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A new approach for the search of biosignatures and assessment of habitability on Mars using a swarm of wind-driven mobile impactors

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Abstract

The search for life and its constituents has been the goal of scientific investigations on numerous Mars missions. Over its history, Mars is thought to have had a thicker atmosphere, and liquid water on the surface, which may have created conditions suitable for the emergence of microbial life. Due to limitations on mobility and the localized nature of observations, the datasets generated by instruments used in contemporary lander and rover-based missions lack sufficient coverage, comparability, and spatio-temporal resolution. This approach has produced inconclusive results for life detection so far, necessitating a diversification of exploration strategy. Hence, a new paradigm and accompanying platforms are needed to continue this search in a holistic and effective manner. The objective of this paper is to describe how a swarm of wind-driven mobile impactors/ rovers based on the Tumbleweed concept, can be used to fulfil this significant scientific gap while exploring Mars.

We construct a preliminary science case delineating how this swarm of rovers can be used for life detection, as a part of the Ultimate Tumbleweed Mission. After presenting the preliminary mission concept and spacecraft architecture, we discuss how putative biosignatures in the near-surface environment can be identified and characterized using a combination of targeted, complementary analytical techniques in conjunction with general monitoring of environmental characteristics at high frequency and resolution. The ability to negotiate hazardous terrain while probing remote and previously inaccessible features such as lava tubes, fossae, polar ice deposits, gullies and steep crater walls is a significant advantage provided by the swarm.

The proposed Ultimate Tumbleweed Mission consists of a swarm of wind-driven mobile impactors with the ability to morph into measurement stations. Hence, the swarm can provide rich datasets with a high spatial and temporal resolution, enabling a significant improvement in the assessment of habitability. As a precursor to responsible and sustainable human exploration in the future, the biological potential of purported regions of interests and exploration zones can be baselined. A set of candidate instruments that can be employed within the payload constraints of the Ultimate Tumbleweed Mission are highlighted. The proposed network of Tumbleweed Measurement Stations can be used to search for biosignatures on Mars with unprecedented coverage and effectiveness. This marks a significant step in the utilization of a broader, more pragmatic strategy for surface-based science and exploration, which would also yield auxiliary benefits in the domains of atmospheric science and surface geology.

Keywords: Tumbleweed mission, Mars exploration rover, Life detection, Mars habitability, swarm based biosignature detection, Astrobiology

1 Introduction

The search for life on Mars and other bodies in the solar system (as well as exoplanets) is considered one of the most important areas of planetary and space science research [1].Mars astrobiology has gained in prominence and momentum, driven by a continuous flurry of orbiters, landers and rover missions in recent decades. Exploration missions since Mariner 4 have contributed to the current knowledge of Mars's ancient climate, surface geology and planetary evolution. It is thought that Mars possessed a warmer, thicker atmosphere and bodies of liquid water on the surface in the past. Based on the ubiquity of life on Earth (which is enabled by the presence of water), life could have emerged on Mars. This speculation has been reinforced by the discovery of existing water ice deposits on the poles as well as signs of flowing liquid water in supposed ancient lake beds and river deltas in the past. Some equatorial regions and mid-latitudes also contain large amounts of water ice bound in the form of permafrost.

However, large gaps remain in our scientific understanding of the possible emergence, evolution and extinction of life on Mars. Life could have emerged in multiple locations and time periods on Mars independently, since the conditions that are thought to constitute habitability have been heterogeneous in time as well as scale over the planet's history [2]. Thereafter, it is also unknown whether suitable conditions existed for a sufficiently long time to allow for continuous evolution, a question which may be related to the longevity of the highly debated Northern Ocean, as well as other bodies of liquid water on the red planet. Since Earth and Mars have exchanged large amounts of material in the form of meteorite impacts, it is possible that life on these planets may have a possible common ancestor. Considering various uncertainties in the current climatological /geological knowledge of Mars through the pre-Noachian, Noachian, Hesperian and Amazonian periods, it is thought that if life ever evolved on Mars, it would likely have consisted of primitive anaerobic microorganisms [2].

1.1 Limitations of current robotic exploration platforms

The current focus of astrobiology programs is the detection and identification of organic substances in the vicinity of the landing sites of robotic spacecraft. In general, the strategy that is being employed for life detection is currently centered around detection of the chemical correlates of terrestrial biology. Measurements are carried out using in-situ instruments applying a variety of analytical techniques. The instruments in question are often miniaturized versions of terrestrial laboratory instruments, adapted to operate within the tight SWaP (Size, weight and Power) constraints of robotic spacecrafts such as landers and rovers. Rovers collect single point measurements along the path of a relatively slow traverse. Landers are restricted to conducting measurements and experiments in a small local area on the surface that is centered around the landing site. Discounting long range contextual imaging, current land based spacecraft are limited to a coverage of tens of square kilometers at most, over their entire lifetime [3]. The coverage and utility of small aerial vehicles (such as the Ingenuity Mars Helicopter) are limited by energy storage and low payload capacity. Orbiters provide global coverage but they do not possess the desired resolution and sensitivity when it comes to the near surface environment due to inherent limitations in remote sensing techniques [1]. Despite the large advances in our understanding that have resulted from these conventional spacecraft platforms, significant gaps still exist in our knowledge of Mars as a potential ecosystem. Due to limitations on mobility and the localized nature of observations, the datasets generated by instruments used in these missions lack sufficient coverage, comparability, and spatiotemporal resolution. This approach has produced inconclusive results for life detection so far, necessitating a diversification of exploration strategy. Hence, a new paradigm and accompanying platforms are needed to continue this search in a holistic and effective manner. Using the advantages provided by the Tumbleweed rover concept, diverse investigations can be conducted to improve our understanding in existing knowledge gaps. For exploration and in-situ investigations, these advantages could be thoroughly utilized and compounded by mission concepts such as the Ultimate Tumbleweed Mission (UTM), which is discussed in the next section.

2 Team Tumbleweed Rover & Ultimate Mission

The central tenet of Team Tumbleweed is to herald a new paradigm of planetary exploration and science via the use of decentralized robotic systems, with the objective of making deep space missions more accessible and effective. To achieve this, Team Tumbleweed is developing a wind-driven mobile impactor/rover for Mars that is based on the existing concept of wind-propelled rolling vehicles known as Tumbleweeds [4]. The rover/mobile impactor, called the Team Tumbleweed (TTW) Rover, is intended to be deployed in a swarm within the framework of an unprecedented mission called the Ultimate Tumbleweed Mission (UTM). The overarching goal of the UTM is to provide detailed measurements from a large fraction of the Martian surface, thereby resulting in a global picture of the Red Planet that could be used for filling the gap left by previous and current Mars missions, varying from orbiters and landers to rovers and aerial vehicles.

