73rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022.

IAC-22,A3,IP,x72458

The Tumbleweed Mission: Enabling Novel Mars Data Sets through Low-Cost Rover Swarms

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Abstract

Current Mars surface exploration is characterized by large, infrequent, risky and relatively high-cost space missions that gather in-depth data on a small area. In order to reach the ambitious Mars exploration objectives set out for the coming decades, a significant reduction of cost, risk and schedule is needed. Additionally, many current science objectives, such as improving models of Martian weather and climate as well as internal structure, require long-term surface data over large areas of Mars.

We propose a mission architecture based on a swarm of wind-driven rovers that can provide these types of observations, while also reducing high mission cost and risk for Martian exploration. Following mid-air deployment, the rovers unfold and touch down on the surface, roll across the surface until a desired spread of the rovers is achieved, and are then stopped. Scientific data is collected both on-the-roll and when stationary.

The Tumbleweed mission provides a unique opportunity to characterize Mars using data over various spatial and temporal scales. We show that a Tumbleweed mission has high utility with respect to Mars Exploration Program Analysis Group (MEPAG) Goal II (Climate on Mars) by providing environmental data including temperature, pressure and wind velocity. Goal III (Martian Geology) is addressed by providing highly precise geodetic data and assisting in gravimetric measurements. Moreover, Goal IV (Human Exploration) is fulfilled by surveying large surfaces of Mars, adding crucial context to the current understanding of the Martian environment.

With a sensor package consisting of a radio beacon, laser retro-reflector, atmospheric sensors and a rudimentary camera the Tumbleweed mission can address objectives relating to all three aforementioned high-level MEPAG goals. While many aspects of the mission can rely on already-proven technology, further development is needed on a miniaturized location determination system, the folding mechanics of the rover structure, and the rover's power systems.

To gain further insight, a half-scale demonstrator of the rover has been constructed and tested in a Mars analogous environment. The results of the test show the general feasibility of the rover and have provided validation of visual instruments. Moreover, a novel reversible, non-destructive method for arresting the rover through reefing sails has been demonstrated. Visual data can be used to further develop a locating algorithm. Another avenue for future research is the communication with the swarm of rolling rovers on the surface of Mars which warrants unique communication strategies.

Keywords: Tumbleweed mission, Mars exploration, rover, swarm, wind-driven, mission architecture

1 Introduction

Our closest analogous planetary neighbor, Mars, has undoubtedly attracted scientific and societal interest for several decades. Once potentially habitable, Mars used to have water cycles, a thicker atmosphere and higher temperatures [1]. However, over the history its climate and surface significantly changed (e.g. [2]). Mars today has a range of surface features (e.g. volcanoes and craters), geophysical processes (e.g. erosion, wind, etc.) and materials (e.g. rocks, sediments, and soil), among others features, that all hint at the planet's past and evolution. With growing evidence of Mars' past similarity to Earth, it can help us understand the planetary formation and evolution. It also makes Mars an excellent candidate for the search for life, as present-day bio-markers could exist on its (sub-)surface [3]. Even though the knowledge on Mars has been significantly increased over the last century, a great deal of questions remain unanswered and are subject to current and future missions.

Currently, these endless scientific possibilities are explored by several spacecraft on or around Mars. With the help of orbiters (e.g. Mars Reconnaissance Orbiter [4], MAVEN [5], or the recent international efforts with Hope [6] and Tianwen-1 [7]) that provide orbiter data, it is possible to investigate atmospheric properties and surface geology remotely. The InSight lander is studying the interior structure by providing stationary data from a singular point [8], while the Curiosity and Perseverance rovers are exploring the planet's habitability and preparing for a sample-return mission by moving at a slow speed and collecting extensive data at different locations [9, 10]. Together with the previous missions, they have collected loads of invaluable data that helped scientists to continuously improve current knowledge of the Red Planet and the Solar System. However, Mars surface exploration is generally characterized by large, infrequent, risky and relatively high-cost space missions that gather in-depth data on a small area, in case of a rover or a drone, or a singular point, in case of a lander. With prospective future missions focusing on finding bio-signatures, sample return and, eventually, landing humans on Mars [11], several issues in Mars exploration remain unsolved. In order to reach the ambitious space exploration objectives set for the coming decades, a significant reduction of cost, risk and schedule, as well as measurements with an improved spatial resolution across a large surface area, are needed.

We propose a mission architecture based on a swarm of wind-driven rovers that can provide novel data sets, while reducing mission cost and risks involved in Martian exploration. The mission consists of 90 large, spheroidal rovers. After a mid-air deployment and dispersing throughout the Martian surface for 90 sols while collecting data on the go, they will arrest and become stationary to continue performing in-situ measurements from various locations on Mars, as further explained in section 3. Unlike the previous, current and planned missions, the Tumbleweed rovers will be able to cover large surface areas at an unprecedented speed. By exploiting wind and solar power, and due to the rover's simple design, the overall mission cost will be minimized, while mid-air deployment and swarm deployment of the rover will reduce the risk of the mission.

The Tumbleweed mission, currently under development by Team Tumbleweed[1], provides a unique opportunity to characterize Mars throuhg data on spatial and temporal scales - it has potential to map and help fill the current knowledge gaps e.g. on Martian climate and atmosphere, or surface geology. With the currently envisioned science package, the Mission addresses three high-level Mars Exploration Program Analysis Group (MEPAG) goals [12]. The Climate on Mars (Goal II) is investigated by providing environmental data including temperature, pressure and wind velocity. Martian Geology (Goal III) is addressed by providing highly precise geodetic data and assisting in gravimetry measurements. Moreover, Human Exploration (Goal IV) is indirectly fulfilled by surveying large surfaces of Mars, adding crucial context to the understanding of the Martian environment and furthering the search of the potential landing sites.

This paper serves as a detailed introduction to the Tumbleweed mission, its science goals, architecture, and the rover design. Starting with section 2, we review the conventional surface mission design and their science objectives, followed by the proposed Tumbleweed mission design in section 3. Further, the mission payload and utility are considered in section 4, after which we present the Earth-Scale Demonstrator of the Tumbleweed rover (section 5). Finally, the findings are discussed and concluded in Sections 6 and 7 respectively.

