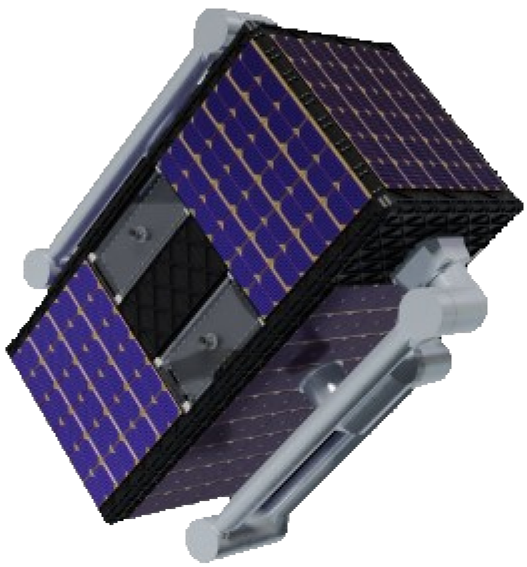

Reusable Orbital Asset Maintenance and Examination Robot (ROAMER) Systems Engineering Report

Arizona State University

Interplanetary Initiative

Signature Page

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Abbreviations and Acronym

ADCS	Attitude Determination Control System
ASU	Arizona State University
BCT	Blue Canyon Technologies
CAD	Computer Automated Design
C&DH	Computing and Data Handling
CDR	Critical Design Review
CONOPS	Concept of Operations
FRR	Flight Readiness Review
ISS	International Space Station
LEO	Low Earth Orbit
MOC	Mission Operation Center
PDR	Preliminary Design Review
RTS	Remote Tracking System
SDR	Systems Design Review
SRR	Systems Requirements Review
SOC	Science Operation Center
TBD	To Be Determined
TT&C	Telemetry, Tracking & Control
U	Unit (Cubesat 1U: $10mm^3$)

1. Introduction

1.1 Mission Description

With orbital crowding of aging technology, the United States requires a cost-effective and time-efficient mechanism for repairing and altering current on-orbit assets. ROAMER will provide an exploratory orbiting microsat capable of maintenance tasks, repairs, and service to orbital assets. The use of a refillable water thruster and the small vehicle size provide safety by design for use near inhabited space stations. Further, ROAMER will be capable of orbit changes and plane changes between space stations for multimission maintenance tasks.

Additionally, ROAMER can assist in transferring orbits, clearing space debris, and maintaining satellite technology. As more missions head to lunar and interplanetary destinations, the ROAMER platform can be extended to accompany these missions for similar maintenance and end of life operations.

1.2 Purpose and Scope

This Systems Engineering Report describes the mission, design, and subsystems to be used in the proposed ROAMER project. The objective of the systems engineering effort is to assure the successful development of the ROAMER system, by defining accurate system requirements and verifying their compliance with respective systems. Further, the System Engineering Report provides an analysis of design budgets, considering the cost, power, mass, and volume throughout ROAMER’s lifetime.

The ROAMER system consists of the space and ground segment as shown in Figure 1-1. The space segment includes the ROAMER flight system and the launch vehicle services. The ground segment is the ground-based facility in control of spacecraft operations, records, and data processing.

1.3 Concept of Operations

In the baseline mission, ROAMER launches to the ISS aboard a re-supply mission and is deployed through the airlock and connects to the exterior of the ISS using robotic arms. The baseline mission provides efficient maintenance to aspects of the ISS and near field operation, as directed by ground control. Later stages of the ROAMER program add provisional missions to other LEO-orbiting assets, as identified by urgency and position. In this, ROAMER seeks to expand its maintenance to +/- 200km of its original LEO orbit. Additionally, having the ability to house, deploy, and resupply with a singular 1U CubeSat within the structure. The final stages of ROAMER could expand applications of maintenance to intercontinental parties' orbital properties.

