Voyaging Intelligence System for Interplanetary Observation and Navigation (VISION)
2024 RASC-AL Proposal
BYU Commerical Space Association
Brigham Young University

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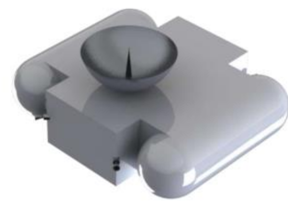
Theme: AI-Powered Self-Replicating Probes – an Evolutionary Approach

Objectives & Technical Approach:

- Mothership (Odin) with twin prospecting probe design for enhanced capabilities and redundancy
- Autonomously navigate asteroid belt
- Scan bodies, make decisions based on data
- Launch probes to promising asteroids, perform surface composition analysis
- Harvest and process materials (water-ice) for fuel and other uses, expanding capabilities

Image of Mothership:



Key Design Details & Innovations:

- Mass: 3090.5 kg
- Volume: 9.55 m^3
- Propulsion – Rotating Detonating Engines, Hall effect thrusters, more powerful and efficient
- AI – Teacher/Student training technique, reduces necessary computing power
- Ability to locate, harvest, and process ice in-situ for fuel
- Power: 1750 W
    - Use of Stirling Converter's for efficient power generation

Schedule:

- Launch aboard a Falcon Heavy rocket
- Arrival at Didymos and Dimorphos
- Begin surface scans from orbit send data to earth
- Deploy probes to land on surface and begin composition analysis and resource harvesting
- Create fuel from harvested ice
- Return to mothership, gather data and navigation decisions are made by the AI for next destination

Cost:

- **$314 Million**

ACRONYMS AND ABBREVIATIONS LIST

AI – Artificial Intelligence
ASRG – Advanced Stirling Radioisotope Generator
DART - Double Asteroid Redirection Test
DSOC - Deep Space Optical Communication
GCR – Galactic Cosmic Rays
GRNS – Gamma Ray Neutron Spectrometer
KA band – radio frequencies in the range 26.5–40 gigahertz
LORRI – Long Range Reconnaissance Imager
ML – Machine Learning
MSOLO – Mass Spectrometer Observing Lunar Operations
PAPA – Plug-N-Play Avionics
PRIME-1 – Polar Resources Ice Mining Experiment-1
RDRE – Rotating Detonating Rocket Engine
RF – Radio Frequency
RIMFAX – Radar Imager for Mars' Subsurface Experiment
TRIDENT – The Regolith and Ice Drill for Exploring New Terrain
VISION - Voyaging Intelligence System for Interplanetary Observation and Navigation

1.0 INTRODUCTION

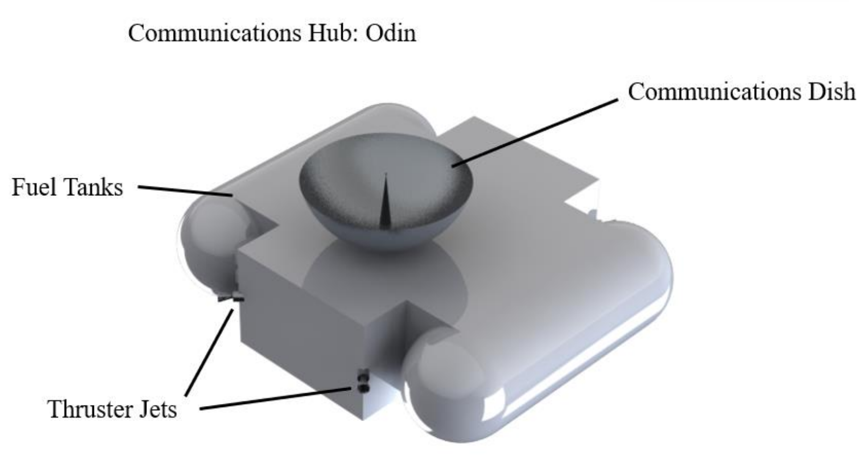
Two large problems stand in the way of successful unmanned deep space exploration. The first problem is the inability to control probes far from Earth in real time due to communication latency. This has the potential to threaten missions in which a series of rapid input are required to perform spatial maneuvers. To resolve this issue, we propose implementing autonomous systems capable of immediate decision-making. The second issue is the limited quantity of resources that can be sent with a probe. The limited amount of consumable resources, namely fuel, greatly restricts mission longevity. We plan to resolve this problem by gathering and refining resourses like ice in-situ to create additional fuel according to our probes' needs. These needs will be reported and addressed via an AI system capable of self-augmentation to reprioritize mission objectives based on the needs that are identified.

