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Identification of Human Landing Sites on Mars with a Swarm of Wind-Driven Mobile Impactors

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Abstract

Interest in human missions to the red planet have seen a spike over the past two decades. However, future human Mars exploration missions require not only the development of advanced technologies but also the collection of extensive, planetary-scale datasets of Mars, which are not met by current mission concepts. The timeline towards settlements on Mars can be accelerated through a swarm of wind-driven mobile impactors to systematically explore the Martian surface on a large scale for sites with a high interest of resources, scientific interest, and safety for a human exploration mission. The Tumbleweed Mission is a low-cost Mars surface mission using a swarm of wind-driven mobile impactors to generate planetary-scale, long-term surface datasets of Mars. It is used to scout a variety of areas of Mars and identify potential landing sites while bringing down the cost of robotic Mars exploration significantly. This paper aims to investigate the use of such rovers to prepare for human exploration of Mars. A science case is developed to obtain relevant data regarding surface and climate characteristics, as well as landing site properties. First, the architecture of the Tumbleweed Science Mission is provided for context, followed by the requirements, constraints, and capabilities of a Tumbleweed Rover swarm with regard to the characterization of landing sites for human mission potential. Such rovers allow greater flexibility and distance in exploring a plethora of sites on Mars as their ability to maneuver through rough terrain provides global coverage of the Martian surface. Various sites can be categorized for their potential to harbor human missions and infrastructure by measuring the quantity of resources and water, as well as surface material composition. The in-situ assessment of atmospheric and climate properties to measure the atmospheric and near-surface dust population provides essential knowledge on the safety of landing sites. In addition, taking terrain measurements such as altitude, rock distribution, and roughness ensures the safety of potential landing sites. The characterization of various sites across different latitudes and longitudes using Tumbleweed rovers provides a better understanding of such sites for human exploration with regard to three main factors: in-situ resource utilization, scientific interest, and safety. As a result, we consider the Tumbleweed science mission to be feasible to survey various areas of Mars and characterize them for human landing sites. The data obtained will be used to better prepare for the human exploration and settlement of Mars.

Keywords: Mars, Tumbleweed rover, human exploration zone, planetary scale, surface data set, low cost mission

1 Introduction

Throughout the span of human history, the quest to expand our horizons beyond our home planet has been a pursuit fueled by curiosity, scientific discovery, and the indomitable spirit of exploration. Mars in particular has amassed tantalizing interest over recent years; the allure of Mars as a potential site for human exploration and even habitation has grown exponentially, driven by a confluence of scientific, technological, and inspirational factors. As we are nearing the decade that shall see the first crewed mission to Mars, the selection of landing and exploration sites is an issue that must be thoroughly addressed. Before landing humans and infrastructure for Mars exploration missions, a comprehensive understanding and analysis of various Martian sites, particularly potential landing and exploration zones, is imperative. The first Human Landing Sites Study (HLS^2) workshop held by NASA in 2015 defined human exploration destinations on Mars as Exploration Zones (EZ). Specifically, an EZ constitutes a set of regions of interest (ROIs) located within a 100 km radius of a landing site (LS) at its center at a latitude band between $\pm 50^\circ$ [1]. The habitation site within the EZ is confined to a 5 km radius of the central landing site. ROIs encompass both scientific areas of interest and regions rich in resources conducive to sustaining human presence on Mars.

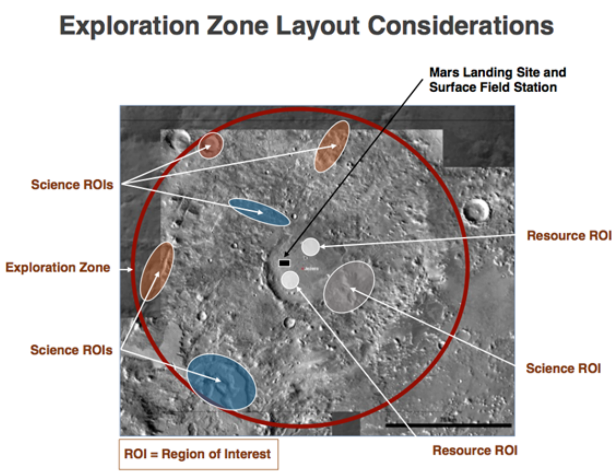

Figure 1: Example depicting Jezero crater as a Mars exploration zone with science and resource ROIs outlined. [1]

Science ROIs must display notable interest to astrobiology, atmospheric science, and geoscience. On the other hand, resource ROIs should display promising indications of mineable metal resources, particularly iron, aluminium, and silicon, within 1 to 2 meters beneath the surface. Notably, at least one potential water resource feedstock must exist within 3 meters or less beneath the surface of the EZ, located no more than 3 kilometers away from in-situ resource utilization infrastructure. This water resource should be extractable by automated systems in a mineable form, possessing adequate extractable water to support around 5 missions or 100 megatons. Adding to the challenge, an EZ spans approximately 200 times the size of the landing ellipses utilized for robotic Mars missions, with inter-ROI traverse distances exceeding those covered by prior and current rovers.

A single EZ will not be explored by a single human mission, but multiple missions will land there to scout the EZ and may perhaps make multiple returns to ROIs; this will lay the groundwork for a future permanent base [2]. The HLS^2 workshop yielded the identification of 47 potential candidate sites. Some of the most promising EZs lie within the Arabia Terra region, an upland area located in the north of Mars [2]. Arabia Terra boasts an intricate geological evolution and a surface morphology of significant scientific appeal.

