EMBRY-RIDDLE AERONAUTICAL UNIVERSITY

CHONK

Ceres Harvesting and asteroid Operations NetworK

Advisor:
Dr. Melissa Morris
Team Lead:
Nikki Smith-Cielo*
Sub-Team Leads
Nicolas Bonasoro
Logan Innes*
Timothy Lemack
Thomas Philip
Samuel Quinutolo
Annaelise Swanson
Jada Totten

Team Members
Xavier Beckwith
Lexi Greenwood
Zoey Hart
Annika Heieie
Jett Hirsch
Cassandra McGinley
Logan Shaffer
Jamaal Smikle
Dori Stein
Anuhya Suhas
Maria Tobarra Meruelo
Tristen Wheaton
Cameron Winkel

There are so many benefits to be derived from space exploration and exploitation; why not take what seems to me the only chance of escaping what is otherwise the sure destruction of all that humanity has struggled to achieve for 50,000 years? - Isaac Asimov, Speech at Rutgers University[48]

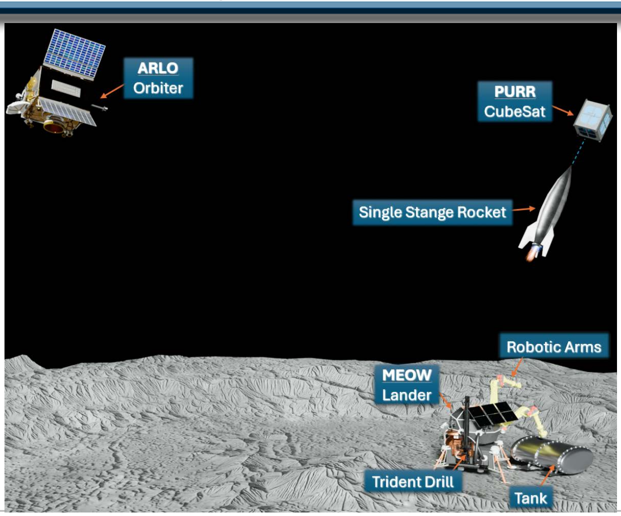
Undergraduate Team
**Graduate students*

CHONK:
Ceres Harvesting and asteroid Operations NetworK

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

Objectives & Technical Approach:

- Establish water-ice extraction/storage facility on Ceres.
- Implement AI for autonomous navigation and problem-solving.
- Demonstrate self-augmentation capabilities through in-situ resource utilization and partial self-replication via additive manufacturing.
- Study Ceres' subsurface and catalog asteroids.
- Leverage the synergy between CHONK's orbiter (ARLO), lander (MEOW), and probe (PURR) units for efficient resource utilization, scientific research, and operational sustainability in space exploration.



Key Design Details & Innovations:

- Mass: 5 mt, Volume: 294 m^3
- Total Power Consumption per Earth Day (kWh):
  - Probe: 14.91
  - Lander: 3276.21
  - Orbiter: 12.97
- X-band RF link: Direct to DSN 70m antennas.
- Optical link: High-speed data between Ceres elements.
- RF fallback: For optical link component failures.
- On-board storage: 1 TB (lander/probe), 2 TB (orbiter).
- EoL Protocol: Shutdown data transmission.
- AI, 3D printing, efficient propulsion, and advanced comms drive safer, cheaper, and more flexible future missions.

Schedule:

- 2028-2032: Preparation & TRL advancement
- 2033: Mission launch window
- 2033-2035: Transit to Ceres
- 2035-2036: Orbital Insertion and Analysis
- 2037-2038: Initial Surface Operations
- 2039: Probe launch from Ceres
- 2040-2041: Transit Through Asteroid Belt
- 2042: Asteroid Landing and probe decommissioning

Cost:

- $1.82 billion life cycle cost from 2028-2042

Contents

I. Introduction

The Ceres Harvesting and asteroid Operations NetworK (CHONK) mission is conceived to bridge the significant gap in our ability to conduct comprehensive deep-space exploration and utilize the resources of the asteroid belt effectively. It introduces an innovative solution through the deployment of artificial intelligence (AI)-powered self-replicating system, drawing inspiration from the concept of Von Neumann probes in science fiction[34].

By focusing on Ceres, a dwarf planet abundant in resources and strategically located in the asteroid belt, CHONK aims to compile essential data from various asteroids and establish a resource storage facility. This initiative not only promises to enhance our understanding of the solar system's formation but also sets the groundwork for future exploratory missions by leveraging the potential of advanced technologies for continuous exploration and resource utilization.

The mission's overarching goal is to create a sustainable infrastructure on Ceres that could support further deep-space exploration efforts. By doing so, CHONK addresses the critical need for a self-sufficient, continuous exploration model that can tap into the vast resources of the asteroid belt. The choice of Ceres as the mission's target underscores its suitability due to its rich resource base, which accounts for a significant portion of the asteroid belt's mass, and its expansive surface conducive to the establishment of a resource storage facility. Through the innovative use of AI and self-replicating technology, CHONK stands as a pioneering endeavor aiming to significantly advance our capabilities in space exploration and resource management beyond Earth's confines.

II. Mission Architecture

A. Concept of Operations

The CHONK mission is a meticulously structured endeavor aimed at revolutionizing deep-space exploration and asteroid resource utilization. The mission anticipates a pre-launch phase from 2028 to 2032 (encompassing development, testing, and quality assurance), a targeted launch window of 2033, and a projected minimum of 9 years of operations concluding in 2042. A Gantt chart in the Appendix depicts the mission schedule3. This ambitious project will see the deployment of the Artificial Intelligence Reconnaissance Logistics Orbiter (ARLO), the Mining and Experimental Operations Workstation (MEOW), and the Probe for Unveiling Rocky Relics (PURR) for detailed asteroid belt exploration. A work breakdown structure (WBS) identifying CHONK's critical areas is included in Appendix A2 .

ARLO is tasked with ensuring robust communication between MEOW, PURR, and Earth, alongside monitoring potential environmental threats to MEOW and continuing the study of Ceres for future operational expansion. MEOW, a pivotal element, focuses on surface and subsurface studies of Ceres, extracting water-ice, storing resources for future missions, and engaging in chemical processing, PURR assembly, and replication through additive manufacturing (AM). It incorporates technologies such as solar panels and a probe launch mechanism, and is equipped with two robotic arms (GITAI Inchworm[23] and HiWonder xArm2.0[25]) and The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) drill by Honeybee Robotics[4] for efficient resource extraction and processing.

PURR is designed to provide invaluable insights into the asteroid belt, aiding in understanding the solar system's formation and identifying potential asteroid threats to Earth. After augmentation via in situ-produced propellant, PURR will launch from MEOW to conduct flyby observations of asteroids, relaying data to Earth through ARLO. Near the end of its mission, PURR will gently land on an asteroid, employing a Laser Retroreflector Array, akin to those on NASA's InSight and Perseverance, to boost its detectability from Earth for precise tracking and thorough analysis.[36] This integrated approach between ARLO, MEOW, and PURR underlines CHONK's innovative strategy to expand human knowledge and presence in space by leveraging advanced technologies and sustainable resource utilization practices.

B. Launch

The CHONK mission aims to launch in 2033, embarking on an ambitious journey expected to span nearly a decade, culminating in the exploration and utilization of resources from Ceres and the broader asteroid belt. The launch payload includes an orbiter (ARLO) to survey Ceres from space, a lander (MEOW) equipped with drilling and resource extraction and storage technology, and the core components for a fleet of probes designed for detailed asteroid analysis. The spacecraft will be configured in an orbiter-lander pairing, with the core components for PURR and PURR's future iterations nested inside the lander. These elements, coupled with advanced AI systems for autonomous navigation and decision-making, as well as innovative self-replicating and additive manufacturing capabilities, encapsulate the mission's pioneering approach to space exploration and resource utilization.

C. Interplanetary Orbits and Trajectories Analyses

The mission's success is decided by its efficiency and longevity, which depends on the method of travel from Earth to Ceres, and Ceres to potential target bodies. Here, we will discuss a Hohmann Transfer and the relevant parameters to the mission. For this scenario, we will assume a co-planar, circular system, and $r_{LEO} \sim r_E$ for simplicity in early mission analysis. For further context on calculations, see Appendix B.

