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Constraining the geological history and modern geomorphology of Mars using high resolution and multispectral cameras on a swarm of wind-driven mobile impactors

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Abstract

To date, in-situ Mars exploration has provided planetary scientists with a unique opportunity to understand the planet and the history of the solar system, as 45% of the Martian surface is comprised of geological units dated more than 3.7 billion years old. However, fundamental mechanisms of surface geological and geomorphological features on Mars cannot be determined by current missions, as they are limited by small surface coverage or limited resolution. As a result, there is a limited understanding of the presence of turbidite deposits along the Martian dichotomy, which would provide direct evidence of ancient deep-water environments. Additionally, the mechanisms of equatorial Recurring Slope Lineae (RSL) are debated along with glacier-like forms (GLFs) present in the polar regions of Mars. Studying them in-situ would enable further comprehension of the extent of surface liquid water, paleoclimates on Mars, and the possibility of future human habitation on Mars.

The need for large-scale spatiotemporal datasets is addressed by a novel mission architecture that uses a swarm of wind-driven mobile impactors - the Tumbleweed Rovers. The Ultimate Tumbleweed Mission is able to provide high coverage and high-resolution imaging at rugged and previously inaccessible locations on Mars. The objective of this paper is to investigate the utility of a multispectral camera and a hand-lens style imager integrated into a swarm of Tumbleweed Rovers, in order to answer long-standing questions regarding the geologic history and modern geomorphology on Mars.

We conduct a definitive feasibility study of the instrumentation on a swarm of Tumbleweed Rovers, defining design requirements to attain baseline science goals. The proposed multispectral camera is capable of distinguishing between the major mineral groups relevant to Mars, e.g. olivine, iron-oxides, and hydrated minerals. We also propose a hand-lens style imager, capable of determining the distribution of grain sizes present in common sedimentary formations (sandstones, siltstones, and mudstones). With this instrumentation, we show that the Ultimate Tumbleweed Mission (UTM) enables searching for turbidites, constraining the composition and mechanics of RSL, and mapping the extent of glacier-like forms in the high latitudes.

In this paper, we demonstrate that Tumbleweed Rovers can significantly improve our understanding of the geology and modern geomorphology of Mars by providing high-resolution images at rugged, high-latitude locations.

Keywords: Tumbleweed mission, Mars exploration, rover, multispectral camera, hand-lens style imager, turbidties, Recurring Slope Lineae, Glacier Like Forms ,

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1 Introduction

Mars is a planet that has captivated our attention since antiquity. Its seemingly ancient surface provides a great opportunity to understand the geological history, not just of the planet, but also the solar system. The surface morphological features (e.g. valleys and deltas) and material - from regolith, sediment, and mineralogy - all provide hints about the past climate of this planet. In fact, 45% of the Martian surface is comprised of geological units dated more than 3.7 billion years old [1]. Importantly, the surface features will help in the assessment of surface habitability by providing geological and geochemical context; especially through the presence of liquid water. Notably, equatorial dark seasonal flows known as Recurring Slope Linae (RSL) potentially indicate surface water and is a large topic of debate with uncertainties in composition, source, and mechanics [2]. In addition, the ancient northern ocean is highly debated in the scientific community and through the help of preserved surface turbidity deposits along the present Martian dichotomy this knowledge gap could be constrained[3, 4]. These are but a few of the many unknowns on the Martian surface that are waiting to be answered and if discovered, have huge implications not just for the advancement of scientific knowledge but also the plans of habitation on Mars and the search for extraterrestrial life.

Instruments on board competing orbital missions, like the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) onboard the Mars Express spacecraft, have detected the presence of a sizeable body of liquid water beneath the ice of the South Polar Layered Deposits. This mission, however, cannot detect smaller bodies of water [5]. Similarly, the Fine Resolution Epithermal Neutron Detector (FREND) onboard ExoMars Trace Gas Orbiter has detected a significant amount of hydrogen in the shallow subsurface, however with only a resolution of 200 km [6]. As shown above, the current orbital scanning equipment lacks resolution and is limiting the execution of measurements pertaining to prevalent science cases. However, the primary research into Martian surface geology is conducted through imaging. Orbiting satellites' imaging capabilities do provide global coverage, however are currently limited to the m-scale; as demonstrated by the Mars Reconnaissance Orbiter (MRO) HiRISE [7]. Single orbiters also have a long revisit time, therefore it is difficult to observe dynamic effects at a given point on the surface over time. Furthermore, current landers and rovers are limited by terrain characteristics and only provide small surface coverage. The MastCam-Z and SuperCam Remote Micro-Imager on NASA's Mars 2020 Perseverance rover can resolve images in the sub-mm to mm range and in many spectral ranges but for a small patch of the Martian surface in favourably flat terrain [8, 9]. Consequently, the orbiting satellites are limited in resolution and temporal continuity, while the in-situ rovers and landers can only provide images over a few kilometres from the landing site. Thus leaving a major capability gap in which a ground-based mission architecture can provide suitably high-resolution temporal-consistent measurements over an expansive and irregular area of Mars. Many such areas include interesting surface geology. In addition, the space sector is becoming increasingly democratised and commercialised, with notable advancements in reusable rockets by SpaceX and BlueOrigin. Consequentially, this has resulted in a plethora of opportunities for novel space missions.