2 Conventional Mars Surface Mission Design

To pinpoint the needs for future Mars exploration missions, an examination of current conventional Mars surface mission design and their capabilities is required. The literature study and market analysis determine the existing competition to the Tumbleweed mission with regard to the relevant research fields, and the areas in which the Tumbleweed mission can outperform its competitors. The surface mission architecture of alternative missions is discussed to shed light on the current state of Mars exploration. The shortcomings of current Martian mission design and the consequent hindrance to the development of prominent Martian research goals (MEPAG) are also investigated. The science objectives set by general stake-

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holders, such as academia and space agencies, are divided into Atmospheric science, Surface Geology and Internal structure for this purpose.

2.1 Surface Mission Architecture

Several mission architectures have been used for extended missions to Mars thus far: orbiters, landers and rovers. As orbiters, spacecrafts orbiting the planet, are by definition unable to perform in-situ surface measurements, their architecture will not be discussed further. For the same reasons flyby mission architectures are also excluded from this analysis. However, as orbital observations form a key part of current Martian scientific endeavors, their scientific capabilities and contribution will not be neglected in subsection 2.2. Flyby missions, unable to provide Martian scientific value for an extended period of time, will however also be neglected in the discussion on scientific capabilities.

Landers

A Lander is a spacecraft that remains stationary after soft-landing on the surface. The InSight robotic Lander landed on Mars November 2018 and is performing measurements of the interior of Mars using specialized and highly focused instruments, such as the Seismic Experiment for Interior Structure (SEIS) and Heat Flow Probe (HP^3), at a single location [13]. This Lander used powered descent for the terminal descent to Mars [14] and is shown in Figure 1. The mass of the entire InSight spacecraft at launch is about 694 kilograms, of which the Lander mass is 358 kilograms and Science payload 50 kilograms. The investment into Insight is approximately $\$994$ million from the USA, France and Germany [15].

A major limitation of landers is the fact that they can only provide data from one position. Furthermore, a swarm of landers using a single launch (similar to the Tumbleweed mission) poses restrictions on the distribution of the landers due to orbital mechanics and entry angle envelopes. While this can be circumvented through intermediate maneuvers between release of the lander entry vehicles, this will require significant capability on the part of the entry vehicles to sustain a long period of coasting, including navigation and maneuvering. This will in turn drive mission cost. If soft landing is required, it is also important to note that lander cost will not scale down well with payload mass, making small missions non-sensical. Another limitation is the significant dust that builds up on surfaces of the spacecraft over time, limiting the lifetime of landers with photovoltaic power systems significantly if not accounted for. Therefore a dedicated system is required to keep the panels clean.

Rovers

A rover is designed to move across the surface of a planet. The rovers that have landed on Mars, such as the Perseverance & Curiosity rovers and Opportunity & Spirit rovers all have complex payloads and allow for focused measurements. These rovers vary in mass, with the Perseverance Rover weighing 1025 kilograms of which 59 kilograms are payload instruments and the Opportunity Rover weighing 174 kilograms. The Mars Exploration Mars Rover program had a cost of approximately $\$820$ million, consisting approximately of 645 million spacecraft development and science instruments. The Mars 2020 Perseverance mission approximately cost the large sum of $\$2.4$ billion to build and launch [16, 17].

A significant constraint of rovers is that only a small area can be covered on Mars by these relatively large systems (Perseverance is about 3 meters long, 2.7 meters wide, and 2.2 meters tall [16]. For example, the Mars Exploration Rover - Opportunity, considered as one of the most successful on Mars, only traveled 45 kilometers in its lifetime [18]. Furthermore, rovers are generally complex and expensive. Also, their drive train is fragile and power is a major constraint to mission performance. This is solved by either resorting to Radioisotope Thermal Generators (RTGs) or having limited lifespans due to dust accumulation [19]. Safely landing a rover on the surface is a great challenge, as they are fragile and dust kicked up by rocket engines can compromise their functionality. For this reason rover missions have resorted to sky crane and airbag landing systems respectively and is shown in Figure 1.

Aerial vehicles

In addition, aerial vehicles are a recent development on the surface of Mars. Ingenuity, a coaxial rotor helicopter, has successfully been deployed on Mars as a technology demonstration. Aerial vehicles provide the ability for landers and rovers to expand their field of view. However, they do not travel large distances, due to the relatively thin atmosphere on Mars and energy constraints. For example, Ingenuity has a total mass of 1.8 kilograms, flight time of up to 90 seconds, flight altitude of 5 meters, and a small, mobile phone class color camera as a “payload” [23]. Increasing the mass limits flight range and flight hours possible and thus far, only carry small-scale payload at a high cost. NASA invested $\$85$ million to build Ingenuity, accommodate it on Perseverance, as well as operate the helicopter [24].

2.2 Science objectives

The current capability and state of Mars science exploration is investigated in this section, ranging from Martian

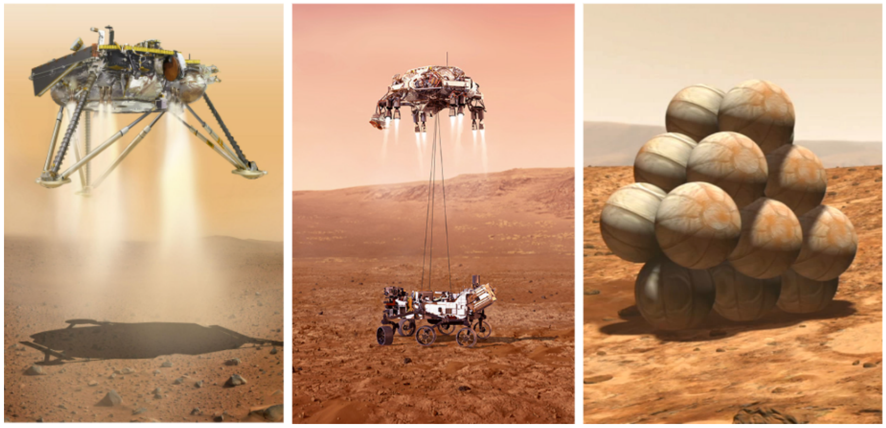

Figure 1: Landing procedures of previous Mars surface missions. From left to right: InSight Lander using powered descent, Mars 2020 Perseverance Rover using a sky crane, and the Mars Exploration Rover - Opportunity, using an airbag landing system [20, 21, 22].

atmosphere, surface geology and the internal structure of Mars. The limitations of the current Martian exploration is discussed and how it further hinders the exploration goals, as outlined in the MEPAG goals [25].