Previous studies on a variety of rolling rover concepts have brought out the vast multitude of applications that such vehicles can fulfill [5]. Although there are other rolling rover concepts which can survive impact forces and navigate hazardous terrain [6], these do not possess the ability to harness the wind in an effective manner. Hence, a large amount of energy expenditure would be required for these rovers to cover as much terrain as a comparably sized Tumbleweed rover.

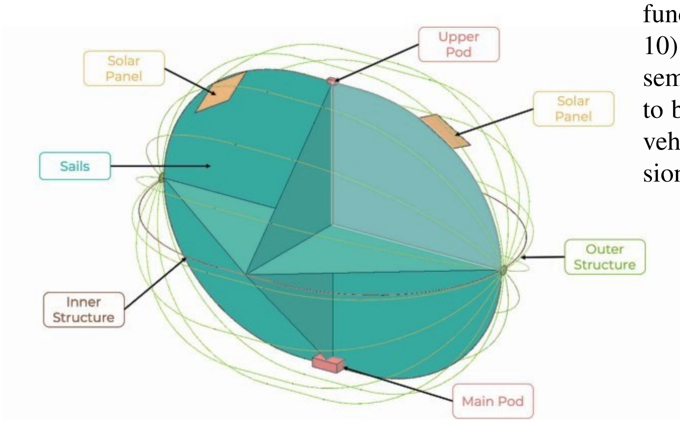

Figure 1: Simplified Tumbleweed Rover schematic [7]

The TTW Rover is loosely based on the box-kite styled spheroidal Tumbleweed concept [8]. However, it consists of some added innovations, such as the decoupling of its structure into two parts: an impact bearing outer structure and a payload carrying inner structure nested within. Figure 1 shows a simplified schematic of the TTW Rover's design. The entire structure is intended to be deployable in construction, such that it can be stowed in a compact state and multiple units can be stacked within the payload fairing of a conventional launch vehicle. Each full scale TTW Rover has a mass of 20 kg and is sized to a nominal diameter of 5 m when fully deployed, with payload constraints as shown in Table 1. More extensive information regarding the design of the TTW Rover can found in [9].

Constraint	Value
Mass	5 kg
Power	20 W (peak) at 100 Wh capacity
Volume	6U

Table 1: Baseline Tumbleweed Payload Constraints [9]

Ultimate Tumbleweed Mission Concept

Tumbleweed based missions have been proposed by various studies in the past [10, 11, 12]. Figure 2 shows a schematic representation of the ConOps of the UTM. The TTW Rovers will be deployed mid-air (represented by steps 5-6 in Figure 2) and land at terminal velocity (point 7) before being propelled by the wind, marking the beginning of the mobile exploration phase of the mission (points 7-9). Once the mobile phase has commenced for long enough such that a satisfactory amount of terrain has been traversed and sufficient distribution of the swarm members has been achieved, the rovers will be stopped and collapsed into a configuration depicted by the schematic in Figure 3. Thereafter, the collapsed TTW Rovers will function as Measurement Stations until end of life (point 10). The UTM will tentatively consist of about 90-100 semi-autonomous TTW Rovers, with the final swarm size to be determined based on various factors such as launch vehicle and entry capsule capacity, desired coverage, mission cost etc.

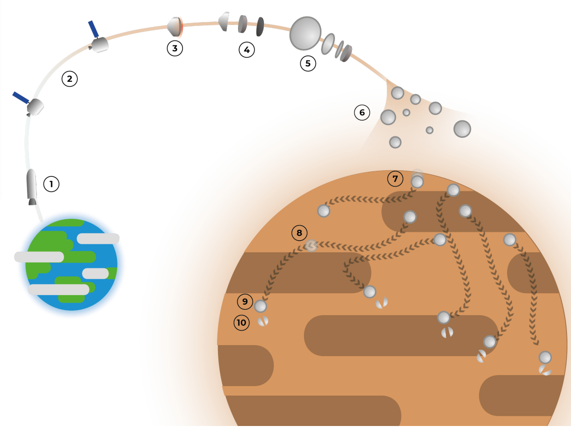

Figure 2: Illustration of Ultimate Tumbleweed Mission Sequence. The white spheres represent individual TTW Rovers. [9]

Each collapsed Tumbleweed will effectively be utilized as a node in a large network serving surface-based applications such as meteorological monitoring, tracking and geodesy, hereon referred to as the Tumbleweed Network. This constitutes the stationary phase of the mission, which will last until the end of life of the spacecraft(s). The payload(s) carried by the TTW Rovers will be operational during both the rolling and stationary phases. The ability to enforce periods in the mobile phase, wherein the rover's motion is temporarily arrested for the purpose of making sensitive measurements of specific targets, is currently being explored.

The bio-inspired Tumbleweed swarm was conceptualized to harness the tremendous benefits seen in populations of r-selective species in nature [13]. For space missions such as the UTM, this approach translates to the use of a large quantity of low cost, risk tolerant identical spacecraft having low system complexity (at unit level) and a scalable architecture. This would result in a more cost-effective mission with higher payload mass fractions and consequently, a higher scientific return due to the distributed nature of measurements and operations.

Arguably, the UTM can be designed and conducted with a more aggressive risk posture than contemporary missions, which can often have an individual piece of hardware / subsystem that is critical to the success of the entire mission. This rests in stark contrast to the design philosophy for TTW Rovers. It is envisioned that the UTM would be prepared in the same spirit as a SIMPLEx class mission [14] (as defined by NASA), in terms of mission cost and risk tolerance. However, the scientific return and mission scope can be expected to be significantly enhanced.

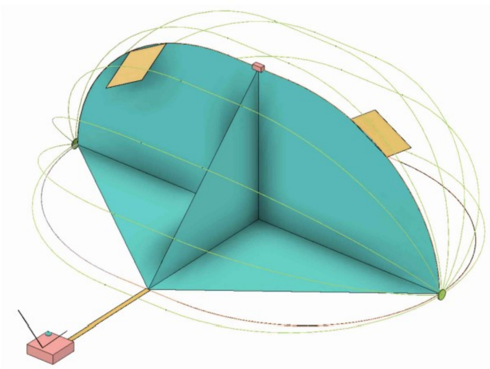

Figure 3: Simplified schematic of Tumbleweed Rover in collapsed state during the stationary phase [7]

Numerous mission concepts and proposals have arisen in the past, with the aim of establishing distributed sensor arrays for planetary science and exploration on Mars [[15, 3, 16]. A recurring limitation of these concepts is the lack of a distribution and deployment method that is technically sound as well as economically feasible. In the case of the UTM, the rover provides advanced mobility and distribution capabilities which are lacking in other proposals. This can be a substantial enabling factor and bridge the chasm in the domain of operation between rover/landers and orbiters.

