can redundancy be built?		5	3	3	1
Technological Risk (New Tech vs Ground tested vs. Used in Space)		2	3	3	3
Aggravation Risk (risk of generating more debris)		2	3	3	1
Score	0.3	0.6	0.6	0.6	0.33
Total Score		71.5	**72.5**	57	36.5

1.3.2 Communication Subsystem

In this trade study, we compare parabolic reflector antennae with toroidal antennae. The parabolic reflector is a high gain antenna with beam width 15 degrees and is more directionalized, as there are less side lobes [14]. This means that it requires more precise pointing [14]. As a result, it will be more difficult to meet performance requirement CM-CPR1. The toroidal antenna, on the other hand, has a very low gain, highly omni-directional transmission (360 degrees), and allows for no commanded pointing [1], so requirement CM-CPR1 will be met with less design complexity. Design complexity will be higher for the parabolic antenna because it will need to move to ensure that it remains pointed to the ground station satellite as the DP is changing attitude (e.g. during a maneuver). This will likely entail use of closed-loop control. The toroidal antenna will not likely need any mechanical control aspect and has a lower design complexity.

From the previous electrical trade study conducted, the parabolic antenna was given preference over the toroidal due to lower power consumption. However, taking into account the fact that the data rates as set out in the Electrical requirements are fairly low for a space mission, use of the toroidal antenna with low power may be acceptable. It can be used in cases where the spacecraft must change orientation frequently during maneuvers, and there would be no interruption of data transfer. This communication method was used in the Juno spacecraft [8]. This would be advantageous for our mission requirements, as the maneuvers performed in the rendezvous and de-orbiting stages are expected to result in significant changes in DP orientation.

From the holistic perspective of all trade studies conducted, the toroidal antenna has been chosen. Although the data transfer rate is low, it is not expected that the mission will need high rates of data transfer. It has the lowest technical complexity from both an electrical and controls perspective, and is still able to meet requirements.

1.3.3 Debris Manipulation Subsystem

From the previous trade studies conducted, it was identified that the robotic arm and ion thruster solutions were the most promising from a mechanical and electrical standpoint. We will evaluate these two solutions based on command and controls considerations in this section.

Table IV. Debris manipulation methods weighted matrix

		Methods	
Debris Manipulation Methods	**Weight**	**Robotic Arm**	**Ion Thruster**
Meet Global system requirements			
Latency Requirement (CGPR1)		2	**5**
Operate under time constraint requirement (CGPR2)		3	**5**
Score	0.15	0.5	**1**
Meet Subsystem requirements			
Ability to exert force precisely (DM-CFR4)		2	**4**
Point force generating mechanism with steady-state tracking error of no more than 0.01m (DM-CPR2)		5	**5**
Score	0.4	0.7	**0.9**
Control & Command Complexity			
Design complexity		2	**1**
Score	0.15	0.4	**0.2**
Risk			
Control Risk (risk of software, hardware, autonomy failure) Will it last 1 year? Can redundancy be built?		4	**2**
Technological Risk (New Tech vs. Ground tested vs. Used in Space)		4	**4**
Score	0.3	0.8	**0.60**
Total Score		65.5	**72**

The robotic arm solution is expected to require human in the loop operations while the arm is grappling the rocket body due to the intricate nature of the problem – with the need to account for rotational motion. The ion beam is able to operate at a distance of 20 metres away. In addition, no contact is made with the debris and the solution could be done autonomously (or with little human-in-the-loop commands).

It would be difficult for the robotic arm to meet requirement CGPR1 because a minimum latency of 0.4005s (and this does not include time for operator to make decision) involves risk of the DP colliding with the rocket body. This is due to the fact that the distance between the DP and the debris will become increasingly smaller as the robotic arm tries to attach to the DP. Moreover, it is also expected that requirement CGPR2 will be difficult to meet because the robotic arm solution involves "docking" with the rocket body. Thus, it is difficult to get in all human operator commands before the next orbit (~ 90 minutes) in less than 15 minutes. The ion beam solution does not encounter the same problem with requirements CGPR1 and CGPR2 because the same "docking" activity is not required. It is also possible for the beam to deliver force for 15 minutes continuously, and stop operating until the next cycle.

The ion beam is a better fit for requirement DM-CFR4 as it is able to direct force onto the centre of mass with no moving parts. Attitude control can be used to aim at the centre of mass using closed-loop control. The robotic arm solution, however, involves having the DP's propulsion unit maneuver the DP-rocket body mass. Without thrust vectoring, it will be very difficult to get the thrust vector to align with the centre of mass of the combined system as the thrust from the propulsion subsystem will be off to the side. This aside, it is expected that with closed-loop control, both solutions are able to point the force vector of the manipulator mechanism within the error set by requirement DM-CPR2 via use attitude control.

In terms of design complexity, the ion thruster is expected to have a much higher complexity because it needs to maintain operational distance throughout the de-orbiting process, which means the propulsive thrust from the Propulsion subsystem has to be balanced with the ion beam thrust. Furthermore, the ion beam has a higher control risk because measurements (force and distance) have to be made at very high frequencies to ensure that the ion thrust delivered allows the DP to maintain the operational distance. If there is a slight force imbalance, the DP can possibly collide into the rocket body.

The algorithm used in the ion beam has low technological risk as similar control algorithms are very common in swarm robotic applications, such as formation flying [7]. The controls aspects for the robotic arm would also have low technology risk in that these algorithms and control laws are widely used in current space applications.

Overall, the controls design for the robotic arm may be simpler, but will is not expected to accomplish the requirements as well as the ion beam solution. Thus the ion thruster has been chosen as the winner of this trade study.

Autonomy

With regards to requirements CGPR1 and CGPR2, having the ion thruster run open-loop is not feasible, as the latency time, including time required for the mission operator to decide on how much ion thrust to exert, is too long. It is expected that the motion of the DP and rocket body will be complex, and thus, the ion thrust required over time is to be varying. Some level of autonomy is needed to fulfill requirements DM-CPR2 and **Error! Reference source not found.** (tracking requirements). A semi-autonomous control system is preferable over a fully autonomous because it allows external commands to start and stop the ion thrust, if for example, unplanned maneuvers need to be conducted to the DP (e.g. the altitude of the DP needs to be adjusted, in which case ground control would need to turn off the ion thrust). Thus, a semi-autonomous implementation has been selected, where the operator on the ground can change values of the inputs to the controller.