In this paper, we propose a high-resolution multispectral camera and hand-lens style imager integrated into the Tumbleweed Mission (also referred to as the Ultimate Tumbleweed Mission (UTM)). The UTM is a mission offering low-cost access to Mars through a swarm of fast-moving lightweight wind-driven mobile impactors. The cameras located in the pods (payload bays) of the Tumbleweed Rovers shall survey and capture swaths of the previously inaccessible Martian surface. Images with spatial resolution of sub-mm will answer gaps in current knowledge, which is expanded upon in section 2.

This paper presents the scientific value of high-resolution and multispectral cameras in the UTM. Beginning with section 2, a concise review of Martian geological knowledge as well as an overview of the Tumbleweed mission is provided. In section 3, the science case is outlined, which involves particular research questions that the UTM addresses. Thus outlining the expected outcomes of the instrumentation integrated with the Tumbleweed Rover. The science case is further discussed in section 4 and concluded in section 5.

2 Background Information

This section first illustrates the current surface geological research and ensuing gaps in knowledge. Following this, the TTW mission architecture and rover design are both outlined.

Status-Quo

Mars is a terrestrial and differentiated planet with an iron core and silicate mantle and crust, similar to Earth and Venus. Currently, Mars' outer core is not experiencing convective motions, so although it is likely liquid, it has cooled significantly faster than Earth's. Remnant magnetism is limited to the crust, suggesting that Mars probably once had a magnetic field [10]. SNC meteorites, in-situ observations, and orbital gamma-ray spectroscopy data suggest that Mars has a crustal composition similar to Earth, with slightly more Fe, Cl, and S, and less Si, which confers its distinct orange tint [11].

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Mars' surface displays visible evidence of extensive alteration by hydrological and aeolian processes. In fact, modern (Amazonian) Mars is dominated by aeolian processes. There is very little (if any) surface water but some highly debated evidence of near-surface groundwater (known as RSL) [2]. There is a band of mid-latitude glaciers between 30-60 degrees north and south of the equator and ice caps on both poles [12]. Both the north and south poles are predominantly water ice, with a meters scale layer of CO_2 that grows and shrinks with the seasons [13]. Noachian terrains in the southern highlands show many mineralogical and morphological signatures of water - Fe/Mg smectites, chlorites, some limited carbonates, river valleys, deltas [14]. The scientific consensus today agrees that Mars had large river valleys, lakes, and possibly a large ocean in the northern hemisphere [3]. These environmental conditions were enabled by a significantly thicker atmosphere than is currently present, possibly dominated by CO_2 or N_2 at up to 3 bar of pressure [15].

While Mars is fundamentally an igneous planet, its six rovers have found significant exposures of sedimentary rocks. The Curiosity rover has found Fe/Mg clays for example, whose depositional conditions are favourable for the preservation of biosignatures [16].

Knowledge Gaps

However, significant gaps in current knowledge exist and are described in the following section, which will serve as background to the proposed research questions in section 3.

The Northern Ocean and turbidite deposits

The Northern Ocean is a significant open question in Martian geological history. If Mars once had an ocean this would raise huge questions about the development of life in the solar system [3]. It is thought that life on Earth began at a black smoker soon after ocean formation (4.4 Gya). If Mars had an ocean at the same time (equivalently the Noachian period), that heavily implies that life had the opportunity to also originate on Mars. It would not even need to go through abiogenesis because of meteorites from Earth reaching Mars. Turbidites are the most prominent sedimentary deposits in deep water on Earth, occurring at gradients such as continental slopes, subduction zones, submarine canyons, and deep-sea basins. Searching for these on Mars, especially at the Martian dichotomy, could help us learn about the extent of deep water bodies on ancient Mars.

Turbidites are a type of sedimentary formation that originates from underwater landslides onto the floor of a deep water body (typically an ocean or a deep lake) [4, 17]. They are density flows similar to pyroclastic deposits and mudflows; but underwater. The rapid sedimentation causes the high potential for the preservation of organic material, in turbidite deposits. Turbidites have so-called 'Bouma cycles' in the rock record and are easy to identify. In addition, Flysch is a transition between shallow water shales/sandstones and turbidity flow deposits that can also be explored in areas with strong evidence of past tectonics (e.g. Valles Marineris).

Mars has a CO_2 atmosphere which in the past was much thicker. If there was an ocean we should expect absolutely massive carbonate deposits [18, 19]. Much of these were undoubtedly covered or eroded away, but there should certainly be some hint of this, particularly in deep impact craters in the northern lowlands. These carbonates have a characteristic band at 2500 nm in the infrared spectrum.

Recurring Slope Lineae (RSL)

Recurring slope lineae (RSL) are seasonal low-reflectance Martian flow features prevalent on sun-facing slopes across the mid-latitude and equatorial regions of Mars. An example is shown in Figure 1. RSL has been the subject of much debate [20, 21]. The scientific community is split over whether or not RSLs are briny water flows or dry grains. This has huge implications because if there is water (even though it has incredibly high TDS (Total Dissolved Salts) flowing on the surface of Mars, it suggests that there are likely large subsurface reservoirs of liquid water on Mars. Since there is life on Earth everywhere there is liquid water, therefore resolving this is a top concern for the astrobiology field. Efforts to use CRISM data, onboard NASA's Mars Reconnaissance Orbiter (MRO) spacecraft, to find hydration in RSL have largely failed or are extremely controversial, such as Ojha claims[20]. As such there is a need to analyse these morphological features in situ.