3 Mars Astrobiology: Background

This section provides context concerning life detection efforts on Mars and presents several knowledge gaps which will be used to bracket the scope and illustrate the potential of the astrobiology science case for the Ultimate Tumbleweed Mission.

Since the Hesperian period (3.7-3.0 Ga ago), the surface conditions on Mars degenerated, leading to the surface environment becoming uninhabitable and harsh [17]. Observations of present day mars indicate desolate and barren conditions. However, the existence of microbial life forms in unlikely environments (analogous to extremophiles and endolithic chemotrophs on Earth) serves as encouragement for the presence of past or extant microbial life on Mars. It is apparent that the subsurface environment has superior chances of hosting life. This would be enabled by the partial sheltering or moderation of the aforementioned extreme conditions - martian regolith and rocks can shield against radiation, gases trapped in the interior of rocks during formation processes could provide ingredients for growth and metabolism, and subsurface water-ice deposits and liquid aquifers could create biologically favorable conditions. The search for these biosignatures of extant or extinct life on Mars and other planetary bodies has been one of the prime objectives of astrobiology related investigations.

The surface/ shallow sub-surface of Mars could harbor markers of extinct life, if preserved sufficiently. Due to various physical, geological, and chemical factors, putative biosignatures on Mars may be altered, preserved or damaged over geological time scales. For example, physical biosignatures could take the form of bio-films, microbial colonies or micro-fossils [2]. However, biosignatures could be rendered undetectable for a variety of reasons. As such, the pristine preservation of these markers is considered a serendipitous outcome due to the multitude of influences and the supposedly long time scales involved between formation and discovery. Hence, assessing the preservation potential of biosignatures is important from a practical and scientific standpoint in the search for indigenous martian life.

3.1 Research Themes & Knowledge Gaps

There are significant gaps in the current understanding and framing of putative martian life. Current approaches are inherently informed by our understanding of terrestrial life. Dependence on liquid water, information encoding in organic polymer chains, susceptibility to ionizing and high energy radiation, presence of organic compounds and chemical processes are some of the factors that are given emphasis in the formulation of the scope and capabilities of life detection missions and engineering of instruments. In other words, a specific type of biochemistry is presupposed. In practice, much of the emphasis of astrobiology has been on detecting signs of liquid water to establish habitability, in addition to inventorying organics and other CHNOPS containing molecules that are known to be ubiquitous in terrestrial biology.

Existence of Localized Microbial Habitats

Macro-scale observations and datasets regarding global Martian climate, geological composition and weather conditions come from orbiters. These lack sufficient resolution and sensitivity to detect subtle fluctuations in environmental parameters, which may contain indications of small-scale localized habitats. Observation capabilities of environmental variability at the [nm-mm] scale are needed to satisfactorily study the possible biological processes in these purported micro-habitats [15]. Due to the diverse and non-homogeneous nature of climate conditions and geological development in various regions over Mars' history, it is possible that multiple isolated and separate locations could have been conducive to the development of complex chemical species such as biomolecules. The lack of detection of promising candidates of this sort on present-day Mars can be chalked up to destruction of potential habitable zones over time due to hostile environmental conditions, as the planet became frigid and barren. Another plausible explanation for the lack of detection by remote sensing is that most of the planetary surface has not been probed to a sufficient level of detail, since such detection may lie outside the observational envelope of currently deployed methods. As far as the target locations for the contemporary search for biosignatures are concerned, landers and rovers have been restricted to searching in very limited zones of the surface and shallow sub-surface environment. This is attributed in part to limitations in the mobility of these platforms and a lack of adequate probing methods (such as deep drilling and ice excavation). Mobility restrictions have dictated that current and previous robotic platforms be confined to searching in relatively flat, non-hazardous terrain in the vicinity of landing sites. This precludes the opportunity to probe truly interesting and exotic terrain features that may contain preserved biosignatures.

Subterranean zones and water ice deposits have not been explored at all. This corresponds to a monumental gap in the current efforts to study martian life [18, 19]. Features such as ancient lake bed cracks, clay rich deposits, rocks, crater walls, lava tubes etc. may also contain preserved biosignatures [20]. Analogous to conditions that have supported endolithic microbes on Earth, some of these features could contain hotspots for biological processes confined within micro-scale pockets. Concretely, probing them by gathering large sets of complementary measurements at appropriate resolution (nm to mm scale in most cases) and frequency (greater than 1 Hz, for instance) could yield promising results [15].

Large Scale Environmental Monitoring

In order to understand the co-evolution of potential life and environment on Mars, it has been suggested that a holistic, ecosystem-based perspective is needed [21]. On Earth, interactions among organisms and their environments across space and time drive changes in energy, material storage and fluxes [22]. The quantification of patterns and processes which govern these changes require comprehensive datasets gathered through sustained monitoring on a large scale.

Measurements gathered by various landers and rovers provide precedent for the study of climate evolution on Mars over different time scales [23]. Due to the limitations of current robotic exploration platforms, a compromise between spatial resolution and global coverage has to be struck when it comes to the quality of data collected by instruments. Hence, there exists a profound gap for sustained in-situ monitoring of the near-surface Martian environment with high surface coverage, measurement frequency and resolution. The application of the principles of terrestrial Long Term Ecological Research (LTER) [1] to the study of a suspected martian ecology could yield enormous scientific and practical benefits. This could be accomplished by a network of environment monitoring stations, collecting information which would be used for measurements concerning establishment of context for life detection investigations. Comprehensive datasets collected by these stations could also be used for targeted investigations of atmospheric phenomena, for building comprehensive inventories of organics and other CHNOPS containing compounds, for identifying sources and sinks of these biologically relevant substance, and for constraining surface processes involved in the formation and evolution of organic molecules. To prepare for sustained human exploration, the data from these stations can be used to build forecasting models to predict hazardous weather phenomena such as dust storms.