Thorough site selection relies on robotic missions to acquire pertinent measurements for human safety and to pinpoint the safest and most scientifically intriguing zones on Mars. The site selection process is multidisciplinary, depending on mission requirements, scientific goals, and a deep understanding of Martian geography and resources. Remote sensing data from orbiters and surface data from landers and rovers are required for this selection. However, the number of sites visited by spacecraft and thoroughly examined is still limited as only ten missions have successfully landed on the Martian surface. Landers offer measurements from a single stationary position, while traditional rovers are often intricate, costly, and relatively large systems constrained in their coverage of short distances. Aerial vehicles, such as the Mars 2020 mission's Ingenuity helicopter, face energy constraints and the challenges of Mars' thin atmosphere, restricting them to short distances. These missions, using landers, rovers, and short-flight aerial vehicles, are constrained to make thorough investigations within their vicinity and cover a limited area of the Martian surface. Although these platforms have contributed to our understanding of the viability of Mars' environment and surface for human exploration, a significant gap remains, stemming from these platforms' limited mobility and the historic lack of a primary focus on human exploration preparations until the Mars Science Laboratory [3]. As most of the potential exploration sites have not yet been visited, our knowledge of an ideal landing and exploration site with high scientific priority, sufficient extractable resources, and high safety for astronauts and equipment in the long term to sustain a habitat is still limited.

As the commercialization and democratization of space gain momentum, a new revolution in access to space has sparked in the previous decade; the costs of sending payloads to low Earth orbit have significantly lowered due to space transportation technologies that were improved and made efficient, such as the advent of reusable rockets. As heavy-lift rockets for interplanetary transport are being developed by private companies such as SpaceX and Blue Origin, the expenses for deep space and planetary exploration will inevitably be lowered in the near future. Consequentially, opportunities for more individuals, institutions, organizations, and companies to develop and launch novel concepts for planetary exploration will arise, revolutionizing the way in which we study our solar system. These opportunities and advantages can be fully amplified and harnessed through missions such as the Ultimate Tumbleweed Mission, which will be discussed in the following section.

This paper presents one of the science cases of the Ultimate Tumbleweed Mission, particularly the science case concerning the preparation for the human exploration of Mars. First, the Tumbleweed mission concept and architecture is presented, followed by an overview of in-situ studies on Mars for human exploration and safety. This is followed by the identification of the knowledge gaps, then the identification of the Tumbleweed's science objectives pertaining to the investigation and characterization of human Mars exploration sites. Next, a potential suite of instruments to be carried onboard to fulfill these scientific objectives is described. Finally, a discussion on the compatibility of the science case with the Ultimate Tumbleweed Mission will be discussed.

2 Tumbleweed Science Mission Architecture

Team Tumbleweed is a research organization devoted to the provision of access to deep space exploration through the development of a cost-effective lightweight spherical mobile impactor or rover. These rovers are wind-propelled "Tumbleweed"-style rovers, which have been previously investigated by NASA [4]. They are referred to as a "Tumbleweed Rover" (TW), intended to be deployed in a swarm for a 2029 mission called the Ultimate Tumbleweed Mission (UTM). The UTM aims to take a series of measurements across a wide coverage and mobility that has never been spanned by previous and current surface missions on Mars. The TW architecture enables wider access for institutions and organizations to Mars exploration and mitigates cost, risk, and resource levels associated with the exploration of Mars. In addition, it allows the collection of data throughout a large area of Mars and the visitation of areas on Mars with rougher terrain properties. This is made possible through a swarm of lightweight wind-driven rovers that can carry a myriad of payloads requested by customers. The phases of the mission architecture are illustrated in figure 2.

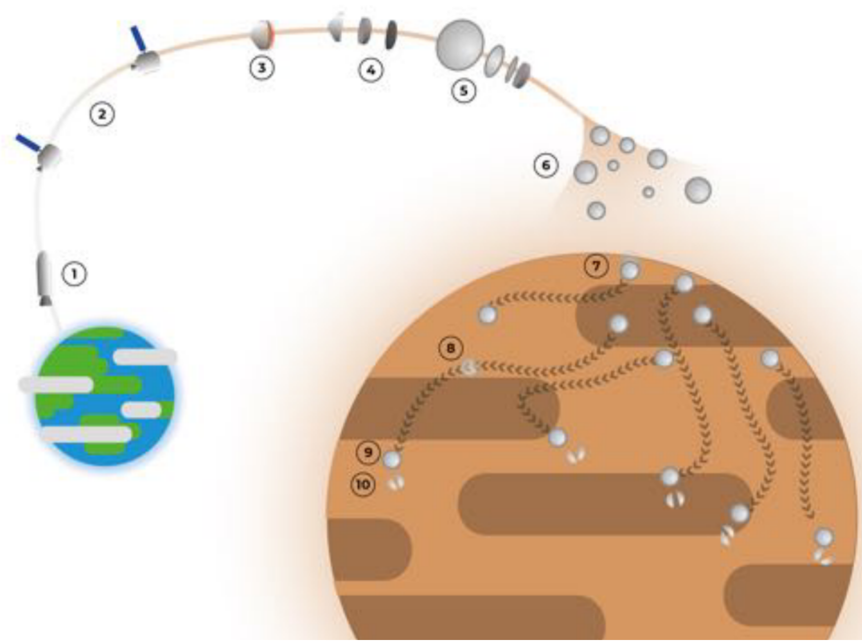

Figure 2: The Ultimate Tumbleweed Mission profile.