1. Earth to Ceres

CHONK will begin at a low Earth orbit (LEO) with a relative velocity similar to Earth's. When positions are optimal, the first maneuver (Hyperbolic Departure) is performed with a burn of $V_{b,1} \sim 12.8$ kms^{-1}. This initiates a Hohmann Transfer to Ceres with a period of 1.28 yr, during which all onboard systems, other than for safety, will be in an optimized hibernation mode. Once conditions are met, the ship will leave hibernation to begin its approach to Ceres and initiate the second maneuver (Hyperbolic Approach) into a Capture Orbit. The burn velocity for this maneuver is $V_{b,2} \sim 6.3$ kms^{-1} considered in the relative negative direction of motion, and the ship is in capture orbit of Ceres with $r_c \sim r_{CER}$.

2. Ceres to Asteroid

As the spacecraft approaches Ceres, ARLO scan the surface to identify pre-determined landing site requirements are present. ARLO will then relay the collected data back to the MEOW. Upon confirmation of safe landing conditions, orchestrated from the command, communication, and control center on Earth, MEOW will separate and descend to the surface. Utilizing the TRIDENT drill, MEOW will extract and process water needed for PURR's thrusters. PURR will then journey to nearby asteroids for targeted flybys. Data collected by PURR's onboard instruments will be transmitted to ARLO, which will remain in orbit around Ceres, acting as a relay to transmit data to Earth for analysis. This voyage promises invaluable insights into asteroid composition, vital for understanding Ceres' formation and the broader solar system dynamics.

D. Landing Sites and Exploration Targets

Ceres, an asteroid and dwarf planet, has been identified as possibly the largest reservoir of water in the inner Solar System, making it a prime candidate for resource exploration. Dawn mission scientists determined the existence of a deep reservoir of salt-enriched water about 40 km below surface.[46, 28] Ceres has bright areas on its surface caused mostly by sodium carbonate deposits left behind after the sublimation of the brine that percolated to the surface.[28] A thin layer of water vapor possibly from the the sublimation of hydrated mineral salts fused with ice appears to show the presence of OH radicals or H_2O molecules above the surface.[31] With no significant viscous relaxation observed in the images from Dawn's framing cameras, scientists estimate subsurface water of 30-40 percent by volume.[31]

Ceres has spots with high albedo indicating relatively recent percolation of liquid mineral salts up to the surface, leaving behind the bright deposits – mostly sodium carbonate.[28] The most extensive such areas are in the Occator Crater region, including the prominent ones, Cerealia Facula and Vinalia Faculae. This makes the vast areas of over 92-kilometers-width in the Occator Region a good spot to land for water resources.[28, 46] According to Dawn Principal Investigator Carol Raymond,[28] the impact that caused the crater, about 20 million years ago, generated enough heat to melt the ice. Though the ice melted over the next few million years, the large fractures from the impact could reach deep into the water reservoir.[28]

E. Science Objectives and Operations

Given the speculative nature of such a project, our primary objectives are scientific curiosity, innovation, and the advancement of technology. This mission will conduct rigorous scientific research on asteroids to deepen our understanding of their composition, origins, and the potential resources that can benefit our society. Ethical considerations such as respect for all forms of life and sustainable exploration of resources will supersede all other objectives of this mission. Our AI-driven operations will comply with the NASA Framework for the Ethical Use of Artificial Intelligence. With these principles in mind, our team has identified two primary scientific objectives for this mission: 1) Analyze the composition of Ceres to explore its mineral and material resources, and 2) study the nearby asteroids in detail and catalog the data to help future missions.

Using onboard scientific instruments like the multispectral and hyperspectral mapping spectrometers and the gamma-ray and neutron detectors, the system will incrementally get a clearer picture as it draws closer to Ceres.[30, 44] While ARLO stays at a predetermined altitude in Cerean orbit, MEOW will separate and guide itself autonomously to a safe site on the Cerean surface in the Occator Region. Subsequently, PURR, after being assembled on Ceres, will proceed to the mission's second scientific objective: studying and cataloging the asteroid belt. While much of CHONK is demonstrative and experimental, our mission objectives and exploration plans are backed by the findings from the Dawn mission to Ceres.[46] With our designs, we intend to build state-of-the-art solutions for efficient asteroid prospecting, mining, and resource utilization.

III. System Architecture

A. Autonomous Systems and Robotics

This section will explore the Autonomous Systems and Robotics (ASR) necessary for an SRM. CHONK proposes a new AI Advanced Deep-Learning Network (ADLN) capable of supporting the entirety of space operations through all life cycles and mission phases, manufacturing more AI-powered space probes. Intelligent Deep Learning Exploration and Replication System (IDLERS) is a novel Advanced Neural Network (ANN) that is comprised of 13 other autonomous sub-systems (e.g., DNN, Long Short-Term Memory (LSTM), Grated Recurrent Unit (GRU, Recurrent Neural Networks (RNN), and Convolutional Neural Networks (CNN). The requirements for high-level design for AI in space are outlined in Table 2 in the appendix. IDLERS will have primary control and command, communication and coordination, navigation and explorations, replication and self-expansion, resource management, fault detection and mitigation, security, and privacy, learning and adaptation, mission data reporting, data processing and analysis, which are all assigned to specific subsystems within IDLERS. Once the spacecraft is deployed IDLERS will receive a startup notification to take command of all operations within the ship and begin its journey to Ceres, once on Ceres IDLERS will oversee all operations and replication of probes. This section will examine the current literature crucial to developing IDLERS, look at an overview of the system, interrelation of subsystems, high-level data processes, hardware requirements for AI in space, robotic components, suggestions for programming languages, and recommendations and conclusions.

B. Background

Advancements in AI and Machine Learning (AI/ML) are addressing historical challenges for Space-based Systems (SBS)[19]. Insomuch that NASA's Jet Propulsion Laboratory has suggested future space operations will be contingent on AI/ML due to its versatility in application for mission sets, mission planning, and execution[11]. For example, the integration of crewed missions with the support of uncrewed systems employing AI/ML is ushering in a novel chapter in space exploration, facilitating extended duration, intricate tasks, and ventures into high-risk environments[43, 19]. AI-powered robotics is also being explored with new designs for robotic manipulators, tele-operations, or exoskeletons for extravehicular activities, enhancing the mission efficiency, autonomy, and decision-making capabilities[12]. Further examination of the deeper integration of AI into space mission architecture is enabling new SBS research on space-based laboratories, through automating research, and maintaining structures on SBS, which are all dependent on AI/ML[45]. As a result, there has been a paradigm shift in the practical implementation of SRM[49], transcending its status as merely a science-fiction notion [49]. Breakthroughs in Software-based Artificial Life (SBRL), wherein AI/ML replicates biological processes and systems to enable more sophisticated operations, are emerging as the cornerstone for SBS, offering significant potential[13]. The emergence of AI swarming, also known as System of Systems (SOS), is a response to the increasing complexity of AI. Progress in AI engineering proposes Multi-Agent Systems (MAS) as a solution for simulating SOS behaviors, highlighting the importance of domain-specific modeling semantics and a unified language to enhance the design of optimal CON-OPS[20]. In an SRM, new machines will need their own programming[27]. Copying the current ADLN into a new probe could present issues of errors in code increasing with each replication of code[10].

