# MAERAL: Scalable, Versatile & Intelligent Swarm Robotic Concept for Mars Surface Operations

by
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## DEDICATION

To George Kalisse, my best friend and better half, without your support and all-embracing encouragement, none of this would have been possible.

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## ABSTRACT

Future human exploration missions to Mars are partially Earth-dependent. The inherent risk and complexity of these missions warrant precursor robotic systems to prepare infrastructure critical to the survival of humans before their arrival. At a minimum, they are required to autonomously deploy, test, and verify systems for essential commodities and life-support (such as power sources, ISRU plants, and thermal control), set up a habitat, and even distribute connections. Once humans arrive, robotic systems are still required to assist humans during their stay and later maintain operations after their departure.

The undertaking of robotically setting up an outpost requires numerous and consecutive missions that build on top of one another. Therefore, precursor robotic systems need to be versatile, robust, modular, scalable, upgradeable, affordable to engineer and produce, autonomous, and intelligent, all the while resilient and adaptive to extreme environments and the high risk of such mission.

However, humanity has built its experience in planetary exploration on standalone unmanned scientific missions. These missions have predefined objectives so far accomplished using rovers operating onboard scientific instruments while traversing harsh terrain. Current robotic systems are highly specialized, non-modular, has no integration capabilities, are expensive, have limited resilience, are non-adaptive, and require constant supervision. Current planetary robotic systems cannot scale up to fulfill prerequisites of future precursor missions.

In this paper, I explore how to transition from the current state of practice to next-generation robotic systems. I describe and assess the methodologies used to design current systems and demonstrate how a complete rethinking of these methodologies is fundamental to generating efficient and feasible systems.

I culminate this research by proposing an alternative to the design process and demonstrate the new methodology by introducing MAERAL, a research by design concept of scalable, versatile, and intelligent swarm robots for future Mars surface operation missions. It combines concepts in modularity, standardization, machine learning, and collective intelligence to accomplish complex activities using simple basic actions. The vision of this research is to prolong and sustain our space-faring future by making space exploration more accessible, more innovative, more feasible, more efficient, more continuous, and more sustainable.

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## LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| *MAERAL* | = Modular Autonomous Evolvable Robot et al. |
| *AI* | = Artificial Intelligence |
| *BUA* | = Bottom-Up Approach |
| *BLSS* | = Biological Life Support Systems |
| *ConOps* | = Concept of Operation |
| *DOT* | = Destination Operations Team |
| *DRA* | = Design Reference Architecture |
| *DRM* | = Design Reference Mission |
| *EAE* | = Embodied Artificial Evolution |
| *ECLSS* | = Environmental Control and Life Support Systems |
| *EDL* | = Entry, Descent, and Landing |
| *EVA* | = Extravehicular Activity |
| *FFBD* | = Functional Flow Block Diagram |
| *FSP* | = Fission Surface Power |
| *HAT* | = Human Spaceflight Architecture Team |
| *ISRU* | = In-Situ Resource Utilization |
| *ISS* | = International Space Station |
| *LEO* | = Low Earth Orbit |
| *MAV* | = Mars Ascent Vehicle |
| *PPA* | = Plug-and-Play Architecture |

# I. THESIS PRELIMINARIES

Fascination with Mars goes back centuries. Ever since the butterscotch-colored planet appeared in Galileo's telescope in the 1600s [1], we were captivated. We wrote novels, produced movies, and visualized the concepts that paved the way for current scientific and technological advancement. We dream one day to become a space-faring civilization. We envision humanity at its finest, living and thriving on a planet so close yet so far away.

Our visions depict Mars as tranquil, picturesque, and hospitable. Mars, after all, is dubbed a sibling to Earth because of the similarities the two planets share. Earth and Mars both have polar caps, the same land surface area, similar tilts in their rotational axis, and similar geological features. One Martian sol is only even 40 minutes longer than an Earth day. Of all the planets in the solar system, Mars remains the most suitable for consideration as a future home.

However, the differences far exceed the similarities. The atmosphere is unbreathable, and the soil is toxic. The levels of radiation are very high, and the partial gravity causes loss of muscle mass and bone density, compromises the immune system, and increases the chance for cardiovascular diseases [2]. Humans are squishy, and Mars is dangerous. Therefore, the decision to send humans on an 8-month trajectory, to a planet a hundred-million miles away, while crammed inside the tip of a rocket, hinges on the success of prerequisites critical for the survival of humans.

The journey to Mars is an undertaking that is fundamentally different from any space exploration we have done since the beginning of the space exploration. It is a much higher threshold to cross that any earlier endeavor; it is a partial-Earth dependent mission.

A lunar landing, the farthest any human has ever traveled, was a full Earth-dependent mission. While on the surface, there was no dependability on the Lunar surface, the crew had supplies from Earth to last the entire duration of the mission, which was measured in days [3]. The crew landed, explored, and returned home. Although our knowledge in space exploration was still at the beginning, we still were able to account for high-risk mitigation strategies that allowed the crew to abort in case of an emergency and be home in just a few days.

Unlike the Apollo missions, a journey to Mars is a partial Earth-dependent mission. While on Mars, dependability on the surface is not only necessary for survival but is inevitable. The shortest surface-stay anticipated on Mars is around 60 days, while the longest surface-stay is 500 days. In both scenarios, we need to establish critical infrastructure before human arrives. Paired with the uncertainty of how long the crew might require acclimating and be able to resume operations, the undertaking becomes more risk for humans.

Building upon decades of research, NASA established a thorough understanding of the challenges and the complexity of going to Mars. The levels of technological advancement, redundancies, and crew safety required for such a mission is an order of magnitude higher than what we have ever developed for a lunar landing.

The inherent complexity of a partial-Earth dependent mission requires a strategy where infrastructure is autonomously deployed and is successful way before the arrival of humans. In fact, according to NASA's Design Reference Architecture 5.0 [4] and The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities [5], the decision to send humans hinges on the success of these precursor robotic missions.

Building an outpost for a future mission to Mars requires that these robotic systems have the capabilities to accomplish complex objectives. These objectives are fundamentally different from the current scientific objectives accomplished by current rovers. Scientific exploration encompasses the design of rovers that are capable of operating onboard scientific instruments and tools while traversing harsh terrain. However, precursor robotic missions preceding human exploration constitute surface operation objectives that require a fleet of versatile robotic systems to achieve.

From deployment of power source (and its backups) and ISRU plants (to produce oxygen necessary for breathing and fuel for a return vehicle) to setting-up a habitat and distribution of connections, precursor robots have a lot to achieve. They need to perform compound and complex behaviors and have characteristics not yet achieved by any current robotic systems.

The inherent complexity and high risk of these missions, paired with constraints in launch and landed payload mass, also requires a new level of high reliability. Reliability that is less about redundancies and more about resilience and adaptability. Reliability that can be achieved by affording to execute numerous and consecutive missions to allow for continuous testing of systems for unpredictability and failure. The complexity also warrants integration of missions within each other. It is important that these robotic systems continue to build on one another, be scalable, and evolve as the mission's requirements inevitably changes with time.

**What we need**

Based on the above, the next-generation robotic systems intended for surface operations will need to be versatile, robust, adaptive, affordable to engineer and produce, scalable, upgradeable, and intelligent, all the while resilient to harsh terrain and extreme environment. They need to respond and interact with the surroundings to find multiple solutions to the same problem. They need to be affordable because if all resilient and adaptive strategies fail, they can be exploited. Next-generation robotic systems need to be bio-inspired in their system engineering and their emerging behaviors and patters.

**Gaps in Knowledge**

The problem is, however, all that we need to do for Mars does not align with our experience in planetary robotic exploration. Since the 1950s, space exploration has been specialized and scientific. Also, except for Apollo and ISS, all space exploration has been conducted by customized rovers, telescopes, and probes engineered to answer particular questions and do very few tasks.

To demonstrate, if we take a look at all Mars landers, which have been in development since the beginning of Mars exploration, they have been engineered to perform two main activities. They operate state-of-the-art scientific instruments and tools while traversing harsh terrain. From the 1975 Viking 2 to the Mars 2020 Rover, lunar and planetary exploration has been aimed at answering scientific questions through standalone missions.

Whether flybys, orbiters, or landers, the capabilities of these custom robots match the requirements set forth by the mission at the design phase. They are scientific labs on wheels. They follow a scripted concept of operations and are supervised continuously from Earth, which makes them highly specialized and non-modular. It takes a long time to design and to engineer them, which also makes them expensive to produce. Moreover, they have limited resilience and no adaptability. They are only reliable to the degree necessary to carry out a defined short-duration mission with a predefined set of exploration objectives.

**Thesis Problem:**

Current rovers and planetary robotic systems designed for scientific exploration cannot scale up or fulfill the requirements for the future autonomous robotic operation missions.

However, the above remains a problem that can only be solved when we address the root problem. The process currently used to design and engineer current rovers will always generate the same highly specialized non-adaptive systems that are inefficient, economically unfeasible, and obstructs the longevity and continuity of missions.