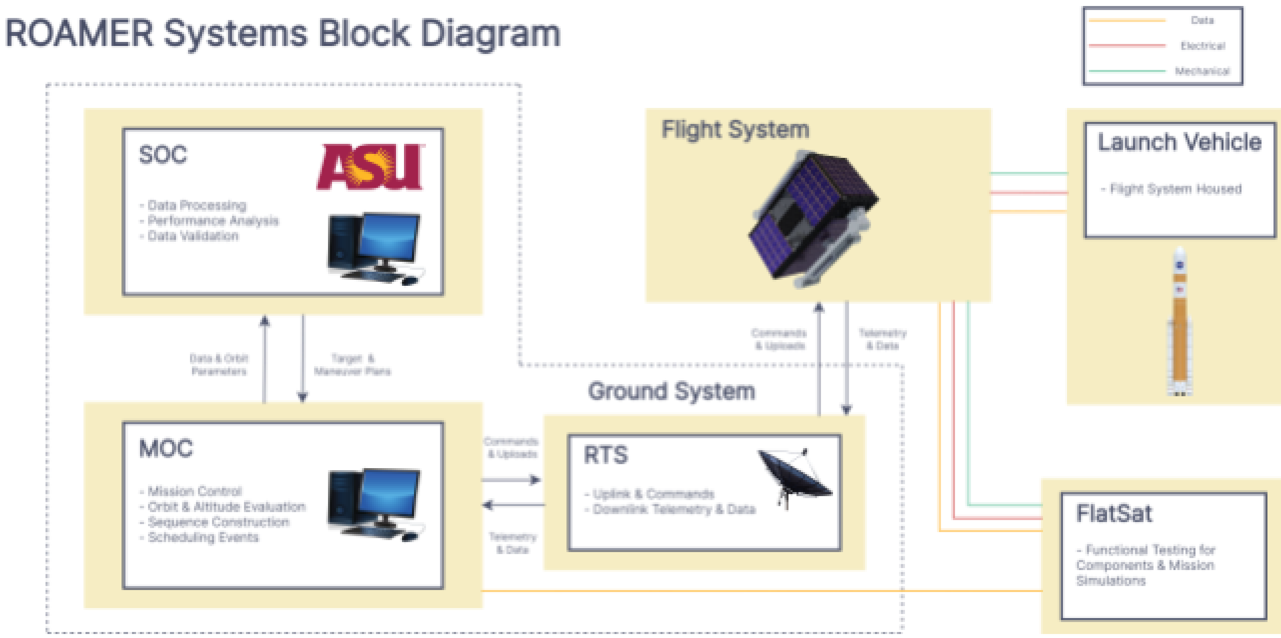

Figure 1-2 ROAMER System Block Diagram

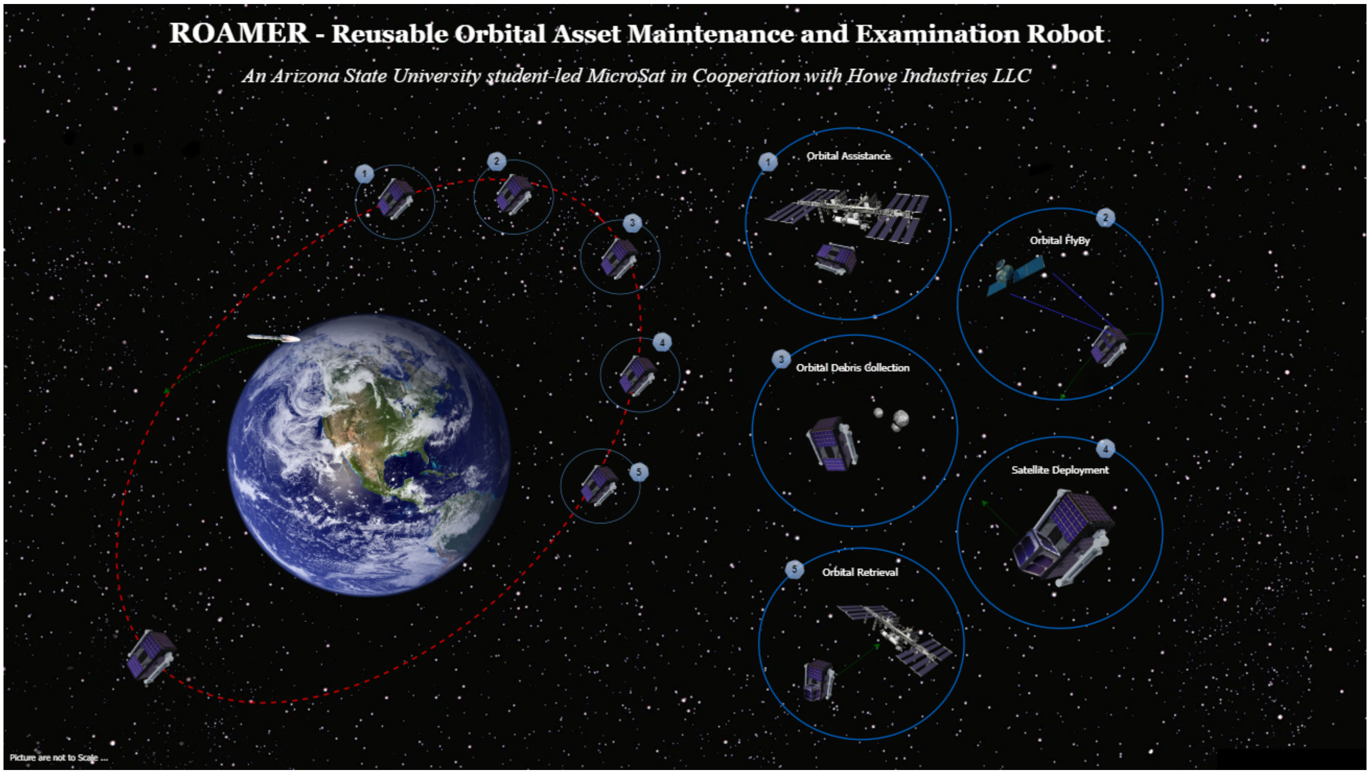

Figure 1-3 ROAMER CONOPS

2. REQUIREMENTS

2.1 REQUIREMENTS DESCRIPTION

Referencing Figure 2-1, requirements for ROAMER flow downward from level 1 (mission), level 2 (launch, space, and ground), and finally level 3 (each subsystem). For the purposes of this Systems Engineering Report, level 1 and select level 2 requirements will be addressed which were used to determine estimated subsystems shown in section 4 Subsystem Specifications. A complete SRR will be developed during subsequent phases of this program.

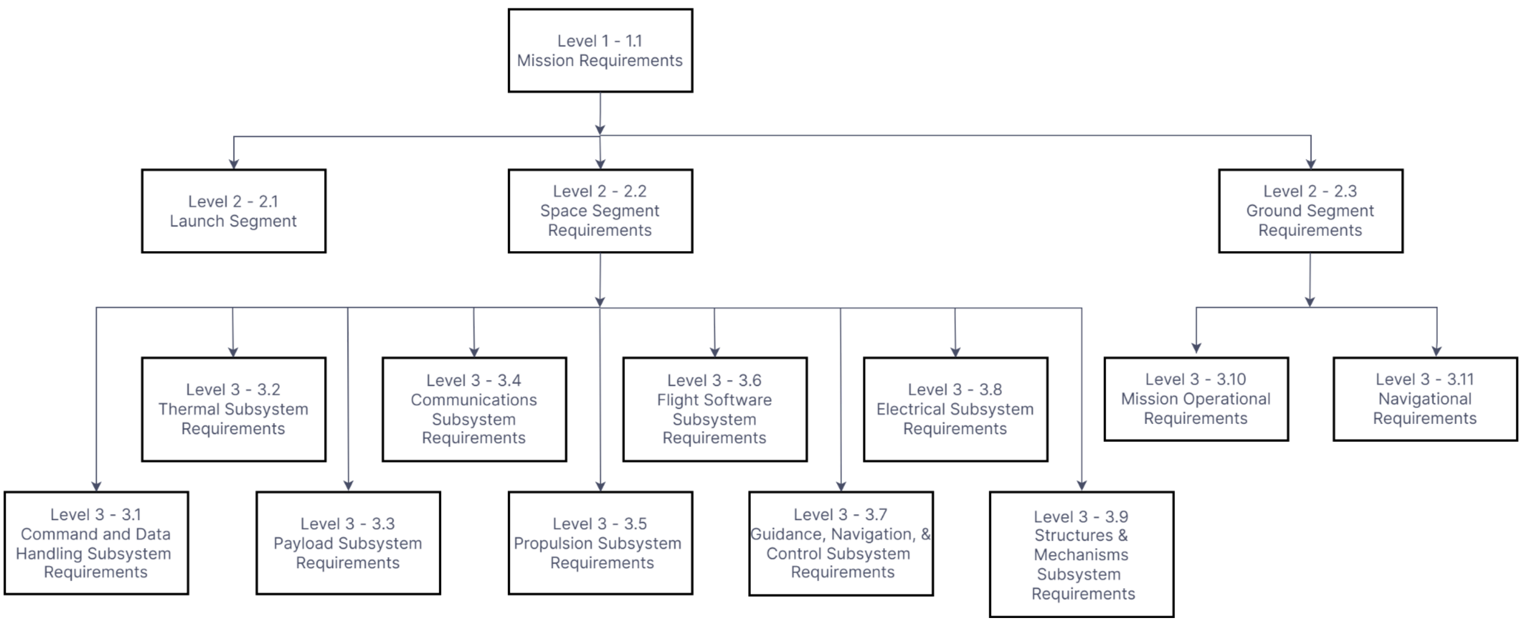

Figure 2-1 Requirements Flow Down

2.2 Mission Requirements

M1.1 - ROAMER shall utilize and be an experimental test for Howe Industries ThermaSat water thruster.

Verification: Demonstration

M1.2 - ROAMER shall provide requested maintenance, service, and repairs to LEO-orbiting satellites.

Verification: Demonstration

2.3 Launch Requirements

L2.1 - ROAMER shall be designed for launch onboard the TBD launch vehicle.

Verification: Inspection

L2.2 - ROAMER shall have primary vibrational modes that do not correspond to launch vehicles primary modes.

Verification: Analysis

L2.3 - Launch System shall have ability to insert ROAMER into LEO orbit.

Verification: Demonstration

2.4 Space Requirements

SC2.1 - ROAMER shall be compliant with 3U x 3U x 7U size.

Verification: Inspection

SC2.2 - ROAMER shall be capable of altering another orbiting spacecraft, of TBD kg, by +/- 200km of original LEO orbit.

Verification: Analysis

SC2.3 - ROAMER shall connect/disconnect with maintenance-requesting spacecraft without damaging said spacecraft.

Verification: Analysis

SC2.4 - ROAMER shall deploy stowed appendages upon TBD rocket delivery into LEO.

Verification: Demonstration

SC2.5 - ROAMER shall power inactive systems upon TBD rocket delivery.

Verification: Demonstration

SC2.6 - ROAMER shall incorporate water refuelability.

Verification: Demonstration

SC2.7 - ROAMER shall have a minimum operational lifetime of TBD days.

Verification: Analysis

SC2.8 - ROAMER shall generate power for each subsystem.

Verification: Demonstration

SC2.9 - ROAMER shall operate autonomously through camera and other sensors for robotic arm motion.