Following launch (1), the transfer to Mars (2), the jettisoning of the Entry and Descent Vehicle (EDV) from the transfer vehicle and its entry and descent through the Martian atmosphere (3), and the separation of the heat shield and aeroshell from the EDV (4), the rovers are deployed mid-air (5). Each individual rover in the swarm is then unfolded (6) and impact the Martian surface (7). Once on the surface, each rover spreads out across the surface through its mobile operations phase (8), whereby it gathers measurements as it rolls along. Following this phase, the rovers are then collapsed into a stationary phase in the configuration illustrated in figure 4 and gather further data at their respective destinations, acting as local measurement stations (9). At the end of the mission, they are disabled and disposed for planetary protection (10). A more detailed description of the mission architecture including mission elements can be found in [5].

3 The Tumbleweed Rover

Each individual rover is a spheroid with a diameter of 5 m when fully deployed, with a mass of not more than 20 kg including payload. Before deployment, they are stacked and housed in the EDV, where they are in a folded configuration.

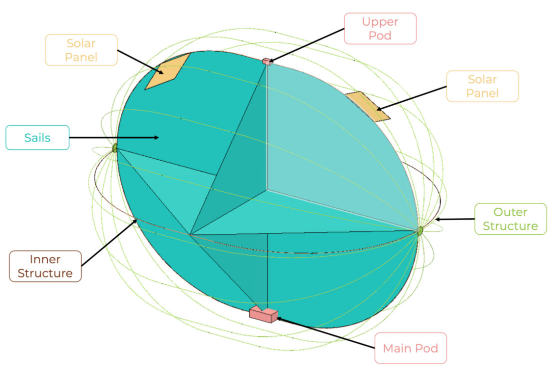

Figure 3: Simplified schematic of a Tumbleweed Rover.

The rover can be divided into three main parts, as depicted in figure 3: the shell, sails, and pods. The shell comprises rigid curved beams, or arcs, which dictate the rover's rolling characteristics. It consists of an impact-bearing outer structure and an inner structure designed to carry the payload. The rover's structure is to be deployable such that, when collapsed, the entire swarm of 90 Tumbleweed Rovers can be stacked on top of each other inside an entry-and-descent vehicle. The sails, taking energy from the wind, give the rover its driving force, are contained within the inner structure, and provide mounting to the solar panels. The pods house the rover's electronics and instruments. Each rover is equipped with at least one pod, which consists of a mainframe for its structural support. The scientific instruments are protected within the pod, with some instruments potentially being located at the side or bottom of the pod. The pods are covered by a non-load-bearing fairing. In addition, each pod consists of a thermal control system. The rover's electronics and software system are housed in the main frame. The electronics consist of an electrical power system (EPS) consisting of a solar array and a battery for power generation, storage, and distribution. Onboard sensors (OBS) gather scientific data and engineering data of the rover. The rover's computers comprise the Onboard Processing Computer (OPC) and the Data Processing Computer (DPS). The electronics also consist of a Mechanics Activation (MVA) to activate unfolding and end-of-life mechanisms. Finally, a Transmit and Receive Module (TRM) maintains communications between the rover and an external station or a communications relay satellite in Mars orbit. Again, a more in-depth description of the Tumbleweed rover can be found in [5].

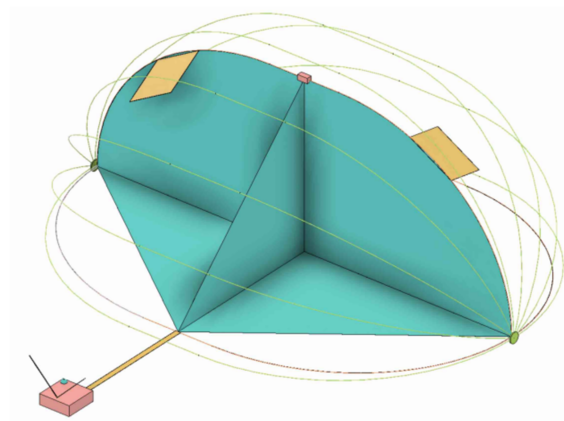

Figure 4: Simplified schematic of a Tumbleweed Rover in stationary configuration.

3.1 In-Situ Studies for the Preparation of Human Exploration

Bringing humans to Mars poses a large series of environmental and technical risks; this includes the entry, descent, and landing environment, surface properties, en-route and surface radiation, the feasibility of technologies, and the effect of the Martian environment and weather on technologies and infrastructure. Comparing the scientific goals and objectives of different Mars missions, the Mars Science Laboratory was the first mission in which studies for the preparation for human exploration were directly integrated into the main science goals [3].

The Phoenix lander, despite not investigating conditions for human exploration as its primary goal, made a significant discovery. Its MECA (Microscopy, Electrochemistry, and Conductivity Analyzer) and TECP (thermal and electrical conductivity probe) payloads studied the bulk properties of Martian regolith. Martian regolith poses no apparent hazards, is structurally competent, disperses easily, and is devoid of particles fine enough to pose an inhalation threat. It however, contains perchlorate ions, which are toxic to humans [6]. Perchlorate can also be present in ground ice, which poses a risk to in-situ resource utilization if the same amount of perchlorate in this ice were present as in dry regolith. Oxygen, however, can be mined from perchlorate.

