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Pre-Phase A study of an innovative, low-cost Demonstration Mission of Tumbleweed mobile impactors on Mars

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Abstract

Mars science is currently being characterized by large, high-value spacecraft, flown in low numbers. This makes deep space inaccessible due to prohibitively high costs, mission risk, complex operations, and long timelines. In order to enable widespread and inclusive participation in space exploration, all these factors must be addressed. The Tumbleweed Mission, consisting of a swarm of wind-driven, circularly symmetrical mobile impactors offers an order-of-magnitude reduction in costs per observable while enabling the direct participation of a large number of individual actors. However, this novel mission architecture requires novel technologies and operational concepts to be de-risked for deep space application.

An in-situ demonstration of the technology on Mars is a critical step in the maturation of the technology. While these de-risking efforts are critical to ensuring mission success, they are also time- and cost-intensive. Furthermore, they make little use of opportunities afforded by the decreased cost of space launches. In order to mature Tumbleweed Rover technology to TRL9, a low-cost Tumbleweed Mars Demonstrator Mission must be developed and integrated into preceding de-risking measures. Through conducting a Phase A-level study on the mission, we derive mission objectives, mission- and system-level solutions. Furthermore, key operational concepts and programmatic aspects of such a mission are defined.

Thereby, we derive a mission architecture featuring a highly simplified prototype Tumbleweed Rover and a dedicated entry vehicle. As a lightweight system, it can be brought along as a payload of opportunity on a wide variety of science mission profiles. To that end, we investigate integration with potential parent missions. Furthermore, we show how the Tumbleweed Mars Demonstrator Mission de-risks all critical phases and technologies of a Tumbleweed Mission architecture. Lastly, we present a cohesive set of precursory technology demonstration missions, including a suborbital deployment demonstrator, an Earth demonstrator to test operations and validate performance, and an in-orbit demonstrator to test critical electronic hardware in an applicable radiation environment.

Ultimately, the demonstrator missions de-risk a promising future space technology, increase the scientific return of planned Mars missions, and overall represent a hallmark mission in the development of miniaturized deep space missions.

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

1 Introduction

The Tumbleweed Mission [1], consisting of a swarm of wind-driven, circularly symmetrical mobile impactors offers an order-of-magnitude reduction in costs per observable while enabling the direct participation of a large number of individual actors. The specific novel architectural design choices made as a concept for this mission, require that its constituent technologies be addressed in depth and de-risked for deep-space applications. As per classical approaches to space engineering, this de-risking is achieved through a Demonstrator Mission concept which shall explore and successfully exhibit the performance capabilities of an ultimate mission that can be used commercially.

In order to design a Demonstrator Mission, thorough systems engineering needs to be performed on its mission and system level objectives and functions. This paper, addresses some of the preliminary challenges associated with the systems engineering of a Tumbleweed Demonstrator Mission.

1.1 Motivation

Mars exploration, spanning decades, began with NASA's Mariner missions in the 1960s, with milestones such as Viking landings in the 1970s. With the evolution of technology, and advancement of scientific knowledge of the planetary systems, the goals of Martian exploration have also evolved. Noteworthy rovers like Sojourner, Spirit, Opportunity, and Curiosity have studied the Martian terrain. In 2021, Perseverance and Ingenuity arrived for astrobiology research. Orbiter missions, including MRO, Mars Express, and MAVEN, have gathered essential data from orbit. As reflected in the research objectives of the missions, the goals have become more comprehensive and data-driven. Methods of characterisation of atmosphere, geology, astrobioliogy, have also been evolving resulting in sophisticated methods and instruments for such experiments. Future missions, like NASA's Mars Sample Return, aim to bring back Martian samples.

As the objectives become more complex, the costs and risks of the corresponding missions as well as the complexity of instrumentation also increases. Therefore, Mars exploration presents an array of formidable challenges for stakeholders. Technological innovation is paramount, with the development of sophisticated systems for spacecraft entry, descent, and landing, as well as the engineering of reliable communication and power systems for Martian missions. The harsh Martian environment, characterised by extreme temperatures, frequent dust storms, and high radiation levels, demands robust spacecraft and protective measures for potential human missions. The breadth of these challenges coupled with the needs of innovation in a deep space environment - results in prohibitive cost and resource requirements ultimately making scientific exploration and investigation inaccessible and exclusive. The purpose of Tumbleweed is to circumvent these specific challenges and achieve orders-of-magnitude low-cost scientific data, while enabling the direct participation of stakeholders.

As presented at the IAC 2022, the Tumbleweed Mission architecture enables exploration of the Martian surface through low-cost, wind-driven, Tumbleweed rovers[1]. The Tumbleweed concept distinguishes itself by being a groundbreaking vehicle designed to harness Mars' abundant natural wind resource. By harnessing this wind resource, it opens up an extraordinary opportunity to improve the mobility of scientific platforms and simplify the vehicles needed for their transportation. This innovative concept has been recognized as a potential solution for efficiently and cost-effectively transporting lightweight scientific payloads over long distances in the future.