Verification: Demonstration

SC2.10 - ROAMER shall have a minimum of one deployment switch.

Verification: Inspection

SC2.11 - ROAMER shall have redundant downlink methods.

Verification: Inspection

SC2.12 - ROAMER shall be less than 100 kg.

Verification: Inspection

SC2.13 - ROAMER shall satisfy NASA low-outgassing criteria.

Verification: Testing

SC2.14 - ROAMER shall incorporate a remove before flight pin.

Verification: Inspection

2.5 Ground Requirements

G2.1 - Ground system shall be operational for the entirety of the mission.

Verification: Inspection

G2.2 - Ground system shall interface with the flight system to upload commands

Verification: Inspection

G2.3 - Ground system shall interface with the flight system to receive and process telemetry data.

Verification: Inspection

G2.4 - Ground system shall ensure reliability and security for the entity of the mission.

Verification: Inspection

3. System Design

3.1 Description

The ROAMER system, as outlined with requirements, will be a water propellant-based satellite articulated robotic arms. In addition to maintenance provision goals, ROAMER shall be compatible with the exploration of other orbital assets. In this, the acquisition of mission goals will impose a prerequisite for specific subsystem components, as identified in section 4 Subsystem Specification. Components shall be justified through analyses of cost, mass, power, and volume budgets. Furthermore, considerations of a link budget and development timeline are also provided.

3.2 Cost Budget

Referencing Figure 3-2, the ROAMER system will incur an estimated cost of $4.3 million for the spacecraft bus hardware, not including the development labor and test costs. Primary components of Robotic Arms, Thruster, and Startrackers source the majority of costs, as such instruments remain essential to the design and mission. The total cost is based on estimates of current technology, providing quotes from collaborating companies, and educated assumptions based on market value. For specific subsystem information and breakdowns, see section 4 Subsystem Specification.

This is the cost for a single hardware unit. Development, Integration and Test costs are not included.

Subsystem	Generic Component Name	Specific Component Name	Qty	Price	Total Cost
OBC	Motherboard (Autonomy)	Inforce 6601 Micro SoM (with carrier board)	1	$1,100	$1,100
	Main Motherboard	Pumpkin MBM2	1	$7,225	$7,225
	Camera	GoPro Hero 11	4	$1,200	$4,800
EPS	EPS	EnduroSat	1	$26,180	$26,180
	Solar Panels	Rocket Lab	74	$400	$29,600
	Deployed Solar Panels	Rocket Lab	226	$400	$90,400
	Battery	EnduroSat	1	$10,000	$10,000
ADCS	Reaction Wheels	RW-1.0	3	$80,000	$240,000
	Startracker	ST-16RT2 Short Baffle	2	$140,000	$280,000
	Startracker	ST-16RT2 Large Baffle	2	$140,000	$280,000
Comms	S Band Transceiver	IQ Spacecom Xlink-S	1	$50,000	$50,000
	X Band Antenna	X Band Antenna IQ Spacecom	1	$6,300	$6,300
	S-Band Antenna	S-Band Antenna IQ Spacecom	1	$6,400	$6,400
	X Band Transceiver	IQ Spacecom Xlink-X	1	$50,000	$50,000
Structure	Robotics	Redwire STAARK Robotic Arms	2	$800,000	$1,600,000
	Bus Structure	Frame	1	$20,000	$20,000
	Cable and Harnessing	Generic Cabling	1	$7,500	$7,500
Propulsion	Thruster	Howe Thruster	4	$200,000	$800,000
	Propellant	Water	18	$2,800	$50,400
				TOTAL COST	$3,559,905
				TOTAL COST WITH 20% MARGIN	$4,271,886

Figure 3-2 ROAMER Estimated Hardware Cost Budget

3.3 Mass Budget

Referencing Figure 3-3, the ROAMER system will weigh an estimated total of 58 kg with a 20% margin. Primary components of the Robotic Arms, Thrusters, and Frame source the majority of the weight, as such instruments remain essential to the design. The total mass is based on estimates of current technology, providing quotes from collaborating companies, and educated assumptions based on prior experience. For specific subsystem information and breakdowns, see section 4 Subsystem Specification.

Subsystem	Generic Component Name	Specific Component Name	Qty	Mass	Total Mass
OBC	Motherboard (Autonomy)	Inforce 6601 Micro SoM (with carrier board)	1	0.02kg	0.02kg
	Main Motherboard	Pumpkin MBM2	1	0.03kg	0.03kg
	Camera	GoPro Hero 11	4	0.15kg	0.61kg
EPS	EPS	EnduroSat	1	0.28kg	0.28kg
	Solar Panels	Rocket Lab	74	0.00kg	0.21kg
	Deployed Solar Panels	Rocket Lab	226	0.00kg	0.64kg
	Battery	EnduroSat	1	1.09kg	1.09kg
ADCS	Reaction Wheels	RW-1.0	3	1.38kg	4.14kg
	Startracker	ST-16RT2 Short Baffle	2	0.19kg	0.37kg
	Startracker	ST-16RT2 Large Baffle	2	0.24kg	0.47kg
Comms	S Band Transceiver	IQ Spacecom Xlink-S	1	0.20kg	0.20kg
	X Band Antenna	X Band Antenna IQ Spacecom	1	0.02kg	0.02kg
	S-Band Antenna	S-Band Antenna IQ Spacecom	1	0.05kg	0.05kg
	X Band Transceiver	IQ Spacecom Xlink-X	1	0.20kg	0.20kg
Structure	Robotics	Redwire STAARK Robotic Arms	2	5.50kg	11.00kg
	Bus Structure	Frame	1	4.50kg	4.50kg
	Cable and Harnessing	Generic Cabling	1	1.00kg	1.00kg
Propulsion	Thruster	Howe Thruster	4	1.18kg	4.71kg
	Propellant	Water	1	19.00kg	19.00kg
				TOTAL MASS	48.55kg
				TOTAL MASS WITH 20% MARGIN	58.26kg

Figure 3-3 ROAMER Estimated Mass Budget

3.4 Power Budget

Referencing Figure 3-4, the ROAMER system will have an estimated power margin of 17 W. The solar panels will generate an estimated 182 W, while the remainder of the spacecraft will consume an estimated 165 W. The total power generated and consumed is based on estimates of current technology, providing quotes from collaborating companies, and educated assumptions from prior experience. For specific subsystem information and breakdowns, see section 4 Subsystem Specification.

Subsystem	Generic Component Name	Specific Component Name	Qty	Instantaneous Power	Total Instantaneous Power	Duty Cycle	Orbital Average Power (w/ Inefficiency)
GENERATED							
EPS	Solar Panels	Rocket Lab	74	1.35W	99.68W	0.5	44.86W
	Deployed Solar Panels	Rocket Lab	226	1.35W	304.42W	0.5	136.99W
	Battery	EnduroSat	1	0.00W	0.00W	1	0.00W
						TOTAL GENERATED POWER	181.85W
CONSUMED							
OBC	Motherboard (Autonomy)	Inforce 6601 Micro SoM (with carrier board)	1	19.80W	19.80W	1	19.80W
	Main Motherboard	Pumpkin MBM2	1	1.75W	1.75W	1	1.75W
	Camera	GoPro Hero 11	4	2.00W	8.00W	1	8.00W
EPS	EPS	EnduroSat	1	0.50W	0.50W	1	0.50W
ADCS	Reaction Wheels	RW-1.0	3	5.30W	15.9	1	15.90W
	Startracker	ST-16RT2 Short Baffle	2	1.00W	2	1	2.00W
	Startracker	ST-16RT2 Large Baffle	2	1.00W	2	1	2.00W
Comms	S Band Transceiver	IQ Spacecom Xlink-S	1	15.00W	15.00W	0.6	9.00W
	X Band Antenna	X Band Antenna IQ Spacecom	1	0.00W	0.00W	0	0.00W
	S-Band Antenna	S-Band Antenna IQ Spacecom	1	0.00W	0.00W	0	0.00W
	X Band Transceiver	IQ Spacecom Xlink-X	1	15.00W	15.00W	0.3	4.50W
Payload	Robotics	Redwire STAARK Robotic Arms	2	7.50W	15.00W	0.1	1.50W
Structure	Bus Structure	Frame	1	0.00W	0.00W	0	0.00W
	Cable and Harnessing	Generic Cabling	1	0.00W	0.00W	0	0.00W
Propulsion	Thruster	Howe Thruster	4	25.00W	100.00W	1	100.00W
	Propellant	Water	1	5	5	0.1	0.5
						TOTAL CONSUMED POWER	164.95W
						POWER MARGIN	16.90W