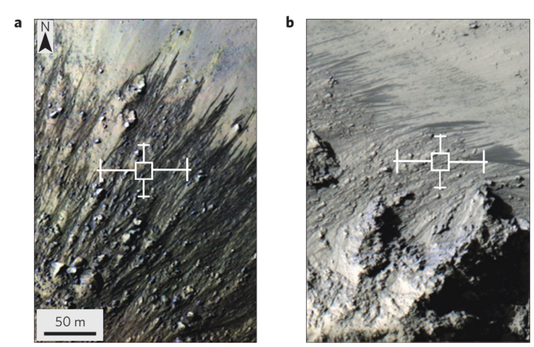

Figure 1: a) HiRISE image of RSL at Horowitz crater's central peak. b) Same RSL from a different peak (same scale)[20].

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Glacier Like Forms (GLFs)

Mars has more than 1300 Glacier Like Forms (GLFs) in the mid-latitudes and polar regions [22]. These are near-surface excess ice (not entirely pore-filling) and are believed to be relatively pure water ice based on Shallow Radar (SHARAD) measurements [23]. In the Northern lowlands, widespread excess ice deposits are found in Arcadia Planitia and Utopia Planitia [24]. The distribution and morphology of these glaciers can constrain the paleoclimate of Mars since the glacial variations provide great insight into past environmental conditions and trends. The extent of the near-surface excess ice also characterizes in-situ resources for future human exploration [24].

Fundamental aspects of GLF's behaviour are unknown, such as the previous extent and motion of GLFs as well as the morphology of GLF-related landforms (e.g. drumlins, eskers, and morianes). The current imaging is limited to targeted orbital HiRISE imaging at a maximised 0.3 m per pixel (shown in Figure 2). Whilst, in-situ imaging can detect evidence of small-scale morphological features such as glacial striation, abrasion, plucking, and glacial flour at mm scale[22].

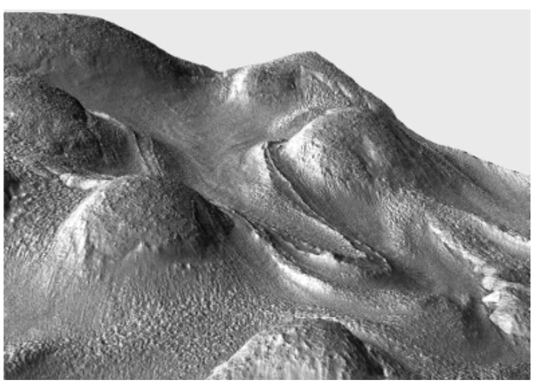

Figure 2: 3D HiRISE image showing (6x vertically-exaggerated) a typical Martian GLF located at Hellas Planitia, Mars [25].

2.1 Tumbleweed Mission Architecture & Design

Team Tumbleweed

Team Tumbleweed is an organisation looking to exploit a new paradigm in space exploration, that provides a decentralised network of rovers on Mars. The mission's goal is to make Mars exploration accessible to a wider community, by providing previously inaccessible detailed surface data over a large area through a cost-effective and low-risk mission to the Martian surface [26]. The organisation is developing novel wind-driven spheroid rovers, known as simply Tumbleweed (TW) rovers, similar to the way in which tumbleweed plants traverse across the desert, hence the aptly named rover.

Mission architecture

In Figure 3 the Tumbleweed swarm-based mission architecture (ConOps)is shown. After the launch, transfer, and deployment the initially folded Tumbleweed rovers unfold mid-air, as depicted by phase 6 in Figure 3. Once the swarm of up to 90 in-situ wind-driven Tumbleweed rovers have landed at terminal velocity the dispersion allows for extensive coverage of the Martian surface, with the rovers being in motion for 90 sols. During the rolling stage, additional capabilities are currently being explored to provide temporary arrested periods during 'quiescent periods' to gain significant findings at specific targets. These are known as stop/start manoeuvres. After the rovers have traversed for 90 sols, the rover's motion is stopped through the collapsing of the sails into two hemispheres and a stationary phase lasting at least one Martian year follows. This stationary phase is limited by dust accumulation, as there is no active removal of dust. During the stationary phase, the rovers will function as stationary measurement stations, presented by the pink box auxiliary to the main structure, as shown in Figure 4. These measurement stations, known as Tumbleweed Measurement Stations are nodes of a large network and due to the dispersed nature of the network have applications such as weather stations, tracking, geodetic measurements and much more[27, 28, 29]. In both the mobile and stationary operational phases scientific measurements will be conducted.

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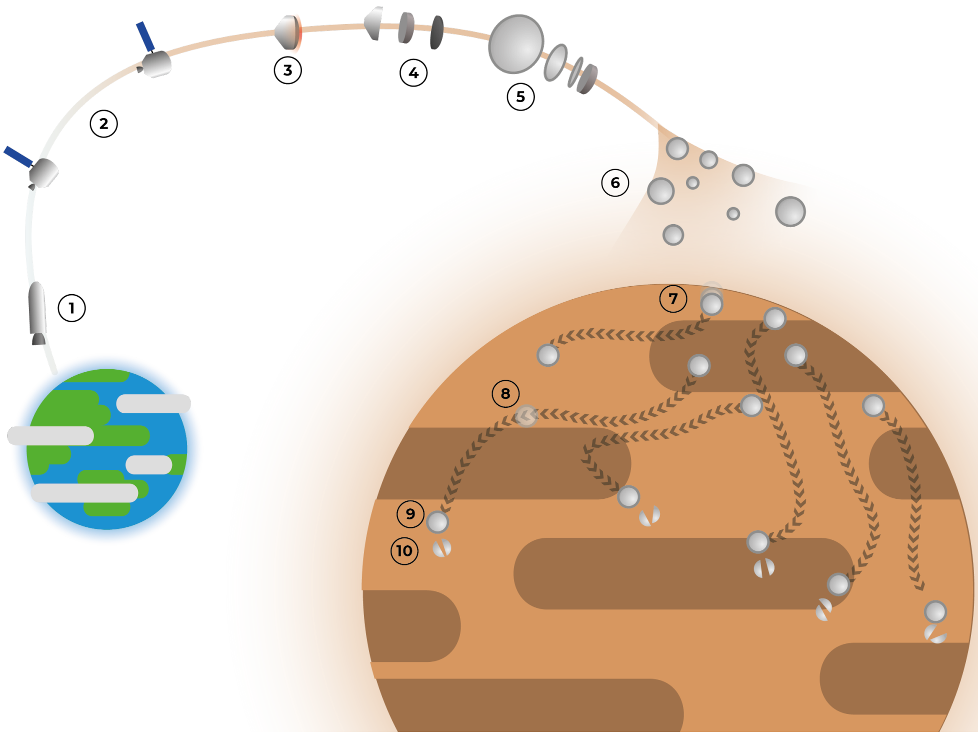