Debris Detection and Tracking

Table V. Trade off breakdown for Debris Detection and Tracking

		Methods		
Debris Detection and Tracking	**Weight**	**Autonomous**	**Human-in-Loop (Semi-Autonomous)**	**Ground-Based (Teleoperated)**
Meet Subsystem requirements				
Capable of dealing with any possible orientation and rotation of the debris (DM-CFR3)		2	5	5
Minimum time needed to compute relative position (DM-CFR1)		5	3	4
The subsystem shall satisfy the PRECISION REQUIREMENT		5	5	2
The subsystem shall satisfy the ACCURACY REQUIREMENT		4	5	2
Score	0.5	0.8	0.9	0.65
Control & Command Complexity				
Design complexity		3	3	5
Mission Execution complexity		5	3	3
Score	0.2	0.8	0.6	0.8
Risk				
Control Risk (risk of software, hardware, autonomy failure) Will it last 1 year? Can redundancy be built?		3	4	4
Technological Risk (New Tech vs Ground tested vs. Used in Space)		4	5	5
Aggravation Risk (risk of generating more debris)		5	5	5
Score	0.3	0.8	0.93	0.93
Total Score		80	**85**	76.5

A major component in Debris Manipulation is the detection and tracking of the rocket body to be deorbited. From a command and control perspective, the level of autonomy involved in this process is a key design decision to be made. Technologies have been developed to allow for detection of space debris using space-based sensors [11]. These sensors can be equipped on space systems and their measurement can be used to decide the actions required to deorbit the space debris. On the other hand, there are also ground-based technologies that could be potentially used to accomplish the task [12], [13]. These options typically require a moderate level of autonomy to set up and verify equipment and measurement.

The options considered in this trade study are classified according to the level of autonomy. Autonomous option refers to the use of space sensor technology with minimum human instructions for detection and tracking of the rocket body. The human-in-the-loop options also entail the use of space sensors but their measurements are subject to modification or verification by humans. The last option considered here is the use of ground-based technology, which demands the critical measurements to be made outside of our space system and directly sent to the system for decision-making.

The result of the trade study shows that the human-in-the-loop sensor option is the best since it combines robustness with high precision and accuracy. Even though it compromises the time required for measurement (need time for a return trip of signals), it avoids the possibility for unverified (potentially erroneous) measurements. Compared to the ground-based option, it has better precision as the sensors are more specific and offer closed-up detections of the rocket body as opposed to estimations from more general long-distance equipment.

1.3.4 Environmental Control Subsystem

Table VI. Environmental Control Autonomy weighted matrix

		Methods	
Environmental Control Autonomy	**Weight**	Autonomous	Human-in-loop (Semi-Autonomous)
Meet Global system requirements			
Latency Requirement (CGPR1)		5	5
Operate under time constraint (CGPR2)		5	3
Score	0.15	1	0.8
Meet Subsystem requirements			
Maintain operational temperature for all subsystems (EC-CFR2)		5	5
Control temperature of other subsystems (EC-CPR3)		5	3
Score	0.4	1	0.8
Control & Command Complexity			
Design complexity		4	3
Mission Execution complexity		4	3
Score	0.15	0.8	0.6
Risk			
Control Risk (risk of software, hardware, autonomy failure) Will it last 1 year? Can redundancy be built?		4	3
Technological Risk (New Tech vs Ground tested vs. Used in Space)		5	3
Aggravation Risk (risk of generating more debris)		5	3
Score	0.3	0.93	0.60
Total Score		**95**	71

In the above trade study (**Table IV**), two control options for environmental control subsystem was conducted. An autonomous system uses thermal sensors as feedback to decide whether to activate heaters or coolers. A semi-autonomous system does the same but waits for command from ground control to decide how to proceed.

Latency requirements are met due to the fact that the temperature in space does not change by large amounts in millisecond time. However, the spacecraft could experience extreme temperature conditions in any section of its orbit due to conditions of space (e.g. solar flare). Thus, the environmental subsystem plays a critical role in controlling operational temperature and cannot wait for commands from ground control. Semi-automated systems may have a higher risk of failure and the subsystem may not be fully capable of keeping the other subsystems within the given temperature brackets.

In the point of view of environmental control, semi-automated systems will require more communication to PCS than fully automated systems. Both will require the same amount of sensors, heaters and coolers. Hence, a semi-automated system will have a higher design complexity than a fully automated system. Moreover, a semi-automated system may have to rely on decisions from ground control to cut off the power in case of a high current draw.

Fully automated temperature control systems are being used many space applications but semi-automated temperature control is not commonly used. As a result, there is higher risk involved with semi-automated control. In conclusion, our system will use a fully automated environmental control system.

1.3.5 Power Subsystem

Table VII. Degrees of freedom for solar array manipulator weighted matrix

		Methods			
Degrees of freedom for solar array manipulator	**Weight**	Fixed manipulator	Manipulator with a single degree of freedom	Manipulator with 2 degrees of freedom	Manipulator with multiple (3+) degrees of freedom
Meet Subsystem requirements					
Voltage supply requirements (PW-CPR1)		3	4	4	5
Exposure to sun		1	3	4	5
Score	0.4	0.4	0.7	0.8	1
Control & Command Complexity					
Design complexity		5	5	3	2
Mission Execution complexity		5	5	3	2
Score	0.15	1	1	0.6	0.4
Risk					
Control Risk (risk of software, hardware, autonomy failure) Will it last 1 year? Can redundancy be built?		5	5	3	3
Technological Risk (New Tech vs. Ground tested vs. Used in Space)		5	5	4	3
Aggravation Risk (risk of generating more debris)		4	4	3	3
Score	0.3	0.93	0.93	0.67	0.60
Total Score		59	**71**	61	64

Fixed solar arrays have no capabilities to move themselves in order to get the best orientation towards the sun. An increase number of degrees of freedom for solar arrays allow them to acquire the best orientation for maximum power generation. However, a high degree of freedom in the solar array manipulator leads to a more complex control problem. This will require more controllers in the system. From our research, it is only necessary to have one degree of freedom for each solar array manipulator for the DP. This gives an excellent balance between design complexity and functionality.

1.3.6 Processing, Control, and Storage Subsystem

Table VIII. Computer system architecture weighted matrix

		Methods		
PCS Architecture	**Weight**	**Centralized**	**Semi-Distributed**	**Distributed**
Meet Subsystem requirements				
Fault Tolerance & Correction (Validation) (PCS-CFR2)		1	3	5
Robustness (PCS-CFR4)		2	4	4
Score	0.4	0.3	0.7	0.9
Control & Command Complexity				
Design complexity		5	3	1
Test & Debug		5	3	1
Score	0.4	1	0.6	0.2
Risk				
Control Risk (risk of software, hardware, autonomy failure) Will it last 1 year? Can redundancy be built?		1	4	5
Score	0.2	0.2	0.8	1
Total Score		56	**68**	64

Centralized architecture is the most common design. They are easy to program, test, and debug as everything is located in one location [2]. However, this is a single point failure system. In other words, when the central computer system fails, the entire processing and data handling unit of the DP fails. This architecture has low fault tolerance and is in risk for a catastrophic single failure. Semi-distributed system is mainly used to increase fault tolerance. This architecture gives the ability to offload time critical functions to microcontrollers to reduce the overall processing time. However, there is an increase in design complexity compared to the centralized architecture. The distributed architecture is similar to the semi-architecture, but there is a network of computer processing units. This is the hardest to design due to a high number of interfaces between subsystems and CPU. One has to decide where software goes and this can add additional electrical and mechanical subsystem requirements [2]. For our DP, we have chosen semi-distributed architecture due to its balance between robustness and simplicity.