4 Tumbleweed Astrobiology Science Case

In this section, a preliminary science case for the UTM, focused on life detection and assessment of habitability on Mars is presented. This science case was created in a synergistic manner with complementary science cases devoted to *Atmospheric Science [24], Surface Geology [25], Geophysics [7], Preparing for Human Exploration* [26]. Taken together, these are intended to provide comprehensive scientific motivation and to lay out the methodology for scientific aspects of the UTM. This section is broken down into the formulation of research questions corresponding to the knowledge gaps and an expedited discussion of heritage instruments and technologies relevant for life detection as well as habitability assessment. To develop and structure the science case, an abbreviated Science Traceability Matrix (STM) is presented,followed by a curated list of candidate instruments which may be included in the payload of TTW Rovers. Following this, some payload design considerations are discussed.

[1] The International Long Term Ecological Research Network, ILTER, encompasses hundreds of research sites located in a wide array of terrestrial ecosystems that help in understanding environmental change across the globe.

4.1 Science Goals & Research Questions

Based on the objectives and goals identified by the Mars Exploration Program Analysis Group (MEPAG) 2020 goals [1] and the priorities laid out by the most recent Planetary Science Decadal Survey (2023-2032) [14], two primary high-level science goals were formulated for the UTM:

1. Search for biosignatures of extant and/or extinct martian life in the near-surface environment

2. Assess habitability and preservation potential for biosignatures near the surface on Mars

A set of relevant research questions were formulated to further scope out the astrobiology science case and correlate it with the previously discussed knowledge gaps. Each research question is decomposed into sub-questions to provide further definition.

RQ1: Does the Martian near-surface environment contain local niches which may function as microbial habitats ?

- Do local niches in the Martian near-surface environment contain biosignatures of past or extant microbial life?
- Is there extant microbial life in deposits of water ice on Mars?
- How can the variability of local environmental parameters be used to identify suitable biological hotspots?
- Are there amino acids or other molecules that are present exclusively, or have a sizeable excess of chiral asymmetry (i.e., L-enantiomers or D-enantiomers)?

RQ2: How can large-scale distributed monitoring of the near-surface environment advance understanding of Mars as a potential ecosystem ?

- How can surface and atmospheric processes involved in the formation and evolution of organic molecules be constrained using such monitoring?
- Where is methane produced on Mars? Is it biogenic in its origins?
- Is there currently a hydrological cycle that can support hypolithic, endolithic or cryptoendolithic microbial presence?
- How can such monitoring be used to assess the preservation potential of biosignatures near the surface?
- Are there regions on Mars which have common traits with desert regions on Earth?

To highlight the relevance of each research question and to provide traceability in terms of the flow down from higher-level goals defined by the science community, the correspondence between these research questions and the MEPAG goals is captured in Table 2.

Research Ques.	Relevant MEPAG Goals / sub-goals
RQ-1	MEPAG I.A1.1-3/ I.A2.3-4
RQ-2	MEPAG I.A3.1/ I.B1.1-3/ I.B2.1-2

Table 2: Correspondence between research questions and MEPAG goals

4.2 Science Traceability Matrix

In order to initiate the development of the science mission in a systematic manner, a notional STM was created, drawing from the science goals, MEPAG objectives and research questions discussed heretofore. An abbreviated version of the STM is depicted in Table 3.

Goal I corresponds to actively searching for biosignatures, especially in suspected local hotspots in the near surface environment (identified on the basis of precursors such as large scale environmental monitoring, identification of minerals associated with biological processes, aqueously altered minerals and landscape, geochemical, and geomorphological context etc.). It consists of detection of organics, observation of morphology on small length scales, measurement of stable isotopes and fractionation, detection of signs of liquid water/water-ice, determination of chirality of identified organic species and detection of inorganic ions which may serve as micrometeorites or be present as byproducts of microbial metabolism. A more general objective is aimed at uncovering possible correlations between small-scale temporal variability of environmental conditions with signs of biological activity.

Goal II corresponds to investigations in the near surface environment, predominantly at a larger scale. This consists of determination of physical/chemical conditions which may have a bearing on habitability and preservation, observation of ionizing radiation and UV impact on present day habitability on the surface and shallow subsurface, and inventorying carbon and related elements near the surface with identification of potential sources and sinks of biologically relevant compounds made up of these constituents. The impact of dust and other parts of the atmosphere that make up surface to air interactions which may affect the preservation of biosignatures would also be assessed quantitatively as a part of Goal II. The formulation of science objectives for the UTM draw from a collection of existing life detection missions and proposals [15, 27, 28, 29, 19, 18].

Table 3: Science Traceability Matrix

Science Goal	Sub-goal	Science Objective	Measurement Observables
Search for biosignatures of extant and/or extinct martian life	Determine the viability of localized microbial habitats in the near surface environment	Determine the abundance and physical/chemical characteristics of biotic and prebiotic organic compounds	Abundance, structure and composition and and concentration of Organics including lipids, amino acids, nucleic acids, carboxylic acids, polycyclic aromatic hydrocarbons, and macromolecular carbon; mass-to-charge ratios
		Characterize morphological indicators of biological processes	spatial variations in visible fine-scale geologic features, mineral size and shape; Imaging along traverse
		Determine stable isotope ratios of biologically relevant elements	Chemical and isotopic data for a number of extant species, including the D/H, 13C/12C, 15N/14N and 18O/16O ratios
		Determine the Stereochemistry of organic compounds in comparison to terrestrial counterparts	Enantiomeric excess in organic mixtures; chirality of detected amino acids, sugars, fatty acids
		Determine whether small scale temporal variability of the local environment is indicative of biological activity	Ambient temperature, barometric pressure, wind speed, relative humidity, ionizing radiation exposure, UV exposure, concentration of methane, oxygen, CO2
		Determine the abundance of potential metabolic byproducts near the surface (Fe, Co, Ni, V, S etc.)	Presence of various inorganic ions in the regolith through soil permittivity & conductivity; soil pH
		Detect and characterize shallow subsurface water ice deposits	Thermal, Epithermal and albedo neutrons (>0.3 eV)
Assess habitability and preservation potential for biosignatures near the surface	Constrain the inventories of carbon and other biologically important elements near the surface	Determine abundance of CHNOPS containing compounds in the lower atmosphere	Quantify atmospheric composition, trace gas abundance and mass-to-charge ratio of gaseous compounds
		Determine the geochemistry (CHNOPS+Fe) of the surface and shallow subsurface	Spatial and chemical composition; alteration spectra of rocks and abraded soil patches, textures, minerals
	Determine physical and chemical properties of the near surface environment	Determine the existence of local niches with environment conducive to past/present habitability	Ambient temperature, barometric pressure, wind speed, relative humidity, concentration of methane, oxygen, CO2, UV/Vis/IR spectra, soil pH, presence of oxidizing species such as Cl, H2O2
		Determine whether the atmosphere is conducive to preservation of biosignatures	Optical depth, dust impact and momentum, UV/Vis/IR spectra
	Characterize the ionizing radiation environment's impact on habitability	Determine the variability in exposure and shielding on the surface with respect to changes in topography and identify sheltered zones	Absorbed dose and dose rate of ionizing radiation from primary sources and albedo; UV flux; context imaging