Figure 3: Depiction of the phases of the Ultimate Tumbleweed Mission (UTM) from launch, transfer, deployment, and operations to decommissioning. More details of the mission phases are expanded upon in [26].

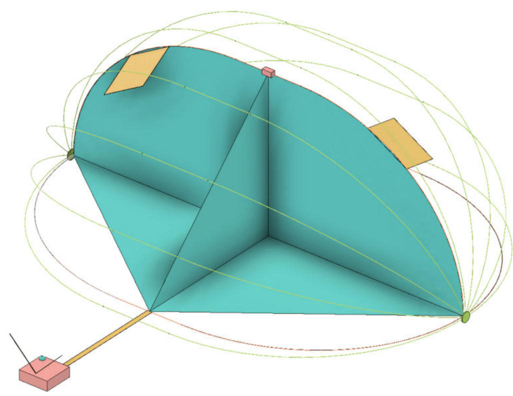

Figure 4: Simplified Tumbleweed Rover schematic in its stationary phase [29].

Tumbleweed rover

The Tumbleweed Rover bio-inspired design concept is not a new concept and its seedlings were conceived of in the 1970s. However, the modern design was discussed in 1998, from the airbag landing system used for the Mars PathFinder mission [30]. Team Tumbleweed's rover design is similar to the 'Box Kite' design concept, outlined in [31], however with vast improvements and refinements. Such as the decoupling of the Inner and Outer structures, as shown in Figure 5. Multiple mission concepts have been proposed with the employment of tumbleweed rovers, ranging from exploring in-situ resources and gullies (Dao Vallis) on Mars to polar regions on Earth [32, 33, 34, 35]

Each Team Tumbleweed rover can be split into two major structural constituents: the Inner Structure (IS) and the Outer structure (OS). The Inner Structure contains the sails, solar cells/panels and pod(s) and the rigid Outer Structure is the protective shell of the rover, comprised of multiple arcs. This is depicted in the updated schematic shown Figure 5. The rover is spheroidal in shape and has a nominal diameter of approximately 5 meters and a total mass of 20 kg. The Inner structure is free to rotate with respect to the outer structure; linked by rotating joints that stabilise the inner structure, which is able to rotate around one axis. It is good to note that the Inner Structure is always upright due to the positioning of the comparatively weighty main pod. The sails provide the drag and resultant movement through the wind and the solar cells the power generation. The rover can carry up to 5 kg of scientific payload(s) which are primarily housed in a main pod 1 m above the Martian surface. These pods house the electrical systems, thermal control systems, and payload. Such a pod will have a volume of 6000 cm^3 or 6 standard CubeSat units (U), a peak power of 20W, and a power capacity of 100Wh. Furthermore, a prototype of an earlier Tumbleweed rover was tested in a Martian analogous area, the

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Negev desert, in 2021, and is shown in Figure 6.

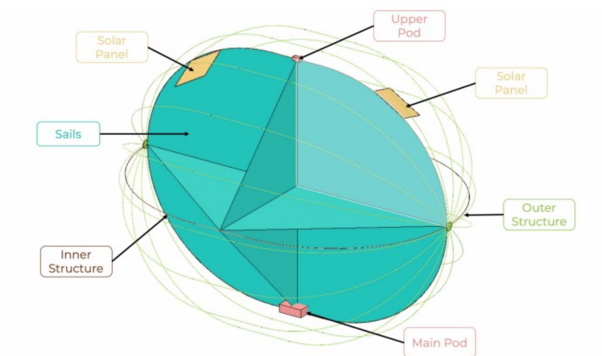

Figure 5: Simplified Tumbleweed Rover schematic [29].

Figure 6: The Tumbleweed V3 Prototype rolling across the Negev desert, during the AMADEE20 Mars Analogous Mission[36].

3 Science Case

This section starts with the applicable Research Questions in accordance with high-level Martian science objectives. Derived from the knowledge gaps mentioned in section 2, these Research Questions form the basis of the preliminary science case presented in this paper. As such a partial Science Traceability Matrix (STM) depicting the flow down from science objectives to instrumentation is created. After this, the proposed instrumentation is expanded upon with heritage instruments along with its compatibility with the Ultimate Tumbleweed Mission (UTM).

3.1 Research Questions

The Research Questions below constrain the paper into three research themes.