Figure 3-4 ROAMER Estimated Power Budget

3.5 Volume Budget

Referencing Figure 3-5, the ROAMER system will require an estimated total volume of 301,200 cm^3. Primary components of Reaction Wheels and Star Trackers are the source of the majority of volume, as such instruments remain essential to the design. The total volume is based on estimates of current technology, providing quotes from collaborating companies, and slightly educated assumptions. For specific subsystem information and breakdowns, see section 4 Subsystem Specification.

This volume budget does not include the robotic arms as part of the bus volume.

Subsystem	Generic Component Name	Specific Component Name	Qty	Unit Dimensions	Unit Volume (cm^3)
OBC	Motherboard (Autonomy)	Inforce 6601 Micro SoM (with carrier board)	1	17 x 17 x 1.4	404.60
	Main Motherboard	Pumpkin MBM2	1	9.6 x 9.0 x 1.26	108.86
	Camera	GoPro Hero 11	4	7.18 x 3.36 x 5.08	122.55
EPS	EPS	EnduroSat	1	9.57 x 9.02 x 2.52	217.53
	Solar Panels	Rocket Lab	74	3.81 x 8.89 x .1	250.64
	Deployed Solar Panels	Rocket Lab	226	3.81 x 8.89 x .1	765.48
	Battery	EnduroSat	1	8.57 x 8.0 x 7.5	514.20
ADCS	Reaction Wheels	RW-1.0	3	15.4 x 14.6 x 4.5	3,035.34
	Startracker	ST-16RT2 Short Baffle	2	6.2 x 5.6 x 6.8	472.19
	Startracker	ST-16RT2 Large Baffle	2	9.9 Ø x 12.0	237.60
Comms	S Band Transceiver	IQ Spacecom Xlink-S	1	9 x 6.5 x 2.53	148.01
	X Band Antenna	X Band Antenna IQ Spacecom	1	4 x 6 x.18	4.32
	S-Band Antenna	S-Band Antenna IQ Spacecom	1	7 x 7 x.18	14.70
	X Band Transceiver	IQ Spacecom Xlink-X	1	9 x 6.5 x 2.53	148.01
Structure	Robotics	Redwire STAARK Robotic Arms	2	68.5 x 27.4 x 70	262,766.00
	Bus Structure	Frame	1	n/a	0.00
	Cable and Harnessing	Generic Cabling	1	n/a	0.00
Propulsion	Thruster	Howe Thruster	4	20.98 x 9.589 x 6.05	13,910.79
	Propellant	Water	1	24 Ø x 40	18,095.57
				TOTAL VOLUME	301,216.40
				TOTAL VOLUME AVAIABLE	24,549.60

Figure 3-5 ROAMER Estimated Volume Budget

3.6 Link Budget

The ROAMER system is unable to provide an estimate for a link budget, as insufficient information was achieved from suppliers about specifications needed. Given the proper time to adequately achieve such specifications, a proper AMSAT-IARU Link budget would be completed. Due to the nature of ROAMER's orbit, communication is a relatively low risk and a positive margin should be easily achievable due to the flight heritage equipment in the telemetry, tracking, and control subsystem, shown in Section 4 Subsystem Specification.

3.7 Development Timeline

Referencing Figure 3-7, the ROAMER system will have an estimated development time of 4 Years. The development timeline is based on estimates of current technology, providing quotes from collaborating companies, and slightly educated assumptions. The process will proceed as a standard mission with milestones to receive funding and provide detailed information of what will be delivered. This begins with the SRR and SDR, getting all requirements and validations confirmed by the customer and suppliers. Preliminary designing begins then after all requirements are established which leads the development to the PDR. Some prototyping will then be done to determine if the design is viable and this leads ROAMER into the CDR. At this stage, all design changes will be finalized and flight components will be purchased. Finally, a last milestone before launching will be an FRR to determine all testing requirements have been met and ROAMER is ready to complete its mission.

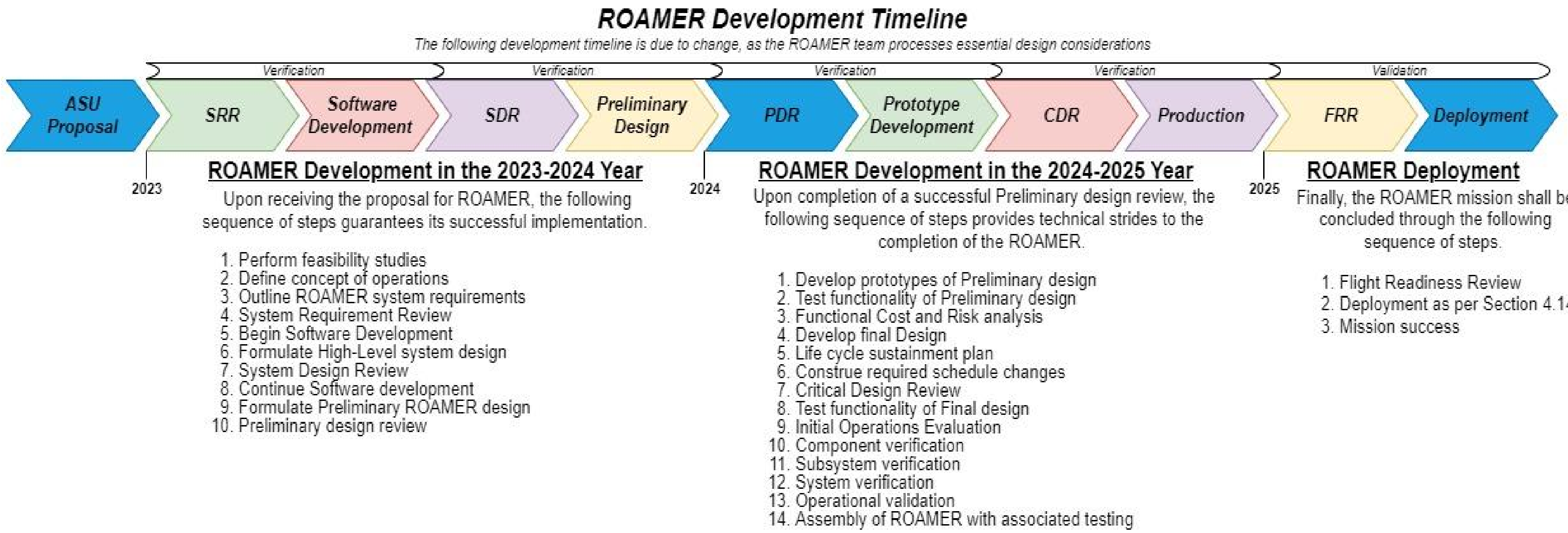

Figure 3-7 ROAMER Development Estimated Timeline

4. Subsystem Specification

4.1 Description

The ROAMER system is broken down into various subsystems: propulsion, navigation, thermal, structural, mechanisms, power, computer and data handling (C&DH), telemetry tracking and control (TT&C), attitude determination control system (ADCS), autonomy, operations, and launch. In the following subsections, each subsystem will be described in detail for the selected components, as shown in the section 3 Systems Design, and then potential alternative components.