**Thesis Question:**

The main focus of this research is to explore the transition from the current state of practice in designing robotic systems for scientific exploration to next-generation robotic systems for planetary surface operations. This research will address how to transition from designing for complexity to designing for simplicity that can in itself generate the complexity.

This is a new future that  to transition from the current state of practice in designing expensive, highly specialized, non-adaptive robotic systems intended for scientific un-crewed exploration to next-generation robotic systems that are adaptive, resilient, versatile, scalable and intelligent that can fulfill the requirements of precursor robotic missions preceding human planetary exploration.

**Thesis Proposal**

In my thesis, I have two main goals. The first is to propose an alternative and a rethinking to the current adopted and legacy methodologies and practices used to design planetary robotic systems. The second is to demonstrate this new methodology by introducing MAERAL, a design concept that puts the methodology into practice. MAERAL is a design of scalable, versatile, and intelligent swarm robotic concepts for future Mars surface operation missions preceding human exploration. It encompasses concepts in modularity, standardization, machine learning, and collective intelligence to accomplish complex activities using simple basic actions and modular standard capabilities.

**Thesis Vision**

MAERAL is more than a design of a modular, autonomous, and evolvable robot; it is a holistic rethinking to legacy methodologies. MAERAL is to prolong and sustain our space-faring future by making space exploration more accessible, more feasible, more efficient, and more continuous.

**Thesis Hypothesis:**

A transition from the current state of practice of rovers to next-generation robotic systems is only possible by a complete rethinking to adopted legacy methodologies used to design and plan for robotic systems. While these methodologies generate reliable and successful systems, they follow a hierarchal centralized process that has more limitations on long-term space exploration. The immediate benefits gained from following this approach hinders progress and adds constraints that can interrupt longevity of a space program.

Decentralizing the design methodologies by learning from other industries, incorporating concepts in modularity and standardization, and harnessing the power of machine learning and collective swarm intelligence is the way to make space exploration more economically feasible, and therefore accessible. Only a real economy of scale can pave the way to innovation, sustainability, and longevity.

## Approach/Methodology

The methodology I used to arrive at a resolution to my thesis question, follow three stages:

(1) The first is to examine and assess the current legacy methodology used in the design of robotic systems intended for planetary exploration missions.

(2) The second is to introduce MAERAL, a rethinking to the methodology and a design concept, through which I can expand on the alternative methodology I propose.

(3) The third is to demonstrate the capability of the new methodology and MAERAL by executing a complex operations activity.

## Research Scope/Out of Scope

MAERAL is a before being a design concept is a methodology and a rethinking to an existing way of thought. MAERAL, as a methodology and a design concept, is not an encompassing solution. It is a research by design concept, intended as a foundation for future research. It requires collaboration and integration of all disciplines.

## Chapter Outline

Given the preliminaries above, I can now describe the general structure of what lies ahead.

Chapter II is an analysis of the current state of practice and adopted methodologies used in the design and planning of robotic systems for planetary exploration. I examine the attributes of such legacy methodologies and look into why these methodologies persisted to this day.

Chapter III is an introduction to MAERAL. I introduce the design concept, design drivers and design considerations that can pave the way for a decentralized approach.

Chapter IV is an exploration to decentralizing the methodologies through MAERAL. I look into how to achieve complexity through simplicity.

Chapter V is a demonstration of MAERAL applied to one major surface operation activity

Chapter VI is a conclusion to this thesis. I discuss opportunities and latitudes of adopting a new way of the thinking.

# II. NASA MISSION DESIGN AND PLANNING LEGACY[1]

Any NASA mission typically starts with a vision, mission statement, goals, and objectives. These overarching statements are critical because they define different aspects of a mission at a macro level as well as at a micro-level. They determine program functions, architectural requirements, the concept of operations, strategies, constraints, and even ensure meeting the stakeholders' expectations. A strong understanding of the Vision, Mission Statement, Goals, and Objectives is critical to the success of a mission. They direct the mission to ensure the original intent is met, and in the case of any ambiguity, they help to clarify the requirements [6].

## Hierarchal Centralized Approach

Figure 1 represents a simplified overview of NASA's mission formulation diagram, adapted from NASA System Engineering Handbook [6]. The Vision is the inspirational statement of the mission. A mission statement is an approach that can achieve the larger Vision in one or more aspects.

Goals are strategies on how to accomplish the mission statement while objectives are the specific tasks that will help achieve the goals.

A mission statement can have numerous goals, and each goal can be accomplished using several objectives.

[1] The chapter's title and is inspired by Malcolm Gladwell's Book "Outliers". In his book, Gladwell highlights the value of cultural legacies in shaping the world we live in. It is when we understand the legacies and how they have come to manifest that we are able to use them as a driving force for a change for success.

Moving downwards from one level to the next is moving deeper into the analysis of a mission. It is when we arrive at the objectives level that mission requirements and intent become more tangible and can be translated into a design reference mission, system and exploration architecture, concept of operations, which in turn are used to determine the requirements at a functional, elements, system, and subsystem level.

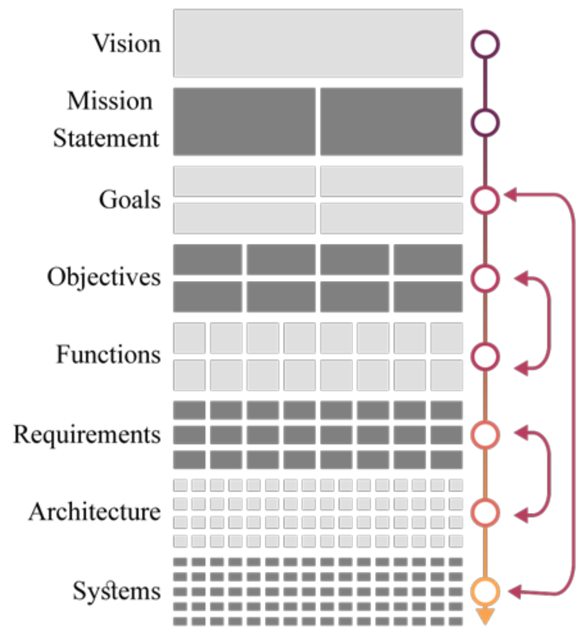

*Figure 1 Mission Formulation Flow Diagram*

The process might seem to be linear, but it is not. From mission announcement to mission execution, engineers and scientist go back and forth between the different levels to ensure that any elements still meet the objectives set forth at the beginning. Iterations are constant as more details, challenges, considerations, and constraints start to surface. But generally, the process follows a hierarchal direction with a centrality being the Vision, which determines the objectives.

This process is known as the Hierarchal Centralized Approach or (Top-Down Approach). It is one of two fundamental models for building robotic systems and intelligent machines [7] and is contrasting to the second model, which is the Decentralized Approach.

In a system's engineering context, a Hierarchal Centralized Approach in design is a process that begins with determining the functions required of a system, which in turn dictates the capabilities and requirements of the system.

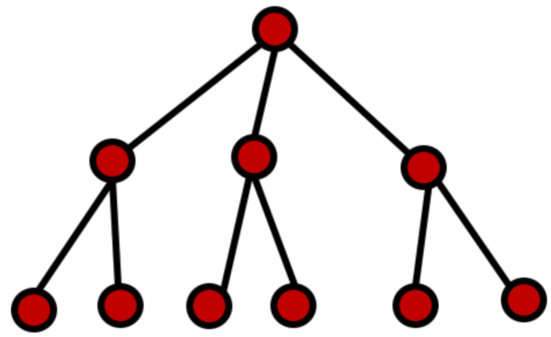

*Figure 2 Hierarchal-Centralized Approach (Top-Down Model)*

The more functions are required, the more capabilities are built into the system. A Vision, Mission Statement, Goals, and Objectives (VMGOs) as the primary inputs of the mission, determine the output at a system engineering level.

The hierarchy or the centrality of the approach means that the result is controlled at the outset of the process. The engineers and scientists, following the VMGOs set forth by the mission directive, decide what capabilities are required at the end and build a system architecture around it. The designed system has the physical and cognitive abilities built right into it [7]. Deviation from initial capability requirements beyond the design and planning phase is challenging since all the elements and systems are design in such a way to achieve a pre-determined set of actions to accomplish the objectives. Therefore, additions or modifications of requirements beyond the design and planning phase might mean a restart to the design phase to ensure that the added or modified requirements are integrated within the whole architecture.

**Case Study, Mars 2020 Rover**

Mars 2020 Rover, recently named “Perseverance”, is the latest of NASA’s state-of-the-art robotic technology for the exploration of Mars. Expected to launch in the summer of 2020, Mars 2020 Rover is an advanced robotic system designed to achieve four scientific objectives that are aligned with the goals, mission statement and vision of NASA’s Mars Exploration Program [8].