C. Overview of IDLERS Systems and Data Processing

Designing a control diagram for a network of interconnected space probes entails identifying and delineating key systems and subsystems, as well as elucidating their interactions and overarching mission objectives [38]. At the heart of this architecture lies the Central Command and Control System, which orchestrates the mission, coordinates tasks, and makes high-level decisions, leveraging components such as centralized AI, mission control software, and communication infrastructure. As shown in Figure 4 in the appendix, The hierarchical structure consists of four primary categories: 1) Risk Management Systems, 2) Life Cycle Systems, 3) Physical Controls, and 4) Data Processing and Response Subsystems. As shown in Table 2 in the appendix, the requirements for high-level design for AI in space are outlined. The Communication Subsystem facilitates seamless communication between the central system and individual probes, employing communication satellites and deep-space communication systems. Meanwhile, the Swarm Management Subsystem oversees the deployment, status, and health of individual probes, integrating probe deployment mechanisms, health monitoring sensors, and tracking systems. Autonomous Navigation Subsystems enable independent navigation and obstacle avoidance, employing a suite of navigation sensors and onboard navigation AI Task-specific AI Subsystems handle specialized tasks such as planet exploration and data collection, incorporating task-specific AI algorithms and relevant sensors. Resource Management Subsystems manage power, computing resources, and data storage on each iteration of PURR, while Redundancy and Fail-over Subsystems ensure mission continuity during probe failures [38]. Security Subsystems protect against cybersecurity threats and unauthorized access, employing encryption protocols and authentication systems. Adaptive Learning and Decision-Making Subsystems allow the system to learn from the environment and adapt mission strategies, utilizing machine learning algorithms and adaptive decision-making systems. The Data Transmission, Storage, and Process Subsystem handles the transmission of collected data to the central system, manages onboard data storage, and aids in data processing and analysis for decision-making. Mission Planning Subsystems optimize mission tasks based on scientific objectives and resource constraints, employing mission planning and optimization algorithms. Finally, the Emergency Response Subsystem handles emergencies and executes predefined response protocols, integrating emergency detection sensors and response algorithms.

D. Hardware and Coding Requirements for AI in Space

For the effective deployment of AI in space, numerous considerations must be addressed, ranging from component selection and hardware choices to programming code and ensuring hardware and system reliability in the challenging space environment. As outlined in Table 4 in the appendix, the hardware requirements for the project have been detailed. Additionally, improvements in commercial-off-the-shelf's (COTS) are making novel space applications cheaper, but also pose significant challenges in ensuring they are sufficiently hardened for the space environment[35]. Aluminum alloys are preferred for their strength, affordability, and corrosion resistance. Anodizing further enhances aluminum's performance by creating corrosion-resistant oxide coatings, ensuring efficient heat transfer. Alloys such as Al6061 and Al7075 are well-suited for space applications[24]. Zirconium boride and silicon carbide can also safeguard carbon/carbon composites against oxidation[17]. Computing and hardware requirements for AI in space are currently being explored, companies such as KP Labs [2] is based out of Poland and offers commercially off-the-shelf satellite and other space applications for onboard computers [5]. KP Labs Space utilizes the PC104 board for modular as well as more expansive customization for plug-and-play assembly [41]. In terms of computing, the primary spacecraft will be equipped with the HPE Apollo 2000 Gen 10 [26], requiring over 250 Watts, and featuring an AMD EPYC 7000 series processor[26]. This will act as a localized computing cloud for various processes and operations. The ship controls will utilize the KP Labs Space Oryx which was recently deployed as the primary spaceflight computer for the European Space Agency's Intuition-1 in 2023 [40]. Similarly, PURR will incorporate a commercially off-the-shelf Astro Pi by Raspberry Pi, specially modified for space missions, utilizing the Rad750 or RAD5543 processor[6]. The IDLERS system will be coded utilizing Python due to its flexibility that allows developers to seamlessly integrate different neural network architectures recommended for various subsystems of the IDLERS architecture. Whether it's convolutional neural networks (CNNs), recurrent neural networks (RNNs), or deep neural networks (DNNs) with reinforcement learning elements, Python offers the necessary tools and libraries[39].

IV. Robotic Component Selection

The robotic arms selected for integration into the IDLERS system, namely the GITAI Inchworm and the HiWonder xArm2.0[25], offer distinct specifications and functionalities for assembly as well as be used for regolith extraction. The GITAI Inchworm boasts an impressive seven degrees of freedom, spanning two meters in dimension and weighing approximately 50 kilograms[23]. Operating within a temperature range of -60°C to 200°C requires a power supply of 24-48 VDC, with power consumption ranging from 60W in standby mode to 200W at peak. With a rated continuous joint torque of 368 Nm and a maximum angular velocity of 32.6 deg/s (at 24V input), its actuation mechanism relies on brushless DC motors and harmonic drives. Equipped with advanced sensors, including 19-bit absolute encoders and temperature sensors, it communicates via the EtherCAT internal communications bus. Additional features include options for redundant avionics and microprocessors based on ESP32 and STM32 architectures. Conversely, the HiWonder xArm2.0 offers six degrees of freedom and compact dimensions measuring 500mm x 295mm x 155mm (millimeters), with a lightweight construction of 1.2 kilograms. Powered by a 7.5V 6A DC adapter, specific power consumption details are not provided. Equipped with a variety of sensors, including ultrasonic, infrared, sound, and color sensors, its microprocessors are also based on ESP32 and STM32 architectures. While precise torque, angular velocity, and actuation mechanisms are not specified, it offers versatile output options and servo configurations, enhancing its adaptability within the IDLERS system architecture. Furthermore, NASA's first polar mission Luna-25 mission uses lunar manipulators which are also equipped with infrared cameras, stereo cameras, and other spectral sensors, along with drilling, scooping, and other manipulation attachments[32].

A. Excavation and Extraction on Ceres

The CHONK mission, through MEOW on the surface of Ceres, utilizes the advanced TRIDENT drilling system for groundbreaking excavation and resource extraction activities on the dwarf planet. Before drilling, a comprehensive survey ensures the landing site's crust is adequately thick for water-ice extraction, aligning with the mission's sustainability and resource utilization objectives.

The TRIDENT drill by Honeybee Robotics, a rotary-percussive system designed for the challenging extraterrestrial environment of Ceres, boasts a 10 cm diameter and is capable of extracting an estimated 0.35 cubic meters of material every 24 Earth hours [4]. This extraction rate is pivotal for the mission, dictating the amount of water-ice available for various uses, including processing into vital resources. An outline of the drilling mechanism is represented in Figure 2.

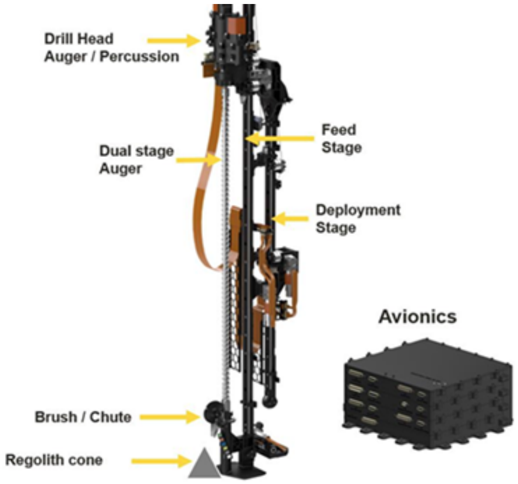


Fig. 1 TRIDENT drilling mechanism.

Emphasizing sustainability, the operation's energy requirements are optimized for efficiency, with the drilling system consuming a relatively low amount of power, demonstrating the mission's commitment to minimizing energy consumption while maximizing resource output. Through careful planning and the deployment of advanced technologies, the CHONK mission sets the stage for future endeavors in space exploration, showcasing the feasibility of extracting and utilizing celestial resources for human advancement.

B. Chemical Processes and Propellant Production

To address the unique challenges of extracting and processing water-ice from Ceres' subsurface, the CHONK mission incorporates a specialized reactor, adapted from designs initially aimed at Martian regolith [47]. This reactor is re-engineered to operate in the near-vacuum and colder conditions of Ceres, utilizing heat and mechanical agitation to efficiently release water from the subsurface ice. This innovative approach not only aligns with the mission's goal of leveraging local resources for propellant and life support but also sets a precedent for future off-Earth resource utilization technologies.

C. Structure and Materials

1. Additive Manufacturing

While an additive manufacturing (AM) unit has not been developed specifically for Ceres, it's possible to modify one designed for lunar applications to suit the unique environmental conditions of Ceres. This would involve adapting the unit's operation to account for Ceres' gravity, temperature, and available materials. Such modifications ensure the AM unit's functionality for building infrastructure like resource storage tanks, leveraging local resources, and supporting extraterrestrial exploration and habitation efforts.