4.2 Payload

The primary mission of ROAMER is a free-flying rendezvous and repair spacecraft for orbit transferring, clearing space debris, and attaching to the ISS. A pair of robotic arms, based on the Redwire Space modular STAARK robotic arm, is the payload for ROAMER. In addition to the robotic arms, scientific sensors and technology demonstrations can be accommodated on the bus. for orbit transferring, clearing space debris, and attaching to the ISS. The STAARK arms offer flight software with optional autonomy, which will be discussed further in section 4.12 Autonomy. Referencing Table 4-2, some general technical information can be seen. The STAARK is an all in one package which offers the vision system for autonomation, the flight software, customizable robotic arm, and the control unit.

Table 4-2 Detailed breakdown of payload system specifications

Component Generic Name	Qty	Unit Price ($)	Unit Instantaneous Power (W)	Duty Cycle	Unit Mass (kg)	Unit Dimensions (cm)
STAARK	2	800000	7.5	.1	5.5	68.5 x 27.4 x 70

4.3 Propulsion Subsystem

The propulsion system is responsible for providing the thrust needed by ROAMER to complete the variety of different missions it is tasked for. Requirement SC2.2 shows the need for including a propulsion system on the ROAMER satellite. A propulsion system makes the ROAMER capable of altitude changes, phase shifts, orbital rendezvous, and other maneuvers that a customer's mission may require. The propulsion system consists of four Howe Industries ThermaStat units accompanied by a central propellant tank. This configuration satisfies requirement M1.1.

The ThermaSat units originally developed by Howe Industries are slightly altered for use with the ROAMER. A ThermaSat unit, being built originally as a stand-alone unit, typically includes its own propellant tank. A modification is made to the ThermaSat design for the ROAMER then, where the single-unit tanks are replaced by a central tank and propellant feed system. Such a design change will allow for easier refueling.

The ThermaSat unit is a liquid water-based propulsion system. A thermal capacitor is electrically heated via conduction through which water passes through. The liquid water is rapidly heated and transitions to steam before being expelled out of the nozzle to provide thrust. A single ThermaSat unit is capable of generating 1 N of thrust and has a burn time of 30 seconds. Therefore the ThermaSat has a total impulse of 30 N-s. Each ThermaSat takes approximately 12 hours to fully charge its thermal capacitor, and requires some power to sustain that temperature until the unit fires. Each unit is expected, in the worst-case scenario, to require 25 W of power to complete the charge cycle and stay charged until the unit fires. The central propellant tank has a max capacity of 18 kg of liquid water. The current tank design is an aluminum construction to hold the water at atmospheric pressure. A low pressure tank allows for the tank to be light, so the tank is not expected to be more than 1 kg.

Although this mission revolves around the notion of using Howe Industries ThermaSat Propulsion system, it was requested to do some preliminary research to identify potential competitors in the water propulsion sector. A key contributor to that sector would be Tethers Unlimited HYDROS-C or the larger version of HYDROS-M, as seen in Table 4-4. It should be noted that the HYDROS-C has flight heritage and the HYDROS-M has delivered flight units, while this mission could potentially be the first demonstration of the ThermaSat system, unless a demonstration mission is established shortly.

Table 4-3-1 Detailed breakdown of propulsion system specifications

Component Name	Qty	Unit Price ($)	Unit Instantaneous Power (W)	Duty Cycle	Unit Mass (kg)	Unit Dimensions (cm)
ThermaSat	4	$200,000	25	1	1.178	20.98 x 9.59 x 6.05
Propellant	4	$12,600	5	0.1	4.75	24 x 40 x 0.1

Table 4-3-2 Detailed comparison of propulsion system specifications

Component Name	Unit Price ($)	Unit Instantaneous Power (W)	Unit Mass (kg)	Specific Impulse (I_{sp})	Thrust (N)	Unit Dimensions (cm)
ThermaSat	$200,000	25	1.178	200	1	20.98 x 9.59 x 6.05
HYDROS-C	n/a	25	2.2	310	1.2	19 x 13 x 9.2
HYDROS-M	n/a	40	7.7	310	1.2	39.1 x 19.1

4.4 Navigation Subsystem

The navigation system is responsible for establishing the general requirements for the propulsion system, and potentially the ADCS system. Knowing your trajectory and potential orbit allows for calculations to be made for orbit keeping, delta V transfers, and similar missions stated in Section 1. For ROAMER, Howe Industries has taken these potential missions into consideration and performed calculations and simulations. See Howe Industries report for more information.

4.5 Thermal Subsystem

The thermal system is responsible for ensuring that the spacecraft has enough heat to remain powering the components through the batteries and EPS, but also removing heat from the spacecraft when overheating. ROAMER will be expecting a LEO orbit and for this, simple thermal modeling has been completed using basic parameters. First, creating a simplifying block model which is 3U x 3U x 7U and has a thickness of 5 mm. This will allow a limited amount of nodes and as the mission becomes more detailed with specific heats, the model will progress. The simplified block model can be seen in Figure 4-5-1. The inputted boundary conditions were that all 6 surfaces have thermal conductance and that the surface heat load on the top surface would be 25W.

Now that the initial model has been completed, some orbit simulation is set at an altitude 417 km, period (T) 92 min, and an inclination (i) 51.6 degrees. The simulation will run for an entire Earth day (24 hr) with a step size of 2 min. See Figure 4-5-2 for an example image of ROAMER orbiting Earth. See the results of the 24 hour (~16 orbits) simulation for the top and bottom side in Figures 4-5-3 and 4-5-4.