Table IX. PCS autonomy weighted matrix

PCS Autonomy	Weight	Methods			
		Autonomous	Human-in-loop (Semi-Autonomous)	Ground-Based (Teleoperation)	Open Loop
Meet Global system requirements					
Latency Requirement (CGPR1)		5	5	5	5
Operate under time constraint (CGPR2)		5	4	2	1
Score	0.15	1	0.9	0.7	0.6
Meet Subsystem requirements					
Validation of commands from other subsystems (PCS-CFR2)		5	3	1	1
Distribute commands to other subsystems (PCS-CFR7)		5	2	1	1
Processing Time (PCS-CPR1)		5	3	2	1
Score	0.4	1	0.533333	0.266667	0.2
Control & Command Complexity					
Design complexity		3	4	4	4
Mission Execution complexity		4	3	3	1
Score	0.15	0.7	0.7	0.7	0.5
Risk					
Control Risk (risk of software, hardware, autonomy failure) Will it last 1 year? Can redundancy be built?		4	5	2	1
Technological Risk (New Tech vs Ground tested vs. Used in Space)		3	4	4	3
Score	0.3	0.7	0.9	0.6	0.4
Total Score		**86.5**	72.33333	49.66667	36.5

Table IX presents a trade study between levels of autonomy of the PCS subsystem. An autonomous PCS will require zero input from human teleoperators from ground control in order for the PCS to function (e.g. distributing commands to individual subsystem, processing and calculating control dynamics). A semi-autonomous system requires human input for certain stages of the mission. Ground-based control fully depends on commands from ground control for the PCS to function. Open-loop control provides no feedback to the PCS. This means the PCS cannot assess its own performance.

Clearly, it is infeasible to use ground-based control as there is only a communication window of 14.3 minutes from requirement CGPR1. It is also ineffective to use open-loop control as the PCS will have no way of telling its own performance. This leads to a less robust system as it cannot validate commands and correct errors in the system. Autonomous PCS has been chosen as our design choice due to the latency requirement, and the ability for the PCS to self-correct without any human assistance. An autonomous PCS can distribute commands faster than humans and it can do it throughout the life cycle of the DP.

1.3.7 Propulsion Subsystem

Table X. Trade off breakdown for thrust vectoring vs. fixed thrust vector

		Methods	
Thrust control	**Weight**	**Thrust Vector Control**	**Fixed Thrust Vector**
Meet Subsystem requirements			
Shall provide the DP with a thrust vector through the center of mass of the DP with an error of 2 degrees (TBC) (PP-CPR3)		1	4
Score	0.5	0.2	0.8
Control & Command Complexity			
Design complexity		3	5
Implementation complexity		3	5
Score	0.2	0.6	1
Risk			
Control Risk (risk of software, hardware, autonomy failure) Will it last 1 year? Can redundancy be built?		3	5
Technological Risk (New Tech vs Ground tested vs. Used in Space)		4	5
Score	0.3	0.7	1
Total Score		43	**90**

Thrust vectoring, also known as thrust vector control (TVC), is the ability of an engine to change the direction of thrust, in order to control the spacecraft's attitude. Some spacecraft use liquid chemical thrusters for propulsion, and these types of thrusters usually use a spherical universal joint (i.e. gimbal), which allows the combustion chamber and engine bell nozzle to move independently of the spacecraft. Requirement PP-CFR3 requires the subsystem to be able to provide thrust vector through the center of mass. With TVC, even when the gimbal is commanded to be at a neutral position (no swivel), there is a high chance that the thrust vector will not be through the center of mass of the DP. The attitude control subsystem will be required to correct the unwanted angular rotation of the DP.

The TVC gimbal on the Saturn V was capable of ± 6 degrees [4] and thrust vectoring was also used on the NASA Space Shuttle [5]. Thrust vectoring is widely used in aircraft today such as the Sukhoi Su-30 MKI, and it gives the aircraft a higher level of maneuverability especially at low speeds. TVC on a satellite would allow greater maneuverability and a faster response time from commands given by PCS to actual attitude change of DP. However, both the Saturn V and the Space Shuttle used thrust vectoring mainly during launch and most small satellites orbiting in LEO do not use thrust vectoring. In orbit, thrust vectoring will have no added advantage over a fixed thrust vector coupled with momentum wheels. Both methods will be able to meet PP-CFR4 equally as well. A disadvantage of TVC is that the gimbal mechanism adds additional mass as well as mechanical complexity and control complexity, since the satellite's attitude is now controlled with momentum wheels and thrust vectoring. The technology risk for using thrust vectoring is high since it is not widely used on small LEO satellites.

For the above-mentioned reasons and by conducting a trade study analysis seen in the table above, TVC will not be implemented in the DP – the chosen option is a fixed thruster.

1.4 Architecture

The control architecture for each individual subsystem is shown in the following section. The controller, sensors, actuators, and compute elements are shown for each subsystem. All data rate of feedback loops are detailed in Section 1.5. Note: In order to satisfy requirement CGFR1, all inputs (i.e. setpoints) to any architecture are assumed to be configurable by human operators in mission control.