1. **Is there evidence of turbidites along the Martian dichotomy?**

2. **What is the composition and mechanics behind recurring slope lineae (RSL)?**

3. **What is the small-scale morphology and extent of glacier-like forms (GLFs) in the northern lowlands?**

The research questions (RQs) above are demonstrated to be pertinent by their ability to be traced back to high-level Mars Science objectives from both NASA's Mars Exploration Program Analysis Group (MEPAG) goals and the recent Planetary Science Decadal Strategy (2023-2032) [37, 38]. Each research question's alignment with MEPAG objectives is displayed in Table 1. This science case predominately addresses Goal III - Understand the origin and evolution of Mars as a geological system - from the MEPAG goals and Q5.4 in the Planetary Science Decadal Strategy known as Origins, World, and Life [37, 38].

RQs	Applicable MEPAG Goal / sub-goal
RQ-1	MEPAG III.A2.1 ; III.A3.1 ; III.A1.2 ; III.A2.2
RQ-2	MEPAG III.A1.1 ; III A1.5 ; I A2.1
RQ-3	MEPAG III.A1.2 ; III.A1.4 ; II B2.1 ; II C2.1

Table 1: Correspondence between Research Questions and NASA's MEPAG goals [37].

3.2 Science Traceability Matrix (STM)

The Science Traceability Matrix, shown in Table 2, is a systematic approach that shall bridge the gap from the high-level Science Goals (derived from MEPAG) to the Research Questions to the observable measurements. This STM solely involves the science model and as such will be complimented with explanations of the associated scientific requirements for each observable measurement.

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ID	Science Goal	Sub-goal	Science Objective	Measurement Observables
O1	Document the preserved geological record in the crust and investigate the processes that have created and modified that record.	Determine the location, volume, timing, and duration of ancient water reservoirs	Determine whether there is evidence of turbidites along the Martian dichotomy	Visual data of turbidites to distinguish between mudstone, siltstone, and sandstone. (mm-scale)
O2		Determine the modern extent and volume of liquid water and hydrous minerals within the crust	Characterise the composition and mechanics behind recurring slope lineae (RSL)	Visual data of RSL and Hydration bands (NIR spectrum 1300 & 1500 nm)
O3		Determine how the vertical and lateral distribution of surface ice and ground ice has changed over time	Determine the small-scale morphology and extent of glacier-like forms (GLFs) in the northern lowlands	Visual evidence of plucking, abrasion, glacial flour, roche moutonnees, glacial striations, lateral and terminal moraines, drumlins, and eskers (mm to 10m scale)

Table 2: Science Traceability Matrix of the surface geology science case.

Originating from MEPAG **Goal III A**, three sub-goals are formulated from more granular MEPAG goals. These are then narrowed down to specific research questions that answer gaps in knowledge. The most difficult step in this process is the transition from the research question to the observable measurements required (science model). Firstly, O1, as seen in Table 2 is derived from a MEPAG higher-priority investigation (Goal III A1.2) that is innately linked to characterising climate history. As outlined by [37], the presence of former surface water reservoirs can be based on geomorphological attributes. Therefore determination of turbidites along the Martian dichotomy at mm-scale imaging resolves this investigation. Secondly, O2 concerns evidence and the extent of modern liquid water within the Martian crust. This higher-priority goal defined by MEPAG requires observable measurements of both liquid water and hydrous minerals, with studies using surface imaging campaigns. Therefore distinguishing the potentially briny water flows of RSL through VNIR imaging aligns with the goal (Goal III A1.1)[37]. Finally, 03 is predominantly attained from a medium-priority MEPAG goal (Goal III A1.4), where it concerns the distribution of surface and ground ice. Specifically, monitoring the modern GLFs in the mid-latitudes through visible imaging at various scales is shown to aid such a goal [37].

It is important to note that these research questions are interconnected to MEPAG Goals I, II, and IV, demonstrating how all Martian research is highly interconnected. Furthermore, this STM is only showing the surface geology science case. More STMs have been produced in different Martian scientific fields, and as such will be combined in the future.

3.3 Instrument Overview

In this section, we propose a multispectral/visible camera and a hand-lens style imager for the UTM. A trade-off between measurements characteristics, to answer the aforementioned research questions (Table 3), and the payload constraints imposed by the TW rover (Table 4) yields appropriate heritage instrumentation applicable for the science case. The low-cost nature of the Tumbleweed mission and lightweight rover design necessitates low mass, volume, and power requirements for payload. Therefore, the instrumentation proposed is inherently miniaturised whilst still maximising scientific value.

ID	Constraint	Multispectral Camera	Hand Lens-Style Imager
SC-1	FOV	20 - 40 $\circ$	30 $\circ$
SC-2	Resolution	30 cm/px at 1 km	60 micron/px at 30 mm
SC-3	Additional	stereoscopic configuration	adjustable focus

Table 3: Measurement characteristics for the multispectral camera and hand-lens style imager.

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ID	Constraint	Multispectral Camera	Hand-Lens Style Imager	Rationale
CO-1	Mass (kg)	The multispectral camera will not exceed a mass of 0.5 kg	The hand-lens style imager will not exceed a mass of 0.3 kg	Derived from the total mass constraint of payload of 5 kg and other instrumentation in the payload bay.
CO-2	Power (W)	The multispectral camera power shall not exceed a peak of 5W	The hand-lens style imager power shall not exceed a peak of 3W	Derived from peak power constraint for total payload of 20W
CO-3	Volume (cm³)	The multispectral camera will fit in a volume of 5x5x5 cm (500 cm³, 0.5U), excluding external hardware.	The hand-lens style imager will fit in a volume of 3x3x3 cm (300 cm³, 0.3U) , excluding external hardware.	Derived from the total payload bay volume of 6000 cm³ (6U)

Table 4: Tumbleweed Payload constraints (SWaP) for a multispectral camera and hand-lens style imager.