At its core, MEOW's AM unit features a specialized 3D regolith printer utilizing extrusion technology for layer-by-layer construction[22]. This printer draws from various 3D printing techniques such as Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS) adapted for regolith utilization. The choice of extrusion technology ensures reliability within the challenging, low-gravity environment of Ceres.

Additionally, the unit incorporates a robust conductive V-belt constructed from Kevlar and renowned for its exceptional strength-to-weight ratio and durability. This specialized belt facilitates power transmission within the system while conducting electricity, optimizing efficiency, and reducing overall weight. Powering the unit are solar panels, serving as the primary energy source to sustain operations. Complemented by a dedicated battery for extended functionality, this setup ensures an uninterrupted power supply for the 3D printer and mobile mechanism. Laser sensors are employed to provide crucial feedback, measuring precise distances between components and monitoring tension. Supported by sophisticated software, the unit is capable of designing objects for printing and controlling the entire printing process by translating 3D models into executable instructions for seamless operation on the extraterrestrial terrain of Ceres.

2. Tanks Structure and Material

MEOW will be equipped with tank storage solutions that employ the SISTEM (Small Inflatable Space Tank Engineering Model) for initial gas and cryogenic liquid storage, incorporating advanced materials like Fluorinated Ethylene Propylene (FEP) and high-strength Poly-Benzyl-Oxylate (PBO) 'Zylon' fibers[18]. This model supports a flexible, low-mass solution with high compaction capabilities, designed to sustain maximum pressures of 60 bar. After SISTEM's initial use, additional tanks will be experimentally printed using regolith and additive manufacturing, showcasing an innovative approach to in-situ resource utilization (ISRU) and infrastructure development on extraterrestrial bodies.

D. Telecommunications, Sensors, and Data Handling Instruments

The telemetry, communications, and data handling (TC-DH) is split into four nodes of communication, which represent a network highway for the data being extrapolated throughout the mission. The four nodes are the following: Earth's Deep Space Network (DSN), ARLO, MEOW, and PURR. ARLO in its final deployed location will be in the orbital path of Ceres, MEOW will be on the surface of Ceres and PURR will be on a journey through the asteroid belt until it runs out of fuel and performs its end-of-life (EoL) protocol in deep-space (greater than 2 million km away from Earth)[9]. Radio frequency (RF) transmissions between all nodes will be time-stamped according to the system's internal time, enabling the entire system to be able to determine distancing from one another and essentially triangulate the locations of each node, including Earth (Distance = speed of light*time)[15]. Additionally, all nodes will incorporate optical and RF links, as they are redundant and are expected to be synergistic in 2030[7].

For major component selections, MEOW will utilize an X-band link directly to Earth's DSN 70m antennas through the means of an X-band high gain antenna on a gimbal (HGA) and a fixed X band low gain antenna (LGA) which is a back-up component including the Iris transponder [29]. Due to the high volume of data foreseen for the mission and as an act of redundancy, an optical link is established between the Ceres elements for high-speed data transmission, but RF is a fallback in case of component failures[33, 50]. MEOW and PURR will utilize a 1 terabyte (TB) solid-state mass-memory within their on-board computers (OBC). ARLO will utilize 2 TBs due to it being the nodal point connected to Earth and the collector of all data as a gateway [3]. Once data is received by ground control, a release command will be sent back to ARLO and MEOW to reset the volatile memory of the bits of data that were sent. During communication blackout events caused by space weather, data will be held within PURR until it can send link data to ARLO or MEOW. PURR will communicate with both ARLO and MEOW via RF and optical links. PURR will contain a deep space transponder and utilize two fixed X-band patch antennas on each side of its body and the navigation attitude system will adjust PURR for antenna positioning [14],[29]. Upon PURR's final moments of exploring the asteroid belt and transforming into a Laser Retroreflector, an EoL shutdown data protocol transmission will be sent to ARLO and MEOW for ground control relay and confirmation that PURR's mission has ended [36].

E. Electrical Power, Propulsion, and Thermal Control Systems

1. Electrical Power Production

Table 1 below shows the overall power consumption of each component, which is a sum of the more detailed tables 5 through 8 located within the Appendix. The power needs were generated with a 20% margin, which accounts for uncertainties in the power requirements of unproven technologies and for decays in efficiency. It's noteworthy that these figures represent maximum power needs when all components are active, though actual power consumption may vary depending on the operational status of specific components.

Table 1 Total Power Requirements

Component	**Total Power +20(%). Margin (kW)**	**Total Element Power Consumption Per Day (kWh)**
PURR	0.621352	14.912448
MEOW	136.508776	3276.21
ARLO	0.540496	12.97

Dual power systems were chosen for the ARLO, MEOW, and PURR for redundancy. The power requirements for ARLO will be met by 3 Radioisotope Thermoelectric Generators (RTGs), each providing 250 watts [21] and Solar Panels. The power requirements for MEOW will be met using the SAFE-400 space fission reactor (Safe Affordable Fission Engine) in combination with Solar Panels. The SAFE-400 provides thermal heat and 100 kWe [37]. The power requirements for PURR will be provided by a NanoDiamond Battery and Solar Panels. Each Nanodiamond cell provides 0.0001736 W [1], therefore, 3,579,217 cells would need to be provided to build a nanoDiamond battery that will be able to meet the Power need. The volume that this would use is .17896 m^3.

2. Propulsion Systems

For the ARLO, MEOW, and PURR, scaled versions of Hall Thrusters will be utilized for propulsion. In addition, ARLO and PURR will also utilize solar sails whenever possible to conserve fuel and provide redundancy within the systems. To get PURR off of Ceres and out of its gravitational field, it will be launched into space using the technology from the Mars Ascent System, more specifically the Mars Ascent Vehicle, which contains a two-stage solid motor vehicle, Pyrotechnic stage separation, electrical-mechanical thrust vector control, and monopropellant reaction control System with orbital trim capability [42]. Once out of the gravitational field, PURR will be released and sent on its way to make observations of another asteroid. It is important to note that there is promising research being done with Vaporizing Liquid Microthrusters (VLMs) that utilize water as fuel. Water is an ideal fuel for PURR since it is available within the asteroid belt and is less at risk for toxicity, flammability, and volatility [16]. The reason why this technology was not chosen for this mission is due to a lack of research available that involves the VLMs traveling long distances, such as the hundreds of thousands of miles between asteroids.

3. Thermal Control Systems

ARLO, MEOW, and PURR, will need sufficient protection from Ceres' cold temperatures. For each, they will be utilizing a combination of active and passive systems. Louvers are installed, covering the radiator area. The louvers are fully closed at +10C to prevent excessive loss of heat, and they are fully opened at +30C for full radiation of heat into space. Heat pipes will also be used along with many heaters and temperature sensors. The tanks and propellant lines are lined with heaters and wrapped in Multi-layer Insulation to keep propellants from freezing[8].

V. Cost and Risk Analysis

A. Mass Budget and Cost Analysis

The CHONK mission's mass budget accounts for a total estimated system mass of 5 metric tons (mt), incorporating Design Maturity Margins (DMMs) to accommodate uncertainties (5% for Off-The-Shelf or OTS, 10% for OTS with slight modifications, and 20% for in-house designed components) inherent in component weight estimations. This approach ensures a robust and resilient design framework, critical for the complex operational environment of deep space missions. The mass estimation includes comprehensive allocations for all mission-critical components, underlining the mission's strategic emphasis on precision and reliability in design planning.

The life cycle cost for the CHONK mission, spanning from 2028 to 2042, is calculated at $1.82 billion. This figure was derived through a detailed analysis of each subsystem's mass, technology readiness levels (TRLs), and associated development, manufacturing, and operational costs. Utilizing a combination of cost estimation models and in-depth market research, the mission team has ensured that the cost analysis reflects both the complexity of deep space exploration and the innovative approaches aimed at cost efficiency and mission sustainability.

B. Risk Analysis

CHONK's risk management strategy extensively incorporates redundancies across critical systems to mitigate the risk of single-point failures. This approach ensures operational resilience by allowing the mission to continue even if a primary component fails. Redundancies are implemented in key areas such as communication links, propulsion systems, and scientific instruments, complemented by rigorous testing campaigns to validate their effectiveness. This layered safeguarding technique is a fundamental aspect of the mission's design, emphasizing the importance of reliability and safety in the challenging environment of deep space.