Mars Atmosphere

The main scientific focus is on providing weather and climate data from the surface over a large area. These science objectives are derived from the Mars Exploration Program Analysis Group (MEPAG) goals and the FAHRENHEIT mission report [26]. MEPAG Goal II, discussed in subsection 4.1, focuses on providing environmental data including temperature, pressure and wind velocity. The understanding of the Martian atmosphere and climate is crucial not only to the success of future manned missions, but also to understanding the dynamics of the planet better. The current exploration of Martian atmospheric sciences are from measurements from orbit as well as from the surface. The Mars Atmosphere and Volatile Evolution (MAVEN) mission is an orbiter that used a Magnetometer, Spectrometers, and many more sensors to determine the role of a loss of volatiles from the Mars atmosphere [27]. In addition, the InSight Lander, on the surface, provides in-depth atmospheric data. The pressure, temperature and wind sensors allow it to act as a singular weather station '[13].

However, current Mars exploration is especially limited in the resolution and the spread of that data over a large surface area. In addition, there is a need to obtain data over a longer time span in important locations. Therefore, the key problem in current martian atmospheric science is the lack of widespread data over a large area on the surface of Mars, inhibiting exploration goals.

Mars Surface Geology

The currently selected investigation is direct, close-up photography of water-indicating geological features e.g. Reccuring Slope Lineae (RSL), as well as young and old craters on the surface of Mars. With a focus on determining the origin of the RSL found on Mars. Presently, competing missions include orbiting satellites. The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) onboard the Mars Express spacecraft has previously performed measurements that indicate the presence of a large body of liquid water below the ice of the South Polar Layered Deposits. However, smaller bodies of water cannot be detected by this mission concept[28]. In addition, FREND is a neutron telescope onboard ExoMars Trace Gas Orbiter, and it has measured hydrogen abundance in the shallow subsurface but has a relatively low resolution of 200 km [29].

Ultimately, the research is conducted mainly through imaging, therefore a lack of resolution and perspective in the current orbiter capability is limiting prevalent science cases. Also, landers and rovers, such as InSight and Perseverance, are limited by inclination and area they can observe. Therefore issues in developing current surface geological science goals is the imaging on the surface of Mars from landers/rovers only provide a relatively small area of a few kilometers and Orbiters lack resolution. Both of these mission architectures do not provide imagery data over a large area, which is needed to advance the science objectives of surface geology outlined above.

Mars Internal Structure

Current investigations into the Martian Interior include exploring planetary precession, nutation and Love number k_2 using radio beacons and laser retro-reflectors [30, 31, 32]. In addition, planetary gravimetry, mantle plume strength and surface support mechanisms can be derived from radio beacons and laser retro-reflectors as well in order to understand the temporal evolution of mantle properties. Fundamentally, comprehending Martian interior structure and formation is key to understanding the formation of planets. Looking at different mission concepts that conduct alternative investigations, orbital missions are relevant for their capability to indirectly measure the gravity field of Mars. Furthermore, conventional landers could provide seismology similar to Mars InSight [31], and deployment of singular radio beacons such as RISE already has flight heritage [32].

However, many of the measurements required for the aforementioned goals are contingent on measurements from more than one point [33, 30]. Consequently, the shortcomings of competing missions has caused a need for the ability to generate RF and light-based geodetic data with cm-level precision over a large (> 5) number of points, ideally distributed over the order of thousands of kilometers. Another consideration is that, ideally, more than one radio beacon should be reachable at the same time from the orbiter used. In summary, the key problem for Martian interior structure science is a lack of an accurate (cm-level), large (> 5), and well-distributed network of geodetic data points.

3 Tumbleweed Mission Architecture

As introduced in the previous sections, the access to the Martian surface is severely limited, meaning that its exploration is the domain of large space agencies and organizations. Even organizations that are able to develop scientific payloads face selection pressure. Many research and commercial organizations do not have the resources to participate at all due to the high cost, high risk, large commitment of resources for development and expertise associated with the development of such a payload. The scientific community is further lacking solutions to survey and deploy sensor arrays over large areas on the Martian surface as well as explore regions currently inaccessible due to terrain characteristics, elevation or latitude.

The Tumbleweed mission architecture is able to address several of these limitations. The mission will open up Mars exploration to a wide audience and provide large-scale and previously inaccessible surface data through a cost-effective, accessible and low-risk mission to the Martian surface, utilizing a swarm of wind-driven rovers carrying a diverse set of customer payloads adhering to a standardized interface.

In the following, the high-level mission architecture is described to give an overview of the major elements in the mission and how they relate through all phases of the mission. For each phase key functionalities and requirements are defined. The realization of these functions is explored through the description of several systems and subsystem elements, with an emphasis on the surface rover system.

3.1 High Level Architecture

The high level mission architecture is discussed in terms of its logical architecture: the elements and segments in the following sections.

The high-level architecture and its logical constituents (elements and segments) are defined in this subsection. These items, their interactions and their tradeability, are presented in Figure 2.

As shown in Figure 2, the mission consists of a space segment, including the payloads which interact with the mission subjects to fulfill the mission objectives, and the Spacecraft Bus (SCB), supporting the payload. The space segment of the mission is integrated into the Entry & Descent Vehicle (EDV) of the parent mission, which also includes the transfer and launch vehicles. Furthermore, the space segment interacts with the relay satellite to transmit data and receive commands, which in turn interacts similarly with the communications, command and control segment. As a result, the mission ground segment, consisting of mission operations, receives the data and passes commands to the communications, command and control segment, and interacts with the end user.