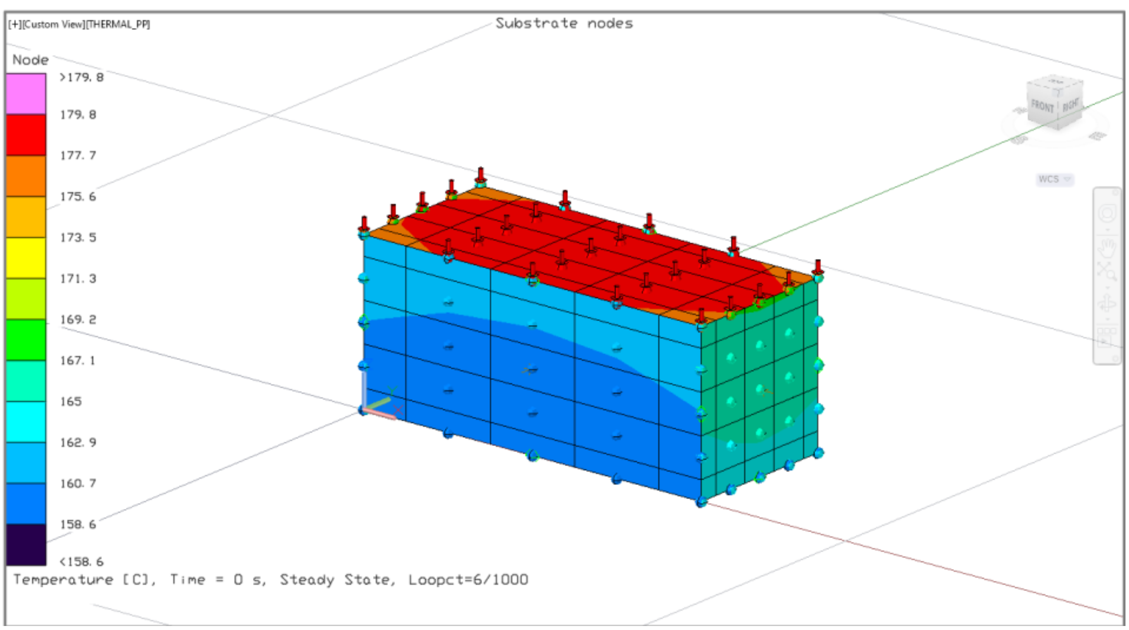

Figure 4-5-1 ROAMER Simplified Block Thermal Model

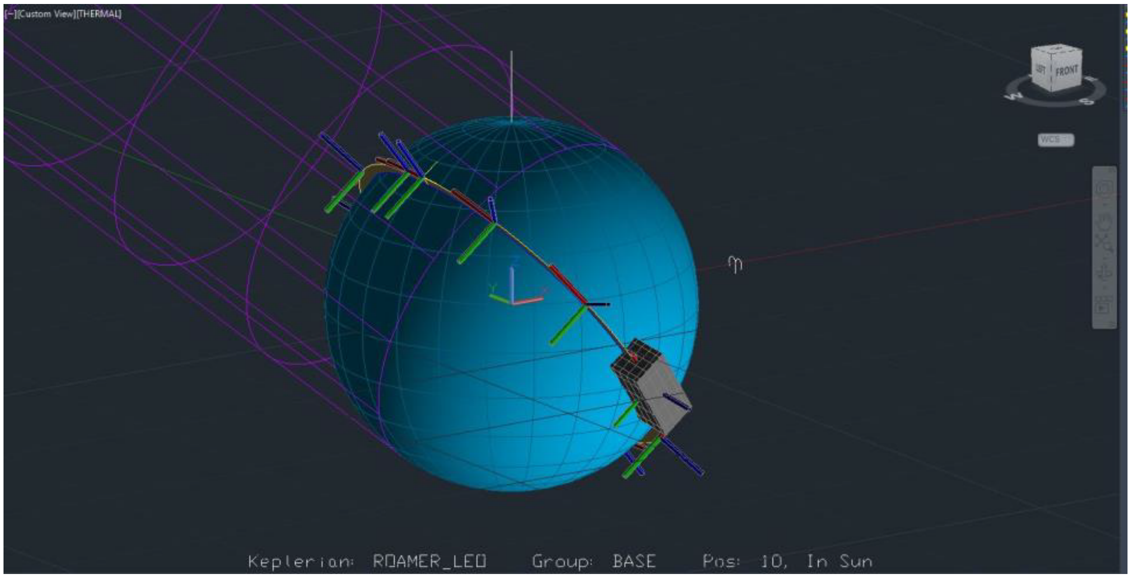

Figure 4-5-2 ROAMER On Orbit Thermal Simulation

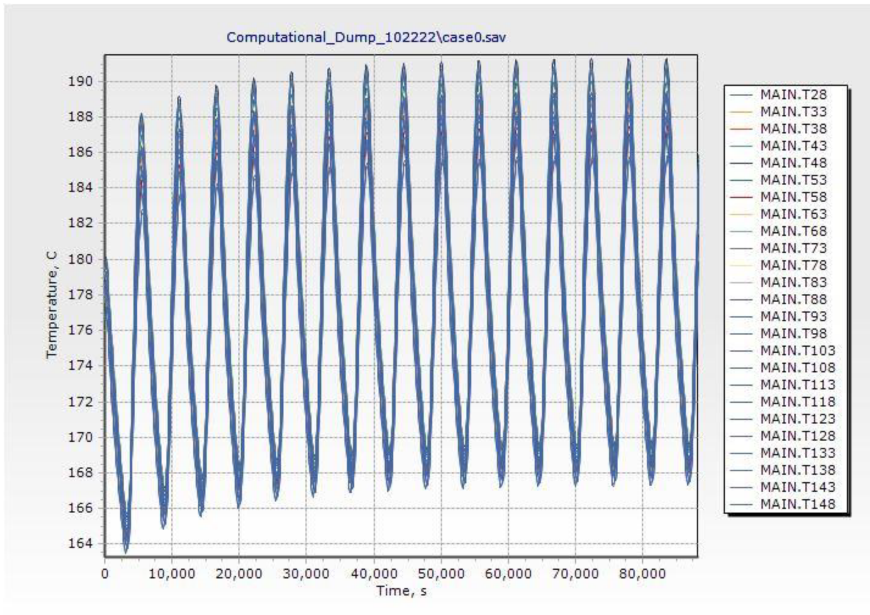

Figure 4-5-3 ROAMER Top Surface Thermal Cycle Simulation

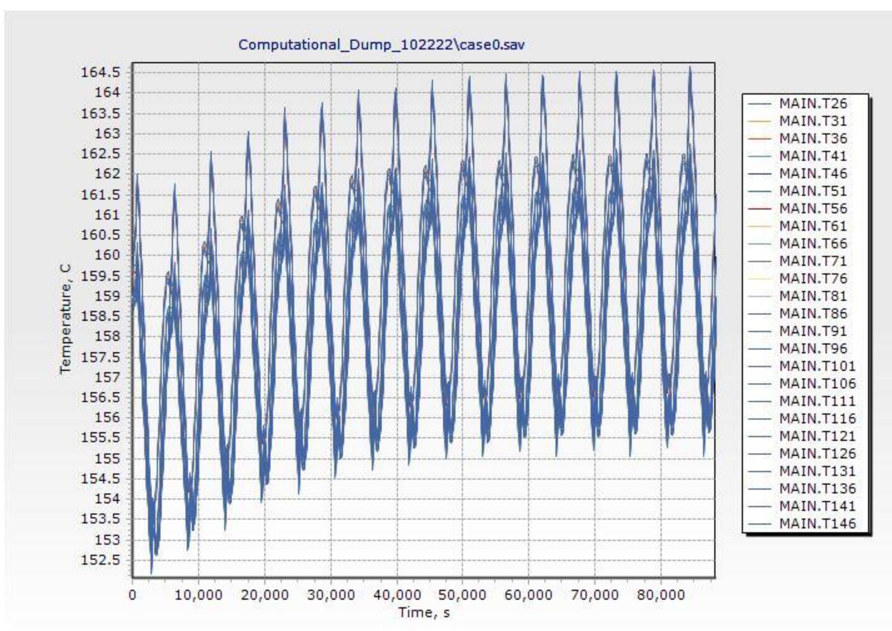

Figure 4-5-4 ROAMER Bottom Surface Thermal Cycle Simulation

The simulation results for the top of ROAMER has a temperature range of 163 C to 192 C, while the bottom of ROAMER has the range of 151 C to 165 C. Given more time, additionally simulations would be run, results will need to be validated and better models will be developed to accurately represent ROAMER and its thermal features.

4.6 Structure Subsystem

The structure subsystem is described exactly as it sounds, it is the structure of the spacecraft. As established in the requirements, the structure will be sized to fit a 3U (30 cm) x 3U (30 cm) x 7U (70 cm) aluminum 6061 frame. Additionally, the structure team holds control over the CAD models and ensures enough space is available for every other subsystem as they are added in the CAD model. The preliminary CAD model of ROAMER populated with components can be seen in Figure 4-6. Note that in this model, the frame was made transparent to display various components and that the purpose of this model was to evaluate whether or not there was enough space in ROAMER for all components and the additional 1U CubeSat.