1.4.1 Attitude Control Subsystem Architecture

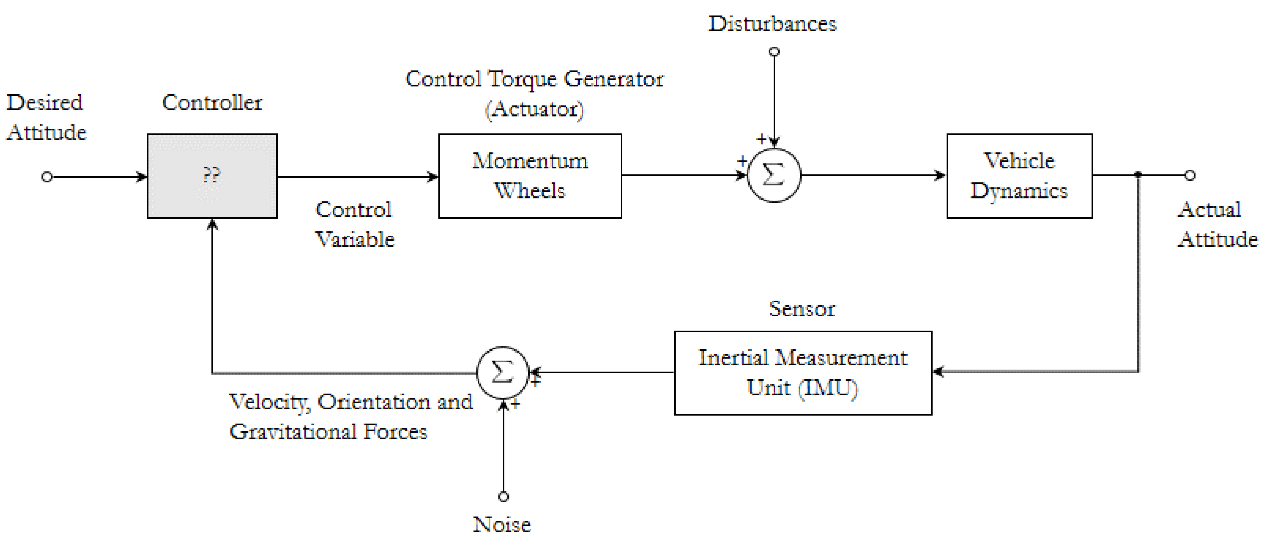

Figure 1. Attitude Control Architecture

Figure 1 illustrates the control process involved in adjusting the attitude of the system. The control architecture adopts a closed-loop structure. The desired attitude signal is fed into the controller, which generates the control variables that are sent to the actuators of momentum wheels in all axes. This in turn leads to the spinning of momentum wheels, exerting torques on the overall system and thus changing the attitude of the system as a result of vehicle dynamics. The actual attitude will be monitored under an Inertial Measurement Unit (IMU), which gathers information on the velocity, orientation and gravitational forces on the global system. This information is passed back to the controller to enhance control efficiency. The feedback loop is thus completed.

1.4.2 Communication Subsystem Architecture

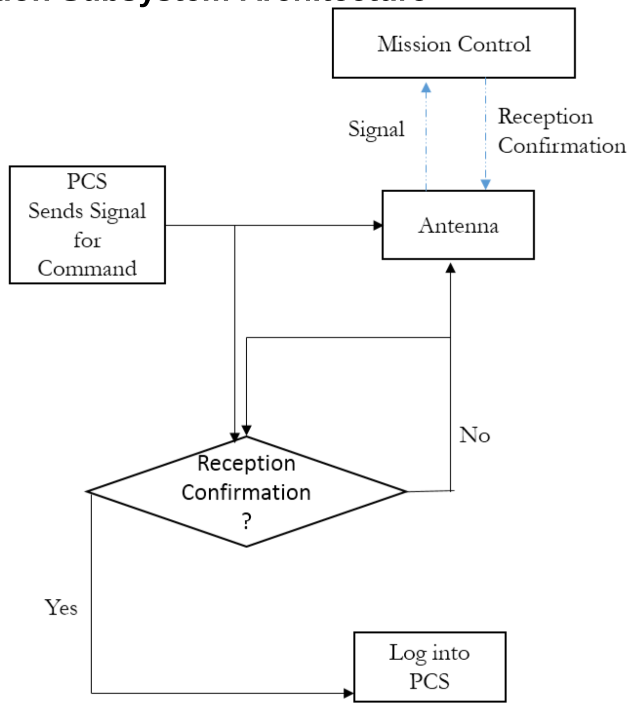

Figure 2: Communication logic flow

The logic flow diagram shows the software logic considerations for the Communications Subsystems. Upon command by PCS, the antenna will send a given data signal (blue dashed line) to mission control (telemetry, etc.). Ground control will send a “reception confirmation” back to the DP upon reception of the data. If this “confirmation” is not received by the DP, the DP will keep attempting to send the data. If the confirmation is received, a signal is sent to PCS indicating that no more attempts need to be made.

1.4.3 Debris Manipulation Subsystem Architecture & Propulsion Subsystem Architecture

Our debris manipulation solution is ion thrusters and our propulsion solution is a fixed vector thruster. We have chosen to use a single controller for both the Debris Manipulation subsystem and the Propulsion subsystem. The rationale behind this is that in the rendezvous and de-orbiting stages (these are shown in the FFBD in our Con-Ops documents), both are used in conjunction to position the DP translationally. Control of both subystems will allow the DP to approach the rocket body; with the Propulsion subsystem providing thrust in the opposite direction to the ion thruster, a single controller will be able to adjust the voltages (*Voltage 1*, corresponding to the actuator voltage for the chemical rocket valve and *Voltage 2*, corresponding to the ion thruster’s electrode voltage) to provide the needed steady state distance or location. The “selector” input allows for 3 different scenarios:

Selector = 1: **Autonomous operation with use of distance sensors** which is needed when rendezvousing and de-orbiting. Distance sensors are used because the relative distance between the DP and the rocket body is small and critical during these 2 stages in the FFBD.

Selector = 2: **Autonomous operation with use of location sensors** which is used in other maneuvers (not including rendezvous or de-orbiting), such as when the DP has to remove itself from its current trajectory and posititon itself at a large distance away from the rocket body, e.g. for maintenance. In this case optical sensors cannot be used, and thus IMU is the sensor.

Selector = 3: **Manual operation** breaks the control loop. This allows human operator to have direct inputs for Voltage 1 and Voltage 2 for the Propulsion and Ion Thrusters respectively. This would be used in instances where feedback is not wanted. The manual inputs are depicted in dotted lines.

In this implementation, the "selector" basically turns on different parts of the controller depending on what scenario is selected.