The Voyaging Intelligence System for Interplanetary Observation and Navigation (VISION) mission provides an opportunity to test solutions to these problems while simultaneously conducting scientific studies in the asteroid belt with the potential of expanding further into the solar system. VISION consists of a mothership probe, responsible for computing power and communications, and two twin prospecting probes (adding redundancy) for landing on asteroids to gather materials and learn about asteroid composition. VISION will be able to function autonomously using a trained AI system capable of directing the probes, making mission objective decisions, and sending information back to Earth. This proposal discusses the hardware, software, and developing technologies required to make VISION possible.

1.1 MISSION PLAN

The entire VISION payload will be launched aboard a Falcon Heavy or equivalent launch vehicle. We will first target the binary Didymos and Dimorphos asteroids and investigate the surfaces of the asteroids to develop a deeper understanding of their physical makeup. We have selected these asteroids because of their binary relationship and potential for comparative study after the DART mission impacted Dimorphos [27]. Our probes will use the data to either continue exploring the cluster or navigate to a new one.

From the asteroid binary, VISION will proceed past the frost line and select a new location of exploration based on the priotization of the AI self augmenting system. If present resources allow it, fuel will be created in-situ. VISION will pursue a cycle of exploration, resource collection, and fuel manufacturing to explore as many of the objects in the asteroid belt as possible.



2.0 COMMUNICATIONS

For this mission, communication between the Odin probe and Earth will be essential. Communication needs to be capable of sending large amounts of scientific data such as photos, sensor readings, and video feeds. It also needs to be reliable and able to transmit over great distances especially if the mission moves deep into the Kuiper belt.

We have determined that the most viable form of long-range communication will be used via the DSOC. This method uses a near-infrared laser transmitter to send concentrated high-speed data across great distances. The DSOC was tested on the Psyche NASA Space Mission [1] and has been proven to be a sound communication technique. The DSOC can send data at a max data rate of 267 Mbps as long as the communication array is successfully pointed at the optical receiver [2]. The power consumption of the DSOC is also less than that of traditional RF communication at only 75 watts [3] which will be essential as power is at a premium for such a space mission.

If by the launch of this mission, an interplanetary communication network of satellites has been established, this network can facilitate Earth communication by passing along the laser signal from satellite to satellite back to Earth [4]. The use of DSOC as communication also requires line of sight between the transmitter and receiver. Using this interplanetary network will help mitigate this interference in earth communication. At minimum, the DSOC would need to communicate directly with satellites orbiting Earth to avoid weather and atmospheric disturbances.

Each of the twin probes will also need a method to communicate with the Odin probe. This communication will need to be reliable, but will only be sent over large swathes of the Kuiper belt as the twins explore away from the Odin probe. Due to the closer distance between these probes and the mother probe, a form of RF communication is the logical choice because of its reliability. It will allow for the probes to freely explore without the direct line of sight necessary to communicate their findings and receive new mission directives. We propose using the KA band of RF for reliability and transmission speed [5].

2.1 COMMUNICATION CONTINGENCIES

In the case of a failure of the DSOC, the RF communication system stored on the Odin can be used to communicate directly Earth. The ideal would be to use the DSOC for better power usage, but the RF system will act as a backup communication system.