VI. Conclusion

The CHONK mission encapsulates a bold step forward in deep-space exploration, targeting Ceres to harness the asteroid belt's resources. By integrating AI and self-replicating technologies, it not only aims to deepen our understanding of the cosmos but also to establish a groundbreaking model for autonomous, sustainable exploration. This mission paves the way for future endeavors, leveraging innovative solutions to overcome the challenges of space resource utilization. CHONK stands as a testament to human ingenuity, marking a significant milestone in our quest to extend the reach of civilization beyond Earth.

References

[1] *'Diamond-age' of power generation as nuclear batteries developed*. bristol.ac.uk. URL: `https://www.bristol.ac.uk/cabot/what-we-do/diamond-batteries/`.

[2] *About us - KP Labs KP Labs is a NewSpace company*. Aug. 2022. URL: `https://kplabs.space/about-us/`.

[3] European Space Agency. *Architectures of onboard data systems*. European Space Agency. URL: `https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Onboard_Computers_and_Data_Handling/Architectures_of_Onboard_Data_Systems`.

[4] Zacny et al. "TRIDENT Drill for VIPER and PRIME1 Missions to the Moon". In: (2022). URL: `https://www.hou.usra.edu/meetings/lpsc2022/pdf/1068.pdf`.

[5] *Antelope - KP Labs Onboard computer*. Sept. 2023. URL: `https://kplabs.space/antelope/`.

[6] AstroPI. "AstroPi [Online]". In: (n.d.). URL: `https://astro-pi.org/`.

[7] Philip J. Baldwin et al. *NASA's evolving Ka-band network capabilities to meet mission demand*. ntrs.nasa.gov, Oct. 2022. URL: `https://ntrs.nasa.gov/citations/20220013867` (visited on 02/27/2024).

[8] Charles Brown. "Elements of Spacecraft Design". In: (2002), pp. 373–380.

[9] Nacer Chahat et al. "Advanced CubeSat Antennas for Deep Space and Earth Science Missions: A review". In: *IEEE Antennas and Propagation Magazine* 61 (Oct. 2019), pp. 37–46. DOI: `10.1109/map.2019.2932608`. URL: `https://pureadmin.qub.ac.uk/ws/files/174234474/IEEE_Magazine.pdf` (visited on 03/22/2023).

[10] Y. Chen, J. Ni, and Y. C. Ong. "Lotka–Volterra models for extraterrestrial self-replicating probes". In: *The European Physical Journal Plus* 137.10 (2022). URL: `https://doi.org/10.1140/epjp/s13360-022-03320-3`.

[11] S. Chien et al. "The future of AI in space". In: *IEEE Intelligent Systems* 21.4 (2006), pp. 64–69. URL: `https://doi.org/10.1109/mis.2006.79`.

[12] R. Doyle et al. "Recent research and development activities on space robotics and AI". In: *Advanced Robotics* 35.21-22 (2021), pp. 1244–1264. URL: `https://doi.org/10.1080/01691864.2021.1978861`.

[13] A. Ellery. "How to build a biological machine using engineering materials and methods". In: *Biomimetics* 5.3 (2020), p. 35. URL: `https://doi.org/10.3390/biomimetics5030035`.

[14] EnduroSat. *X-band patch antenna - CubeSat antenna*. CubeSat by EnduroSat. URL: `https://www.endurosat.com/cubesat-store/cubesat-antennas/x-band-patch-antenna/`.

[15] A. Fallahi. *RF-Based Triangulation System*. Tech. rep. California State University, Northridge, May 2010. URL: `https://scholarworks.calstate.edu/downloads/r494vq45h`.

[16] Gianine Figliozzi. "NASA CubeSat to Demonstrate Water-Fueled Moves in Space". In: (Jan. 2021). URL: `https://www.nasa.gov/centers-and-facilities/ames/nasa-cubesat-to-demonstrate-water-fueled-moves-in-space/`.

[17] M. M. Finckenor. *Materials for Spacecraft*. Tech. rep. NASA Technical Reports Server (NTRS), 2016. URL: `https://ntrs.nasa.gov/api/citations/20160013391/downloads/20160013391.pdf`.

[18] *Flexible Storage Solutions for Human Spaceflight Activities*. European Space Agency. URL: `https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/Flexible_Storage_Solutions_for_Human_Spaceflight_Activities%20`.

[19] G. Furano, A. Tavoularis, and M. Rovatti. "AI in space: applications examples and challenges". In: *IEEE Xplore* (2020). URL: `https://doi.org/10.1109/dft50435.2020.9250908`.

[20] Y. Gao, K. Liang, and X. Ren. "Architecture and strategy of the Intelligent Hybrid Autonomous System for complex mixed spacecraft". In: *Journal of Physics* 1682 (2020), p. 012038. URL: `https://doi.org/10.1088/1742-6596/1682/1/012038`.

[21] *General Purpose Heat Source*. NASA.gov. URL: `https://rps.nasa.gov/power-and-thermal-systems/thermal-systems/general-purpose-heat-source/`.

[22] F. Giacoma and G. Giordano. "Additive manufacturing demonstration technology mission for lunar application". In: (2023). URL: `https://doi.org/10.1109/METROAEROSPACE57412.2023.10189930`.

[23] GITAI. *Inchworm Robot | GITAI*. Sept. 2023. URL: `https://gitai.tech/inchworm-robot/`.

[24] A. M. A. El-Hameed, Y. A. Abdel-Aziz, and F. S. El-Tokhy. "Anodic coating characteristics of different aluminum alloys for spacecraft materials applications". In: *SCIRP* (Feb. 6, 2017). URL: `https://www.scirp.org/journal/paperinformation.aspx?paperid=73992`.

[25] Hiwonder. *Hiwonder ArmPi FPV AI Vision Raspberry Pi ROS Robotic Arm with Python*. URL: `https://www.hiwonder.com/products/armpi-fpv?variant=40123331412055`.

[26] *HPE Apollo 2000 Gen10 Plus System*. Feb. 2023. URL: `https://www.hpe.com/psnow/doc/a00056110enw.pdf?jumpid=in_pdp-psnow-qs`.

[27] A. Jones and J. Straub. "Simulation and analysis of Self-Replicating robot Decision-Making Systems". In: *Computers* 10.1 (2021), p. 9. URL: `https://doi.org/10.3390/computers10010009`.

[28] Jet Propulsion Laboratory. *Mystery solved: Bright areas on Ceres come from salty water below*. National Aeronautics and Space Administration, Aug. 2020. URL: `https://www.nasa.gov/centers-and-facilities/jpl/mystery-solved-bright-areas-on-ceres-come-from-salty-water-below/`.

[29] NASA Jet Propulsion Laboratory. "Iris Radio (Deep-space radio for CubeSat missions)". In: (2017).

[30] NASA Jet Propulsion Laboratory. *Planetary Data System: Catalog Page for PIA20353*. Mar. 2016. URL: `https://photojournal.jpl.nasa.gov/target/ceres?subselect=Instrument%3AGamma+Ray+Spectrometer+Suite%3A`.

[31] M. E. Landis et al. "Conditions for Sublimating Water Ice to Supply Ceres' Exosphere". In: *Journal of Geophysical Research: Planets* 122 (Oct. 2017), pp. 1984–1995. DOI: `10.1002/2017je005335`.

[32] M. L. Litvak et al. "Luna – 25 robotic arm: Results of experiment with analog of lunar regolith in lunar like conditions". In: *Acta Astronautica* 200 (2022), pp. 282–290. URL: `https://doi.org/10.1016/j.actaastro.2022.08.003`.

[33] Catherine G. Manning and Katherine Schauer. *Optical Communications - NASA*. NASA.gov, Sept. 2023. URL: `https://www.nasa.gov/technology/space-comms/optical-communications-overview/#section-3`.

[34] G. L. Matloff. "Von Neumann probes: rationale, propulsion, interstellar transfer timing". In: *International Journal of Astrobiology* 21.4 (2022), pp. 205–211. DOI: `10.1017/S1473550422000027`. URL: `https://doi.org/10.1017/S1473550422000027`.