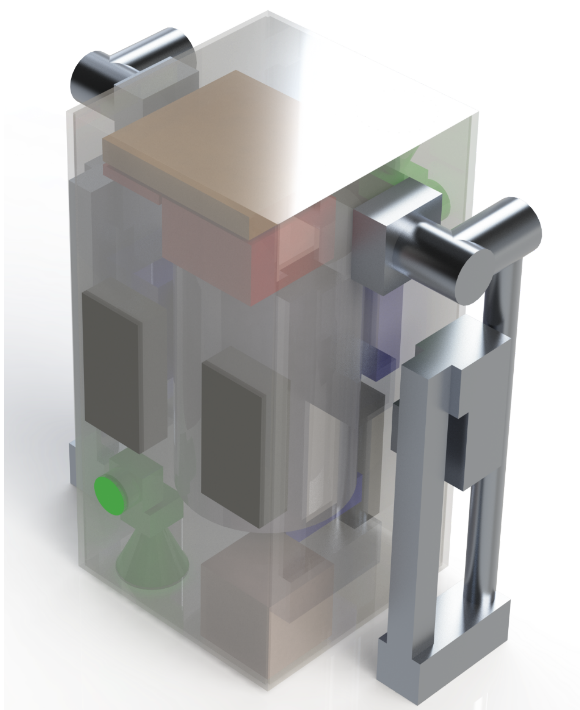

Figure 4-6 ROAMER Preliminary CAD Model

Additionally, a few calculations were completed to determine the maximum moment of inertia acting on the system if the STAARK robotic arms were fully extended. The results of these calculations and further specifications can be seen below in Table 4-6.

Table 4-6 Detailed breakdown of structure system specifications

Component Name	Unit Price ($)	Unit Mass (kg)	Max MOI on Structure (kg m^2)	Unit Dimensions (cm)
Structure Frame	$20,000	4.5	22.76	30 x 30 x 70

4.7 Mechanisms Subsystem

The mechanism's subsystem is responsible for providing information on any deployable or in motion item acting with the spacecraft. Typically mechanisms on a spacecraft are antennas and solar panels which deploy. Due to the mission nature of ROAMER, it will require a high amount of energy from the Sun and thus, require deployable solar panels. This was undesirable when initially looking into ROAMER, but as the power being consumed grew, so did the amount of required generated power. It is due to this that a singular solar panel will be deployed during a charge and communication phase. This will be the most efficient time to communicate data back to Earth, as well as deploy a solar panel from below the spacecraft, to eliminate potential interference with the robotic arms. Potentially, given more time, an analysis could be completed to determine if one singular deployable solar panel from the bottom is more efficient than having two deployable solar panels, both on top and bottom of ROAMER. With two, there is an increase of risk by having two different mechanisms. Although there was an initial desire to not have deployable solar panels, this is comparable to several missions of similar scale. An example of this would be the standard microsat bus, X-Sat Mercury BCT provides.

In terms of the antennas, TT&C has selected patch antennas and due to this there will be no need to have a deployable sequence for them as they will attach to the ROAMER body.

4.8 Power Subsystem

The power subsystem will provide, store, regulate and distribute electrical power to all the subsystems and is composed of the following: electrical power supply (EPS) board, the solar photovoltaic panels, and the battery module. For ROAMER, referring to section 1, these components will be powering the payload that is the robotic arms, ADCS system, ThermaSat propulsion system, on-board computer processing, TT&C system, and Thermal control system. The following table outlines the different specifications for each component in the power subsystem.

Table 4-8-1 Detailed breakdown of power system specifications

Component Generic Name	Component Name	Qty	Unit Price ($)	Unit Instantaneous Power (W)	Unit Mass (kg)	Unit Dimensions (cm)
EPS	EnduroSat	1	$26,180	0	0.281	9.57 x 9.02 x 2.52
Solar Panels	Rocketlab	74	$400	1.347	0.002845	3.81 x 8.89 x .1
Deployed Solar Panels	Rocketlab	226	$400	1.347	0.002845	3.81 x 8.89 x .1
Battery	EnduroSat	1	$10,000	0	1.092	8.57 x 8.0 x 7.5

EPS II (PDM) has state of the art redundancy architecture which ensures seamless operation of the module with aluminum housing to improve its thermal capabilities, reduce EMC and protect the electronics from radiation. The multiple output channels supply other satellite modules with dedicated voltages.

Features:

- Three Solar Panel input channels and three solar panel connectors with input voltage range: 10-36V, and Input current limitation up to 5A per channel
- Fully redundant output channels: 2 x 3.3V, 2 x 5V, and 1 x 12V (programmable for 5.4V-13.6V), 1 x battery Raw voltage output, and 1 x 3.3V VRTC with current limitation at 2A to 5.5A per channel and 11A for Battery Raw
- Full protection (OV, OC, OP),
- Subsystem compatible interface available: 2xRS-485; I^2C; UART(chosen)
- Hardware and Firmware Single Event Upset (SEU) mitigation. Radiation protection shield included and embedded radiation dose monitoring up to 100kRAD
- Additional safety features: Remove Before Flight key and Kill switch connectors available

The energy produced by solar panels has to be stored partially to deal with the eclipse period, therefore the 8 cells stackable modular pack was the optimal battery module chosen that was compatible with the state-of-the-art features of PDM and stores energy from solar panels. With a capacity of 84Wh for 8 cells and Peak $Power_{min}$[W] of 250 W, the battery can be ordered as Li-Po or LiFePO4 configuration. Lithium-Polymer batteries are generally lighter and more compact than LiFePo4 models, giving high power capacity with the same volume. And since they both produce a similar ratio of energy output to input and discharge rates, LiFe's only advantage is safety and robust features that makes them more suitable for the mission profile. Each battery pack has an integrated battery protection functionality preventing over-current, over-charge, over-discharge, and over/under-temperature events. Configurable charge mode (up to 8A) and discharge mode (up to 20A), with a heating system, to preserve battery energy at low temperatures.

The solar cells selected for the design of the bus are the ZTJ+ Space Solar Cells. The following table displays the specifications of the solar cells:

Table 4-8-2 Detailed breakdown of solar cell specifications

BOL Performance Quantities	
Efficiency (%)	29.4
Vmp (V)	2.39
Jmp (mA/cm^2)	16.65

In order to meet the power consumption of 164.95W, a deployed solar panel is incorporated in the design. While the bus will contain 74 solar cells around the body of the bus, the deployed solar panel will contain

226 of these solar cells, and this will ensure that the bus has a 10% margin of power for redundancy purposes.

4.9 C & DH Subsystem

The computing and data handling subsystem is most similar to the brain of the satellite. It will be in control of each of the subsystems and relay data back and forth between them.

The current Computer and Data handling architecture has two on-board computers, one that will handle the autonomous controls which will control the autonomous cameras, robotic arms, navigation and image calculations. The other computer will handle the general flight software which will control the telemetry communications, electrical systems and lower level Attitude Determination and Control system (ADCS).

The Inforce 6601 with the Qualcomm Snapdragon 805 processor will be the autonomous computer and the Pumpkin MBM2 is our choice for the general flight software computer. The GoPro Hero 11 camera would be used by the autonomous computer to process the images to map and navigate to its destinations.

Table 4-9 Detailed breakdown of C&DH system specifications

Component Generic Name	Component Name	Qty	Unit Price ($)	Unit Instantaneous Power (W)	Unit Mass (kg)	Unit Dimensions (cm)
Motherboard (Autonomy)	Inforce 6601 Micro SoM	1	1100	19.8	0.02	17 x 17 x 1.4
Main Motherboard	Pumpkin MBM2	1	7225	1.75	0.031	9.6 x 9.0 x 1.26
Camera	GoPro Hero 11	4	1200	2	0.152	7.18 x 3.36 x 5.08

4.10 TT & C Subsystem

The telemetry, tracking, and control system details the communication link between the ground station and the satellite. ROAMER, being a microsat and requiring high data rates due to the multitude and complexity of the mission requirements, will be utilizing X-band and S-band radios and antennas. As implied, the TT&C system will communicate with the identified ground station in Section 4.13, through the specified X-band and S-band operators below.