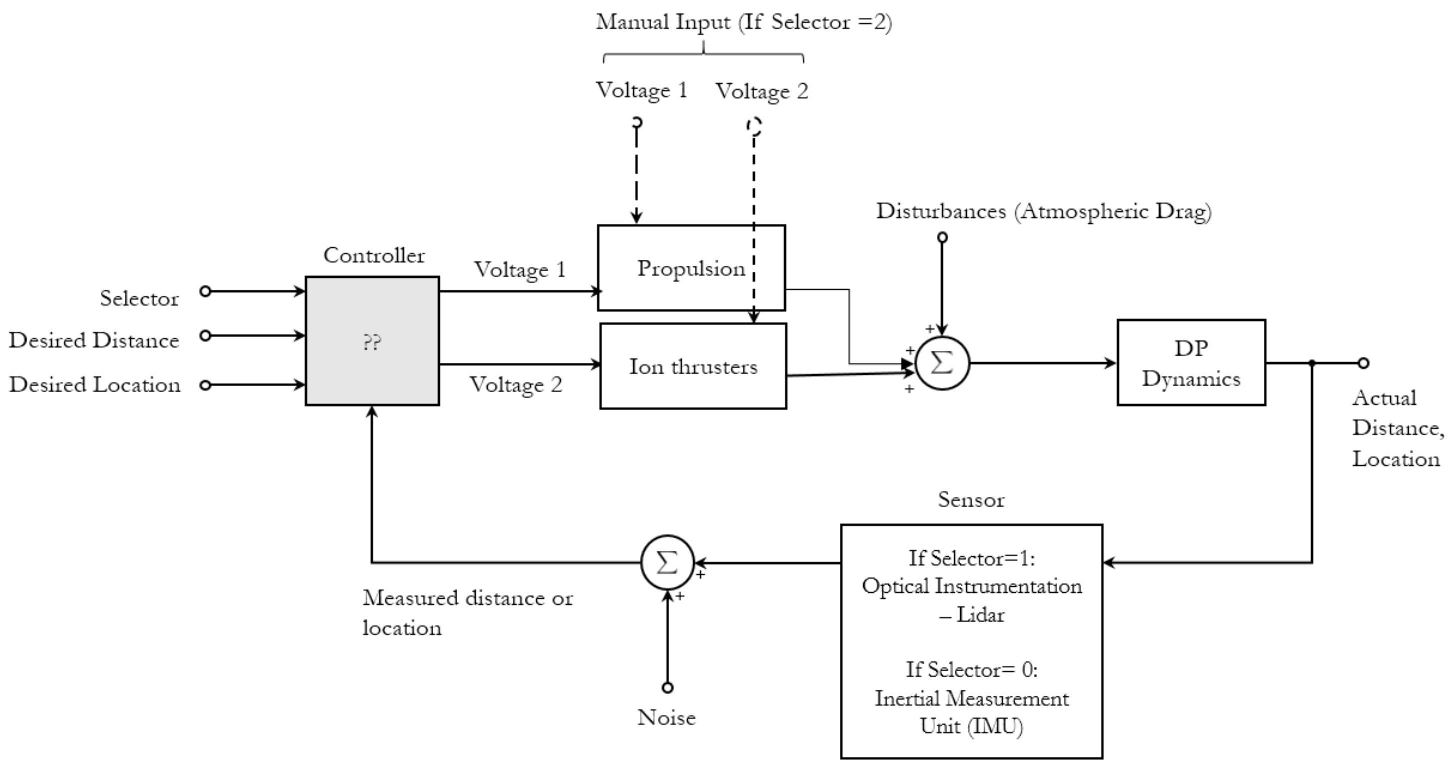

Figure 3. Debris Manipulation and Propulsion Architecture

Figure 3 depicts the interactions between the Manipulation subsystem, Propulsion subsystem, and Attitude Determination & Control subsystem for the three different scenarios described above.

The semi-autonomous nature of the Debris Manipulation subsystem is evident here. While there is closed-loop control, there is room for a human operator in mission control to change the value of the desired inputs (either distance or location) throughout the mission. For example, while rendezvousing, the operator may reduce the desired distance incrementally as time passes.

Figure 4 below shows the software behaviour diagram of this architecture.