3.0 POWER AND PROPULSION

All probes will need to have a system of power generation and a system of propulsion to maneuver. The proposed system components are detailed below.

3.1 POWER

This power source will need to be consistent and able to perform for up to 20 years; it will need to operate in regions of the asteroid belt or beyond. We recommend an ASRG as our power source. This is a powerplant that is capable of long-duration power generation [6], and an individual ASRG is capable of producing consistent power up to 130 W [7]. Its compact space and weight estimates [7] allow us to link multiple ASRG units together to produce the necessary power draw for our probes. For Odin, we expect a power draw of about 1500 W; for the twins, we expect a power draw of 245 W each; which should cover all required functions. We chose the ASRG as our recommended power system as it has a proven track record of longevity and successful use in space, and unlike solar, it will not have its power generation diminished as our probe system travels further from the Sun. This will require the ASRG to be continually invested in and developed to enable it to supply our probe. This is one of our key assumptions.

3.2 PROPULSION

Propulsion requirements vary by probe. Odin must be a system capable of maneuvering and traveling in the asteroid field but does not need to land on any celestial bodies. The twins must be capable of rendezvousing with Odin and landing on celestial bodies and taking off from them. Both systems will have to last for the duration of the mission. Due to the above facts, we recommend a different propulsion system for each craft.

Odin will require an electric propulsion system similar to the hall-effect thrusters used on Psyche and other missions [8]. These thrusters provide stable long-term thrust in the order of a few newtons for maneuvering. Odin's thrust requirements are limited mostly to course correction and rendezvous with the twins.

The twin probes will require chemical thrusters because they will have to repeatedly land and take off from various asteroids. As asteroids' mass varies considerably the twins will require a thruster that can provide at least 6 N of thrust, preferably up to 27 N. The RDRE is one of the few tested chemical thrusters with the ability to provide this variation in thrust and force and is far more efficient than conventional thrusters [9]. The mission lifespan is influenced by the thruster lifespan. 60-70% of the twins' initial launch weight will be dedicated to fuel for these thrusters. We expect to manufacture additional fuel contingent upon the discovery and ice on the surface of the bodies we explore.

3.3 CONTINGENCIES FOR POWER AND PROPULSION

As this is a long-duration mission, our system must be robust enough to survive the length of the mission. All components must have some element of redundancy. The ASRG has proven capable of operations for the length of our mission [6]**.** With power requirements being met by twelve ASRGs on Odin and two per twin, this would allow both some redundancy and the ability to continue limited operations even under catastrophic condition where one converter fails or produces less power than expected.

Hall-effect thrusters have a proven track record of long-term operations in space [10]. Three such thrusters on Odin would cover all necessary movement and provide slight redundancy should one or two fail. While Odin does need some maneuver elements, its communication range with its twin probes should be sufficient to maintain operations for an extended period even if the mission span exceeds the thruster lifetime.

The RDRE for the twin probes is still in its testing stages and has less of a proven track record [9]. Care must be taken in the ensuing years of development to ensure it meets all expected challenges of its lifetime. As the chemical thrusters' fuel reserves will likely be the first point that could end mission capabilities, our main contingency will be ensuring adequate initial fuel reserves and limited refueling capabilities (covered in the finding/ processing materials section) to extend mission duration.

4.0 MAPPING & SENSING

To support our mission of exploring the asteroid belt, we will outfit each of our three probes with an array of sensors designed for use in their respective ground and orbital capacities. Each of the sensors will employ passive sensor technology to minimize power consumption. We are most interested in identifying the physical and chemical makeup of the asteroid. The sensors have also been chosen to look for signs of ice beyond the frost line of the asteroid belt. The following information gives a breakdown of our chosen sensors, the justification behind their use, and general technical specifications relevant to our mission.