(1) Looking for Habitability

(2) Seeking Biosignatures

(3) Caching Samples

(4) Preparing for Humans

The four scientific objectives above are translated into 21 scientific instruments and tools onboard an autonomous planetary locomotive mobility system. Mars 2020 Rover is a moving scientific lab on wheels. It will be traversing the harsh terrain to seek answers on the habitable conditions of Mars, search for signs of past microbial life, and collect samples that might be retrieved in a future return mission to Mars [8]. Mars 2020 Rover I also an intelligent rover that can plan for and execute tasks and activities based on its understanding and interpretation of the data it collects [9].

The Mars 2020 Rover mission has a duration of at least one Mars year (around 687 Earth days), therefore, as part of fulfilling the initial VMGO’s, systems are designed for reliability as needed to last for a minimum of intended duration [8].

## Attributes of the Hierarchal Centralized Approach

Attributes of this approach fall under two main categories. The first is related to System Engineering aspects, and the second is related to the "Economic and Political" aspects.

## System Engineering Attributes

### Value of the mission = built-in requirements

A primary attribute of the centralized design process is that the value of the mission equals the built-in requirements within the system itself. This is a critical aspect of the process because it has an impact that spill can spill to other areas.

The preceding example of the Mars 2020 Rover is a good example that demonstrate this attribute. The value of the mission is the ability to achieve the four scientific objectives that support the program science goals. The functions performed by the rover and the tasks that can be executed using the scientific instruments are specialized tasks that can directly fulfill the objectives. We cannot expect the rover to have capabilities that exceed the initial system requirements set forth in the design phase. In simpler terms, what the rover is able to do is aligned with what the rover has been designed to do.

### Great for Specialization

A mission, especially an exploration mission, with a defined set of tasks and where the possibility of unpredictable events that lead to planning for contingencies is acceptable, then a top-down approach has proven to be, a reliable approach.

### Built-in redundancy (limited resilience and no adaptability)

Having predefined objectives and as a result, a predefined set of functions and systems reduces the complexity of the architecture and allows us to have a main system and a backup to deal with possible malfunctions.

The more complex the set of systems and the integration between them, the higher the risk of an unpredictable or unaccounted for failure occurring. Defining systems that can execute specific tasks based on objectives allows the engineers to predict points of failure. During the design phase, the vulnerability of the systems can be assessed and solutions to mitigate failure can be built right into the system.

A reduction in complexity by having specialized systems executing tasks is not only beneficial from a system-engineering and redundancy perspective but has benefits during supervision from mission control. Built-in redundancy defines the course of action in case of a failure. Solutions to predictable problems are identified prior to launch and can be followed in case of a system malfunction.

However, pre-determined course of action, or solutions, means there is not an infinite number of solutions to counter problems. For specific systems, when the problem is predictable, and the course of action is also pre-determined, generally there are few solutions per problem.

**Maximum reliability**

Defining potential problems and having a predetermined course of action to deal with them have provided NASA a reliable basis to deal with the unpredictability in the environment. A true testimony to NASA’s system engineering methodology can be seen when looking at rovers, proves and robotic system that lasted years beyond their planned mission duration. Mars Exploration Rovers Spirit and Opportunity both lasted thousands of days beyond the 90 sols mission duration [8]. Voyagers 1 and Voyager 2 are still roaming interstellar space decades after they completed their missions [10].

Built-in redundancy and highly system reliability result in successful mission and can ensure systems last beyond its set duration. However, this strategy is possible when the systems and the tasks to be executed are not complex. In the case of a Mars 2020 Rover, traversing harsh terrain and taking samples, measurements, and recording data is complex but is still relatively simple if we compared it with an activity where the rover need to offload, transport, unload, deploy, and install systems. Therefore, predicting risk is easier when the rover has a specialized task to do, but predictions become more challenging when the tasks as well as the rover behavior are an order of a magnitude higher than a typical system that has few tasks to accomplish.

Therefore, built-in redundancy while attempts to increase the chances of a mission success in face of problems, it is only a reliable when problems are predictable. Afterall, how much redundancy a system can have before the cost exceed the benefit?

The mission duration of Mars rover 2020 is one year. This means that confidence in the hardware and the reliability of the rover is expected to last for at least the duration of one year. Surface operations required to build and maintain infrastructure needed for crew survival requires successive missions for prolonged periods of time measured in a timescale of years and even decades. As the mission duration and complexity increases, so does unpredictability factor, which makes adaptability a primary strategy and built-in redundancy secondary.

**Design phase is reset for every mission**

Having customized missions, each with a different set of objectives, results in requirements that are different for every mission. Even when missions share some system engineering parts, the process is generally repeated for every mission. Mars 2020 Rover was announced in December of 2012, and launch date is projected for Summer of 2020, which means the rover has been 8 years in the making.

This hierarchal approach in the design and execution of the mission system architecture results in a slower design process. Because of the continuous iterations required as part of ensuring mission objectives are constantly being met, the linearity within the process, which, even when certain tasks are done in parallel, still requires a hierarchical decision-making process. The design and planning phases are longer, validation and verification phase are also slower.

In addition, the current approach in the design and engineering of specialized robotic systems makes it challenging to apply changes to requirements if not done during the early stage of design. Therefore, due to the high risk of the mission and the unpredictability of the ConOps, necessary changes to the design is costly and risks delaying schedule.

**Limited accessibility**

The Architecture of the mission is not open-source and is accessed by a central team. When the requirements vary between the different missions, it obstructs the access to innovation and spin-offs that could be implemented by accessible components.

During the Apollo program, there were different groups within NASA each with a different set of priorities of what the program needs to revolve around. The two major groups with the most impact on the program's priorities are the scientists and the engineers. While the scientists were concerned with research and extracting as much knowledge as possible from landing from the moon by designing opportunities for experiments and scientific exploration, the engineers were more concerned with building hardware that could carry out a successful moon landing by the end of the decade [11]. The competing forces of functionality versus versatility could have only be resolved by following specified objectives and requirements that ensure that the value of science is maximized while the mission is reliable and successful. While engineers are the main collaborators to the process, this places a burden where engineers are a central entity that has a lot of decisions to make.

### Changes after design are premiums

Changes of an endeavor measured in the timescale of years are inevitable. When requirements are set at the design phase, changes beyond that are hard to capture if not impossible or costly to implement.

In addition, technology typically advances at a rate that is faster the rate at which missions are executed.  The time it takes to design, plan for and execute a mission, is long, and by the time a lot of progress has been made in a mission, the technologies implemented can either become obsolete or are still used but lack the necessary integration.

## Economic / Political Attributes

### Customer Lock-In

For the years 2017, 2018, and 2019, 65% of NASA exploration contracts were given to 5 recurring companies [12]. Considering the specific requirements of each mission, few companies have access to achieving those requirements. Which means that NASA is locked-in with specific vendors in terms of cost as well as time.

### One-Mission-At-A-Time

Being locked-in with few vendors, having specific requirements and a slow design process, results in slow execution of missions. Since 1957, NASA has been conducting space missions at an average rate of 1 mission/year and the same is projected for the next four years 2020-2024.

**Susceptible to delays and cancellations**

All the reasons combined result in making missions more susceptible to delays and cancellations.

**Why Methodology Remain in Use?**

(1) Since 1957, all missions conducted have been specialized exploration missions requiring specific requirements and customized systems to achieve it. Therefore, the approach was ideal to the purpose it served.

(2) Hierarchal Centralized Approach generates reliable and successful engineering systems. There is a risk to changing an approach that works.

(3) It is a legacy approach. 600 million people watched Neil Armstrong and Buzz Aldrin take their first steps on the moon [13]. It was a historic moment, not only for the United States but for the world. The black and white footage accompanied by the crews' friendly banter from launch to landing to splashdown held the record for the most-watched broadcasts in the history of television for over a decade [14]. And while this was not the first success for NASA, for the first time, earthlings reflected on this tremendous feat of humanity as one, and a Legacy was born.

# III. MAERAL, A RESEARCH BY DESIGN CONCEPT

MAERAL (Modular Autonomous Evolvable Robotic et AL) is a research by design concept of scalable, versatile, and intelligent swarm robots for future Mars surface operation missions. It combines concepts in modularity, standardization, machine learning, and collective intelligence to accomplish complex activities using simple basic actions.

MAERAL started as a sketch, and as more research and analysis were done, the design evolved.

## What is MAERAL?

MAERAL is a basic swarm bot, designed to be simple. The design is an amalgamation of four concepts: modularity, standardization, collective intelligence, and machine learning. MAERAL is self-configurable and self-assembling. It is autonomous with artificial intelligence capabilities. MAERAL is composed of standard, upgradeable systems, and modular, scalable components. All technologies embedded within MAERAL are based on existing and upcoming technologies.

MAERAL has four identical sides and is the same upside down as it is right-side up. MAERAL has multiple degrees of freedom depending on its configuration when docked with other MAERAL modules or assets.

Figure 3 to Figure 6 show a detailed design view of the modules.

## MAERAL Main Module

### Dimensions and Size

MAERAL is small and light. Each module is one meter (width) x one meter (length) x half a meter (height). It becomes a one meter-sided cube when docked with MAERAL Wheel/Chassis Module, its default attachment module.