Note that these later systems are depicted outside the system boundary for this report, indicating that supporting systems, such as the relay satellites, are assumed to be existing and available. In reality, they might have to be developed as part of the mission. However, such systems already exist, and are thus not further discussed in this paper. A detailed account for a communication system design supporting a Tumbleweed mission can be found in [34].

There also exists an additional, non-functional segment - the trajectory segment. It consists of the launch and transfer trajectory to Mars, the entry and landing trajectory to the surface and the rolling trajectory on the surface.

The following list describes the mission outline & timeline, and their various purposes of each mission phase:

1. Launch: the space segment is launched with a respective launcher to orbit.
2. Transfer: the mission is given and completes a trajectory towards Mars.
3. Entry & Descent: the EDV enters the Martian atmosphere.
4. Separation: the aeroshell and heat-shield separate from theEDV.
5. Deployment: the Tumbleweed rovers are deployed from the EDV.

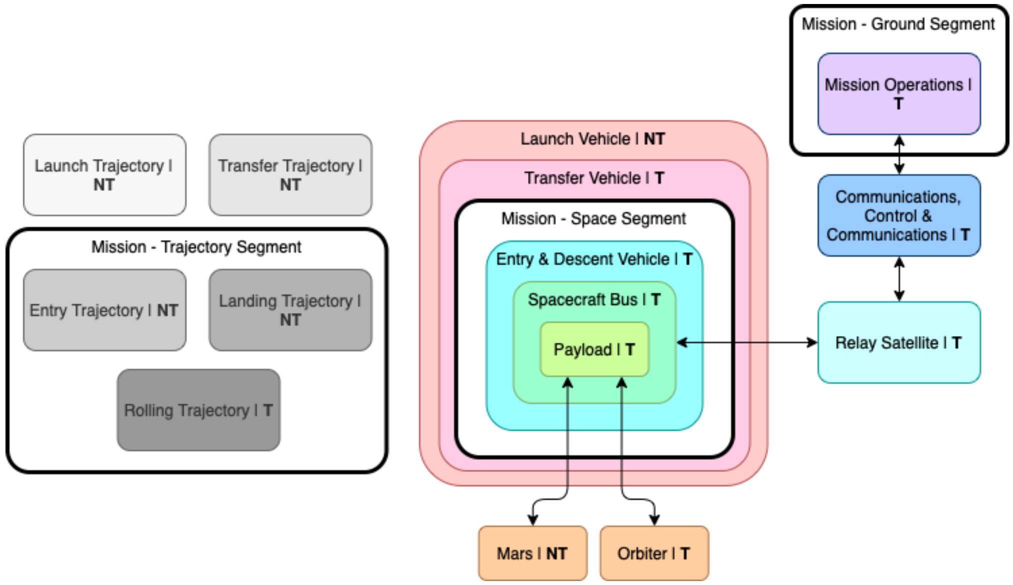

Figure 2: The logical architecture of the Tumbleweed mission. The thick black lines show the systems boundary of the mission, and T stands for tradeable, whereas NT stands for non-tradeable.

6. Unfolding: the individual rovers unfold from a stowed configuration to fully deployed.
7. Landing: the rovers land on the Martian surface.
8. Mobile Operations: the Tumbleweed rovers traverse the Martian surface collecting data and spreading out. The mobile operation is currently estimated to be three months long.
9. Stationary Operations: the Tumbleweed rovers arrest motion and collect data at stationary points across the Martian surface.
10. Decommissioning: the mission hardware is safely disabled and disposed for planetary protection.

These phases can also be recognized in Figure 3, which depicts the concept operations of the mission.

3.2 Functionalities and Requirements

To specify how each of the elements should perform together to fulfill the mission objective, functions define what they should do. The Tumbleweed mission is divided into the following 8 functional mission phases.

- F1 - Development
- F2 - Manufacturing & AIT
- F3 - Launch
- F4 - Transfer to Mars
- F5 - Entry to Mars
- F6 - Operations Mobile
- F7 - Operations Stationary
- F8 - Decommissioning

The Tumbleweed mission can, as the most scientific space missions, be divided into scientific pre-operational, operational and post-operational mission phases. During the pre-operational phase the mission elements are launched into a trajectory towards Mars. When the transfer is completed, the system enters the Martian atmosphere and starts to decelerate. The rovers are deployed and the operational phase can begin.

The operational phase of the Tumbleweed mission consists of two parts. The first phase consists of mobile operations. There a swarm of approximately 90 rovers move, propelled by the wind, across the Martian surface. By deploying them mid-air during the terminal phase of the entry and descent procedure, an initial rover spread can be created. Using the Martian winds the rovers are able to spread themselves further over the Martian surface. The second phase consists of stationary operations. After the desired distribution of rovers across the Martian surface is reached, the mobile phase terminates. The rover's motion is disabled and their position is held. This leaves the Tumbleweed mission system as a network of stations that are able to perform science that the rovers cannot perform during the mobile phase. The science capability of the architecture is explored in section 4.

The current baseline includes 90 rovers to strike a balance between individual rover performance and total size swarm performance. Bringing too many rovers limits their size, and by extent their capability to provide scientific data. Bringing too few reduces the benefits gained from the swarm architecture, that are further explored in section 4.