[35] E. Miller, C. Heistand, and D. Mishra. "Space-operating Linux: An Operating System for Computer Vision on Commercial-Grade Equipment in LEO". In: *IEEE Xplore* (Apr. 2023). URL: `https://ieeexplore.ieee.org/abstract/document/10115703`.

[36] NASA. "Retroreflectors: From Apollo to Mars". In: (Sept. 2020). URL: `https://www.nasa.gov/image-article/retroreflectors-from-apollo-mars/`.

[37] *Nuclear Reactors and Radioisotopes for Space*. world-nuclear.org, 2021. URL: `https://world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-reactors-for-space.aspx`.

[38] Paul A. Oche, Gideon A. Ewa, and Nwanneka Ibekwe. "Applications and challenges of artificial intelligence in space missions". In: *IEEE Access* (Jan. 2021), p. 1. DOI: `10.1109/access.2021.3132500`. URL: `https://doi.org/10.1109/access.2021.3132500`.

[39] T. E. Oliphant. "Python for Scientific Computing". In: *Computing in Science & Engineering* 9.3 (May 2007), pp. 10–20. DOI: `10.1109/MCSE.2007.58`.

[40] J. Palmer. *ESA's InCubed-Enabled satellites MANTIS and Intuition-1 launched: a leap for AI in space*. Nov. 2023. URL: `https://www.msn.com/en-us/news/technology/esa-s-incubed-enabled-satellites-mantis-and-intuition-1-launched-a-leap-for-ai-in-space/ar-AA1jQLq4`.

[41] *PC104 Consortium Home - PC/104 Consortium*. Jan. 2024. URL: `https://pc104.org/`.

[42] Tara. Polsgrove et al. *Mars Ascent Vehicle Design for Human Exploration*. National Aeronautics and Space Administration, Aug. 2015.

[43] A. Russo and G. Lax. "Using Artificial Intelligence for Space Challenges: A Survey". In: *Applied Sciences* 12.10 (2022), p. 5106. URL: `https://doi.org/10.3390/app12105106`.

[44] Marianne Vang Ryde. "Sensitive instruments to explore metal-rich asteroid". In: (Oct. 2023). URL: `https://phys.org/news/2023-10-sensitive-instruments-explore-metal-rich-asteroid.html`.

[45] L. Sanders et al. "Biological Research and Self-Driving Labs in Deep Space Supported by Artificial Intelligence". In: *Nature Machine Intelligence* 5.3 (2023), pp. 208–219. URL: `https://doi.org/10.1038/s42256-023-00618-4`.

[46] J. E. C. Scully et al. "The In Situ Exploration of a Relict Ocean World: An Assessment of Potential Landing and Sampling Sites for a Future Mission to the Surface of Ceres". In: *The Planetary Science Journal* 2.3 (May 2021), p. 94. DOI: `10.3847/psj/abee28`. URL: `https://doi.org/10.3847/psj/abee28`.

[47] A. Trunek. "Extraction of Water from Martian Regolith Simulant via Open Reactor Concept". In: (2018). URL: `https://ntrs.nasa.gov/api/citations/20180002377/downloads/20180002377.pdf`.

[48] Isaac Asimov's Universe. *A speech given by Isaac Asimov at Rutgers University*. Isaac Asimov's Universe, Oct. 2009. URL: `https://isaacasimovs.wordpress.com/category/isaac-talks-about/`.

[49] Wikipedia contributors. *Self-Replicating Machines in Fiction*. Oct. 2023.

[50] Xinchang Zhang et al. "Integrating fiber optic sensors into metallic components for sensing in harsh environments". In: *Optics and Laser Technology* 170 (Mar. 2024), pp. 110188–110188. DOI: `10.1016/j.optlastec.2023.110188`.