Each of MAERAL's main modules has an estimated mass ranging from 150-250 kilograms depending on the type, specific energy, and specific density of the rechargeable batteries used.

By default, MAERAL Main Module comes docked with MAERAL Wheel/Chassis Module.

### MAERAL Primary Structure Material [A]

In order to mitigate the Martian surface geological and physical hazards, MAERAL's exterior is made of dust-tolerant, high strength, lightweight composites material, such as carbon fiber composites or carbon nanotubes. Composites have qualities that make them durable and enable them to withstand extreme temperatures and pressures, qualities that are necessary for extreme environments. In addition, composites can drastically reduce in mass, an aspect that is critical for payload landing.

### Dust Tolerant Connector and Docking Interface [B]

Each MAERAL module has three small-scale docking interfaces [B-i] on each side and one large-scale docking interface [B-ii] at the top and bottom.

Reference technologies of the docking interface used in the design is HotDock by Space Applications [15] [16] or Honeybee's Dust Tolerant Connector (DTC) by Honeybee Robotics [17].

The docking interface allows the transfer of power, mechanical and structural loads, torque, control, and thermal energy. It also allows for docking with other MAERAL modules and extra attachment tools.

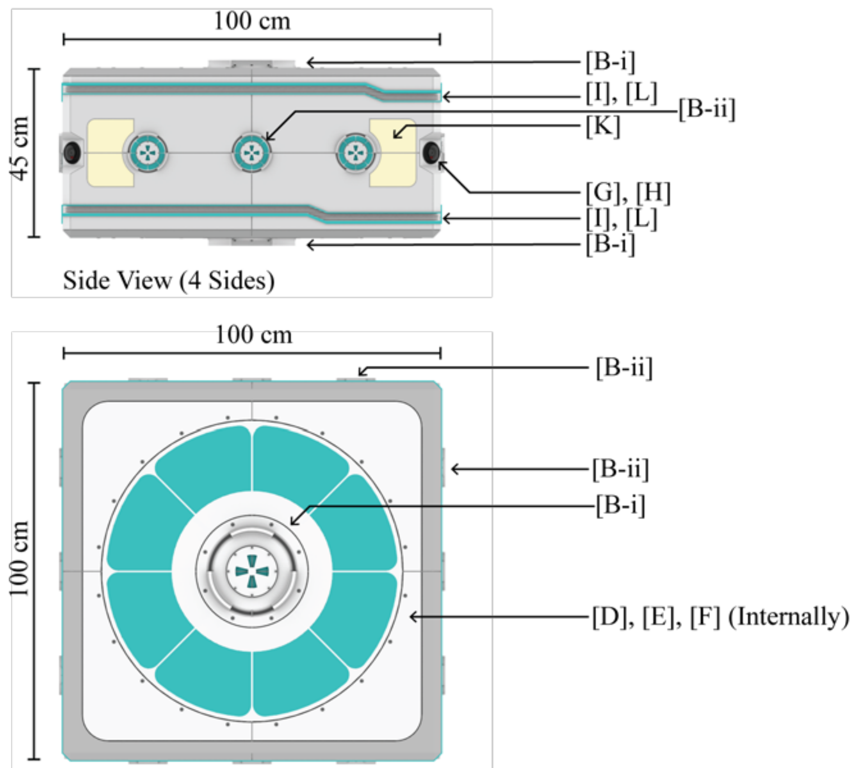


*Figure 3 MAERAL Main Module Design Details*

## Drivers and Actuators [C]

MAERAL's internal drivers, motor, and actuators are used for manipulation and actuation. Reference technology of the motor used in the design is HOTTech Venus Motor by Honeybee Robotics [18].

**Power Source [D]**

For a Mission to Mars, batteries need to have capabilities to operate in a low-temperature environment, have a long-life capability, have high specific energy (to reduce mass), high energy density (to reduce volume), and be compliant with planetary protection requirements [15] [19] [20].

Each MAERAL has a primary battery and a backup battery pack. The current proposal MAERAL uses advanced Li-Ion rechargeable batteries with high specific energy (150-200 Wh/kg), a long cycle life, and calendar life. The intent is that it can be upgraded to next-generation batteries such as Li-ion Solid State batteries once the technology becomes available [20].

**Other Components**

Each MAERAL module has an onboard microprocessor [E] with data handling and storage capabilities. It has command and control systems [F] for communication, transmission, and receipt of data connected to a swarm shared network architecture.

Each module also has a field of view cameras [G] on all four corners for vision and recording. Within the camera comes embedded a variety of electromagnetic sensors [H] for navigation, perception, cognition, and sensing for collision avoidance, cooperative spacing, and traffic control.

Each module has louvers [I] for heat rejection strategies.

Each module is equipped with a unique address identifier [J], ID, detected by other MAERAL's and visible by crew for future operations.

MAERAL has primary lights [K] as well as secondary lights [L] around the louvers.

### MAERAL Wheel/Chassis Module

This is the mobility module that is the default companion to the MAERAL main module. The wheels [M] are flight-grade advanced "rocker-bogie" mobility system with steering, suspension, and auto-navigation. MAERAL is using the same size wheels used by the opportunity rover. Wheels can retract and extend as needed to

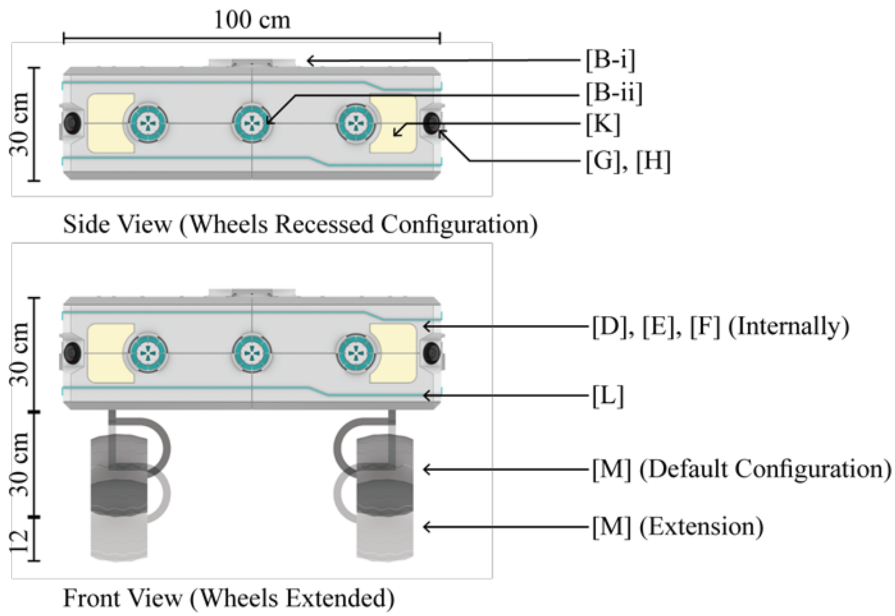


*Figure 4 MAERAL Wheel/Chassis Module Design Details*

maneuver and overcome obstacles. Reference technology of the mobility system is Autonomous Planetary Mobility System [21].

## MAERAL Battery Rescue/Solar Module

The simplicity in the design allows for access to design spin-off concepts that allows for innovative solutions that can be of support to the missions. One of such design spin-offs is the MAERAL Battery Rescue/Solar Module that consists of the same components of the original MAERAL with an added functionality of foldable

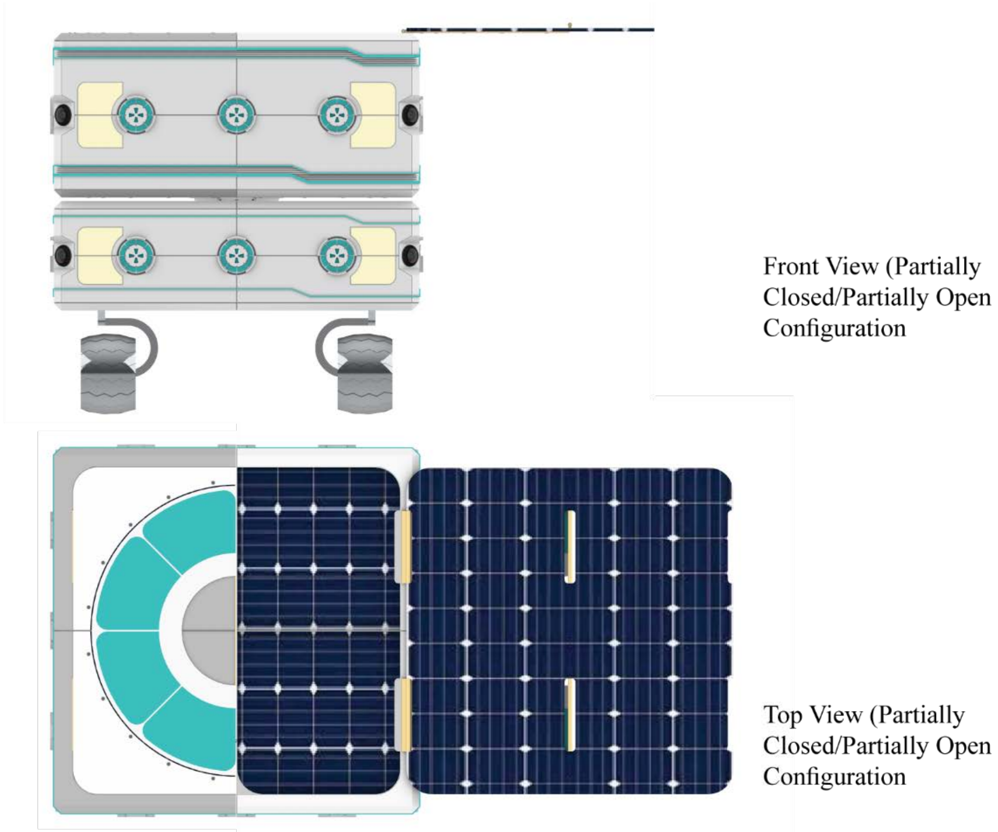


*Figure 5 MAERAL Battery Rescue/Solar Module*

solar panels that can deploy to recharge its batteries and to charge other modules using the docking interface.