After the operational phase, the post-operational phase starts. This consists solely of the decommissioning of the

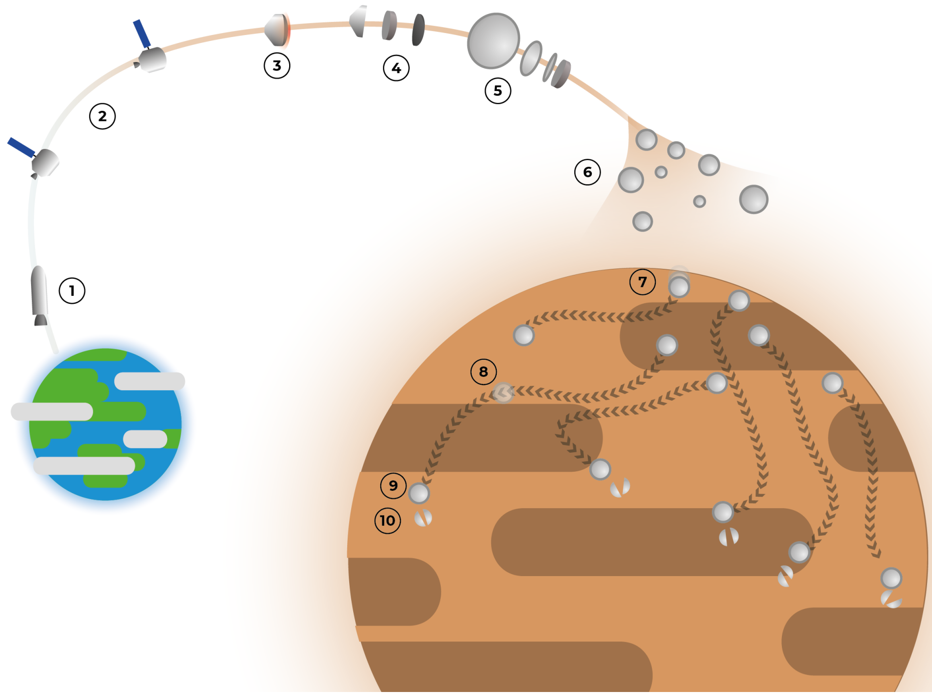

Figure 3: Tumbleweed Mission Architecture Concept Operations.

rovers. This section focuses on inerting the rovers.

3.3 Mission Elements

The Tumbleweed mission's space segment consists of several elements. These products can be seen organized in Figure 4, depicting how they relate to each other. Note that supporting systems are out of the scope of this paper, as explained in subsection 3.1. The rover, the focal point of the mission, and its elements are discussed separately in subsection 3.4.

Transfer Vehicle

During transfer to Mars, the transfer vehicle is tasked with providing power and communications, but also attitude control and propulsion, as well as possibly thermal management to the spacecraft. The latter aspects of the transfer vehicle's functionality are not clear yet, as they may also be realized within the entry stage & stack. However, for the purpose of the following analysis, they are assumed to be integrated in the transfer vehicle.

During transfer, the modules attaches to the tip of the conical entry stage & stack. The module is jettisoned shortly before entry into the Martian atmosphere, as is standard practice for Martian surface missions.

Entry Stage & Stack

The entry stage & stack houses the folded Tumbleweed rovers for the duration of the transfer. Its main function is to protect the stack of rovers during entry into the Martian atmosphere. To manage the high heat associated with entry, the entry vehicle features a conical design, with a heat shield on the blunt side of the vehicle. To further reduce velocity during Mars entry, the entry stage & stack is equipped with one or more parachutes, which are deployed from the back side of the entry vehicle. The heat shields are jettisoned once no longer needed after the ballistic entry phase is complete to allow for the stack of the Tumbleweed rovers to be deployed.

3.4 Rover

The individual rovers of the mission are spheroids 5x5x6 m in size, with an all-up mass of only 20 kg. They house the scientific payloads, as well as various electronic and electrical systems. Propelled by wind, the rovers are individually designed to cover around 5000 km over the course of the mission. Ahead of their deployment on Mars, the rovers are folded into flat disks, stacked and housed inside the Entry Stage & Stack.

The structure of the Tumbleweed rover consists of three elements: the shell, the sails, and the pods. The shell of the rover forms the spherical structure. From a functional perspective, it provides the rolling surface, mounting to all other systems and structural integrity. Furthermore, the shell must be collapsible for transfer and then capable of unfolding in mid-air during deployment.

The shell consists of interconnected, rigid, curved beams, called arcs. These arcs together give the rover its spheroid shape. They must be sufficiently rigid to assure good rolling behavior while also meeting stringent mass limits. Furthermore, the positioning of these arcs has a large influence on the rolling behavior of the rover and the way the shell may be folded. The shell interfaces with the sails, which are directly attached to the radially inwards side of the arcs, and the pods.

The sails provide the propulsive force to roll the Tumbleweed rover on Mars. They must also be capable of providing mounting to the solar array of the rover. The shape and arrangement of the sails greatly influences drag coefficient and overall drag that the rover experiences through the wind. Hence, maximizing the drag is paramount to optimizing the performance of the rover. The drag force must be roughly constant, irrespective of rover attitude. Additionally, sails might be designed to be lift-generating, similar to sails on sailboats, to provide additional force.

The pods house the other rover systems, including the scientific instruments. On each rover, one or more pods are mounted, which are expected to be 30 x 30 x 10 cm in size. These pods consist of a compartment for all rover systems which also forms the structural backbone of the pod (the 'mainframe'), and the scientific payloads are mounted to the outside of that mainframe. The scientific payloads are covered with non-load bearing fairings (the 'covers'), enabling cutouts to be created within these covers to enable various interfaces between the scientific payloads and the Martian environment. Having multiple pods allows for imrpoved mass distribution and more control in thermal design.

Furthermore, as part of the pods, the thermal system manages the internal temperature of the individual systems. Current analysis suggests that this system consists of heating elements, and radiators with an adjustable heat conduction path from the systems and scientific payloads to the radiator and the heating elements. This allows for excess heat to be dissipated during the day, and for maintaining internal temperatures during the night. The thermal interface to the scientific payloads is part of the standardized scientific payload interface.

The mainframe of the pods stores the electrical and software system. The latter is the congregation of all non-structural subsystems of the spacecraft bus of the the Tumbleweed rover. It is responsible for the autonomous operation of the rover which entails power supply, sensing rover health and environment, command and control of all subsystems and payloads, data storage and processing and communication. Computational capabilities are provided by the Onboard Processing Computer (OBC) and the Data Processing Computer (DPC). For data sensing, the Onboard Sensors (OBS) are responsible, including both engineering and housekeeping data of the rover itself and external scientific context data. The Electrical Power System (EPS) and the Photovoltaic Array (PVA) are responsible for power generation, condition, storage and distribution. The Mechanisms Activation (MA) activates the mechanisms of the rover namely trigger unfolding and End Of Life (EoL) mechanisms. Finally, the communication with an outside station, a communications relay in Martian orbit [34] is fulfilled by the Transmit and Receive Module (TRM).