Appendix A

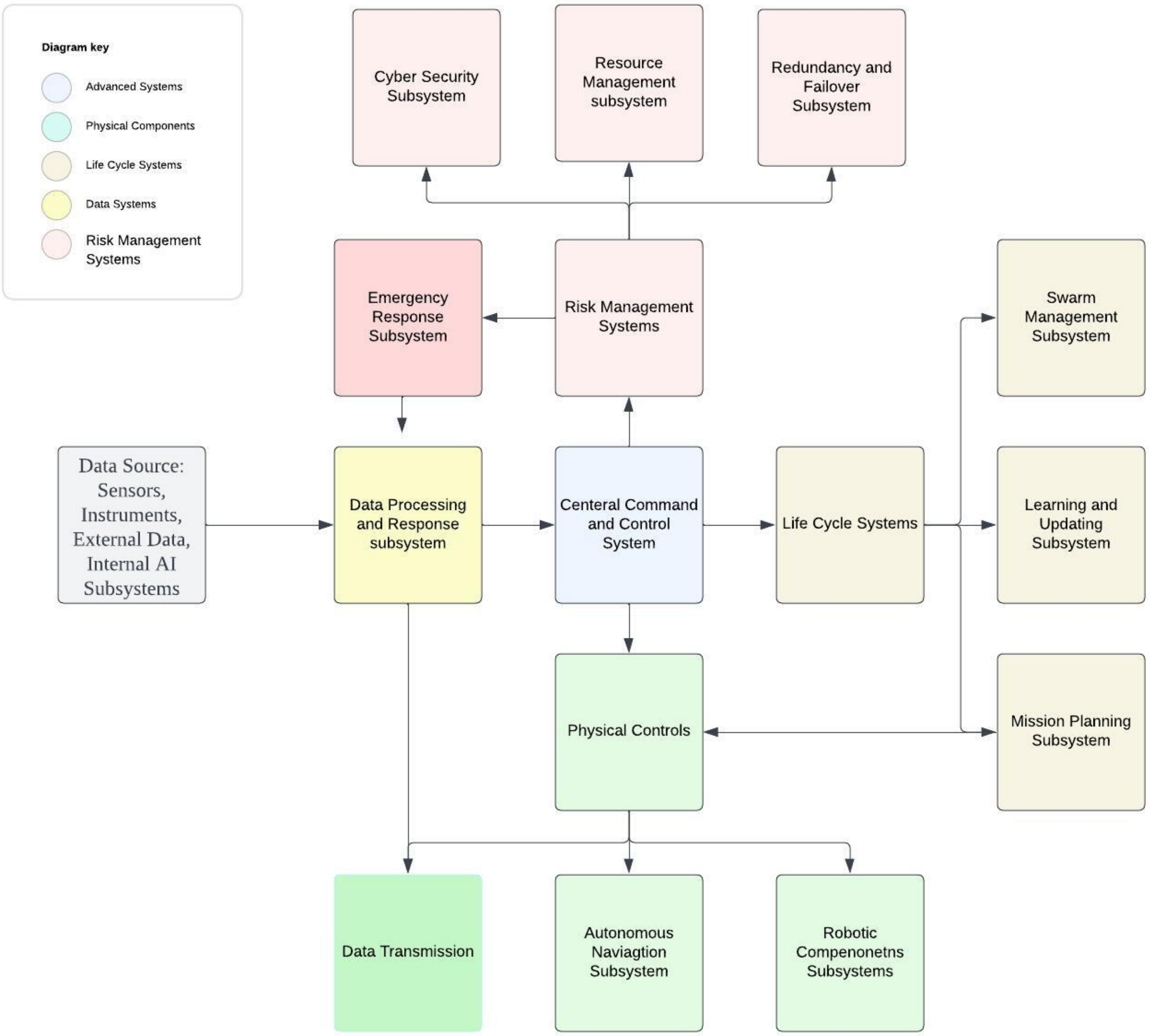


Fig. 4 System Architecture and Hierarchy of IDLERS Subsystems

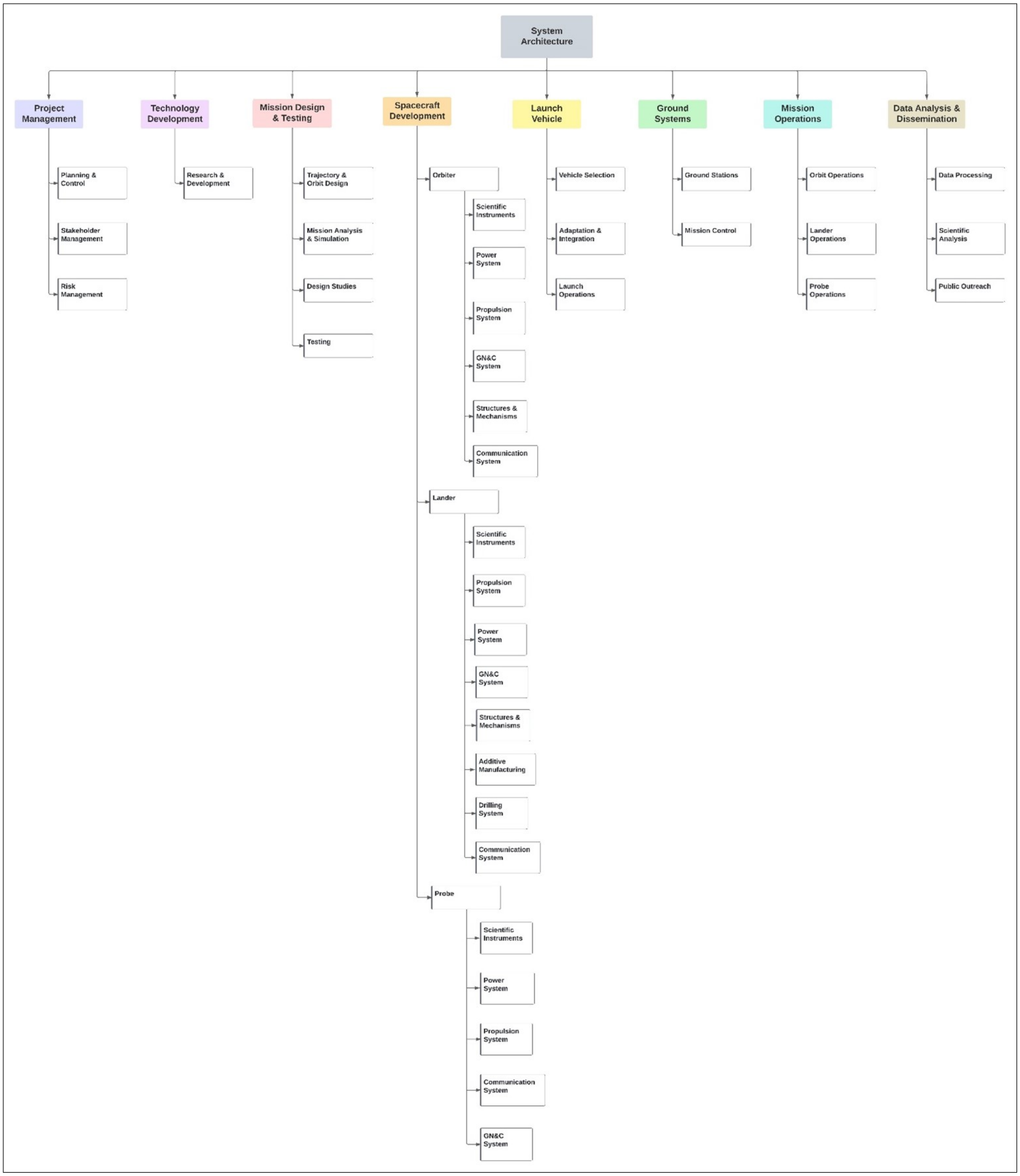
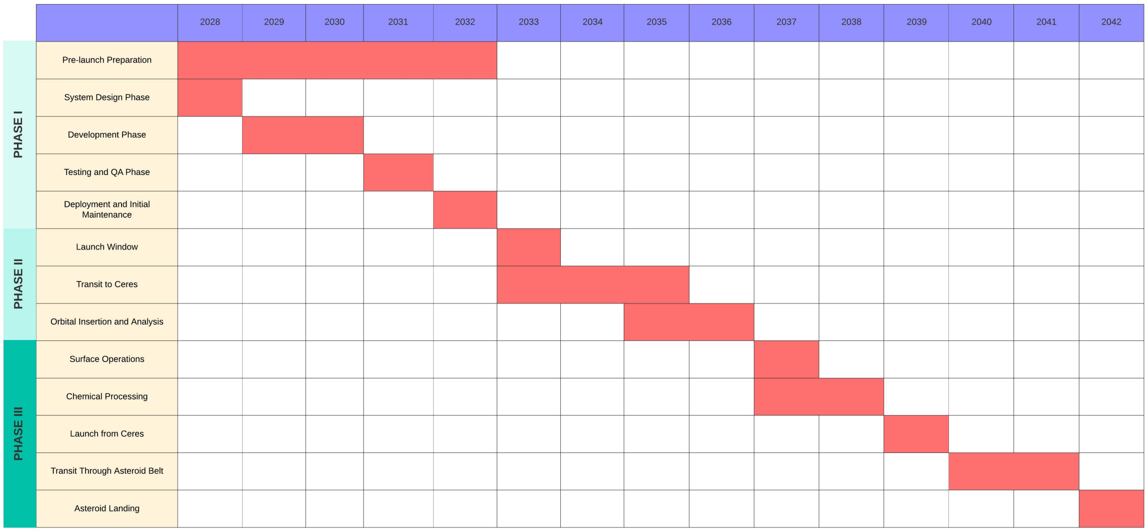


Fig. 2 CHONK WBS



		2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
PHASE I	Pre-launch Preparation	🟥	🟥	🟥	🟥	🟥										
	System Design Phase	🟥														
	Development Phase		🟥	🟥												
	Testing and QA Phase				🟥											
	Deployment and Initial Maintenance					🟥										
PHASE II	Launch Window						🟥									
	Transit to Ceres						🟥	🟥	🟥							
	Orbital Insertion and Analysis								🟥	🟥						
PHASE III	Surface Operations										🟥					
	Chemical Processing										🟥	🟥				
	Launch from Ceres												🟥			
	Transit Through Asteroid Belt													🟥	🟥	
	Asteroid Landing															🟥

Fig. 3 CHONK - Mission Schedule

$$a_{HT} = \frac{r_2 + r_1}{2}$$

[1] – Semi-Major axis of Hohmann Transfer

$$V_{1A} = \sqrt{\frac{\mu_s}{r_1}}$$

[2] – Earth's speed relative to the Sun at (pt. A)

$$\mu_s = 1.37\ x\ 10^3\ [km^3 s^{-2}]$$

$$V_{ta} = \sqrt{\mu_s\left(\frac{2}{r_1} - \frac{1}{a_t}\right)}$$

[3] – Spacecraft's relative speed to the sun at Perihelion

$$V_{tb} = \sqrt{\mu_s\left(\frac{2}{r_2} - \frac{1}{a_t}\right)}$$

[4] – Spacecraft's relative speed to the sun at Aphelion

$$V_{2B} = \sqrt{\frac{\mu_s}{r_2}}$$

[5] – Ceres' relative speed to the Sun at (pt. B)

$$\Delta V_A = |V_{ta} - V_{1A}| = V_\infty^+$$

[6] – Spacecraft's speed relative to the earth's SOI boundary

$$\Delta V_B = |V_{2B} - V_{tB}| = V_\infty^-$$

[7] – Spacecraft's speed relative to Ceres at Ceres' SOI. V_∞ is the Hyperbolic Excess speed (+ for exiting, – for approaching)

$$T_{HT} = \pi\sqrt{\frac{a_{HT}^3}{\mu_s}}$$

[8] – Heliocentric Hohmann Transfer time in years

$$V_{esc} = \sqrt{\frac{2\mu_E}{r_p}}$$

[9] - General formula for escape velocity for body with radius (r_p), where $\mu_1 = 3.986\ x\ 10^5\ [km^3 s^{-2}]$

$$V_{b,1} = \sqrt{(V_\infty^+)^2 + (V_{esc}^2)}$$

[10] – Burn velocity initiating Transfer Orbit (pt. A)

$$V_{LEO} = \sqrt{\frac{\mu_E}{r_{LEO}}}$$

[11] – Velocity of Low Earth Orbit [r_{LEO}~r_p]

$$\Delta V_1 = V_{b,1} - V_{LEO}$$

[12] – Delta-V needed to find mass of propellant for 1st maneuver

$$V_{b,2} = \sqrt{(V_\infty^-)^2 + (V_{esc}^2)}$$

[13] – Burn velocity to a Ceres Capture Orbit (Use [9] with Ceres' radius and $\mu_2 = 62.63\ [km^3 s^{-2}]$ for escape velocity)

$$\Delta V_2 = V_{b,2} - V_c$$

[14] – Delta-V needed to find mass of propellant for 2nd maneuver

$$V_c = \sqrt{\frac{\mu_2}{r_c}}$$

[15] – Velocity of Capture Orbit [r_c~r_p]