## MAERAL Asset Housing

MAERAL asset housing is another design spin-off from the basic MAERAL module. It is intended for asset storage, handling, transportation, and deployment of payloads and assets. It has deployable legs that can allow it to raise itself and level with other MAERALs for transportation. The asset housing has a tractable enclosure to adapt to different sizes of assets.

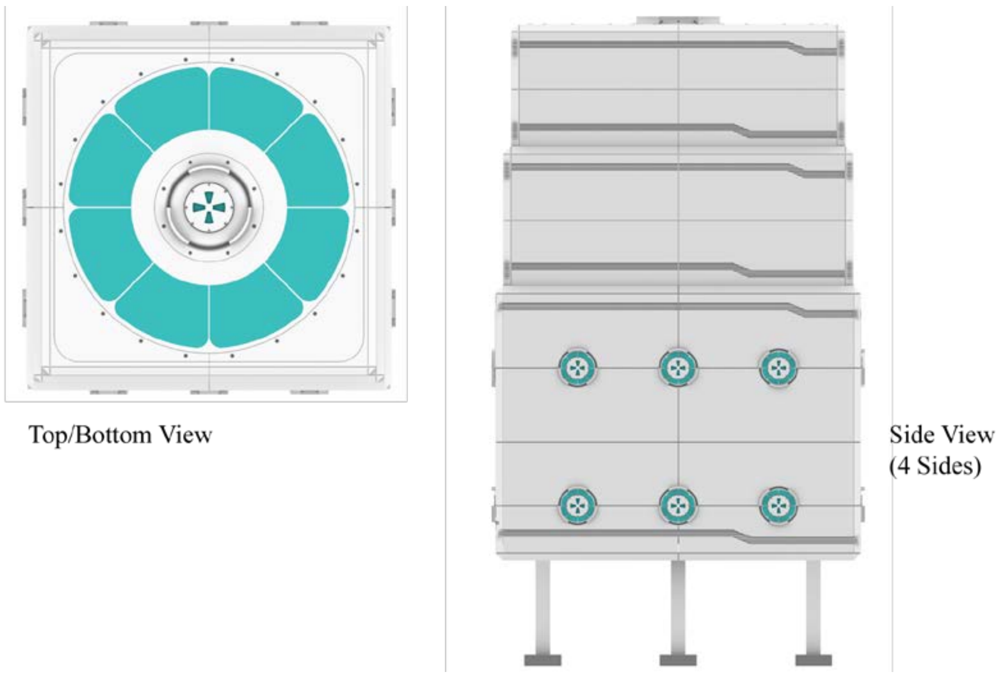


*Figure 6 MAERAL Asset Housing*

# IV. DECENTRALIZATION, SIMPLE TO COMPLEX

In the 1940s, computers were filling an entire room, designed for few functions, and expensive to engineer, produce and own. However, it is now 2020, an era of the ubiquitous personal computer. Affordable and accessible, the PC is used for a broad spectrum of applications, tasks, and functions. With its open-source architecture, the same device can be used for work, communication, and entertainment alike. Technological advancement indeed resulted in this drastic shift in the computer industry, but another reason is responsible for the drastic shift.

The concept of the personal computer was not new and was in place in 1980. At the time, only a dozen companies were shipping PC worldwide. However, in 1981, IBM set a precedent by releasing open PC architecture that quickly became the de-facto-standard of the computer industry. The decentralization was a result of standardizing components. Parts and components became interchangeable, quick to assemble with high performance, and a substantial decrease in cost [22]. **Error! Reference source not found.** demonstrates a general overview of the process of decentralization that occurred as a result. Having a standard therefore enabled expansion of the market, which included even IBM’s competitors. This decreased the price, while increasing quality, performance, ease-of-use, wide application, and compatibility [22].

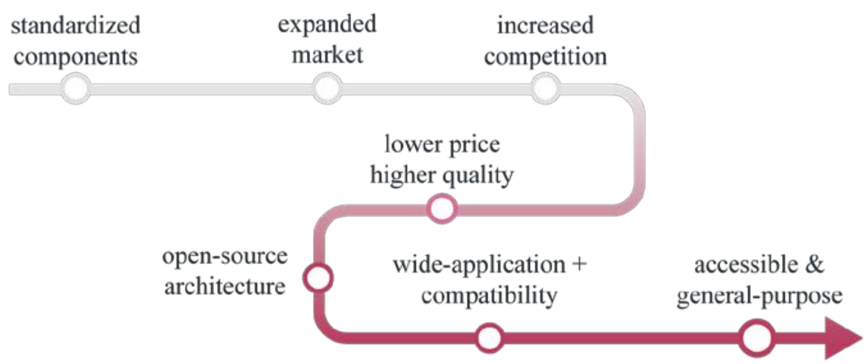


*Figure 7 IBM decentralization of the computer industry*

However, the PC revolution is more than a reduction in costs and an increase in performance. The accessibility afforded by having standard components allowed for innovation which paved the way for having a general-purpose PC. At a time where only very few have enough knowledge to assemble a PC, accessibility allowed even a non-expert be able to build their own in few hours, a feat that would be impossible without a standard to follow [22]. Innovation became much more attainable. Companies were able to start creating spin-offs that augment the possibilities afforded by having standard components all the while maintaining compatibility with the industry.

**Decentralization and MAERAL's Key Concepts**

MAERAL encompasses three concepts:

(1) Collective Intelligence and Machine Learning

(2) Standardization

(3) Modularity

It is the combination of the above concepts that makes MAERAL a well-rounded solution to complexity of operations. The next few pages will describe the method on how to decentralize the design approach by explaining it through MAERAL.

**MAERAL's Collective Intelligence and Machine Learning**

MAERAL is a mini AI. Each MAERAL is one node in a network of swarm intelligence. By itself, MAERAL is not smart. However, MAERAL uses the concept of collective intelligence to build the knowledge, learn from its mistakes and surroundings, and learn from other MAERALs. With supervised learning, MAERAL correct its knowledge and decision-making algorithms along the way. A single individual MAERAL module can do very few things, navigate, the terrain, survey the site, respond to stimulus, and perhaps sense the presence of other MAERALs and obstacles. When MAERALs start working on concert, collective intelligence allows for the development of compound and complex behaviors that can be remarkably intelligent.

**Swarm Intelligence for Complex Operations**

Before I explain how MAERAL executes operations, it is important to understand how current robotic systems execute operations. Figure 8 is a graphical representation of how this works in action


*Figure 8 How current robotic systems execute operations*

On the other hand, MAERAL takes the input as simple basic actions, and through an AI neural network, it combines the simple actions into compound behaviors. Figure 9 is a graphical representation of the process.

To get MAERAL to perform complex behaviors, we need to feed MAERAL the simple actions it needs to generate the compound behaviors.

We can take a basic case study of the process but looking into the activity such as clearing the site and the task of removing a stone.

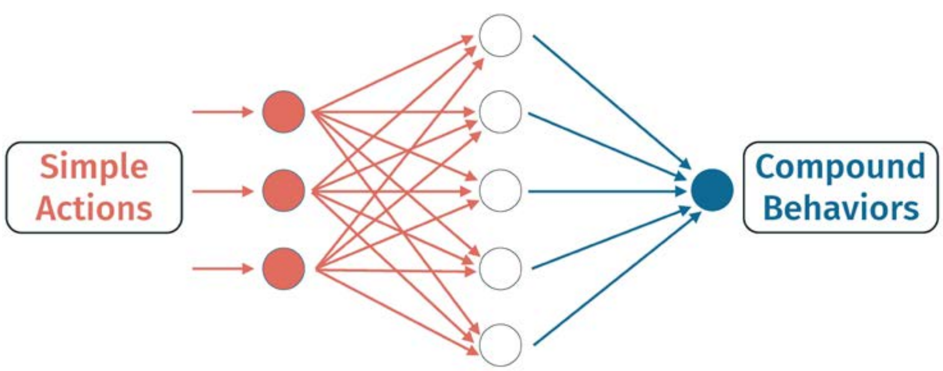


*Figure 9 How MAERAL execute operations*

Once MARAL assesses the site and collects the information it needs, it might detect the stone to be removed. Therefore, the basic action required to remove the stone is to grasp it, raise it, move it to a specified location, lower it, and then release.