Multispectral/ Visible Camera

A multispectral camera is an imaging device, that does not only capture visible light but also electromagnetic radiation at multiple distinct spectral bands or wavelengths. In this context, the most relevant wavelengths are the Visible (including colour) and Near Infrared, also known as the VNIR range. Additional capabilities such as stereoscopy enables surveying of the Martian landscape and regolith in three-dimensions. Also, filters are added to transmit and block specific wavelengths, which is particularly useful for distinguishing between the major mineral groups relevant to Mars, e.g. olivine, iron-oxides, and hydrated minerals. These are versatile instruments that image the surrounding geomorphological landscape not for only scientific purposes but also rover assessments. They have been used in many past and present in-situ missions, such as MastCam and MastCam-Z [8]. Currently, more complex hyperspectral cameras are also being developed, with advantageous numbers of very narrow and contiguous bands.

Visible (colour) images from a multispectral camera are critical when identifying and mapping morphological features of the GLFs in the Northern lowlands (O2). With the scientific requirements outlined in Table 3 it will provide the ability to identify morphological structures such as moraines (lateral and terminal), eskers, and roche moutonnees. Regarding RSL, cm-scale Near Infrared (NIR) imaging is sufficient to determine whether the RSL are liquid or dry flows. These measurements would be over extended time periods due to the seasonal nature of these flow features, to characterise the mechanics of the features. In fact, if RSL are liquid, there has to be a large weight percent (wt%) of Total Dissolved Solids (TDS) in order to depress its freezing point. Specifically, perchlorate salts are the most likely candidate. These salts are therefore hydrated, so if we have the filters go from 1300 1500 nm hydration bands in the NIR, the multispectral camera can distinguish these flows from dry grains [20]. Furthermore, as mentioned in section 2, if there was an ocean it is plausible there could be large carbonate deposits. The 2500 nm characteristic band of carbonate is not feasible with the proposed multispectral camera. However, wider morphological evidence of carbonates, sulphates, and other minerals that result from aqueous alteration is scientifically valuable for this secondary objective.

The Beagle 2 stereo camera system (SCS) 'microcamera modules' is a miniaturised wide-angle multispectral stereo imaging payload designed over 20 years ago. The instrument has 12 filters in the VNIR range (400-1000 nm) to isolate geological mineral spectral signatures, such as hematite and ferric oxides. It has a maximum Field of View (FOV) of 48 ○. However, the science objectives of the Beagle 2 mission required close-up imaging surrounding the lander, as such the resolution is not comparative to what is required for the TTW rover at 30 cm/px at 1 km [39]. This instrument needs to be tailored and modernised for the science objectives discussed above. One such change are filters in the spectral-band 1300-1500 nm to identify the hydrated salts in RSL. In addition, doubling the 1-megapixel images of SCS to 2-megapixel MP colour images will enable finer details in the Martian landscape to be distinguishable. The SCS is also considered in the Human exploration science case for the evaluation of potential site characteristics (terrain, hazard avoidance) [40].

Mass (kg)	0.360
Power (W)	1.8
Volume (cm³)	520
FOV	48 ○ (max)
Resolution	N/A

Table 5: Characteristics of the Beagle 2 stereo camera system [39].

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Figure 7: The two micro multi-spectral stereo cameras of the Beagle 2 stereo camera system (SCS)[41].

As another option, a computed tomography imaging spectrometer (CTIS) designed by NASA JPL generates snapshot spectral images. The snapshot nature of the CTIS means that the highly dynamic environment and noise of the Tumbleweed mission, especially during the rolling phase is nullified with this method of imaging [42]. More miniaturised spectral camera options are discussed in section 4.4 with both high TRL and emerging products.

Hand-Lens Style Imager

A hand-lens style imager or hand-lens is a camera with magnification/ high-resolution abilities applied for near-target examination. For this reason, it is a highly pertinent instrument for the sub-mm measurements of turbidites and small-scale glacial morphological features. Colour images of 60 μm (microns) resolution at an mm scale stand-off distance, as mentioned in Table 3, would be ideal to distinguish between sandstones, siltstones, and mudstones in sediment deposits.

The Mars Hand Lens Imager (MAHLI) instrument, onboard the Curiosity rover is one such imager that provides 15 μm at a 25 mm stand-off distance. This exceptional resolution (approximately 4x what is needed in the UTM), adjustable focus, and Field of view (FOV) ranging from 34 $\circ$ to 39 $\circ$ means that it would adhere to scientific requirements [43]. However, solely the camera head has a relatively significant mass of 0.578 kg and the size would have to be miniaturised for the UTM [44]. The MAHLI heritage instrument is shown in Figure 8.

Alternatively, the Microscopic Imager (MI) is a high-resolution macro digital camera that has proven itself of great success and resilience on the Martian rover Spirit (2004-2010) and Opportunity (2004 - 2018). MI captures images in the visible spectral range (400 to 700 nm) and has a Field of View (FOV) of 30 $\circ$. The image definition is 1024x1024 pixels, each discerning 30 μm from 66 mm of distance, captured with a focal length of 20 mm and a fixed 0.4x focus. As such is analysing the geological textures of terrains 66 mm afar from the external protective sapphire window. Additional features, such as the effective depth of field from multiple snapshots at slightly different distances from the target generate a composite result where even rough, deeply porous surfaces are captured in full focus [45]. Consequently, is able to provide many of the measurement characteristics for the research questions. In Figure 9 it shows the MI attached to the Opportunity rover. The MI is also applicable to the Human exploration science case to characterise regolith [40].