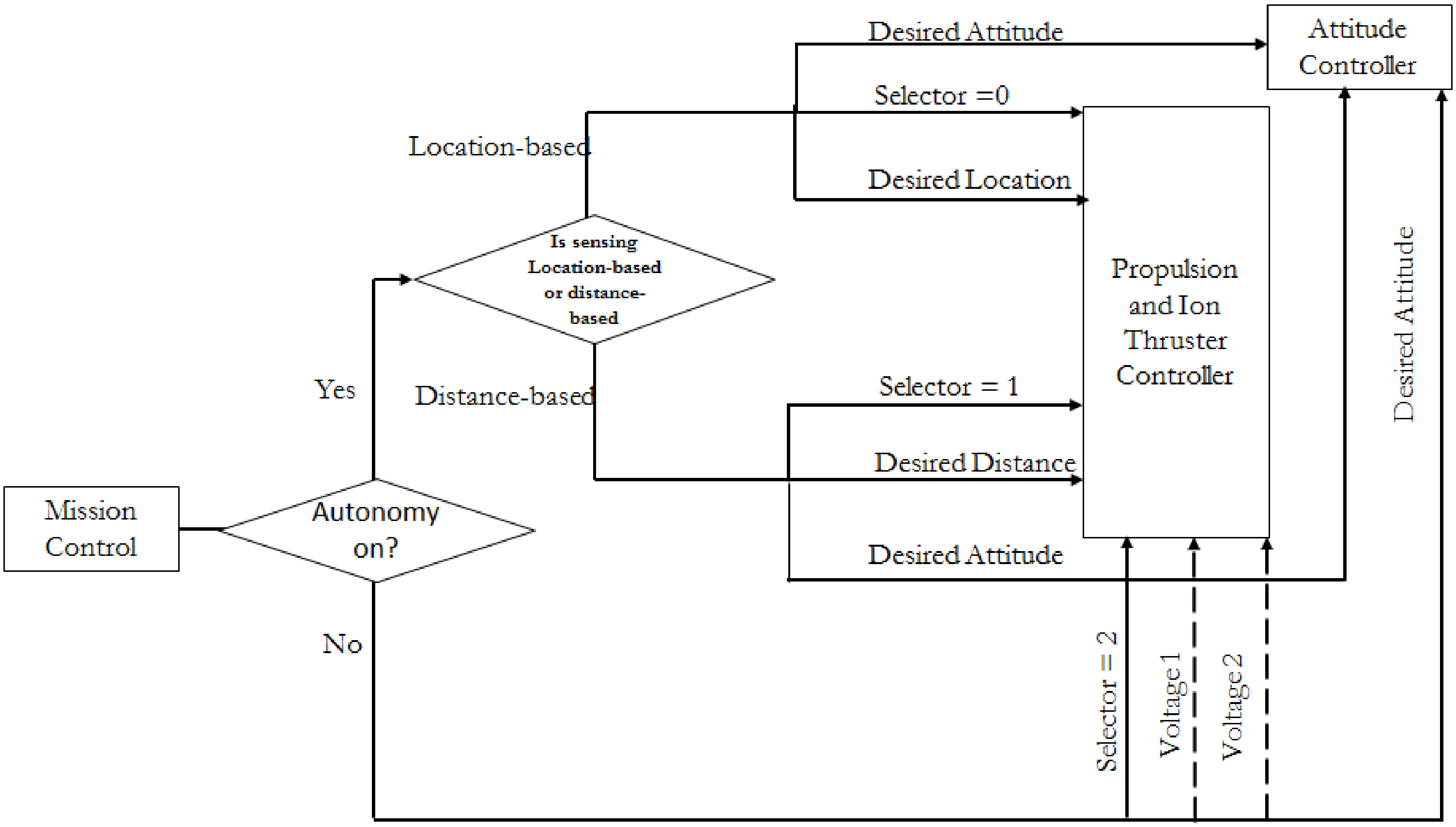

Figure 4. Software behaviour diagram for controlling pose of DP

1.4.4 Environmental Control Subsystem Architecture

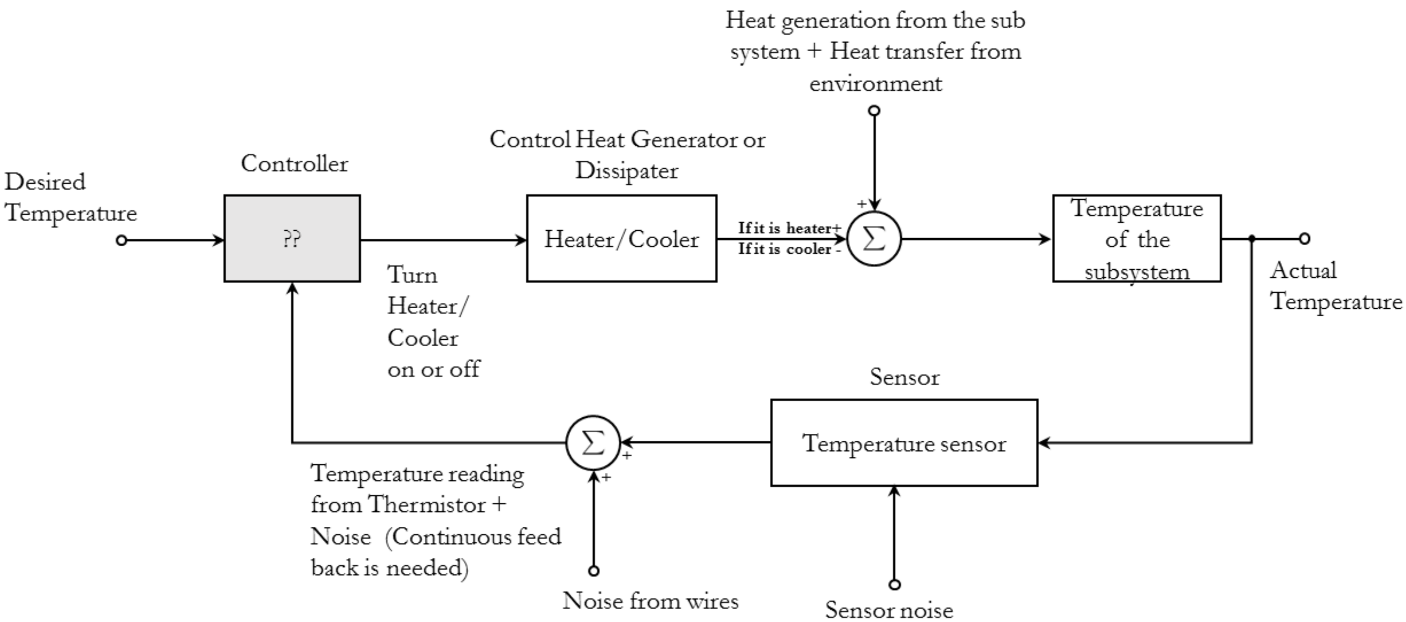

Figure 5. Environmental Control Architecture

Figure 5 illustrates the control process involved in adjusting the temperature for each of the subsystems in the DP. In this closed-loop control architecture, the desired temperature signal is fed into the controller, which generates the control variables that are sent to heaters or thermo-electric cooler depending on whether the system needs an increase or decrease in temperature. The temperature of the subsystem is measured by the temperature sensor attached to the subsystem and the information is passed back to the controller for feedback control. The feedback loop is thus completed.

1.4.5 Power Control Subsystem Architecture

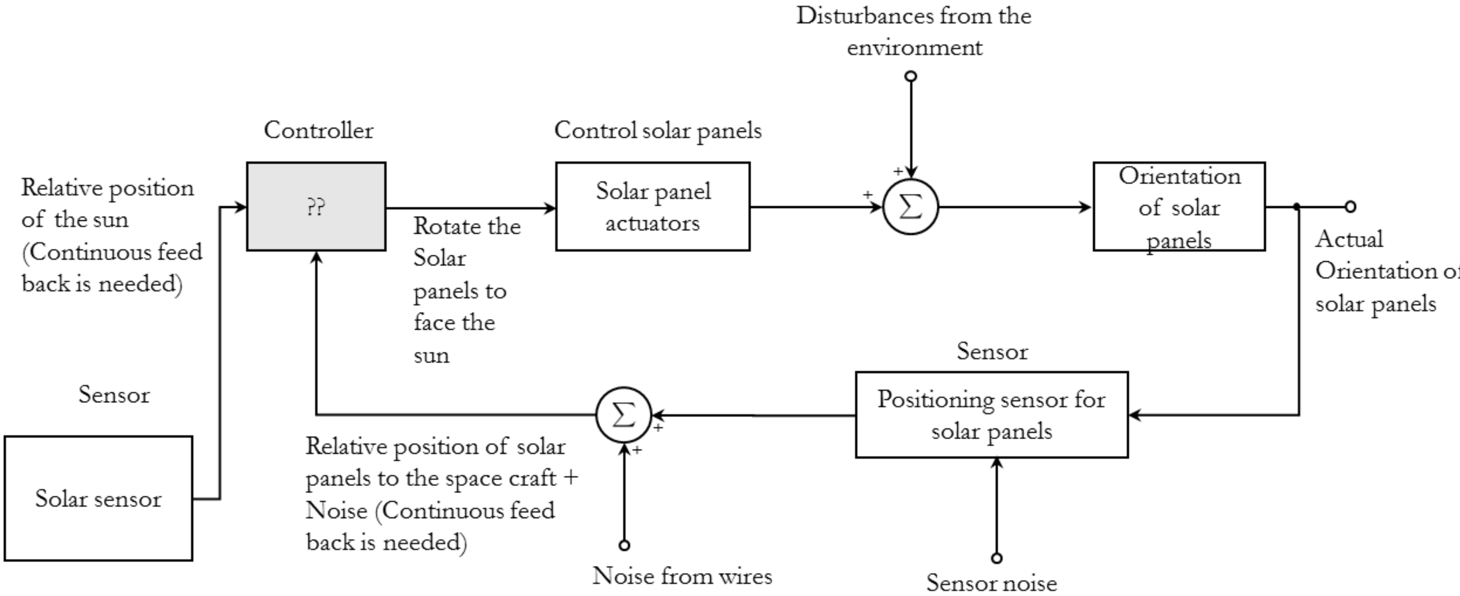

Figure 6. Power Control Architecture

Figure 6 illustrates the control process involved in adjusting the solar panels to achieve the maximum exposure to solar rays. In this closed-loop control architecture, the signal from solar sensor is fed into the controller giving the controller relative orientation of the sun, which generates the control variables that are sent to motors in solar cells to achieve the best solar array orientation. The orientations of the solar panels are measured relative to the DP and the information is passed back to the controller. The feedback loop is thus completed.