The combination of the three simple actions such as detect/assess, grasp/release, and raise/lower, introduces compound behaviors, which in combination, leads to attempting to removing a stone. This might be a complex pathway which leads to removing a stone, however, it is this complexity from simplicity, where a resolution is achieved.

Removing a stone is only a variation associated with the strength of the grasp or the distance from the ground that MAERAL has to lift, factors that are associated with the stone itself and not with the activity inn genera. However, applying the same behavioral logic in other areas, means another set of compound behavior, such as deploying an asset, transporting an asset and replacing an asset.

Those three behaviors generated from three simple actions constitute a big part of future Mars Surface Operations.

Taking this approach to a more advanced level, and the combination of the compound behaviors generate complex actions that far exceed that the initial embedded capabilities of the robotic systems. Deployment, transportation and replacement of an asset are only a part of bigger activities such as preparing the site, deploying a habitat, collecting and storing samples and even housekeeping.

**Decentralization of the Design Process**

To decentralize the design process is to go through found fundamental steps:

(1) Analysis of Design Reference Architecture Mission (Holistic Overview)

(2) Extraction of Functions and Objectives

(3) Decomposition of Functions and Objectives into Simple Actions

(4) Give Maeral Physicality

**Step 1: Analysis of Design Reference Architecture**

The first step in design is to examine an entire design reference mission from beginning to end. A holistic overview of the objectives, functions and concept of operations is necessary.

NASA has been formulating plans and studies to land on Mars for at least 3 decades. NASA's Human Exploration of Mars: Design Reference Architecture Missions 5.0 (DRA) with its addendums, supporting documents and supplementary reports are the most detailed references ever done by a governmental or private entity to date. DRA 5.0 is only one of the latest updates to a series of earlier references that have been in development since the late 1980s. At the time, the Office of Exploration was entrusted with finding a long-term goal to galvanize the US civilian space program, and what started as a few detailed case studies gradually grew into NASA Mars Design Reference Mission (DRM) 1.0 in the early 1990's and eight years later into DRM 3.0, the predecessor to DRA 5.0 [4].

Throughout the years, extensive collaboration occurred between NASA teams, groups, committees, and centers resulting in valuable references that discuss almost all aspects of a mission to Mars. Such as advanced in-space Transportation and propulsion systems, Mars entry, descent and landing maneuvers and vehicles (EDL), descent and ascent vehicles, Earth-Mars trajectories, Space Launch Systems (SLS), Mars ground system architectures, Mars surface strategies and systems, technological and environmental constraints, surface strategies, missions overview, length of stay of crew, the infrastructure required prior to human's arrival, the psychological and physical issues that crew has to contend with and even discussion about ethical questions and challenges relating to planetary protection and crew protection were also a part of it [4] [5] [23]. In addition, DRA 5.0 supplementary report: The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities, describes the minimum set of activities expected to be performed by robots and crew, both autonomously and in the presence of humans, as well as tasks to be performed prior to human's arrival, all assistive tasks and those required after departure [5].

Having a thorough basis such as NASA's DRA and its supplementary references provided a good foundation for the holistic overview needed for this step. Figure 10 is adapted from NASA's Design Reference Architecture 5.0 [4] [5] [23] and represent a typical mission provide for a Mars surface mission. The information related to the duration required to deploy the autonomous systems and prepare the site as well as the number of launches required is my own interpretation based on the apparent uncertainty at this stage of the type of robotic systems and technologies used.

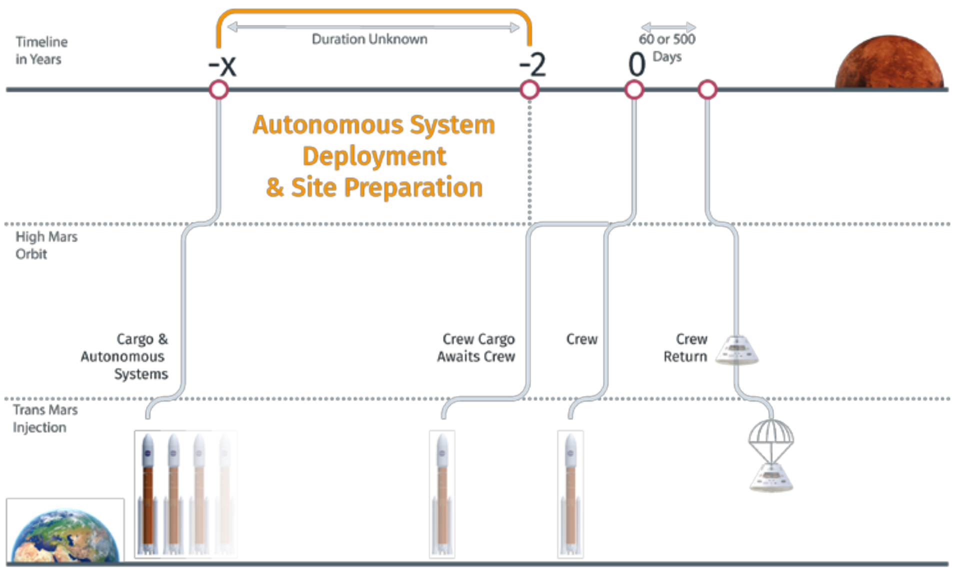


*Figure 10 Typical mission profile for a Mars surface mission*

**Step 2: Extraction of Objectives and Functions (Robotic and Human Activities)**

After analyzing DRA5.0 in terms of major mission stages, we need to extract all the objectives and functions expected to be performed robotically or by humans. Identifying human activities provides the opportunity to find tasks that can be automated and performed by robots, freeing humans for the ultra-specialized tasks.

The following are a high-level categories of the major activities anticipated for a Mars Surface Operation mission [4] [5]:

(1) Site preparation and terrain leveling

(2) Asset and payload handling and transportation

(3) Power source deployment

(4) ISRU deployment

(5) Habitat setup and deployment

(6) Drilling for, digging, placement, and anchoring of assets

(7) Routine Operations: Repair, servicing, inspection, and verification operations

(8) Housekeeping

(9) Toxins and bio-hazard assessment

(10) Sample collection and storage

Looking back Figure 1 Mission Formulation Flow Diagram in Chapter II, we see that extracting the major activities is similar to outlining the objectives and functions.

**Step 3: Decomposition of Major Activities into Simple Actions**

This step can be considered the start of the design process. The robotic design process generally follows two primary steps. The first is identifying the main purpose of the robot and then outlining the specific requirements to achieve that purpose, which is what we have seen using the hierarchal centralized (Top-Down Approach). However, in the decentralized approach, the process is somewhat reversed.

Decomposing the major activities back into compound behaviors and finally into basic actions allows us to look at all the tasks at once and generate what tasks can be combined using the same requirements to achieve the same result.

On the outset, major activities appear different. For example, deployment of a power source, and clearing the site seem to be divergent tasks, each requiring a separate robot to execute. However, by decomposing the major activities into compound behaviors and further into their basic tasks, a pattern starts to emerge. It seems that no matter how complex the activities are, they end up sharing recurring tasks and common basic actions. Figure 11 is a graphical representation of the process.

This decomposition decentralizes the process. With no specific objectives to constrain our actions into systems, MAERAL, with initial supervision, will be free to amalgamate actions to rebuild/recreate tasks and activities. Therefore, the capabilities of the mission will be an order of magnitude higher than the predefined capabilities. With Artificial Intelligence, MAERAL might be able to find new solutions to problems, deal with the unpredictable, an reduce the risk of mission failure. When many solutions are available to the same problem is the true meaning of dealing with the unpredictability.