As aforementioned, the Mars Science Laboratory was the first mission in which studies for the preparation for human exploration were directly integrated into the main science goals [3]. The science goal pertaining to human exploration in particular is to take detailed measurements of and characterize the radiation environment on the surface of Mars, both in the atmosphere and in the regolith. Using the Radiation Assessment Dosimeter (RAD), the energetic particle spectrum on the Martian surface was characterized, radiation dosage rate, and radiation hazards for human missions to Mars [7]. Measuring the subsurface radiation environment relates to the future of settlements on Mars as regolith is considered the primary candidate to produce radiation shielding materials for astronaut habitats. RAD was built to detect the most harmful energetic particle radiation, both charged and neutral, to human and microbial life on the surface of Mars.

Mars 2020 (Perseverance) presented more goals that are tied to the future human presence on Mars and features a collaboration between NASA's Science Mission, Human Exploration and Operations, and Space Technology directorates [8]. It carries the MEDA (Mars Environmental Dynamics Analyzer) instrument, which consists of six sensors to measure environmental factors. MEDA characterizes the near-surface Martian climate and measures environmental conditions across sites to gain an understanding of the micro-environments that astronauts will encounter [9]. It gives regular reports on Martian weather, near-surface humidity, wind patterns, and radiation, providing us with a more accurate weather and climate model. It is also able to characterize dust properties in great detail, which includes dust particle size and scattering phase function [8]. This gives us a better understanding of the effects of Martian dust on human health and equipment. In addition, Mars 2020 also carried the MOXIE (Mars Oxygen ISRU Experiment) instrument as the first demonstration of In Situ Resource Utilization (ISRU) technology beyond Earth. The instrument was designed to extract oxygen from the carbon dioxide-rich atmosphere as a first step of propellant production in future human Mars missions. The instrument was a success and proved that it is scalable and quality and efficiency requirements were met [10]. However, its resilience and long-term durability in the Martian environment are yet to be investigated further. Finally, 5 spacesuit materials are carried as calibration targets for the SHERLOC instrument and to study their decomposition after long-term exposure to the Mars environment [11]. The degradation of these materials, namely Polycarbonate, Orthofabric, nGimat coated Teflon, Dacron, and Teflon glove material, will give insight into Mars EVA spacesuit design as well as crew safety. Despite the incorporation of human exploration preparation goals into the science cases of these missions, the in-situ characterization of the Martian surface for human exploration is still limited as the integration of these goals is relatively recent.

3.2 Human Exploration Science Goals

As identified in section 3.1, there still remains a significant gap in knowledge pertaining to human exploration zones, such as safety, habitability, and resource abundance. In addition, as Mars exploration is currently limited to landers, traditional rovers covering a limited range, and aerial vehicles such as Ingenuity with short flight times, there is no method currently on the surface to collect data from an extensive surface area across Mars. There are a significant number of potential landing sites for human crews and settlements on Mars, of which a vast majority have not yet been explored. MEPAG defines the current goals or themes in Mars exploration (studying past and present life on Mars, understanding its climate, its geological history, and preparing for human exploration). The MEPAG objectives of Goal IV ("Prepare for Human Exploration") accurately summarizes the current research gaps in Martian exploration [12] for human exploration zones. This goal consists of five objectives (studying Mars with regard to human landing, safe surface human exploration, ISRU of the Martian atmosphere and water, planetary protection in human missions, and missions to Martian moons), each with sub-objectives.

The Tumbleweed Rover aims to help fill the gaps and questions identified by MEPAG; this section explains the human exploration science goals for the Tumbleweed mission in accordance with MEPAG. As in-situ studies directly related to the human exploration of Mars are limited, there still remains a significant gap in knowledge in this field. Numerous potential landing and exploration sites for human missions on Mars have been suggested, of which a vast majority have not yet been explored. The climate of Mars needs to be understood further to produce more accurate dust storm forecasting results in order to land systems on desired sites when dust storms are certainly not present. Dust storms, in addition, affect surface operations and solar power collection. More in-situ measurements around various Martian sites of the atmosphere and near-surface atmosphere are to be taken in order to improve weather and climate models to accurately predict Martian dust storms. The characteristics of potential landing sites in relation to crew and system safety and trafficability in the vicinity need to be studied, which includes altitude, rock density, dust size, shape, and distribution, as well as surface conditions such as radiation, pressure, and temperature. Potential landing sites also need to be characterized in-situ for potentially extractable water resources to support crews and settlements. The presence of a site on Mars rich in resources, particularly water, with sufficient quantity to influence and support Mars mission architecture and infrastructure for multiple missions, remains uncertain. Currently, there is research underway regarding the recycling of water and closed-loop life support system within habitats and human Mars mission architectures. [13].

With these gaps identified, the primary goals for the human exploration science case for Team Tumbleweed can now be stated:

Characterize and identify ideal candidate human exploration sites with regard to resources and scientific interest: The selection of an ideal landing site on Mars requires a balance in a sufficient wealth of resources to sustain crews and landing infrastructure and adequate scientific potential. In order to characterize candidate sites for human landing and exploration, there needs to be an understanding of resources that are vital to supporting human presence on Mars and the characteristics of surface sites such as the concentration of (hydrated) minerals and mineable and extractable water, slopes, and rock size distribution. In support of this goal, the Tumbleweed network will therefore characterize sites across a multitude of regions across Mars by identifying ideal candidates of water resource deposits that have potential for extraction, as well the detection of minerals necessary for habitat construction and agriculture such as nitrates, phosphates, and carbonates. In addition, the topography and geology of various candidate landing sites will be mapped, and how these factors affect the distribution of ISRU potential and scientific interest will be investigated. This allows better insight into narrowing down the selection of exploration sites.