Table 4-10 Detailed breakdown of TT&C system specifications

Component Name	Qty	Unit Price ($)	Unit Power (W)	Unit Mass (kg)	Unit Dimension (cm)
IQ Spacecom Xlink-S	1	$50,000	15	0.2	9 x 6.5 x 2.53
X Band Antenna IQ Spacecom	1	$6,300	0	0.02	4 x 6 x .18
S-Band Antenna IQ Spacecom	1	$6,400	0	0.049	7 x 7 x .18
IQ Spacecom Xlink-X	1	$50,000	15	0.2	9 x 6.5 x 2.53

4.11 ADCS Subsystem

The Altitude Determination Control System (ADCS) is responsible for orienting the satellite so it can perform its mission. The ADCS consists of two main components: reaction wheels and star trackers. A reaction wheel is used by spacecraft for three-axis attitude control, and does not require external applications of torque. They provide a high pointing accuracy and are useful when the spacecraft must be rotated by very small amounts. For three-axis control, reaction wheels must be mounted along three directions. Reaction wheels work by equipping the spacecraft with an electric motor attached to a flywheel which changes its rotation speed and causes the spacecraft to to counter-rotate proportionately through the conservation of angular momentum. StarTrackers are an optical device that measure the positions of stars using photocells or a camera. The positions of certain stars have been measured to high degrees of accuracy, a star tracker on a satellite can be used to determine the orientation and attitude of the spacecraft with respect to those stars. In order to do this, the star tracker must obtain images of the stars, measure their position in the reference to the satellite, and identify the stars so their position can be compared with their known absolute position from a star catalog.

The RocketLab RW-1.0 reaction wheels were chosen because it provides the required torque needed for the response time we want in order to complete the mission. In addition the RW-1.0’s power consumption matches our needs. Both the ST-16RT2 Short Baffle and ST-16RT2 Long Baffle were chosen because they match our power requirements and are capable enough to perform the mission.

Table 4-11 Detailed breakdown of ADCS system specifications

Component Name	Cost ($)	Qty	Mass (kg)	Power (W)	Unit Dimensions (cm)
RW-1.0	$80,000	3	1.38	5.3	15.4 x 14.6 x 4.5
ST-16RT2 Short Baffle	$140,000	2	0.185	Average: < 0.5 W Peak: 1.0 W	6.2 x 5.6 x 6.8
ST-16RT2 Large Baffle	$140,000	2	0.235	Average: < 0.5 W Peak: 1.0 W	9.9 Ø x 12.0

4.12 Autonomy

The Autonomy system is the control mode of the spacecraft when it receives specific inputs from the host. For ROAMER, this will mostly entail around the robotic arms, and the resulting missions surrounding the arms. The STAARK arms have three separate modes in the flight software: teleoperation (L1), assisted operation (L2), or supervised autonomy (L3). Using these three modes, and additional modes from our computing and data handling, ROAMER shall be capable of performing a variety of operations while under either pure autonomy, assisted autonomy, or supervised autonomy. This will ensure that the customer's mission is controlled with the most limited amount of risk. Further information on autonomy for ROAMER would be provided upon collaboration with fellow ASU experts.

4.13 Operations

Operations of the ROAMER will regulate its mission objectives and corresponding navigational strategies. These operations should be analyzed and conveyed by an earth-based team. This operations team encapsulates the sustained support for ROAMER in its lifetime, post-launch, and post-orbit injection. In this, the operation team is responsible for the health and safety of ROAMER, throughout the continuation of space missions within orbit. The operations team will monitor relayed ROAMER data, responding to technical anomalies when needed. Here, required software updates, or required improvements in upcoming ROAMER iterations, should be noted. Further, Operations teams will exclusively determine the ROAMER ranges of application, to maximize ROAMER efficiency through navigational considerations. Finally, the operations team will initiate ROAMER's end of life execution plan.

To complete mission operations, the ROAMER team shall receive relayed data through a partitioned ground station. In this, the ASU team recommends the AWS ground station, due to ROAMER's short-term applications. Nevertheless, additional ground stations were quantified through considerations of cost, bandwidth, and regions of compatibility.

Table 4-13 AWS Ground Station Specifications

Ground Station	Narrowband Cost	Wideband Cost	X-Bandwidth	S-Bandwidth
AWS	$3/min	$10/min	125kHz - 500Mhz	125kHz – 54MHz

For now, AWS ground station provides the most efficient application of resources, through minimized costs and effective bandwidth ranges. However, additional research will determine alternative commercial ground station providers, capable of better-fitting ROAMER's needs during the PDR stage. Research is being done into TDRS, Leaf Space, and Atlas, for ground station capabilities.

4.14 Launch

The launch sequence for ROAMER was evaluated to understand the limitations for size, mass, and cost. Using available commercial rocket companies, this information was discovered and noted in Table 4-14. There are currently two commercial rockets that can rendezvous with the ISS, SpaceX and Northrop Grumman Innovation Systems (NGIS).

Table 4-14-1 Detailed comparison of launch provider specifications

Company	Commercial Rockets	Spacecraft	Max Payload (Kg)	Payload Volume (m^3)	Cost to ISS per kg	Cost to LEO per kg
SpaceX	Falcon 9	Dragon 2	6,000	34	$23,300	$2,720
Northrop Grumman Innovation Systems	Antares 230	Cygnus	3500	27	N/A	Up to $10,000

As can be interpreted from the data the cost to reach LEO and travel to the ISS are vastly different. This is due to the fact that a spacecraft needs to be sent from the rocket in order to reach and dock at the ISS. A cost to the ISS for NGIS could not be found as it has only been sending satellites contracted with NASA, so the commercial price is not yet known. However, it is still apparent that the costs for such are still much higher than that of SpaceX's Falcon 9 rocket which has a higher payload tolerance. Due to these circumstances it would be best to go with SpaceX for launching the ROAMER satellite.

The process of launch for SpaceX to the ISS needs to be outlined for the project to be successful, which starts with the ROAMER satellite being stored within the Dragon 2 spacecraft prior to launch. Post launch, the Dragon 2 will go through processes of docking to an ISS port. Understanding the differences of the ISS ports will yield requirements based on size and mass. The two main airlocks used for commercial and satellite use on the ISS are the JEM and Bishop airlocks. Both of these airlocks fit within the constraints that have been set for size and weight of the ROAMER satellite.

Table 4-14-2 Detailed comparison of ISS port specifications

ISS Airlock	Length (m)	Width (m)	Height (m)	Payload Weight (kg)
JEM	0.64	0.83	0.8	300
Bishop	1.072	1.072	1.27	321.597

5. Conclusion

5.1 Description

The conclusion will highlight next steps on the journey of ROAMER.

5.2 Path Forward

This report provides a feasibility study for the ROAMER mission. The hardware costs are outlined. Development, testing and operations costs are not included, these can be 3x the hardware cost. The next step is to develop the requirements to the next level and conduct a System Requirements Review and a more detailed development plan.

The large ratio of the robotic arms inertia compared to the inertia of the spacecraft make the control system development for this mission will be a challenge. The development of a ground based demonstration of the system using a 2-dof air table, a 3-dof air bearing or a hardware/software simulation would greatly reduce this risk. This will allow the development of the control system to begin using representative system dynamics and retire the risk prior to committing resources to the development of the more mature technologies of the spacecraft bus.