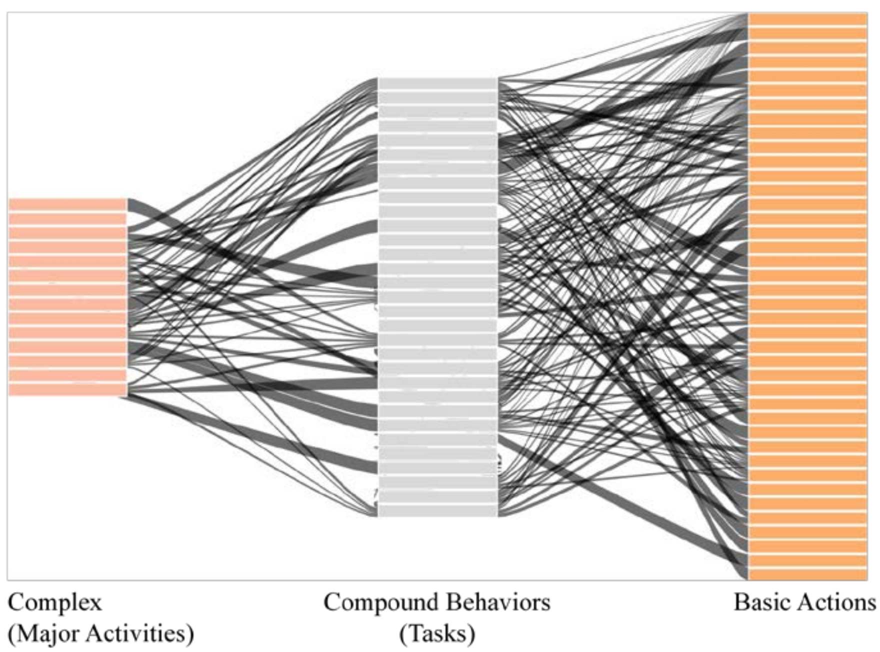


*Figure 11 Decomposition of Complex Activities to Basic Actions*

**Step 4: Give MAERAL Physicality**

The physicality of a robot that transforms basic actions into complex activities is best served by concepts of modularity and standardization. Instead of designing systems with defined capabilities that each can accomplish a specific task, we can look into few aspects that collectively can accomplish the most of what is required.

A simple action, such as movement, which is recurring in different activities, requires the capability of locomotion. Studying system engineering and environmental aspects provides us with information as to the ideal characteristic (in this case, the wheel) that can aid in performing the tasks. Going through further analysis can provide us with the properties (for example, the material of the wheel).

Modularity and standardization in this case can be complementary to the studies in system engineering, environmental constraints, existing technologies and human-centered design. Altogether, can provide us with modular components that work on different tasks and activities, and standard parts, that can be integrated between missions and scaled as necessary to achieve a specific task.

# V. DESIGN DEMONSTRATION

To demonstrate how MAERAL works, I picked the activity of deployment of a Power Source to demonstrate the capabilities. As we advance our plans to get to Mars, deployment of a Kilopower Nuclear Reactor seems to be the direction to power an outpost. However, there are few challenges to this activity which makes it idea as a choice to demonstrate MAERAL.

(1) Deployment of a power source is the first task to be accomplished autonomously by a robotic system [4].

(2) The task is challenging due to the Kilopower size, mass & number of Kilopower reactors required. The height of one Kilopower reactors can be anywhere between 3.3 meters to 7 meters. In a deployed configuration, it can be 1.5 meters in diameter. Mass also varies with the power output generated, from 1 ton (for a small-scale 5 kWe) to 1.5 tons (for the full-scale 10 kWe) [19] [15] [24].

(3) A regular outpost needs 5 full-scale (10 kWe) [19] [15] [24].

(4) A Kilopower need to be transported 1 km away from landing site, area of crew operations and habitats [4] [5].

**Mission: Deployment of A Kilopower Nuclear Reactor**

To autonomously deploy the Kilopower, MAERAL needs to go through few steps. First, it needs to survey a radius of 1 km for journey path, transport asset 1 km distance, deploy asset, operate, charge, and send update

### Survey the Site

After they land, they will need to navigate the site in pairs in order to find the flattest pathway with the least obstacles to deploy the Kilopower, Figure 12.

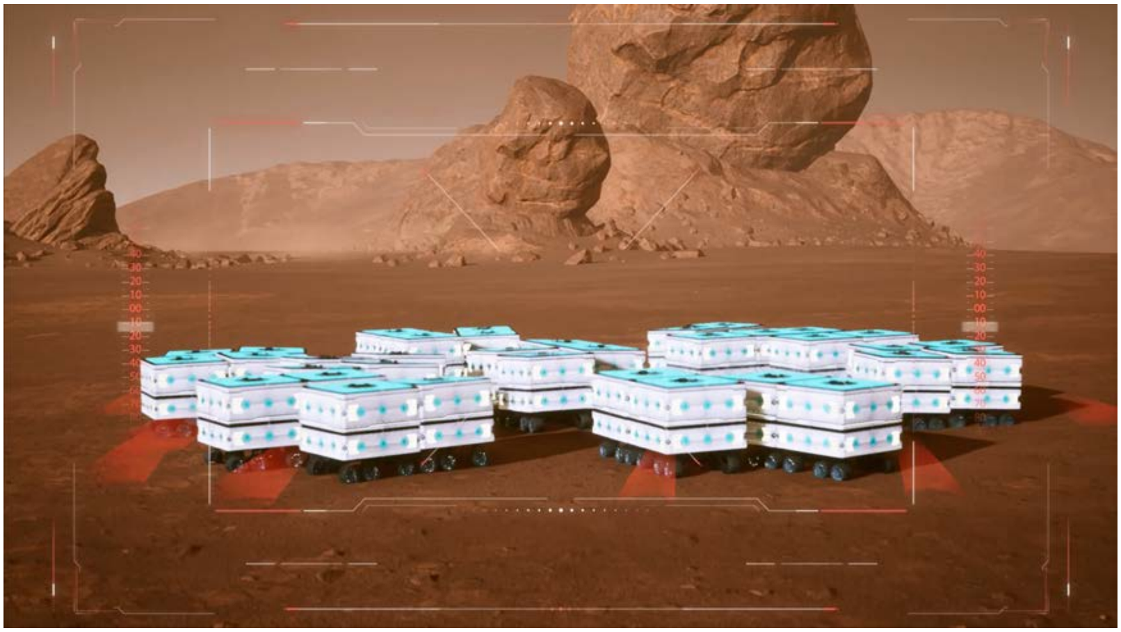

*Figure 12 MAERALs surveying the site*

### Dock with the Kilopower

The Kilopower is housed in the MAERAL asset housing module. After determining the correct location to transfer the Kilopower across for a 1 km distance, MAERAL will go and dock with the Kilopower, Figure 13. MAERAL being an AI will always have different attempts to move the Kilopower using a different number of MAERAL until it is able to move the Kilopower.

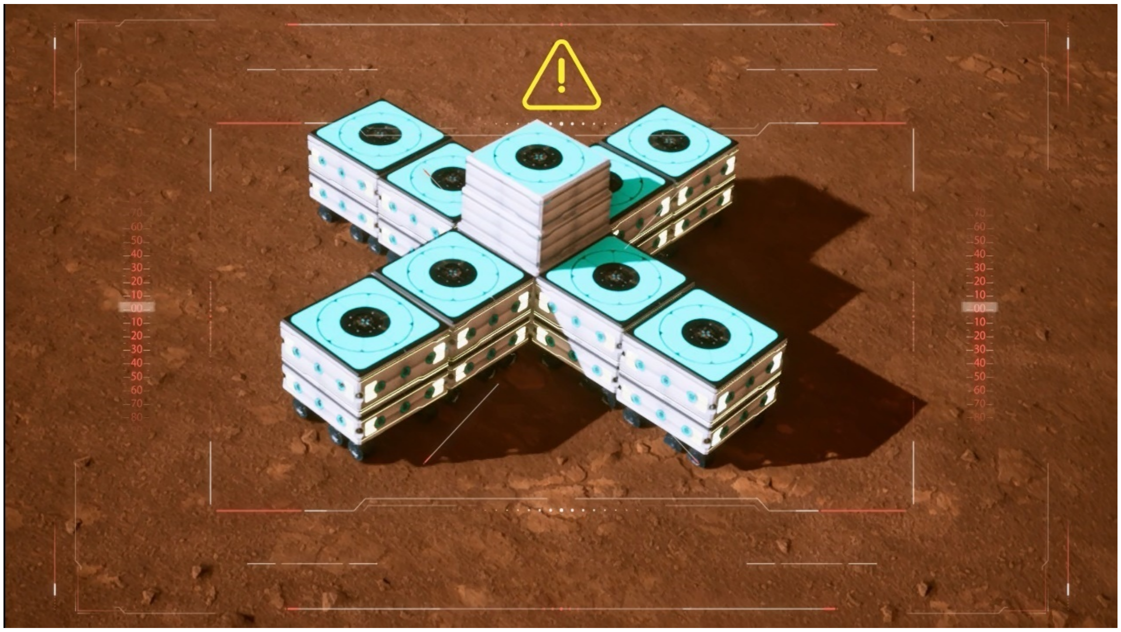

*Figure 13 MAERALs docking with MAERAL Asset Housing Module*

## Transport to 1 km Distance

Moving the Kilopower across harsh terrain requires navigation to avoid running into unnecessary obstacles. MAERAL with its swarm intelligence, follows the pattern of leader-follower,  Figure 14. One MAERAL will assume leadership and guide the robots through the best route they discovered during the mapping of the site.

A guiding Maeral and a companion for redundancy can also be a replacement in case one of the robot’s malfunctions.