Characterize potential hazards at human explorations sites on Mars with regard to surface conditions, climate conditions, and terrain: Safety is a vital factor in the consideration of a human exploration site. Dust storms and associated climate patterns need to be understood further as dust is detrimental to spacesuits, equipment, and landing. Exploration sites for human missions must have suitable flat terrain away from rock fields, boulders, and steep slopes, which pose a threat to landing and rover trafficability. For this research question, dust storms and their formation will be studied; their frequency at different candidate sites and the local atmospheric and (near-)surface conditions at different sites are explored. The geological and topographical characteristics of candidate exploration zones that may affect safe landing, EVA and mission operations, and rover trafficability will also be investigated.

3.3 Science Traceability Matrix

A science traceability matrix (STM) shows how instrument and mission requirements can answer and address the scientific goals of a mission. This section, however, focuses particularly on the scientific measurements requirements column of the STM, which can be broken down into measurement objectives and physical parameters. The measurement objectives specify the features to be measured to address a research question, while the physical parameters state the data products that need to be provided to characterize a measurement objective along with its required accuracy range. Table 1 shows the scientific measurement requirements to fulfill the first goal stated in the previous section, and table 2 for the second goal.

Measurement Objective	Physical Parameter
Distribution and location of (subsurface) ice water	Spectral distribution of neutrons 0.4 to 500 keV up to a depth of 1 meter
Composition of surface material	Multispectral reflectance data between 400 and 1000 nm at a spatial resolution of 1 to 5 cm per pixel at a distance of 1 km
Geological structure and surface roughness of the landing site	Close-up imaging with a spatial resolution of less than 0.05 mm per pixel, Multispectral reflectance data between 400 and 1000 nm at a spatial resolution of 1 to 5 cm per pixel at a distance of 1 km
Elevation/ topography	Stereo imaging at a spatial resolution of 20 to 30 cm per pixel at a distance of 1 km

Table 1: Measurements to be taken and their corresponding physical parameters to fulfill science goal 1.

It was determined that the range of energies of neutrons to be detected to indicate the presence of subsurface ice water shall be between 0.4 to 500 keV as this is the energy range of epithermal neutrons, which are most sensitive to hydrogen [14]. The multispectral reflectance data range of 400 to 1000 nm corresponds to the visible and near-infrared spectra (VNIR) as VNIR is best suited for studying the physical properties of Martian materials, characterizing them, and identifying their mineral composition. The spatial resolution for close-up imaging has been determined at less than 0.05 mm, due to the imperative need for capturing fine details essential for analyzing the physical characteristics of and properties of Martian regolith.

Measurement Objective	**Physical Parameter**
Atmospheric composition and dust concentration	Spectral radiance measurements at a spectral range of 0.4 to 2.5 microns
Atmospheric temperature and humidity	Measurements from wind sensors with a 2 m/s accuracy in the range of 0 to 40 m/c and a resolution of 0.5 m/s and at least one measurement per hour.
(Near-) Surface pressure	Continuous measurements from pressure sensors taken every ten minutes with a precision of 10^{-1} Pa.
(Near-) Surface Temperature	Continuous measurements from temperature sensors taken every five minutes with a precision of 0.1°C.
Surface hazards and surface roughness	Stereo imaging at a spatial resolution of 1 to 5 cm per pixel at a distance of 1 km

Table 2: Measurements to be taken and their corresponding physical parameters to fulfill science goal 2.

A spectral range of 0.4 to 2.5 microns was selected to characterize dust concentration and atmospheric composition. This is due to the fact that the overall amount of light reflected back from the edge of the Martian atmosphere at the range between 0.4 to 4.0 micrometers is dominated by light scattering due to aerosol particles suspended in the atmosphere. These smaller particles have a greater tendency to scatter shorter wavelengths within the spectral range of 0.7 to 2.5 micrometers [15]. In addition, constituents of the Martian atmosphere such as carbon dioxide and water vapor contain absorption bands within this range. The precision of 2 m/s corresponds to the requirements for near-surface winds stated in MEPAG [12]. The range between 0 to 30 m/s was chosen as this is the typical range for Martian wind speeds, with wind speeds of 40 to 60 m/s rarely occurring [16]. The surface pressure accuracy of 10^{-1} Pa directly correspond to MEPAG requirements [12].

4 Mission Payload

The candidate instruments for the scientific payload to fulfill the goals of the human exploration science case are discussed in this section. The technical constraints for the payload are based on the specifications of the latest iteration of the Tumbleweed rover: the total payload mass to fulfill all the science cases should not weigh more than 5 kg and the total power required by all instruments should not exceed 20 W. In addition, each instrument must fit into a pod size of 20x10x30 cm (equivalent volume to a 6U-Cubesat); the instruments, therefore, have to be miniaturized.

4.1 Stereo Camera

As the human exploration science case largely involves the evaluation of site characteristics, such as elevation, terrain features for hazard avoidance, and atmospheric dust conditions, a stereo camera is a necessary and versatile instrument that can satisfy these objectives.