4 Mission Payload and Utility

The Tumbleweed mission presents scientific opportunities not possible in the current design of conventional Mars surface missions. It therefore contributes in a unique way to the scientific goals defined by NASA's Mars Exploration Program Analysis Group (MEPAG). The impact of the Tumbleweed mission on these goals will be discussed in subsection 4.1, followed by the payload instruments employed to advance these goals in subsection 4.2.

4.1 MEPAG goals

The Mars Exploration Program Analysis Group (MEPAG) defines the science Goals, Objectives, Investigations, and Priorities related to the exploration of Mars. Within each Goal, Objectives are established that contain the knowledge, strategies, and milestones necessary for success. Investigations make up the tasks for each sub-objective within an objective. This completes the four-tiered hierarchy: Goals, Objectives, Sub-Objectives, and Investigations. Within each goal, prioritization is distributed to the investigations to influence which should be conducted first.

The MEPAG Goals are divided into four major scientific categories: Life (Goal I), Climate (Goal II), Geology (Goal III), and Preparation for Human Exploration (Goal IV). The Tumbleweed mission focuses on advancing the latter three Goals. It is important to note that these goals are not disjoint - fulfilling investigations from separate goals can contribute to one another.

Goal II: Climate on Mars

Goal II has the aim of understanding the processes and history of climate on Mars [12]. This involves characterizing the processes of Mars' climate in the present-day, in the recent past, and in the distant past. The Tumbleweed mission contributes significantly to this goal: it allows for much higher spread, as well as long-duration regional and global presence, and a large quantity of data that can be gathered by a swarm of rovers. The Tumbleweed rovers

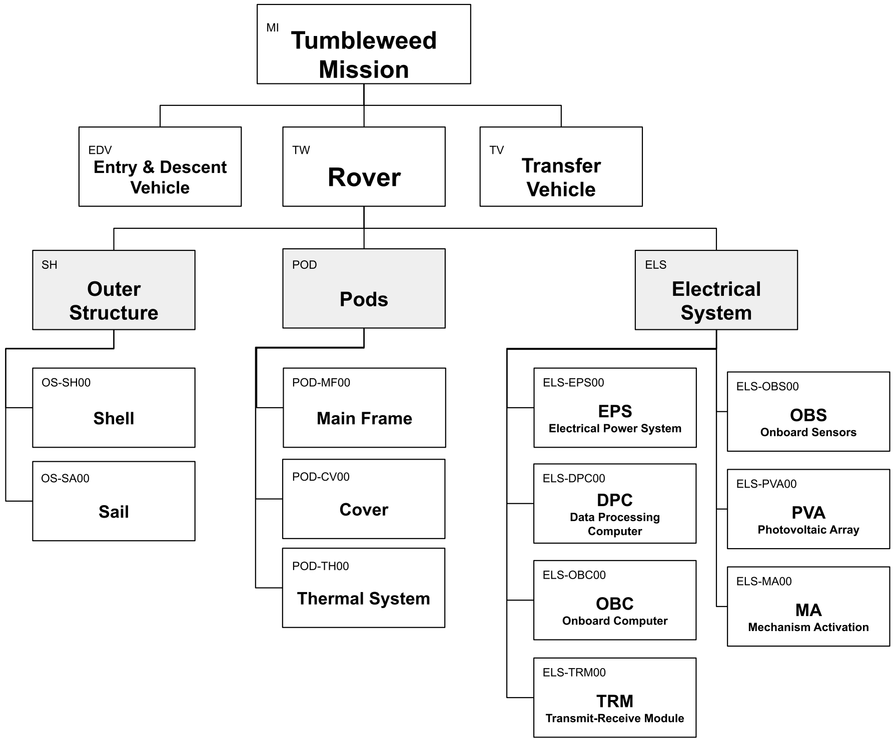

Figure 4: Preliminary product tree of the Tumbleweed mission.

can also be used to complement the orbit measurements by providing a distributed weather station network.

Goal III: Martian Geology

Goal III relates to understanding the origin and evolution of Mars as a geological system [12]. This involves investigation the geological composition of the crust, as well as the dynamics of the interior and its evolution over time. Furthermore, the origin and geological history of Mars' moons is also of importance. The value of the Tumbleweed mission towards this goal follows similarly to as explained above. The use of multiple Tumbleweed rovers allows the possibility to investigate many local areas at a high resolution to detect smaller geological features that may indicate liquid water. Furthermore, the mobility of the Tumbleweed allows the study of e.g. recurring slope lineae and craters. Finally, covering a remarkable amount of surface area over the mission duration also allows the possibility of studying sizeable geological features that could not be investigated with a conventional surface mission.

Goal IV: Human exploration

Goal IV represents, "prepare for human exploration" [12]. This final goal involves the determination of suitable landing sites and surface exploration locations, as well as the possibility of in-situ resource utilization of the atmosphere and/or water on Mars [12]. Furthermore, ensuring that biological contamination and planetary protection protocols can be maintained is also an objective. While current Mars orbiters serve to locate new areas of interest, Tumbleweed rovers can provide atmospheric and geological data to such areas, as well as new ones, to aid in the prioritization of mission planning.

4.2 Payload instruments

To advance the MEPAG goals relevant for the Tumbleweed mission, a set of payload instruments is necessary. Specific instruments have been selected based on the contributions to these goals, including: a radiobeacon, a laser retro-reflector, a set of atmospheric sensors, and cameras.

Radiobeacon

The inclusion of a radiobeacon is a consequence of the proposition of the **I**n-situ **MA**rs **G**eodetic **I**nstrument **NE**twork (IMAGINE), discussed in [35]. Through the use of two-way time-of-flight and Doppler shift measurements, navigation of the Tumbleweed rover can be achieved. This allows for the investigation of Mars' internal structure and formation, such as the existence and strength of convective mantle plumes [35], furthering the knowledge in the third MEPAG goal.