4.1 ORBITAL IMAGING (sensors on the main probe)

A multispectral imager will be used on the main probe to provide information within spectrums commonly used by lansubdsats [17]. Looking in these bands offers insights into the physical and chemical properties of the asteroids. This method would require using a lower amount of power than if a hyperspectral imager were used. If power and data transmission requirements are a non-issue, then we could consider using a hyperspectral imager for a wider range of data.

The GRNS provides subsurface details that the multispectral imager is unable to achieve. It uses neutron detectors to measure the level of hydrogen in the upper level of the asteroid's surface [18]. This capability is useful for providing more detailed compositional maps of the asteroids we plan to observe. Both this and the multispectral imager can be used to map the surface of the asteroids and provide insights as to the likelihood of ice being found on the celestial body.

In order to assist with navigation and mapping, we will employ a long-range light imager on the main probe that will supply high-resolution images of the asteroids that we plan to visit. We expect this imager to have similar capabilities to that of the Long-Range Reconnaissance Imager used on the New Horizons Probe. [19]

4.2 GROUND IMAGING

We will attach a subsurface ground imager similar to that of the RIMFAX [14] device used on the Mars Perseverance Rover on both of the twin probes. This device will allow our probes to collect detailed information on the ground makeup of our asteroids up to a depth of 10 meters. The orbital scanner will be used for broad-sweeping scans. From this information, our AI system will determine a landing site for one (or both) of our twin probes for closer ground-level analysis.

Additionally, we will include an optical navigation camera on each of the twin probes which will be capable of capturing high-definition video and color images of the surfaces we explore similar to that of the mastcam-z used on the Curiosity Rover [20]. Providing these cameras on both probes gives us the option to take images from multiple angles. This camera will also aid in navigation and positioning.

4.3 MAPPING

The data that we receive from our imagers will be passed on to the integrated systems we have onboard the mothership to map our findings. These will be used by the AI system in making navigation and exploration decisions to expand our mission capability that can be sent back to Earth in our communication stream.

5.0 FINDING & GATHERING MATERIALS ON A SURFACE

Once long-range scans of neighboring asteroids have been completed and the AI has decided on which asteroids are worth visiting, the twin probes will be sent to the most promising asteroids where water-ice is likely to be found. Upon landing, the probes will perform more accurate scans of the asteroid material using a scaled-down version of the PRIME-1 [26] consisting of TRIDENT and MSOLO [26], a commercial, off-the-shelf mass spectrometer fitted for spaceflight. This technology is scheduled to be launched as part of the IM-2 mission where PRIME-1 will be tested in-situ, prior to the VISION mission. PRIME-1 drills surface material at varying depths, depositing the material above the surface where MSOLO determines a detailed composition of the substances present. Upon confirming the presence of water-ice, a robotic manipulator arm will scoop up the excavated materials and deliver them to the first processing chamber. [26]

5.1 PROCESSING MATERIALS

Once a sample is delivered to the sublimation processing chamber, the chamber is sealed and the sample is heated by exposure to the ASRG heat exchanger [25]. Once the ice within the sample begins to sublimate, an atmosphere in the chamber will be created that will increase the processing speed. With ice and other volatiles converted, the gas can be siphoned off to storage tanks for later use, or to the second processing chamber where electrolysis occurs. Electrolysis will separate the hydrogen and oxygen to be used as chemical thrusters on the probe. This essentially refuels the probe, providing a way to extend the capabilities of the probe to travel farther and explore more celestial bodies. Once processing is done in the first chamber, it will open again, and a piston connected to the back wall of the chamber will push out any dust or debris left over to keep the chamber clean for further use.