[Assumptions]

Solar System is Coplanar

Orbits of (e = 0), Circular

Fig. 5 Orbital Mechanics

Table 2 Requirements for High-Level Design for AI In Space

Requirement Title	**Requirement Description**	**Verification**	**Qualification Method**
Fully Autonomous	The AI design should be innovative, fully autonomous, requiring no human input.	Design AI Architecture Using the latest AI methods and means to develop sophisticated autonomous systems.	Analysis
Ethics and Containment	AI design should incorporate ethical and containment protocols to prevent unintended consequences or environmental impact.	Analysis of ethical guidelines, simulation of potential ethical scenarios, and demonstration through documented protocols and adherence to ethical standards.	Simulation
Computer, Hardware, and Storage	AI will need high-performance computer and data storage systems.	Minimally achievable components for system design.	Test
Navigation and Positioning	The AI should be capable of precise navigation and positioning within a specified margin of error, using onboard sensors and/or external references.	Analytical assessment of navigation algorithms, testing in controlled environments (simulations), and demonstration through real-world tests.	Analysis
Self-Replication	The AI should be able to start the self-replication process and install AI onto new probes.	AI should be able to replicate itself within a sandbox environment, and that AI should be to the same level of functionality as the first.	Simulation
Resource Management	AI integration should link to diverse spacecraft systems, overseeing power, fuel, and raw materials throughout the self-replication process to enhance efficiency and promote sustainability.	Analytical assessment of resource management algorithms, simulation of resource use in controlled environments, and demonstration through real-world resource management tests.	Demonstration

Table 3 Neural Network Usage in IDLERS Subsystems

Subsystem	Convolutional NN	Recurrent NN	Feedforward NN	Hybrid NN
Central Command and Control	✓		✓	
Communications		✓		✓
Swarm Management		✓		
Autonomous Navigation	✓			
Task Management			✓	
Resource Management				✓
Redundancy and Failover			✓	
Security		✓		
Adaptive Learning	✓	✓	✓	✓
Data Transmission				✓
Mission Planning			✓	
Emergency Response	✓			
Learning and Updating	✓	✓	✓	✓

Table 4 Hardware Requirements for AI in Space

Nomenclature	**Manufacturer**	**Power Requirements**	**Processor/Chip**	**Compatible Native Code**
Apollo 2000 Gen 10	HPE	> 250 Watts	2nd and 3rd Generation AMD EPYC 7000 Series Processors	C/C++, Python, R
BIZON ZX9000	Bizon-tech	> 240 Watts / > 360 Watts	AMD EPYC 7003-series and 9004-series	C/C++, Python, R
ThinkStation PX Workstation	Lenovo	Depends on Configuration	4th Gen Intel Xeon	C/C++, Python, R
NVIDIA Jetson Xavier	NVIDIA	Depends on Configuration	NVIDIA Jetson TX2i	Linux
Oryx	KP Labs Space	Depends on Configuration	RM57 Hercules Microcontroller	KP Labs, CMake, GCC, Python
Antelope + Data Processing Unit	KP Labs Space	Depends on Configuration	RM57 Hercules Microcontroller	KP Labs Oryx

Remarks:

- Power requirements are approximate values and may vary based on specific configurations.
- Compatibility with native code depends on software support and development environment.

Table 5 Structures and Mechanisms Power Consumption

Component	Element	Quantity	Unit Power (kW)	Total Power +20% Margin (kW)	Total Element Power Consumption Per Day (kWh)
MEOW	Drilling system	1	0.25	0.3	7.2
	Ascent Vehicle	1	8	9.6	230.4
	Water Distillation Reactors	1	83	99.6	2390.4
	Robot arms	1	10	12	288
	Additive Manufacturing Unit/3-D unit	1			
Total SM Power Consumption:				121.5	2916

Table 6 Autonomous Systems Power Consumption

Component	Element	Quantity	Unit Power (kW)	Total Power +20% Margin (kW)	Total Element Power Consumption Per Day (kWh)
MEOW	Computer	6	9	10.8	259.2
Total AS Power Consumption:				10.8	259.2

Table 7 Telemetry and Communication Power Consumption

Component	Element	Quantity	Unit Power (kW)	Total Power +20% Margin (kW)	Total Element Power Consumption Per Day (kWh)
ARLO	Optical antenna (MEOW, ARLO, & PURR)	1	1	1.2	28.8
MEOW		1			
PURR		1			
ARLO	RF X Band HGA + gimbal (MEOW, ARLO, & PURR)	1			
MEOW		1			
PURR		1			
MEOW	MEOW contingent LGA	1			
ARLO	OBC + Data Storage	1			
MEOW		1			
PURR		1			
Total TC Power Consumption:				1.2	28.8

Table 8 Scientific Instruments Power Consumption

Component	Element	Quantity	Unit Power (kW)	Total Power +20% Margin (kW)	Total Element Power Consumption Per Day (kWh)
PURR	Mutispectral, hyperspectral, thermal, imaging cameras	5	0.0118	0.0708	1.6992
MEOW		7	0.0118	0.09912	2.37888
ARLO		3	0.006	0.0216	0.5184
PURR	Gamma-Ray detectors and radiation sensors	4	0.015	0.072	1.728
MEOW		2	0.015	0.036	0.864
ARLO		3	0.015	0.054	1.296
PURR	Magnetometer	1	0.015	0.018	0.432
MEOW		0	0.015	0	0
ARLO		1	0.015	0.018	0.432
PURR	Space dust analyzers	1	0.01138	0.013656	0.327744
MEOW		0	0.011	0	0
ARLO		1	0.01138	0.013656	0.327744
PURR	Dust particle analyzers	1	0.01138	0.013656	0.327744
MEOW		1	0.01138	0.013656	0.327744
ARLO		0	0.01138	0	0
PURR	Seismometer	0	0.05	0	0
MEOW		1	0.05	0.06	1.44
ARLO		0	0.05	0	0
PURR	Ion Microprobe (SIMS)	0	3	0	0
MEOW		1	3	3.6	86.4
ARLO		0	3	0	0
PURR	Ion-Neutral Mass Spectrometer (INMS)	1	0.0277	0.03324	0.79776
MEOW		0	0.0277	0	0
ARLO		1	0.0277	0.03324	0.79776
Total SI Power Consumption:				4.170624	100.094976

Acknowledgments

As we reflect on the journey of our research, it is imperative to acknowledge Cody Shepard for his unwavering support and unique insights that have been indispensable. Alongside Cody, we are immensely thankful to Paul Thompson for lending his time and expertise out of passion for his craft. We express our sincere gratitude to Enrico Bassissi, Pasquale Castellano, Vittorio Baraldi, and Sotiris Zormpas, whose knowledge and support have been pivotal in bringing our project to fruition. Lastly, we thank Dr. Burak Cankaya for his support and dedication throughout this endeavor. We deeply appreciate the time and effort he invested in our project.

Conflicts of Interest

In addressing the potential conflict of interest, it's noted that Logan Innes may have a stake in the selection of components by AMD made by the team. While the components chosen may include products from a company in which he has invested, it's essential to clarify that he had no involvement in the decision-making process. The team underscores the significance of upholding impartiality and integrity in decision-making, prioritizing technical merits and project requirements above all else. Logan Innes' investment played no role in the team's independent decision-making process.