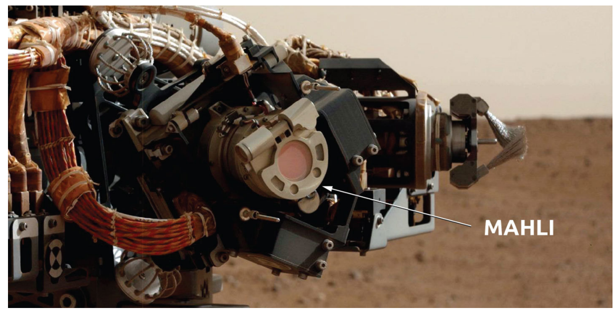

Figure 8: Mars Hand Lens Imager (MAHLI) attached to the Curiosity rover [46].

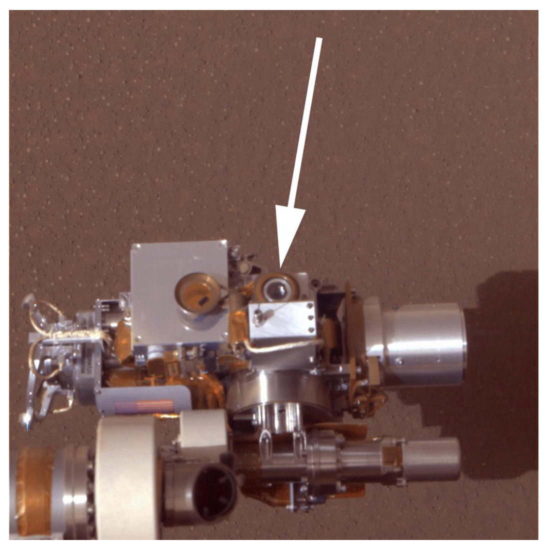

Figure 9: The Microscopic Imager on the arm of the Opportunity rover [45].

In Table 6 the characteristics of the MI are outlined. A preferential mass of 0.210 kg, which is half of MAHLI, and a diminutive volume comprising only 5 % of the total main payload bay of the TTW rover. However, the high power requirement of up to 4.3 W would need further modifications to comply with the constraints of the UTM. Also, further modification is needed to provide an adjustable focus for the highly dynamic UTM.

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Mass (kg)	0.210
Power (W)	4.3
Volume (cm³)	300.8
FOV	30 ◦
Resolution	30 μm/px at 66mm

Table 6: Characteristics of the Microscopic Imager (MI) [45].

3.4 Integration with the Tumbleweed mission

The multispectral cameras shall be fitted on the upper pod to grant an elevated point of view to help capture the overall geological features of the landscape. The upper pod is shown in Figure 5. From a height of approximately 5 metres, the twin stereoscopic array will capture the wider environment with panoramic qualities (high FOV). At this elevated position, a rotating swivel will provide full coverage of the surrounding topography, meaning no mosaics are required when compiling images. The imaging will be largely operational during both the rolling and stationary phase of the mission, and as such images must be taken at high frame rates or taken at particular pre-determined way-points during the temporary stop-start phases in the mobile phase. It is important to limit the mass of the multispectral camera to adhere to the stringent mass budget of the rover and improve the stability of the rover, due to its peripheral location on the rover.

The hand lens-style imager will be strategically located on the bottom of the main lower pod (Figure 5. The main payload bay is 1 m from the ground, therefore an extensional system is required for mm stand-off observations. This will allow for close-up observations of the minerals and grain sizes of the soil.

4 Discussion

In this paper, three preliminary science cases are presented with corresponding legacy hardware of both a multispectral camera and hand-lens style imager. To this end, demonstrating the technical feasibility of the science cases with the evaluation of the Beagle 2 stereo camera system and MI, in conformity with the technical constraints of the Tumbleweed Rover. In this section, technical challenges and limitations, planetary protection laws, novelties of the mission architecture, and subsequent developments in instrumentation and mission design are discussed.

4.1 Challenges & Limitations

Dynamic Martian Environment

The highly dynamic environment of the Tumbleweed rover especially during the rolling phase results in both cameras experiencing an arbitrary amount of vibrations, degrading the quality of the image. The hand-lens style imager captures images at a resolution of 60 μm/pixel at roughly 30 mm, meaning small mechanical noise may potentially cause blurring and shaking effects. These effects are currently being modelled by the Mission Science team. Both cameras are required to be extendable or at the periphery during operational measurements. To this end, vibrations and swaying effects will be intensified in contrast to instrumentation in the centre of the supposedly stabilised Inner Structure. Alternatively, measurements could be taken during temporary quiescent periods of wind, which occur mostly during the Martian night but also some daytime hours. Thus allowing imaging to be taken in a stationary and less mechanical dynamic environment.

The Martian Environment is infamous for being hostile, with daily temperature variations over 100 C◦ and the thin atmosphere providing low shielding against the ionizing radiation environment. Causing undesirable effects in electronic circuits, such as changes in the behaviour of transistors and integrated circuits [27]. In particular, when exploring GLFs in the northern lowlands, at high latitudes, the thermal and power situation may become unfavourable.