It is to be noted that the scope of this STM is largely restricted to the domain of astrobiology. A larger, consolidated STM for the entire UTM is currently under preparation. It is anticipated that the STM will be iterated extensively in the future based on feedback from the planetary science community, as well as the feasibility of making certain sets of measurements using compatible instruments. This would allow for the specification of instrument performance parameters and science mission requirements in the future.

4.3 Identification of Relevant Measurements & Instruments

The Ladder of Life Detection (LoLD) provides a comprehensive framework to aid the design of robotic space missions for life detection [30]. The most valuable features of the LoLD for the UTM to target are represented by the intermediate rungs: *Metabolism, Molecules and Structures Conferring Function and Potential Biomolecule Compounds* [2]. These rest in a favorable balance between ease of detection and likelihood of constituting life, offering a pragmatic compromise that maximizes expected scientific value for the UTM. Physical quantities corresponding to relevant biosignatures can be obtained using various techniques. The current crop of in-situ life detection technologies [31] come with a variety of opportunities and challenges, which need to be weighed carefully while selecting instruments and designing payloads for the Tumbleweed swarm. A non-exhaustive discussion of viable candidate instruments and sensors for the TTW Rover is provided in the rest of this subsection.

The use of an Environment Sensing Suite (ESS) to monitor parameters such as atmospheric pressure, air & ground temperature, relative humidity, trace gas concentration, wind speed and direction, dust loading and radiation dose can provide holistic capability for large scale distributed monitoring of the near-surface environment, analogous to an ecological research or meteorological station. In this way, frequent measurements over a considerable period of time ($\approx$ 1 Mars year) can be collected. The ESS can provide a broad and improved near-surface characterization of thermophysical properties (based on the temperature sensors) [32], hydrological cycles (based on relative humidity sensors [33]), diurnal to seasonal changes and ionizing radiation exposure profiles, which are known to be relatively high on the martian surface [34]. Understanding the range of environmental conditions and fluctuations, based on daily and seasonal changes is the first step in identifying potential ecological niches for habitability. Based in part on the makeup of the ESS carried by the Beagle 2 lander [35], commercial-off-the-shelf (COTS) sensors could be used to great effect, for relatively low resource consumption and hardware cost.

Optical or multispectral cameras (either monocular or stereo), would be useful for capturing geological context, documenting the surroundings and terrain properties such as rock distribution, sediment texture, soil composition. Transient events like clouds, dust devils, remnants of the rover's locomotion and the physical characteristics of sampled features could also be documented. This information can be used further to identify targets for detailed follow-up observations with other techniques. A hand-lens style micro-imager (such as the Mars Hand Lens Imager (MAHLI) [36]) could also be utilized for identifying minerals and textures at high resolution. A secondary use for cameras would be for engineering purposes such as navigation and diagnostics. Contextual images from a micro-imager or conventional optical camera can be used for mechanical characterisation [3] and identification of clay-rich soils that may protect physical biosignatures. The preservation potential of biominerals (formed passively as a result of metabolic processes) depends on alteration over time [1]. This can be studied using qualitative measurements of mineral abundance for geologic context, in addition to quantification of alteration mineralogy and geochemistry through measurements of CHNOPS, Fe, Ca, Mg, Si, Al and other relevant rock forming elements [27].

Raman and/or UV Fluorescence spectroscopy can be used for detection, classification and identification of a diverse set of organic molecules and minerals [37]. Fluorescence spectra can be used for the detection of polycyclic aromatic hydrocarbons (PAHs) and aromatic amino acids which are associated with terrestrial life. While fluorescence spectra are not unique enough to enable easy identification of particular compounds, both aromatic and aliphatic compounds can be identified by their Raman spectra [38].

Akin to most contemporary life detection missions, a gas chromatograph–mass spectrometer (GC-MS) could be used to analyze local atmospheric and soil composition at various locations to identify organic compounds and look for signs of CHNOPS containing substances. As discussed later on, the adaptation of a GC-MS for the TTW Rover would require it to be scaled down appreciably in mass, size and power consumption [39]. To this end, a compact mass spectrometer such as an Ion Trap MS could be used onboard the TTW Rover in conjunction with an electrochemical separation methods [40, 41]. Once identified, organic molecules can be studied further in terms of isotopic ratios of C, H, O and chirality in order to deduce whether they have a biogenic origin. In addition to mass spectrometry, a micro-polarisation imager could be used for this [42].

[2]Each rung in the LoLD corresponds to a feature of life, in decreasing order of the strength for evidence of life

[3]especially when the TTW Rover interacts with the soil and disturbs its upper layer by rolling over it

An X-ray fluorescence (XRF) spectrometer would allow for the detection of sources of sulphates, phosphates, nitrates near the surface and the heavy metal content in martian regolith, and on exposed rock surfaces [5].Mineralogical analysis is important in this regard since a variety of mineral phases can preserve biosignatures, including carbonates, silica, phyllosilicates and evaporite phases, in surface as well as subsurface environments. It is known that clay rich minerals such as phyllosilicates have high propensity for trapping, chelating and protecting organic molecules [20]. Surface mounted soil moisture and pH sensors could be used for high-coverage reconnaissance of the chemical properties of Martian regolith. These would be implemented in the form of 'Magnetic Field Response Sensors' accommodated on the outer structure of the TTW Rovers, to make measurements concerning ambient gas concentration, wind speed, and presence of shallow sub-surface water ice/metal content [43]. Ion Selective Electrodes (ISE), can also be used to study properties of the soil, including the identification of inorganic ions (such as Fe, Ni, Co, S), some of which may be relevant to metabolic processes for microbial life [16].