Laser retro-reflector

Without knowing the location in which a dataset was taken, the data itself loses value. For this reason, a laser retro-reflector is mounted to provide precise geo-referencing to the Tumbleweed rover. These instruments reflect incoming radiation (laser) back to its source, allowing tracking and ranging of the Tumbleweed rovers to be performed, as well as orbit calibration and determination for orbiters. The inclusion of a laser retro-reflector helps all MEPAG goals, especially the determination of surface exploration locations.

Atmospheric sensors

Atmospheric sensors are mounted to further the second and fourth MEPAG goals, the knowledge of the Martian climate and habitability. The inclusion of a pressure sensor, temperature sensor and humidity sensor aim to study the fundamental atmospheric properties. Furthermore, given that wind speeds on Mars can reach hundreds of kilometers per hour, a wind sensor is also included. The last atmospheric sensor is an optical sensor to measure direct solar irradiance and diffuse light on the Martian surface. The latter converts electromagnetic radiation to an electrical signal to determine the amount of incoming light.

Cameras

Cameras are arguably the most valuable instruments in any payload ensemble. Being able to take images beyond the visible spectrum allows the study of the composition of the Martian regolith, contributing to the third MEPAG goal. Normal images help to determine suitable landing sites and surface exploration locations (MEPAG Goal IV), as well as for public interest back on Earth.

5 Demonstrator

To gain further insight into the behavior and performance of mission systems and as a high level concept validation step, a half-scale prototype rover was constructed. The previous two versions before the half-scale prototype were of smaller scale and basic proof of concept prototypes. Therefore, they are not presented further in this paper. Other objectives for the demonstrator are testing the performance of concepts for rover subsystems, such as the structural and rolling performance of the shell, aerodynamic performance of the sails and efficiency of the resting system.

First, the Earth-scale demonstrator is described in more detail. Then, the different tests performed on the demonstrator are described and their results stated.

5.1 Earth-Scale Demonstrator

The half-scale demonstrator's structure is made up of the components described in subsection 3.4: the shell (the main structural component), the sails (required to be able to use the wind as locomotion) and the pods (component housing the electronics). The following key requirements were set for the demonstrator's development:

- Keep the structural integrity of all elements during all mission phases (transfer, folded, unfolded and rolling).
- Withstand the emerging forces when rolling.
- Sustain a consistent and quasi-linear rolling path.
- Prove the basic feasibility of this specific Tumbleweed rover design, featuring tetrahedron sails and two electronics pods.

The overall shape consists of 6 interlocking rings, based on a tetrahedron. At eight of the nodes, three rings meet symmetrically spaced 60 degrees apart, whilst at the other 6 nodes, only two rings meet, 90 degrees apart. Each of the ring segments consists of an arc. The arcs are made out of a foam with glass-fiber strands embedded within and a glass fiber shell around the foam. The glass fiber itself is soaked and cured in epoxy resin, making the structure very rigid. The 3-ring nodes consist of a metal 3D printed hub that allows the mating end of the arcs to be connected. The 2-ring nodes consist of a PVC tube embedded trough the middle of one, double-length arc, that allows two shorter arcs to mate with it. The arcs are kept in the nodes using the tension force provided by a rubber tube, looped around hooks on each arc-end. Figure 5 showcases the structure of the demonstrator.

Figure 5: Earth-Scale Demonstrator at Mars Analogous Mission.

The sails are mounted to each of the 6 double-length arcs on one side, and joined using string loops to two other sails, pulling each other in towards the center of the demonstrator. A reefing system is in place allowing the sails to retract. This is realized by rubber elastic tubes pulling the sails in. The strings joining the sails together resist this motion, until released using the actuation of a servo motor.

The electrical components are stored in two pods on opposite sides of the demonstrator, mounted to the inside of two arcs. One of the pods holds the battery and power supply electronics. The other one houses the rest of the electronic systems, for example: a magnetometer, a gyroscope and GNSS tracking sensor. Furthermore, a camera is mounted to each pod, facing radially outwards.

5.2 *Mars Analogous Test*

The Earth-Scale demonstrator was tested in a Mars Analogous Test in the Negev Desert in Israel. In preparation for the Mars Analogous Test, multiple testing phases were performed. First, field tests showed the functionality of the demonstrators ability to be built up from a set of protocols, and also tested its rolling behavior on solid ground. Furthermore, a test was performed in a wind tunnel in order to demonstrate the resting system. In this test, the mounted solar panels on the sails had to be dismantled, which was done in the Mars Analogous Test as well. The solar panels were not tested for the structural capabilities in these tests, making it a limitation in the results of this prototype. Further results from this test showed that the prototype started to roll at windspeeds between 3 and 5 m/s depending on its orientation. Also it is important to note that the maximum usable speed was 7 m/s, as the structure could not be stopped by the resting system if the wind speed exceeded this threshold. Thus giving the the Earth-Scale demonstrator only a narrow window to test in, considering the wind speed. This was then confirmed by the final test in Israel, showing that future designs need to be even more light-weight.

The Mars Analogous Test was performed in October 2021, in collaboration with ÖWF (Austrian Space Forum). In a three day test-mission, multiple members of ÖWF acted as analog astronauts who were receiving orders from their ground station, which was a small team of members from Team Tumbleweed. A protocol was given to ÖWF, and with online communication with Team Tumbleweed, the demonstrator was able to be built on-site. The Tumbleweed rover was then tested in a Mars-like desert to test basic operational concepts and evaluate the structural performance of the outer structure, as well as quantify degradation caused by motion across a mars-like surface. In the end, 10 complete test runs were performed. A test run is defined as:

- Building up the demonstrator on-site.
- Setting up the electronics and preparing the resting system.
- Releasing of the demonstrator into the Martian and to have it roll across the desert surface.
- Collecting measurements as the demonstrator is moving.
- Actuating the trigger of the resting system and letting the demonstrator come to a halt.
- Shutting off of the electronics to stop measurements.

The measurements taken during each measurement run were accelerometer data internal to the Tumbleweed as well as imagery from the outside as it rolled. Furthermore, the arcs were inspected before and after the test runs. The result of these test runs showed that the structure, optimized for high stiffness in order to maximize rolling efficiency, had several key issues. While it worked well overall, the structure proved susceptible to high-frequency bouncing as a result of the gaps between the arcs. However, this bouncing was observed only for some axes of rotation, where the length of the gap excited the resonant frequency of the rover. This exacerbated the bouncing to the point of partial structural failure. This was unexpected, as in static tests and shorter test runs the structure had fared well.