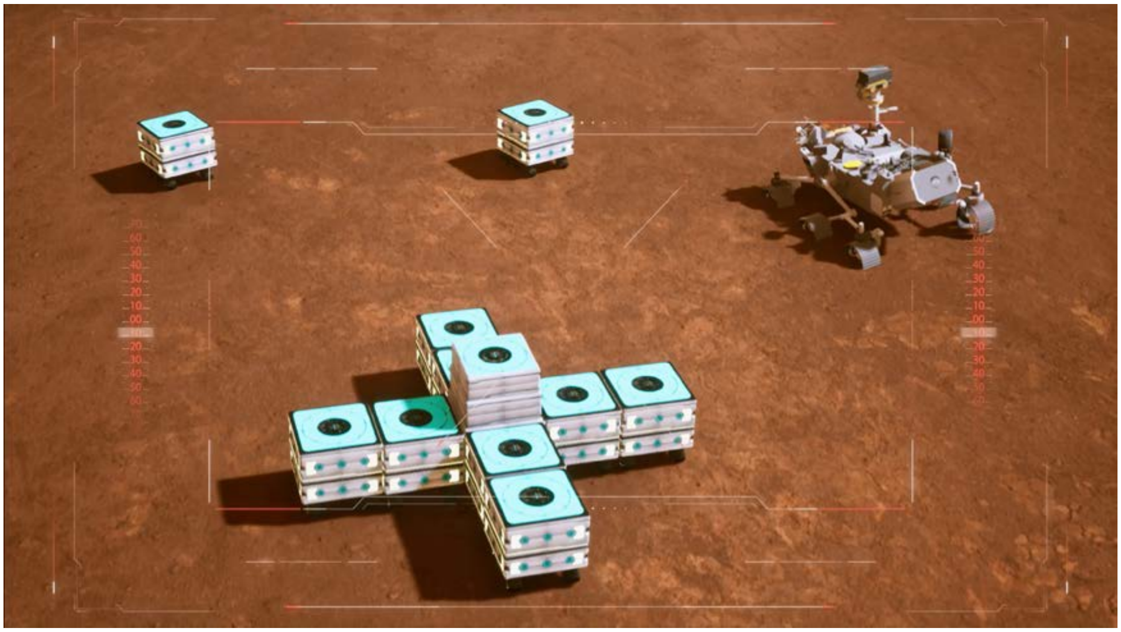

*Figure 14 Guiding MAERAL leading transportation of asset*

### Charging

A 1 km journey on harsh terrain is a long time and batteries might need to be recharged. In this case, MAERAL Battery Rescue/Solar Module, can come and charge the other MAERALs, Figure 15.

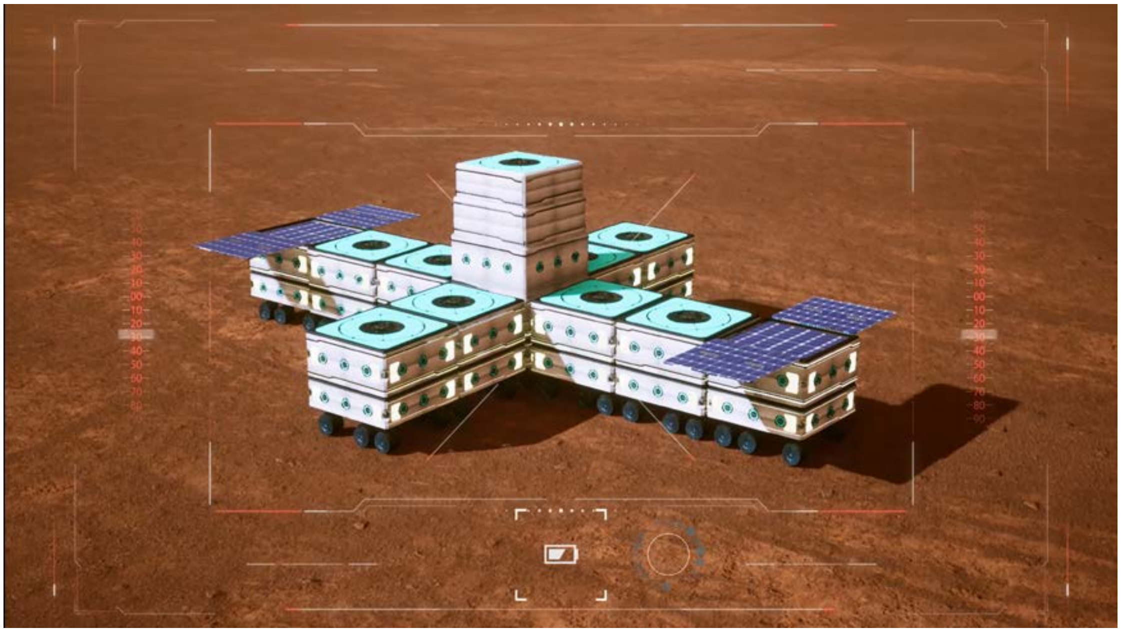

*Figure 15 MAERAL Battery Rescue/Solar charging other MAERAL*

**Deployment**

After the long journey of crossing harsh terrain, MAERAL arrives at the specified location and starts deploying the Kilopower. The Kilopower, being inside the modular asset housing, MAERALs can come and dock with the Kilopower to charge themselves, Figure 16.

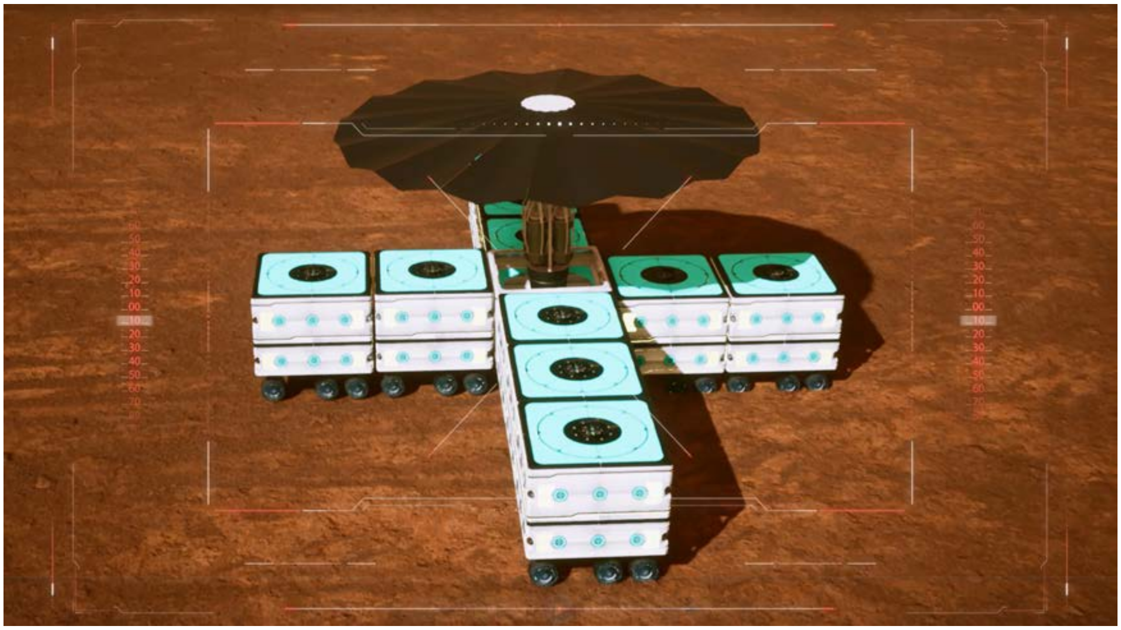

*Figure 16 Asset successfully deployed.*

# VI. CONCLUSIONS AND LATITUDES

A transition to a new generation of robots capable of handling the unpredictability and high risk of future missions requires decentralization of the design and planning process. This decentralization opens the door to latitudes higher than designing for Mars surface activities. MAERAL is to prolong and sustain our space-faring future by making space exploration more accessible, more feasible, more efficient, and more continuous.

## Accessibility and Innovation

Decentralization, and adopting standardization and modularity while harnessing the power of swarm robotics allows for mass production, affordability, and speed in execution of mission. Combined, these aspects can allow for accessibility to innovation. Requirements of how to design robotic systems would no longer be the major constraint, and individuals can be free to explore different ideas and design spin-offs from very-basic original module.

## Dealing with the Unpredictability

Dealing with unpredictability requires strategies of resilience and adaptability. It doesn’t mean that the robots will not break, they certainly will, but there should be more than one way as a solution around it.

**Lasting Progress**

Lasting progress comes from many successive small increments of improvement that build on one another. To succeed in a complex endeavor, we need to find a way to “mass produce missions” and work on an economy of scale. It is only when it is cheap enough to afford the failed missions that we can become better. So, with customization, high price and slow development, how can we afford failure to make progress?

More than a 100 Atlas missiles had been launched before the rocket carried astronaut John Glenn to an Earth Orbit [25]. Reliability and progress came from ability to continually test for failures.

Future robotic missions preceding human exploration are likely to be a series of many missions one after the other that build on top of each other, integrate within each other, and allow for incremental progression towards an outpost. It is not a one-robot job, not even a two-robot job. It requires a fleet of robots, over many missions to succeed. The current timeframe of missions is one specialized rover every two years and cost billions to design, launch, and land. Affordability to failure is important in an endeavor this complex.

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