A potential miniature stereo camera to be carried on the Tumbleweed mission with a technology readiness level of at least 8 is the Stereo Camera System (SCS), shown in figure 5, developed by the UCL Mullard Space Science Laboratory. It was carried on the failed Beagle 2 lander [17]. Weighing 360 g with a volume envelope of 520 cm^3, it was designed to take up minimal mass as the Beagle 2 lander had a payload to support mass ratio of 33%. It has a mean power consumption of approximately 1.8 W. The SCS was designed to take wide-angle multi-spectral stereo images of the Beagle 2 landing site, with the primary goal of constructing a digital elevation model of the landing site in reach of the lander's robotic arm. Its multi-spectral imaging capabilities would allow us to study the structure, composition, mineralogy, and geochemistry of Martian rocks and regolith, as well as observe their texture and physical properties. The stereo camera will be mounted on the upper pod as it must be placed at an optimal height in order to obtain the best possible field of view.

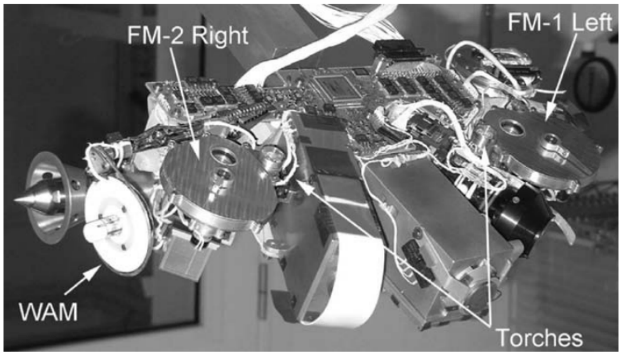

Figure 5: The flight model (FM) stereo camera system and their positioning on the Beagle 2 lander. WAM stands for "Wide Angle Mirror". [17]

4.2 Multispectral Imager

To study the surface mineral composition and to characterize the size and shape distribution of regolith, a multispectral imager is a strong candidate to carry on board the Tumbleweed rover. A computed tomography imaging spectrometer (CTIS), in particular, is an ideal candidate as it is a snapshot imager; gathering spectral images will therefore not be an issue in a rolling platform with random movements. A CTIS is able to obtain spatial and spectral information in just one snapshot [18]. In addition, CTIS have been miniaturized. Researchers at the University of Stuttgart developed a miniaturized CTIS with dimensions of 36 mm x 40.5 mm x 52.8 mm and a diagonal field of view of 29° [19]. With a CTIS, minerals essential to in-situ agriculture such as phosphates and nitrates can be identified, as well as building materials for future habitats present in regolith. A schematic diagram of a CTIS is shown in figure 6.

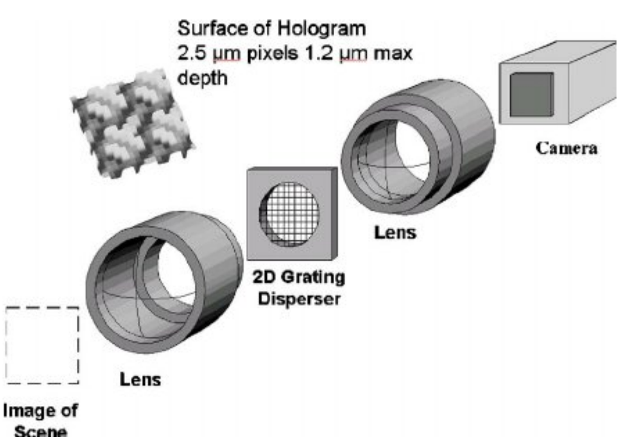

Figure 6: Schematic of a CTIS [20]

4.3 Microscopic Imager (MI)

A hand-lens style imager will be used for close-up images necessary to study and characterize regolith, its properties, and surface hazards related to regolith. The Microscopic Imager (MI) as carried on Spirit and Opportunity, with a power rating of 4.3 W and a mass of only 290 grams, is a model example of a hand-lens style imager with flight heritage that fits within the Tumbleweed payload requirements [21]. The MI takes monochrome images within a spectral range spanning the visible light spectrum, between 400 to 700 nm, and comes with a dust cover to filter light on the lower end of its range to allow for chromatic comparison. The MI is also useful for the surface geology science case to study features such as glacier-like structures and sand dunes [22].

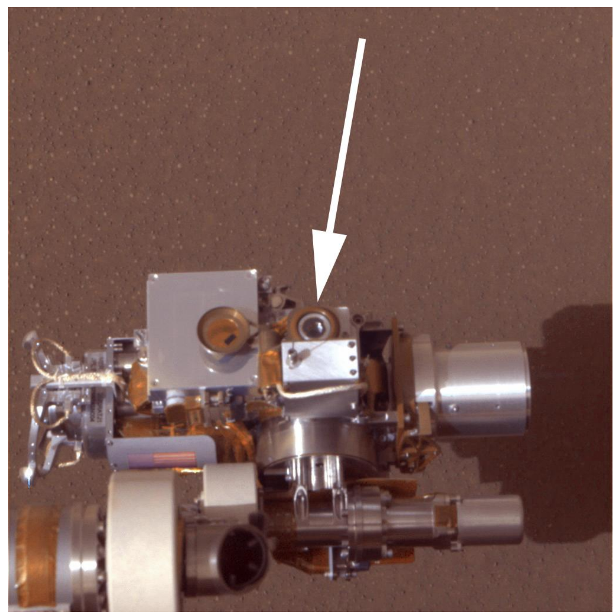

Figure 7: The Microscopic Imager situated on the arm of Opportunity rover. [23]

4.4 Neutron Spectrometer

A miniaturized neutron spectrometer will be particularly useful for the detection of hydrogen beneath the Martian surface for characterizing the presence of water across different sites and providing insight into the Martian subsurface composition to assess the habitability and ISRU potential of an exploration site. Because regolith properties affect neutron flux measurement, by studying the interaction between regolith and neutrons, the instrument can be used to gather data on the physical properties of regolith such as density and porosity.