Similarly, a miniaturized Laser Induced Breakdown Spectrometer (LIBS) could be used to study elemental composition of rocks, clay deposits and abraded soil patches [44, 45]. Atmospheric composition and the presence of biologically relevant gases such as methane, water vapor, carbon dioxide and other trace gases can be measured using a mini-Tunable Laser Spectrometer (TLS), in addition to stable isotopes in C, H and O [46]. Vast quantities of methane and oxygen are known to be formed on Earth by biogenic processes, making them interesting targets for astrobiology missions on Mars [47]. So production of O_2 and small fluctuations in its composition in local niches on Mars, would be a significant find. Here, the analysis of isotopic ratios would provide further insight into biotic/abiotic origin [30].

For in-situ astrobiology investigations, the ability to collect and analyze environmental samples is important because it enables the application of a variety of analytical techniques and controlled experiments to identify the biochemical nature of sampled material and its constituents. The advent of microfluidic devices and miniaturized electrochemistry techniques can be exploited to this end, in place of elaborate sample acquisition, preparation, and processing apparatus.

4.4 *Identification of Suitable Instruments*

To assess the feasibility of using instruments and sensors as a part of the TTW Rover's scientific payload, the characteristics of relevant technologies found in the literature (and discussed in the previous subsection) were compared to the baseline payload constraints for each TTW Rover, which are tabulated in Table 1.

The TTW Rover will rely mostly on compact, high TRL and heritage instruments, with the addition of some promising lower TRL instruments. Thus, the instrument list is segmented into two tiers based on the scientific value and technology readiness level (TRL). Table 4 contains mature instruments with high flight heritage, to be used on the TTW Rover in a modular fashion without the need for extensive hardware re-development. The instruments in Table 5 would require more miniaturization and adaptation to the Tumbleweed platform, in comparison. From the constraints, it is apparent that the TTW Rover can also leverage the recent advances in miniaturized payloads developed for nano-satellite platforms. At present, significant scientific capability can be incorporated into a payload sized at approximately 6U (standard CubeSat units) [48]. Despite this, integration related challenges are to be expected due to the innovative nature of the Tumbleweed platform and the harsh conditions on Mars. An additional list tabulated in Table 6 presents next-generation, low TRL instruments that may be promising for the TTW Rover in the future. The presence of multiple TTW Rovers during the UTM opens up a wide range of possibilities for instrument selection and operations. The swarm can be homogeneous i.e. identical Pods can be manifested to provide perfect redundancy, or heterogeneous i.e. with a variety of payloads distributed among different rovers. Using a selection of Pod design variants can add the unique capability to study targets using multiple complementary techniques in concert (using multiple TTW Rovers at the same time). Hence, the instruments from the list shown in Table 4 can be distributed among one or more TTW Rovers. Collectively, the Tumbleweed swarm could carry an eclectic set of instruments in large quantity.

Overall, it is important to have a multi-scale and multi-technique approach for detecting a variety of complimentary biosignatures [20]. The use of co-located measurements from different techniques can serve to overcome limitations posed by a specific technique as well as background effects/artefacts as a consequence of the spacecraft platform or the observational environment [49]. This would lead to more concrete and robust data for life detection that can be subjected to detailed deliberation and scrutiny by scientists from cross-disciplinary backgrounds, enabling holistic determinations about past (and possibly extant) Martian microbial life. The use of next generation instruments, especially in electrochemical sample analysis and nucleic acid sequencing, can be promising for the UTM upon further development. Auxiliary sensors such as engineering cameras and microphones [4] may also be adopted for the TTW Rover.

[4] Microphone data can be used filtering out noise from certain measurements, analyzing wind behaviour and for situational awareness, especially while the TTW Rover is rolling

#	Instrument	Example / sources	Measurements	Measurement characteristics
1	Raman Spectrometer	RAX [50]	Raman spectra for identification of minerals and organic species	Raman shifts with a resolution of 10 cm^{-1} or better and range (250–355 nm)
2	Visible/ Multispectral Camera	MastCam-Z [51], Hyperscout 2 [52]	Contextual images of martian landscape and soil	Color images at better than 2 Mpx resolution and 20-40 FOV
3	ESS	Beagle 2 ESS [35]	Atmospheric pressure	Barometric pressure measured at frequency $\geqslant$ 1 Hz, with resolution $\leqslant$ 0.01 mbar
			Temperature	Ambient temperature measured at frequency $\geqslant$ 10 Hz with resolution $\leqslant$ 0.1 K
			Relative humidity	Relative humidity at resolution $\leqslant$ 1 % RH , at frequency $\geqslant$ 1 Hz
			Wind speed & direction	Wind speed in range (0.3-30) m/s, at frequency $\geqslant$ 10 Hz
			Dust saltation	Dust impact, momentum and rate at frequency $\geqslant$ 0.2 Hz
			Ionizing radiation dose	Time resolved absorbed dose and dose rate measured with a resolution $\leqslant$ 1 uGy/hr. Total Ionizing Dose delivered till Mission End of Life
			UV Flux (and dust loading)	UV flux in 200-400 nm band, measured at least once per minute
4	Ion Trap Mass Spectrometer	Ptolemy Ion Trap MS [53], ExoMars MOMA MS [54]	Identification of various organic molecules; isotopic fraction of C,H,O	Mass spectra in range 10 u to 140 u atomic masses, with resolution of 2u or better
5	Laser Induced Breakdown Spectrometer	VOILA [45], Pragyan LIBS [44], ESA Raman-LIBS [55]	Mineralogical composition of rocks and soil	Spectra in range (350 to 790) nm at resolution $\leqslant$ 1 nm
6	Neutron Spectrometer	LunaH-Map mini NS [56]	Presence of hydrogen , water ice in the soil	Flux & spectra of thermal and epithermal neutrons (>0.3 eV)

Table 4: List of candidate instruments

4.5 Payload Design Considerations

As described earlier, the payload(s) for the Tumbleweed rover will be incorporated into physical compartments called *Pods*. Each Tumbleweed rover will be equipped with one or more Pods. The pods will be engineered to provide data, power, thermal and mechanical interfaces to the manifested scientific instruments and sensors.

For the Tumbleweed Pods, a prudent development strategy for the payload complement would be to combine the salient features of two different instrument types. Highly miniaturized semiconductor and MEMS sensors contained within integrated circuit packages can be incorporated on a circuit board, with minimal size, weight and power allocation. These sensors can be used to provide unceasing, high-frequency measurements of various environmental parameters. The lack of capability and performance (in terms of accuracy, precision and dynamic range) for these chip-based sensors can be supplemented by the use of more elaborate and sophisticated instruments which would be used more selectively (in most cases) to make measurements of relatively higher scientific value. Overall, this approach would ensure maximum data coverage and provide options in the case of outages caused due to operational issues with the rover or other instruments.