6.0 AI AND COMPUTING: TRAINING THE AI

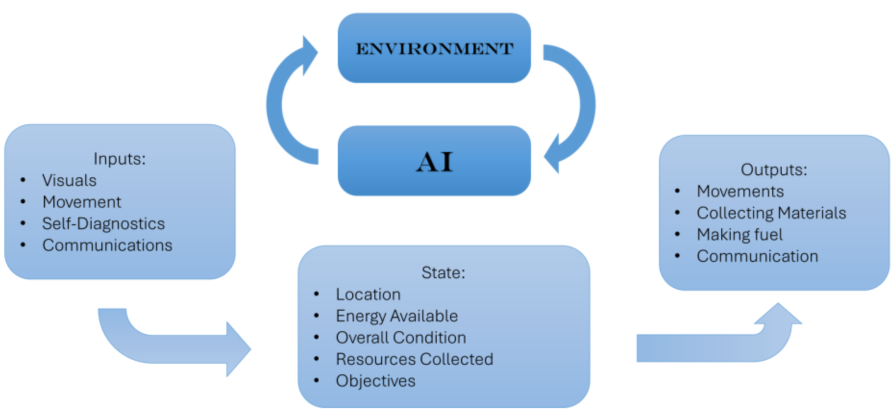
The hostile environment of deep space creates several challenges for computation. It is an understood problem that GCR's, as well as radiation from the sun, can manipulate processors and create computational errors that can be mitigated using radiation-hardened systems. The situation with regards to ML is further complicated, as ML typically utilizes GPUs, something that is not flight proven to the same degree as CPUs.

Our plan to address these issues is to employ a unique training process to utilize smaller yet still effective models that are less computationally expensive and can run on CPUs that have already been proven in deep space environments. This training process is referred to in the literature as the Teacher-Student architecture, specifically applied to knowledge compression [21].

The way that this works is descriptively straightforward: a large, computationally expensive deep neural network (the teacher) is trained, and then used to further train a smaller model (the student) that is narrower (fewer neurons on each layer) and deeper (more layers), rendering equal or slightly reduced performance for a much smaller model, yielding decreased computational requirements [21].

This has already been done for computer vision systems, as outlined here [22]. There is further utility in this training approach, demonstrated in [23] where the paper demonstrates how a teacher trained on high resolution images can distill this information to a student to be able to perform well with lower resolution images. This type of approach can be particularly useful in a context like ours, where images may be taken at a distance and resolution may be less than optimal. Also, to mitigate costs and increase effectiveness we will train the AI on Earth.

Using NASA image and physical parameter databeses such as [12], the AI can be trained as stated above to recognize materials and make decisions discussed bellow. Other datasets to train the AI can include subsurface scans from RIMFAX, in order to allow the probe to detect ice, and databases of information collected using the scanners mentioned above.



6.1 DECISION MAKING

The probes will contain several sensors. The computer will take data from these sensors, alongside NASA's orbital data about the asteroids, to build a database of information used to effectively make decisions. This database will hold five general states; location, energy available, overall condition, resources collected, and objectives. These states will then be used to make decisions using AI and will act as our main method of self augmentation to further our mission objectives.

The AI will make navigation decisions, classify materials, and relay information to Earth. First, it will make navigation decisions by comparing and analyzing asteroid volume, density, and subsurface scans. This analysis will guide the probes to asteroids with the most interesting features and the best potential for ice deposits, which are crucial for fuel production and long-term mission survival. In addition, the AI will classify materials based on density and subsurface data gained. Throughout the mission successful augmentations (major decisions) will be communicated back to Earth. As data is gathered and processed by the AI, it will send back new findings to Earth for scientists to examine. The AI will also be monitoring the system conditions and notifying Earth if a component fails. Operations will be adjusted based on what systems can be utilized and how well they are working.

Although the AI will be used to determine the next asteroid each probe visits, a PAPA software architecture will be used to compute how to get there[24]. This approach allows the AI to input a desired location (the plug) and then through the software it will adjust and execute to reach the desired target (the play). The software will be configured to work with the probe's hardware systems. Part of moving efficiently requires correct launch and landing time for the twins so that they are closest to their target and have the correct trajectories. The probes will be loaded with orbital data for the asteroids from NASA's database allowing for timing the closest approach. They will also know when to release from an asteroid to ensure as safe a flight as possible. Repeatable tasks, such as taking off, landing, and gathering and making fuel will not use the AI to decrease latency and computational overhead. Since the AI will be on Odin and not the twin probes, the twins will have sufficient computational power to perform tasks specific to surface research and material gathering

Odin represents a leap forward in space exploration. The ability to adapt, learn, and communicate will revolutionize our understanding of asteroids and pave the way for future interplanetary missions.