Neutron spectrometers have been miniaturized, such as the primary instrument for the LunaH-Map 6U cubesat to map the abundance of hydrogen down to 1 meter below the lunar south pole to investigate the presence of water ice [24]. The instrument weighs 3.4 kg, has dimensions of 25x10x8 cm^3, and uses 9.6 W of power. HardPix, a miniature semiconductor neutron spectrometer, has been developed by Filgas et al [25] for use on future ispace rover missions. Based on Timepix pixel sensors, which have flight heritage, it weighs 150 g, measures 81×40×32 mm^3, and consumes 2 W of power. Due to its low mass and power requirement, the Hardpix spectrometer is a promising baseline for the neutron spectrometer to be carried onboard Tumbleweed rover. For the neutron spectrometer, a lower placement to the ground is beneficial to the depth of penetration due to better depth penetration and depth sensitivity. The spectrometer should therefore be mounted to the bottom of the pod's main frame such that the detectors are facing the ground. Detecting the presence of water ice is a crucial element within the context of the astrobiology science case enabling the investigation of the potential existence of biosignatures and, potentially, microbial life concealed within the subsurface ice. [26].

4.5 Environmental Sensing Suite

An environmental sensing suite is required to study the local environmental conditions of various sites over short as well as seasonal timescale variations in order to characterize their safety and suitability for human exploration and the effect of the Martian environment on dust storm formation. Dust storms pose a risk to Martian human exploration such as landing, EVA operations, and solar power degradation; the data obtained from surface measurements taken by an environmental sensing suite on Tumbleweed rovers combined with remote-sensing data from satellites can be used to produce Martian atmospheric models with enhanced accuracy to improve dust storm forecasting.

With a focus on minimizing mass for its instruments, the Beagle 2 lander serves as an exemplary model to consider for TW rover's environmental sensing suite. The Beagle 2 environmental sensing suite, not exceeding 100 g, consists of eight sensors measuring atmospheric temperature, pressure, dust, windspeed and direction, oxidizers in the atmosphere, and radiation dose [27]. For temperature and ultraviolet radiation sensing, the incorporation of Commercial Off-The-Shelf (COTS) components was leveraged. Given the low-risk nature of the Tumbleweed mission, an optimal approach involves incorporating a significant portion of its instruments using Commercial Off-The-Shelf (COTS) components. It may be necessary to tailor these Commercial Off-The-Shelf (COTS) components to enhance their suitability for in-situ radiation protection requirements through the employment of enclosures or housings made of radiation-resistant materials such as titanium and composite materials. The ESS is also clearly a fundamental component within the atmospheric science case to contribute to our understanding of the near-surface atmospheric conditions on Mars and the interaction between the lower atmosphere and the surface [28].

5 Discussion

This section further elaborates on the integration of the science case with the TW rover and the UTM by discussing the mission phases in which the instruments are to be operated, the suitability of the science case with the UTM, and the expected challenges that arise from the rover's operation.

5.1 Periods of Operation

As aforementioned in section 2, the rovers will experience a mobile phase and a terminal stationary phase. The mobile phase of the TW rovers presents a limitation on the operation of instruments due to the induced vibrations and being a moving platform. The multispectral imager, however, if a CTIS, can be operated as the TW rover rolls across the surface due to its snapshot nature and spectral images be acquired from a randomly-moving platform. Throughout the mobile phase, however, there are phases in which the rover becomes temporarily stationary due to lower wind speeds than that required to set the rover in motion, which are expected to take place during the Martian night. This means that only instruments with low operating power will be activated to collect measurements at the current location, such as the environmental sensing suite, due to limited solar power generation. In addition, the lack of sunlight restricts the use of the stereo camera and imaging instruments. It is expected, however, that the rover will undergo start/stop periods of an indefinite period to temporarily bring the rover to a standstill for dealing with contingencies and to aid in navigation. Location-based waypoints are a potential solution for this temporary start/stop period; the rover will come to a halt when its onboard navigation system detects proximity to a predetermined point within a specific radius. As each rover in the swarm acts as a measurement station during the terminal stationary phase, it is ideal to have all instruments operate at this stage at their respective locations, providing a stream of comparative data across various locations around the Martian globe.

5.2 Science Case Compatibility with UTM

The TW rover and its swarm are attractive for low-risk and adaptable planetary missions; the rover itself provides a CubeSat-like philosophy that allows for adaptability such that it can serve as a versatile platform to accommodate a range of (miniaturized) payloads and sensors, thereby enabling diverse mission possibilities. The swarm architecture of the UTM leveraging multiple rovers concurrently reduces the risk of failure while allowing vast surface coverage along with the capability to navigate diverse landscapes.