In addition to the Pods, it is also envisioned that certain sensors which acquire measurement through direct contact with the Martian environment and ground can be mounted on the body of the rover, including the contact surfaces of the outer structure. For instance, patch electrodes for sensing electrical permittivity and detection of shallow subsurface water ice would be accommodated in this manner.

#	Instrument	Measurements
1	Mini GC-MS	Air & soil chemical composition
2	Microspectrometer (UV/Vis/NIR)	Spectra from air, soil, ice samples at UV , Visible and IR wavelength bands
3	Mini- TLS	Atmospheric composition: concentration of CO2, methane, O2
4	XRF/XRD spectrometer	Spatial variations in elemental composition, changes in texture, biofabrics, fine-scale geologic features
5	Ion Selective Electrodes (ISE)	Presence of various inorganic ions in the regolith through soil permittivity & conductivity; soil pH
6	Micro-Polarization camera	Enantiomeric excess in non-racemic organic mixtures

Table 5: Intermediate TRL Instruments (to be adapted and/or miniaturized for TTW Rover)

#	Instrument / Technology	Measurements
1	Magnetic Field Response Sensors / Patch Electrodes	Electrical permittivity of soil (for water ice detection)
2	Capillary Electrophoresis - Mass Spectrometry (CE-MS)	Molecular biosignatures
3	Capillary Electrophoresis - Laser Induced Fluorescence (CE-LIF)	Detection of amino acids and carboxylic acids
4	Microchip Electrophoresis - Laser Induced Fluorescence (ME-LIF)	Detection of organics
5	Antibody Microarray	Detection of organic biomarkers using antibodies and fluorescence
6	xNA sequencer	Sequencing of nucleic acid polymer chains

Table 6: Next-generation instruments for the TTW Rover

5 Discussion

This section expands on the science case by providing a discussion of the utility provided by the TTW Rover, with respect to the science case. Some remarks and observations on the methodology of conducting measurements and data collection are provided, before shifting to the expected technical challenges and limitations.

The TTW Rover provides an attractive multitude of capabilities, including vast surface coverage at low internal energy expenditure, access to diverse and rugged terrain features (such as gullies, fossae, steep crater walls, lava tubes, karsts and plains with loosely bound soil) and robustness to environmental conditions in general. Equipped with the payloads mentioned in section 4, each rover can map out coarse mineral distribution (through multispectral imaging) and geologic context while rolling, in addition to mapping spatial variations in atmospheric parameters (and radiation exposure) over land. The 'temporary arrest' periods will be utilized to make detailed measurements of interesting local hotspots/niches. These will include Raman and UV/Vis/IR spectra, micro-imaging and analysis of soil, air, rock and dust with LIBS, mass spectroscopy and possibly polarimetry. Hence, each TTW rover will dynamically map the mineralogy, organic abundance, geochemistry, geomorphology and textures of the landscape along its traverse. Intermittently, one or more rovers may end up in close proximity, whereby co-located measurements will be performed on identified targets in an opportunistic manner. For each explored region on Mars, the data from multiple rovers would be collected and consolidated to build larger maps of physical and chemical characteristics of the near-surface and shallow-subsurface environment.For multiple spells of time during the mobile phase, and for the entirety of the stationary phase, the environmental sensing suite in each node of the Tumbleweed network will collect measurements that will capture variability in environmental parameters: dust impact, UV flux, ionizing radiation exposure, ambient pressure, temperature, wind speed and direction. Along with contextual images, these will allow the assessment of habitability and help in identifying interesting local niches and sheltered zones for detailed analytical observation, as described earlier.

Emergent properties exhibited by the swarm can be exploited to generate new observational and operational capabilities. For instance, communication of science data between rovers in the TTW swarm could be used for corroboration of the data, extending to error detection and correction. Algorithms used for aggregation and update of measurements and confidence levels for large datasets could be used for this purpose. The same target can be observed by multiple rovers with the same instruments to cross-check and build consensus in case anomalous/unexpected measurements are obtained from a given rover. In the context of habitability assessment, this would add a high degree of confidence and veracity from a scientific viewpoint. For astrobiology investigations, especially for claims of life detection, this would be invaluable. Swarm behaviour can also be used for navigation, storage and distribution of scientific data, instrument calibration, and troubleshooting in the case of technical issues. Needless to say, the spatio-temporal resolution offered by the network while engaged in the UTM's stationary phase is another highly desirable aspect. The progression of large-scale near-surface phenomena such as dust storms could be actively tracked and monitored with the Tumbleweed Network. In summary, the UTM can deliver on the decided science goals and objectives in an inherently robust and risk tolerant manner.

5.1 Science Operations: Practical Considerations

The impact site of TTW Rovers and the commencement of surface exploration (and science operations) is dependent on multiple science and engineering considerations. Hence, upcoming mission analysis and feasibility studies will be used to narrow down the potential landing sites over time.

Moving on to the mobile phase, locomotion of the rovers will be directed on the basis of local environmental gradients and control inputs. The policy of direction will be based on a dynamic trade-off between: (a) maximization of the amount of land area covered by free exploration and (b) collective exploration of specific regions of interest in a detailed and deliberate manner (using small groups of TTW Rovers acting in concert). A subset of instruments will remain in use while rolling. A mechanism for temporarily arresting the rolling motion of the rover will allow for detailed measurements to be acquired by instruments that require long sensor integration times or have low vibration thresholds, (such as spectrometers and sampling mechanisms). The mobile phase will be punctuated by 'quiescent periods' where the terrain is relatively flat and wind speeds are lower than the threshold speed required to displace the TTW Rover. These periods are expected to occur mostly during the night. During these periods, the rover will remain stationary and due to the lack of solar power generation, only low-power instruments such as the ESS will continue collecting data.

The stationary phase will be initiated once the rovers have dispersed enough to achieve a desirable spread in terms of inter-rover distance, total coverage and density distribution of nodes. The optimal parameters depend on various factors such as communication capabilities, topography, relief and minimum desired footprint over land so as to capture meaningful variations in wind, pressure, temperature, mineralogical and soil chemical composition, water/ water-ice content and atmospheric composition. The Tumbleweed Network will also fulfill the critical function of providing ground truth at a large scale for a variety of remote sensing measurements collected by orbiters.