Based on this result, the following design changes were made for the next iteration of prototype: firstly, the rigidity of the structure will be reduced greatly to lower the natural frequency to a point where it will be more easily controlled through dampening effects of the structure itself and the sails. Furthermore, the structure will be elongated along one rolling axis and there will be a mass offset in order to attain rolling along only one axis. This in turn will allow for regular spacing of arcs along this axis, leading to better control of rolling dynamics.

Furthermore, there are additional technical challenges not yet proven with this design. The key objectives for the next prototypes are:

- Demonstrating a fully self folding mechanism.
- Joining solar sails with flexible sails that need to be retracted.
- Assuring a consistent and linear rolling path around just one rolling axis.

Achieving these goals will then ultimately contribute to maturing the Tumbleweed rover technology towards a Mars mission.

6 Discussion

We show that the Tumbleweed mission is able to provide a cost-effective solution for sending scientific payload to Mars, due to firstly using the wind as a method of locomotion, which allows for a light-weight structure, and secondly for the structure to be foldable and therefore efficiently packed into spacecraft volume limitations. Mid-air deployment enables a significantly simplified landing method compared to conventional rovers. In comparison to conventional rovers, by using the wind as a method of locomotion, it is able to increase the scientific payload mass per total mass of the mission, and its simple design using sails allows it to also have a reduced cost per payload mass. Current payloads, like instruments as seen in section 4.2 are also easily integrable into the mission which reduces the development cost and risk of the mission. The swarm design is able to reduce the risk of the mission as it allows a small amount of rovers to fail without compromising all of the scientific data collection. The modularity of the Tumbleweed rover to be used for various instrumentation also allows the rover design to be easily reused in several types of missions.

Furthermore, the Tumbleweed mission is able to meet three of the MEPAG goals effectively. It is able to gather this data at a larger, more dispersed area than current rover designs and provides to ability to record close-up photographs and measurements from the surface - something that orbiters are inherently unable to offer. In its stationary phase, it is also able to gather detailed information regarding several specific surface locations over a larger period of time, which is not possible with singular rover missions.

The results of the Mars Analogous Test shows that it is possible to create a simple and lightweight prototype which is able to withstand a similar mechanical environment as Mars.

In comparison to alternative Mars surface missions, the Tumbleweed mission is not focused on one of the main MEPAG goals, Goal 1 which is interested in finding life on Mars. This is due to the limitations which the current design offers in terms of using in-situ instrumentation. However, it can be argued that the mission improves greatly on the other MEPAG goals effectively enough to justify its independent purpose for scientific value. However, the Tumbleweed mission has several critical technology dependencies. The critical items to increase the technology readiness level (TRL) of and to validate is include the foldability, the power system and the communications architecture. Furthermore, the Mars Analogous Test is not able to prove all of the required key requirements in order to prove the manufacturability and mechanical properties of the rover.

As complete Risk and Failure Mode Effect & Criticality Analysis (FMECA) is outside the scope of this paper, we have refrained from touching upon the risks of the tumbleweed mission. However, a few key risks must be pointed out. the Tumbleweed failing to unfold upon deployment presents a large risk as it likely results in the complete loss of the rover. It can only be mitigated by reducing the likelihood of occurrence. Other major risks are a rover getting stuck during sand and dust storms/gusts and structural damage to the shell and sails during storms. It's worth pointing out that as the mission consists of a large swarm of rovers, the total impact of the loss of a single rover is reduced. This means the swarm architecture functions as a mitigation strategy to certain risks.

The potential of the Tumbleweed mission to deploy large numbers of sensor on Mars at low cost and in a scaleable manner offers unique opportunities. It has applications in a whole host of science fields on Mars, including surface geology, the planetary interior and its atmosphere. Furthermore, it has the potential to open up Mars exploration to a wider array of organization by virtue of its low cost and scale-ability. The tests performed on Earth, reflecting previous work, show the general feasibility of the Tumbleweed rover in a Mars-like environment.

We recommend that further work be done on development of this technology. The risks of this type of mission need to be better understood and systematically evaluated to conclusively show the low-risk nature of swarm-driven exploration. Moreover, further prototyping and other derisking efforts must be performed in order to continually mature the technology towards a Mars mission. Also, the design of future Tumbleweed rovers should necessarily include provisions to guarantee one singular axis of rotation, and special attention must be paid to the dynamic behavior of the rolling rover.

7 Conclusion

The Tumbleweed mission presents the opportunity for many research and commercial organizations, as well as the scientific community, to participate in the exploration of the Martian surface through low-cost, wind-driven, Tumbleweed rovers. Current, conventional Mars surface missions design are limited in its ability to further the knowledge towards NASA's Mars Exploration Program Analysis Group (MEPAG). There is a need for better resolution and spread of data over a large surface area temporal datasets. These are the shortcomings that the Tumbleweed mission aims to rectify.

The mission consists of a swarm of individual spheroidal Tumbleweed rovers 5x5x6m in size, with a total mass of only 20 kg. Propelled by wind, the rovers are individually designed to cover around 5000 km over the course of the mission. Ahead of their deployment to Mars, the rovers are folded flat into disks, allowing numerous rovers to be launched on a single launch vehicle. With a payload package consisting of a radiobeacon, a laser retroreflector, atmospheric sensors and cameras, advancements can be made towards the MEPAG Goals II, III, and IV: Climate, Geology and Preparation for Human Exploration. Phenomena such as recurring slope lineae and convective mantle plumes now present themselves to be studied in-situ on the Martian surface with the Tumbleweed mission architecture.

When the technologies are developed and proven, this mission offers an alternative platform for researchers which is able to carry instrumentation and collect data at a wider spread than any other alternative mission concept currently. The Tumbleweed mission offers the opportunity to make deep space accessible for everyone by enabling novel Mars data sets through low-cost rover swarms.

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