The landing site of the UTM has yet to be determined; the impact location as well as the degree of spreading of TW rovers from mid-air deployment have a profound impact on the paths taken and the sites visited by the TW rovers. A prudent location of impact for the swarm has to be chosen such that multiple exploration zones can be surveyed; given that a human exploration zone must encompass significant interest across multiple scientific domains, these sites would also be interesting for the UTM's other science cases in the domains of astrobiology [26], atmospheric sciences [28], and surface geology. While warmer temperatures to keep equipment and infrastructure at optimal operating temperatures are located closer to the equator at lower latitudes, large amounts of subsurface ice can be found at mid-latitudes at depths between two to three meters below the surface. By landing at mid-latitudes, the Martian winds can additionally propel some TW rovers towards the northern polar region, a significant area for astrobiology investigations to survey areas around the polar ice cap for potential biosignatures. Team Tumbleweed is currently engaged in the development and investigation of simulations regarding the swarm's dispersion from various landing sites.

A fleet of TW rovers is highly beneficial to the science case to assess the potential of multiple sites for human exploration. A swarm intelligence-based algorithm can be installed in the TW rover software to allow data communication between the rovers. This algorithm can be used for verification to reduce errors in measurements and observational data within an exploration zone. Each TW rover can be equipped with distinct sensors or advanced long-range communication equipment. This way, each rover can transmit a significant finding in a particular area to other rovers in the network and utilize the swarm intelligence algorithm by signalling several other rovers to approach the area to take further measurements. Other benefits of the swarm algorithm include navigational support, data storage and distribution, and calibration of the rover's navigational equipment [29].
With the rovers spread out across the Martian globe at individual locations during the stationary phase, dust storms, a global scale event, can be surveyed from the surface in real-time, providing answers to global climate patterns and their effects on local sites for human exploration safety.

5.3 Challenges and Limitations

Undoubtedly, the unique design and inherent nature of the TW rover give rise to a set of challenges, which are subjects of present and future work. These challenges include the ability of a TW rover to reach a designated point of interest while having limited control. The visitation of specific human exploration zones and landing sites requires the rovers to reach desired locations safely. The TW rover's motions are dominated by wind direction, making it difficult to precisely control its trajectory and target specific areas of interest. Enhanced control over motion will be achieved by optimizing the rover's structural dimensions, incorporating a mass offset, and strategically positioning the payload pod within the rover's center. This configuration ensures that the rover rolls along a single axis, promoting a more linear trajectory. The current baseline assumption is that the Tumbleweed rover will only use passive mass-offset systems to generate a force to keep the pod upright. Navigation towards a target is a potential point of consideration to incorporate into a swarm intelligence-based algorithm by taking the desired dispersion direction and the desired target direction into account and comparing them to the current direction of travel. Rover control needs to be highly autonomous as having humans take manual control to an extent is not a sustainable option for the entire swarm . In addition, communicating with objects on Mars involves long latency times.

The rover's dynamics are an inevitable source of disturbance for its payload due to the rolling motion of the rover. While the Tumbleweed rover can gather data during its movement, the continuous rolling motion may affect the accuracy and stability of measurements. The operation of optical instruments and those with longer integration times and maintaining precise pointing are clear challenges that arise from this rolling motion. The vibrations generated from rolling can propagate through the structure. These vibrations can introduce noise into sensitive instruments, affecting their ability to make precise measurements as well as their calibration. Team Tumbleweed is currently developing an instrument environment model to predict how the rover's dynamics and the influence of external factors such as surface roughness and realistic wind forces affect the noise levels affecting the instruments and the overall response of the system. In addition, it is suggested that mechanical dampers be installed on the instrument or instrument platforms to reduce the noise detected by the instruments.

6 Conclusion

A science case concerning the identification and characterization of exploration zones for the human exploration of

Mars for the Ultimate Tumbleweed Mission has been outlined in this paper. The use of Tumbleweed rovers presents a viable approach to conducting comprehensive surveys of diverse Martian sites, assessing their potential for human exploration and safety. The knowledge acquired through these assessments, coupled with the capability to refine our selection to the most optimal exploration zones is attributed to the expansive coverage provided by the swarm architecture. By studying an exhaustive range of potential exploration zones for their safety and local environment, scientific potential, and wealth of resources, the TW rovers will play a notable role in filling the gaps presented by the MEPAG goals. Tailorable and adaptable in its payload, the TW rover presents an opportunity for a wide range of industry players and research institutions to not only participate in Martian exploration but also attract funding for investments in Martian endeavors.

A half-scale prototype has been built and demonstrated on the analog mission AMADEE-20 in 2021, proving that the baseline design can withstand thermal conditions comparable to those encountered on Mars [5]. On the roadmap towards the UTM, three more demonstration missions within the decade are planned for execution. This includes an orbital deployment demonstration mission to test the entry, descent, and landing stage for the UTM, particularly the structural deployment of the rovers and impactor technologies. Another terrestrial analog demonstration mission, called the Earth Demonstrator Mission, will be performed and outfitted with similar payloads to those of the UTM. Finally, a Mars Demonstrator Mission to test one TW rover on Mars will precede the UTM.

In conclusion, the UTM would mark a significant stride in the way in which humanity explores Mars and the surfaces of other bodies with atmospheres. The UTM would vastly contribute to our understanding of Martian science and future Mars mission planning, as well as democratize planetary exploration.

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