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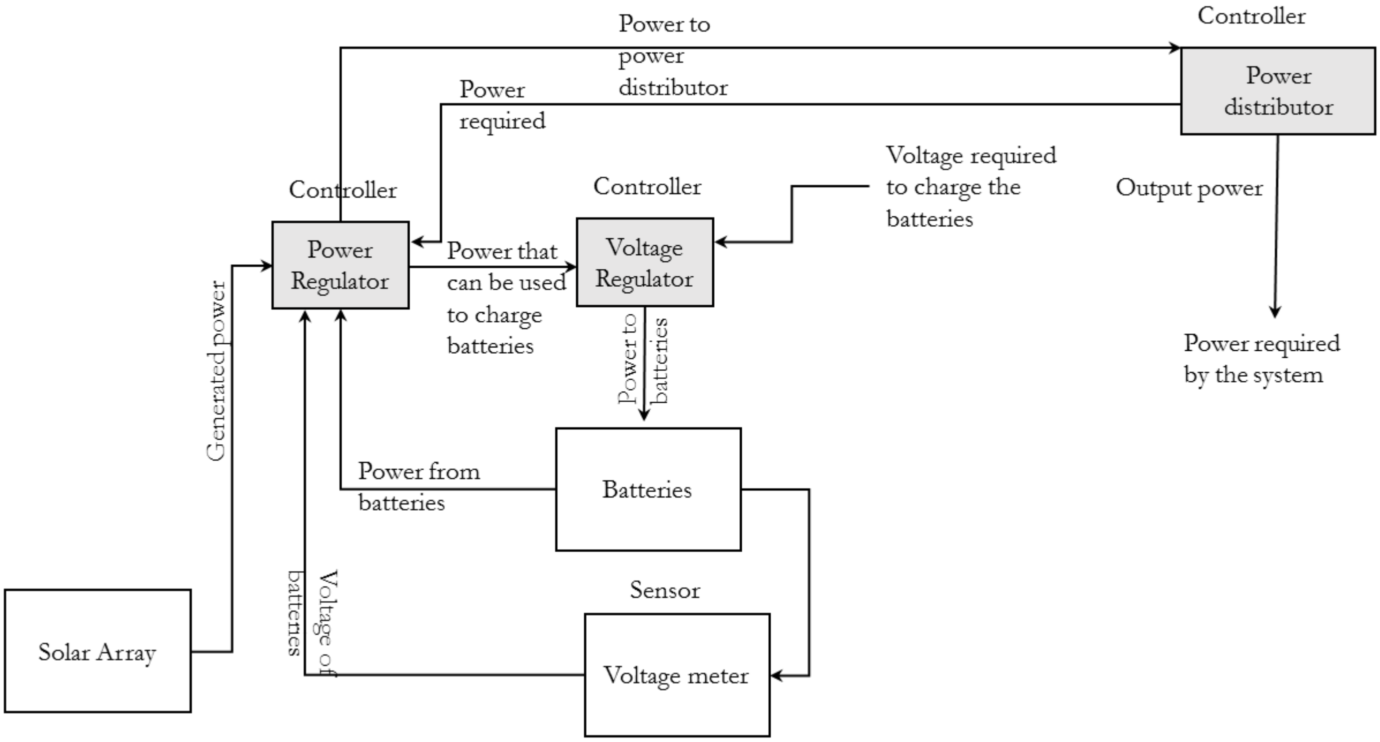

Figure 7. Power management process diagram

Figure 7 illustrates the power management process of the DP. There are two scenarios to consider for power management.

1. ***Solar Arrays generate available power:***
   Power is sent to the power regulator and inputs from power distributor and voltage sensors decide whether to store power in batteries or use it right away. This depends on the power requirements of other subsystem and the battery voltage (i.e. if the battery is fully charged, the power distributor will no send power to charge the batteries). Consider the following cases:

   i) If the batteries need to be charged, the power from solar arrays is fed into the power distributor and sends the extra power unused to the voltage regulator, where it will increase or decrease voltage in order to charge the batteries.
   ii) If the batteries are fully charged and there is extra power available from solar arrays, the power regulator will dissipate the power accordingly and feed the power distributor with the needed power.
   iii) If the power generated from solar arrays is not sufficient to power subsystems, the power regulator will draw power from onboard batteries and feed it into the power distributor.

2. ***No power generation from solar arrays:***
   The power regulator will draw power from onboard batteries and feed it into the power distributor.

1.4.6 Processing, Control, & Storage Subsystem Architecture

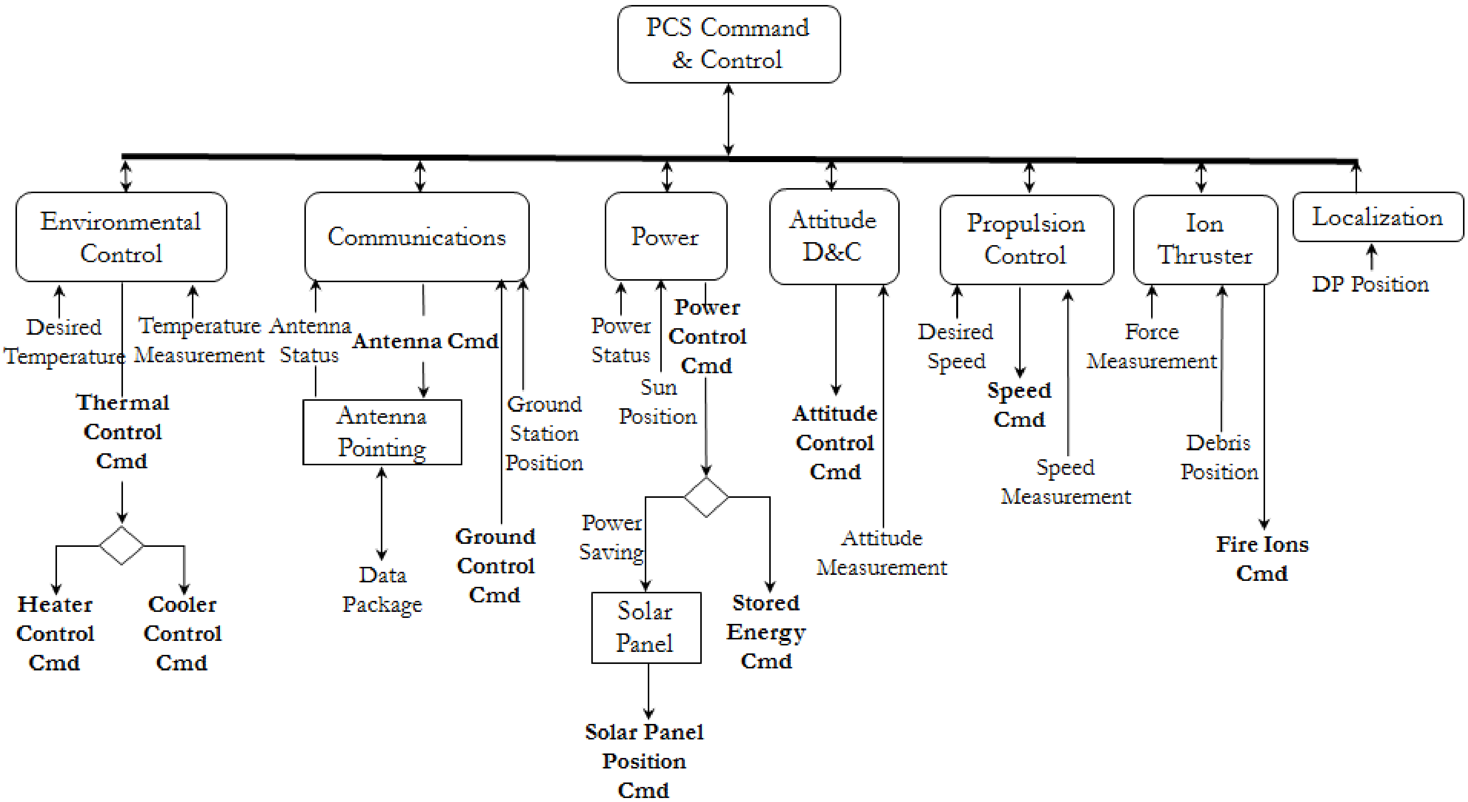

Figure 8. Level 1 Software Behaviour Diagram

Figure 8 shows the level 1 software behaviour diagram for the PCS subsystem. The diagram shows commands (*Cmd*) and control interfaces between the PCS and the other subsystems. In addition, inputs into each of the subsystem that needs to be processed by the PCS are shown. The diamond shapes in the diagram show conditional behaviour. This diagram provides a nice control overview of the subsystems onboard the DP.