6.2 HARDWARE REQUIREMENTS

In this section, we will address the specific computational hardware that the mothership needs to compute and store data. The probe must be configured for real-time computing for movement and flight, AI inference models, and other operational programs. Past NASA Missions have used the RAD750 for the mission's computational load of flight, movement, and operational systems. Considering the requirements of our mission with prolonged flight and computational systems, we have decided that the best system to use is the RAD5545™ SpaceVPX single-board computer of Bae Systems [15]. With the use of AI models by inference, the RAD5545 alone will not be optimal to handle the computational load effectively. Therefore, to have optimal performance and computational task allocation, we would have to incorporate more RAD5500 cores and L1/L2 cache memory modules. We would use the cores for handling more asynchronous load, and the cache memory would be used to reduce the computational latency of the computer. We would scale to meet the speed necessary to run the mechanical systems of the mission.

7.0 CONTINUATION

This mission acts as a proof of concept for independent probe operations and a system capable of in-situ resource extraction. The VISION system will demonstrate the feasibility of a system capable of autonomously fulfilling and extending its mission lifespan through AI navigation and fuel production. It is hoped that this will act as a stepping stone for future operations and the eventual development of a true von- Neumann probe.

Technology Readiness Levels of VISION systems

System	TRL	Explanation
DSOC	6	Prototype tested on NASA PSYCHE mission
Multispectral Imager	9	Used in multiple satellite/probe missions
GRNS	9	Used in multiple satellite/probe missions
LORRI Instrument	9	Used in multiple satellite/probe missions
RIMFAX	7	Technology used on Martian environment
Optical Navigation Camera	9	Used in multiple satellite/probe missions
RDRE	4	Early stage tested in lab environment
SPT-140 Hall Thruster	9	Currently in use in Psyche Mission
ARSG	6	Continuous running test for 14 years
RAD5545™ SpaceVPX	7	Additional components required
PRIME-1	7	Planned for use on moon as part of IM-2 mission, 2024
AI: Teacher-Student Trianing	4	Training model used in other applications
AI: Classifing Materials	6	AIs have been used to classify space based objects
AI: Navigation	4	Can make weighted decisions on Earth
GNC PAPA Software	4	Concept yet to be applied that this complexity

Estimates of VISION systems

System	Power Draw (W)	Volume (m^3)	Cost ($ millions)	Mass (kg)
DSOC	75	0.05	30	25.0
Additional equipment & communications	125	0.275	4.5	13.0
SPT-140 Hall Thrusters (x3)	900	0.4	10	25.5
RDRE (x2)	20	0.3	60	20.0
Radio/communications with Odin	25	0.05	6	6.0
PRIME-1 (x2)	114	0.23	94	72.0
Material Processing Chambers (x2)	50	0.15	15	20.0
Multispectral Imager	4.5	0.016	15	20.0
GRNS	4.5	0.016	10	13.1
LORRI Instrument	10.6	0.14	10	12.0
RIMFAX	5-10	0.002	20	3.0
Optical Navigation Camera	17.4	0.003	8	4.0
ASRG (x16)	-2080	2.176	20	323.2
Compuational Proccessing	500	0.24	3	14.5
Xenon Fuel for SPT-140	NA	3	5	1500.0
Oxygen and Hydrogen Fuel for RDRE	NA	2	3	1000.0
Plutonium-Oxide Fuel for ASRG	NA	0.004	0.5	19.2
Total Estimates	1750	9.55	314	3090.5

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