Based on operational considerations, constraints [5], measurement parameters and scientific value, individual instruments or sensors would be grouped into operational clusters with different priority and relevance levels, with the aim of easing data collection, extraction and risk management at the spacecraft level. On the swarm level, all data clusters collected by individual rovers would be consolidated and processed quickly to inform some short-term science and engineering decisions. In the background, more extensive and comprehensive data processing and analysis would be conducted on Earth (with humans in the loop) as is the case for conventional missions. The collected data can be extracted and transferred to Earth via ad-hoc networks resulting from inter-rover communication, or by relaying the data through orbital assets [57].

5.2 Challenges & Limitations

Given the unconventional and innovative design of the TTW Rover, there are several challenges associated with its utilization, which are addressed hereby.

The tumbling and dynamic nature of the rover (caused by its dependence on environmental gradients), can pose problems for some instruments whose measurements require long integration times. Pointing, integrating and operating optical instruments on a rolling platform is a challenge. Hence, a temporary arrest of the motion could prove to be useful, so that the rover can halt momentarily during the mobile phase of the mission. These concerns are alleviated in the stationary phase and quiescent periods of the mobile phase. However, the lack of mobility in these periods would not allow getting in close proximity to interesting locations. To compensate for the bulk motion and vibrations of the payload pods, a model of the mechanical behavior and dynamics of the TTW Rover will be used for post processing of scientific data, using feedback from real time information collected by inertial measurement sensors on-board the rover.

Taken in isolation, an individual TTW Rover is more limited in terms of the payload SWaP constraints than large, wheeled Mars rovers. Hence, sensors and instruments that consume minimal spacecraft resources need to be developed, or adapted from existing technologies. The application of thermal control techniques which can cope with the adverse temperatures on Mars, while protecting and maintaining sensitive payloads is another challenging avenue. The Tumbleweed network is expected to produce enormous amounts of data, creating challenges with respect to data storage, extraction, and transfer. On a related note, edge computing capabilities would be needed onboard each rover to process and analyse vast amounts of information produced by instruments such as cameras. The ionizing radiation environment poses hazards for rover avionics, necessitating mitigation via shielding, use of radiation tolerant design and space environment monitoring for minimizing exposure [24]. A high level of autonomy is needed to be able to operate a swarm of Tumbleweeds on Mars, since having human operators in the loop akin to current Mission Operations practices will not be a scalable or prudent strategy. During the mobile phase, access to martian caves and lava tubes could be

[5] For instance, due to power limitations and thermal constraints on the operation of certain instruments, these may not be operated outside of time intervals during each sol when the ambient temperatures become more suitable

achieved through skylights [58]. Thus, some subterranean regions could be explored and searched in a limited manner for biosignatures using a small fraction of the swarm. However, this is complicated by environmental and control factors. Hence, this avenue will be explored in greater detail in the future.

The TTW Rover is not suited for sophisticated active sampling mechanisms such as highly dexterous robotic arms. This implies that sampling has to be carried out in a passive manner, or by using lightweight active sampling systems with low complexity. Passive sampling would entail the collection of soil and materials being transported by aeolian processes or by the interaction of the rover's outer structure with the martian surface. Active sampling may be carried out using devices such as the harpoon-like mechanism used by the Gulliver experiment [6]. [59].

Life detection involves large uncertainties which need to be managed using a rigorous and systematic approach across planning and realization of exploration targets, instrument development, measurement methodology, contamination prevention and data analysis. Researchers have demonstrated the difficulty of reliable biosignature detection using in-situ instruments [60]. Biosignatures may prove to be below the detection thresholds and capabilities of the instruments carried by TTW Rovers. Furthermore, biosignatures may not be found sufficiently preserved in the regions explored by the swarm.

6 Conclusion

Team Tumbleweed seeks to leverage the inherent robustness and versatility of decentralized, r-selective systems [13], for conducting Mars science and exploration missions. The current approach to Mars surface exploration consists of large, infrequent, risky, and relatively high-cost missions that gather restricted and sparse datasets. In order to overcome the drawbacks of this approach, we have proposed a solution that involves using a swarm of autonomous, wind-driven, and solar-powered rovers/mobile impactors to gather data over large areas and extended periods of time. The implications of this solution have been illustrated in this paper through the construction of a preliminary astrobiology science case, layered on top of a mission concept called the Ultimate Tumbleweed Mission (UTM). It has the potential to deepen our understanding of the possible origin, evolution and distribution of life on Mars. Importantly, the UTM mission would mark a significant step in the utilization of a broader, more pragmatic strategy for Mars science and exploration, which would also yield auxiliary benefits in the domains of atmospheric science, surface geology and preparing for human exploration [25, 24, 26].

6.1 *Recommendations & Further Work*

Further development of science cases for the UTM will involve the preliminary design and implementation of payloads for the purposes of testing in a laboratory environment, followed by space environment conditions and analogue sites. To assess the basic feasibility of the TTW Rover, a half-scale early stage demonstrator was constructed and tested in a Mars-analogous environment in 2021 [9]. The current roadmap toward the UTM is preceded by a set of three demonstration missions to prove capabilities and raise the TRL of key technology blocks in an incremental fashion. The general approach and methodology of the proposed UTM mission can be demonstrated and validated in Mars analogue environments, as part of an Earth Demonstrator Mission (EDM). In addition to validating payload design, integration and some operational aspects, an analogue mission could serve to improve vital attributes (such as detection thresholds, sensor integration times, expected noise and error margins) of the detection techniques and methodology for payload operations. This will be followed by the Mars Demonstrator Mission (MDM), a technology demonstration consisting of one TTW Rover on Mars. Thereafter, the UTM will involve scaling up of the MDM to achieve swarm-based exploration and establishment of the Tumbleweed Network in the end.

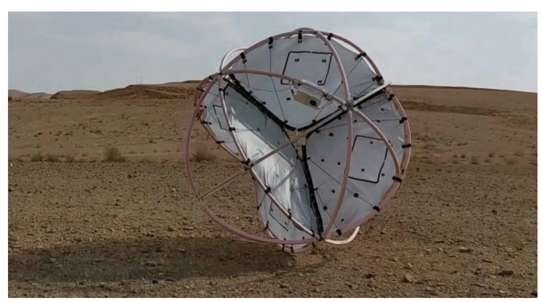

Figure 4: Tumbleweed Rover V3 prototype in an analogue campaign at AMADEE-20 [9]

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[6] In this mechanism, a projectile cup is shot out toward the ground with a sticky string attached to it. The string is reeled in afterwards, which draws sample material for analysis inside an enclosed chamber

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