Planetary Protection

On Mars, there are multiple regulations concerning areas that can or can not be traversed depending on their scientific importance. Fundamentally this means that some areas can be restricted from the mission. This is extremely pertinent for the RSL, as it is at the top of the list of NASA's "protected regions" also known as "Mars special regions" in the planetary protection ECSS standard ECSS-U-ST-20C [47]. Therefore rolling toward the RSL would require certain agreements to be made. The international governing body, Committee on Space Research (COSPAR), has outlined the policies for planetary protection to avoid organic or biological contamination in space exploration.

4.2 The Novelties of the Tumbleweed Mission

Unlocking New Geological Frontiers

The swarm-based mission provides novel opportunities to survey gullies, canyons, and mountainous terrain. From the Recurring Slope Lineae found mostly on equatorial-facing slopes in the southern hemisphere to the GLFs found in the northern lowlands, and the turbidites along the Martian dichotomy. All science cases can be surveyed in the UTM. This is demonstrated by the validated spreading simulation of 90 Tumbleweed rovers over a fixed lifetime of 80 sols at random starting locations in Figure 10 [48]. This is the first iteration model that will be further developed with a high-resolution base topographic map

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that introduces regolith, gullies and more intricate terrain. Around the Tharsis region in Figure 10 a clear spread from high to low altitude is shown, with an evident convergence at a NE area of the volcanic plateau. This simulation provides promising coverage, especially in the northern mid-latitude to polar regions.

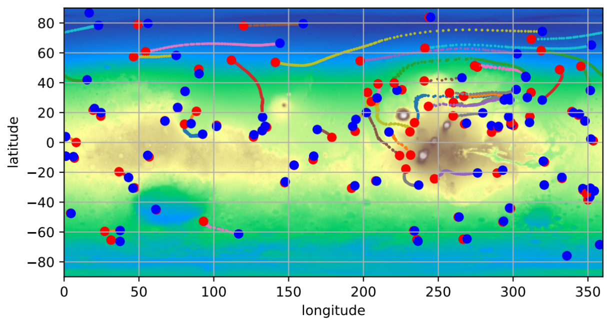

Figure 10: Spreading Simulation of 90 Tumbleweed rovers over a fixed lifetime of 80 sols at random starting locations. The red and blue dots represent the starting and end points of each rover traverse respectively [48].

4.3 Versatile Decentralised Network

Once there is sufficient spatial spreading of the rovers they will switch to the permanent stationary phase. Thus forming a network of Tumbleweed Measurement Stations. These nodes communicate with each other using the IMAGINE instrument (radio beacon and laser retroreflector) and orbital relays [49, 50, 29]. As such this network of rovers provides an alternative tracking solution for ongoing and future missions to Mars [28]. The expansive decentralised network of Tumbleweed Measurement stations enables researchers to have data global datasets over long time intervals in many scientific fields. One such application is the network of Environmental Sensing Suites (ESS) measuring the near-surface atmospheric environment across Mars[27]. The stationary network shall also improve Martian Geological and Climate models.

4.4 Subsequent development

Evolution of Tumbleweed Cameras

The in-house development of a multispectral camera and a hand-lens style imager are in the preliminary phases of scoping-out, design, and experimentation by the Mission Science Team. Drawing from miniaturised legacy hardware and the wider commercial market it is evident that a plethora of low-medium-high-TRL instrumentation is compatible with the UTM. This includes:

- The cosine Remote Sensing HyperScout M - a hyperspectral camera with up to 50 spectral bands that is designed to fit in a standardised CubeSat volume (1U) used in mostly Earth observation[51].
- The Headwall Photonics Micro Hyperspec Ext. VNIR 640 (600 - 1700 nm)- a compact hyperspectral camera with three wavelength configurations [52].
- The 3D PLUS highly miniaturised micro-cameras used in many previous missions such as the Mars 2020 mission [53].
- The CLUPI, short for "Close-Up Imager", is a hand-lens style imager with an approximate resolution of 20μm/pixel (approx. 20 micron/pixel instrument and 27° FOV onboard the ExoMars rover [41].

The extensive heritage instrumentation in the space industry provides a great base for prototyping from the outset.

Flexible Mission Design

The Tumbleweed Mission Architecture and Design are still in the early development phases (Pre-Phase A), therefore the swarm and network have the possibility to alter into many configurations [54]. One such proposal is to have different Tumbleweed Rovers for different purposes. Resulting in select rovers with specific science objectives. Furthermore, the team is also developing the idea of steering or controlled functionality of each individual rover, enabling conscious movement to pertinent scientific targets.

5 Conclusion

In this paper, we present the novelties and benefits that the swarm of Tumbleweed mobile impactors would offer to the Martian research field of Surface geology. The Ultimate Tumbleweed mission (UTM) holds great potential for addressing questions yet unanswered by the gap of knowledge that cannot be filled by orbiters and traditional rovers. We propose an imaging suite of a high-resolution multispectral camera and a hand-lens style imager integrated into the Tumbleweed Rover to measure turbidites deposits, Recurring Slope Lineae (RSL), and Glacier Like forms (GLFS). Drawing from the legacy instruments MI and SCS, it shows that it is possible to capture such geologic deposits at both a 0.06 mm resolution from an mm stand-off and cm-scale from a kilometre stand-off, whilst still largely conforming to technical constraints imposed by the Tumbleweed Rover. Thus, being able to constrain the geological history (paleoclimate) and modern geomorphology of Mars. Further research into the capabilities of the proposed instrumentation, integrated with the Tumbleweed rover, needs to be addressed with future experimentation in Martian Analogous Environments.

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