1.5 Feedback Loops

The following table identifies all the feedback loops we have in our DP architectures.

Table XI. List of feedback loops

Sub-system	Feedback loop	Description
Attitude Determination & Control	Attitude Control	The Inertial Measurement Unit (IMU) sends the orientation, velocity and gravitation data to the attitude controller. Attitude controller processes these data and controls the momentum wheels accordingly to adjust the attitude. High frequency of **~ 100 Hz** is required to ensure rapid re-orientation to the desired angular velocity / attitude.
	Debris location	Information about the relative location of the debris will be fed to the DP. *This information can be obtained from a debris tracking agency located on the earth*. The DP will then point its on-board debris tracking system in the direction of the debris. Next, the DP will transmit its results to ground control. This loop will continue till the ground control confirms the exact relative position of the debris. The frequency of this operation will be limited to ~ **0.0002 Hz** (TBC) due to communication delays to the satellite *(The DP is spinning around the earth at 1 rotation per 2 hours)*
Environmental Control	Temperature Control	The thermal controller takes the desired temperature from the PCS. The thermal controller also receives data from thermometers for the temperature in various regions of the system and uses the data to decide whether to turn the heaters or the coolers on or off. At the same time, the thermal controller reports the success / failure of temperature adjustment to the onboard computer system. Frequency of **~ 1 Hz** (TBC) is required as the thermal system should correct for the deviation in temperature immediately to ensure the system is operating within the expected environment.
Power	Solar cell orientation	Sun position sensors provide the relative orientation of the DP to the sun. Sensors on the solar arrays provide the orientation of solar arrays relative to the DP. A controller sends a signal to rotate the solar panels accordingly. The sensors measure relative orientation of solar arrays sends a signal to the controller completing the feedback loop. Minimum frequency of **~ 1 kHz** (TBC) is required due to the high speed motion of the satellite.
	Solar panel deployment	A human issue a command to deploy the solar panels, this would be received by a PCS subsystem, which would command the power subsystem to move the motors to deploy solar cells and lock them. Binary signal would come back from motor controller to PCS indicating success / fail, which would be communicated back to the human on Earth. Frequency of ~ **0.0002 Hz** (TBC) will be required due to communication delays. *(The DP is spinning around the earth at 1 rotation per 2 hours)*

Propulsion & Debris Manipulation	Propulsion control & ion thrust control	PCS sends the desired distance or location command to propulsion and debris manipulator controller. Depending on the type of input, the sensor takes readings either using the Inertial Measurement Unit, or the optical sensors. The PCS then commands the subsystem to fire the propulsive thruster and ion thruster accordingly. A relatively high frequency of approximately ~ **10 Hz** (TBC) is expected to be needed. During the rendezvous and de-orbiting stages, the operational distance between the DP and rocket body will be small (20 m). Thus, it is essential that the distance be maintained accurately, otherwise there will be a risk of the DP colliding into the rocket body.
Communications	Signal processing	The communication subsystem will send a signal to ground control at a rate of ~ **1 Hz** (TBC). If the ground control receives this signal, the ground control will send a signal back to the spacecraft to initialize the communication. This will give an indication to the ground control to be ready to receive and download data and status from the DP. Ground control can then upload their data back to the DP. This will complete the communication feedback loop.

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3.0 Appendix

3.1 Calculations

3.1.1 Global command calculations

Latency for one trip from ground control station (Earth) to 800 km orbit (worst-case):

T= 800km/ (299792.458 km/s)=0.00267s

Latency due to ground communications=0.2s (estimate)

Total round-trip=2(0.00267+0.2)=0.4005

This does not include time for the user (e.g. mission control coordinators) to make human decisions.

Communication Window (Ground Satellite Visibility Time) [6]:

Speed at 800 km= 7.46km/s

Speed at 200 km (where atmospheric drag will take-over sufficiently)=7.79km/s

From Ross Gillet's lecture, at 800 km, there is approx 15 min window (assuming one ground station).

At 200 km, window:

T=15 min*7.46/7.79=14.36 min

3.1.2 Propulsion Subsystem Speed Measurement Requirement Calculation

During De-Orbiting stage, the DP is approximately 20 m from the rocket body. The error in sensor measurements should be such that a collision will only occur if no trajectory corrections are made for 5 minutes (300 s). This time will allow the DP to correct its trajectory and avoid a collision.

V = 20 m / 300 s ~= 0.07 m/s.

3.1.3 Propulsion Subsystem Valve Control Time Requirement Calculations

Need to keep DP within 3m of desired position (From mechanical requirements)
Thruster force = 0.1 N
F = m*a → a = F/m = 0.1 N / 1815 kg = 0.000055096 m/s^2
To travel 3m → t = sqrt(d/a) = sqrt(3 m / 0.000055096 m/s^2) = 233 s

Since the DP will require 233 s to travel 3 m, the maximum time requirement for opening and closing the thruster valve can be relaxed, since it is not mission critical. Solenoid thruster valves supplied by MOOG have a response time of 20 ms or less [3].

3.1.4 Debris Manipulation Calculations

20m is deemed as the operational distance. Assuming DP locomotion subsystem is exerting 0.1N of force, and ion thruster manipulation subsystem has been turned off, exerting 0 N of force in the opposite direction, for the worst case scenario. The DP will collide with the rocket body in:

d=(1/2)*a*t^2

t=sqrt(2d/a)=(2*14.475/(5.62*10^-6))=5151245s

Where d has been calculated to be, in the worst case scenario where the rocket body's rotation has pointed it in the trajectory and assuming rotation around CM at half of the cylinder height:

20m - 0.5(11.05m)=14.475

The acceleration a, was calculated as:

A=F/m=0.1N/1815*9.81=5.62*10^-6

3.1.5 Global Requirements Calculations

Latency for one trip from ground control station (Earth) to 800 km orbit (worst-case):

T= 800km/ (299792.458 km/s)=0.00267s

Latency due to ground communications=0.2s (estimate)

Total round-trip=2(0.00267+0.2)=0.4005

This does not include time for the user (e.g. mission control coordinators) to make human decisions.

3.1.6 Communication Window (Ground Satellite Visibility Time) [6]

Speed at 800 km= 7.46km/s

Speed at 200 km (where atmospheric drag will take-over sufficiently)=7.79km/s

From Ross Gillet's lecture, at 800 km, there is approx 15 min window (assuming one ground station).

At 200 km, window:

T=15 min*7.46/7.79=14.36 min

Note: There will be no Requirements for PCS subsystem, since everything will be distributed to other subsystems.