1.2 Mission Challenges for Mars Explorers

Literature on Mars Mission Design, enlists the following as major challenges for a Mission concept. These are the aspects where the Tumbleweed concept proposed in this paper, is superior to classical missions.

Payload Capacity Limitation

When designing spacecraft for Martian exploration, system engineers must carefully select the mission instruments. This selection process involves a technical, as well as cost based tradeoff and the need for diverse scientific instruments and the constraints of space, weight, and power limitations. To address this challenge, engineers had to develop innovative solutions, such as the use of the ChemCam laser, which can remotely analyze the composition of rocks and soil from a distance. This allowed Curiosity to gather essential data without needing to physically sample every rock it encountered, saving valuable time and resources.

Surface Mobility Limitation

Surface mobility is a critical aspect of Mars exploration. Rovers are designed to traverse the Martian terrain, but they have limitations in terms of distance and obstacles they can overcome. The Mars rovers, including Sojourner, Spirit, Opportunity, Curiosity, and Perseverance, have all faced mobility challenges. For example, Spirit encountered difficulty when it became stuck in soft Martian soil, limiting its mobility and ultimately leading to its loss. Curiosity, on the other hand, faces the challenge of navigating the rough terrain of Mount Sharp. To address these challenges, mission planners carefully select landing sites and plan rover routes to maximize scientific returns while minimizing risks. Additionally, engineers continue to improve rover designs, with advances in mobility systems and autonomous navigation, allowing rovers like Curiosity and Perseverance to autonomously select safe paths and avoid obstacles.

Sample Return Challenges

The ambition of returning Martian soil and rock samples to Earth is accompanied by complex challenges. Collecting, storing, and safely returning these samples without contaminating Earth's biosphere is a top priority. The Mars Sample Return (MSR) mission, a collaborative effort between NASA and ESA (European Space Agency), is a prime example of this endeavor. In the MSR mission, a rover will collect rock and soil samples and store them in sealed containers. These containers will be left on the Martian surface for a future mission to retrieve and return to Earth. Ensuring sample containment is crucial to prevent potential contamination. To address these challenges, MSR mission planners are developing a complex, multi-mission approach involving robotic systems, ascent vehicles, and Earth re-entry vehicles.

Mission Duration and Life Expectancy

Mars missions are typically designed with specific mission durations in mind, but the actual life expectancy can vary due to the harsh Martian environment and potential equipment failures. For instance, the Opportunity rover was designed for a 90-day mission but operated for over 14 years before a massive dust storm in 2018 ended its mission. On the other hand, Curiosity, designed for a 2-year mission, continues to operate beyond its initial mission duration. Mission planners anticipate and plan for potential mission extensions, but extending mission lifetimes can be challenging due to resource limitations and the risk of equipment degradation. Increasing longevity of the rover is constrained by mass, power and cost considerations associated with increasing mass, power per mission in consideration - for the same payload as well as the quantum of scientific information that can be achieved by increasing longevity. Building forever-lasting durable rovers can be expensive and counter-intuitive when the cost to send the rover to Mars is put in consideration.

Cost of Mission

Mars exploration missions require substantial financial investments which can be a significant challenge. Budget constraints can impact mission scope, technology development, and the frequency of Mars missions. In addition, the scale of the mission and the quantum of risks involved with such missions also add to the indirect costs associated with such missions. For example, the ExoMars mission, has faced budget challenges that led to delays and changes in mission plans. These constraints forced mission planners to prioritize certain objectives while deferring others. Investments in the space sector are therefore largely, publicly funded. While this opens an opportunity for everyone to participate in scientific investigations, it means that prioritization of goals is required, for a given planned mission against others. A mission which achieves a larger number of urgent scientific objectives is certainly better than the one with lesser equivalent scientific outcomes.

1.3 *Outline of the paper*

This paper explores the system engineering and mission design of a demonstrator mission for Tumbleweed mobile impactors on Mars. Starting in section 2, A framework for the de-risking of, demonstrating feasibility- and proving relevant technologies for the Tumbleweed Mission concept is derived and justified. This is followed by the mission and system engineering of the Mars demonstrator mission in section 3. Finally the demonstration strategy and Mars Demonstrator Mission aspects are further discussed and concluded in section 4 and section 5, respectively.

2 Derivation of the Mars Demonstrator Mission

The Tumbleweed Mission capabilities, as described in the [1], show that the novel structure and design elements of the Tumbleweed, present numerous challenges and risks. The logical elements of this mission, however, allow us to decouple these capabilities (discussed further in a later section). This (functional) decoupling helps in quantifying the technology readiness levels of its constituent functions and design solutions; they also provide a measurable means of assessing and demonstrating the feasibility of the mission components and ultimately help in de-risking the overall Mission Concept.

To motivate these systems engineering steps, firstly, the Tumbleweed Mission is briefly reviewed. Next, the challenges associated with its realization are presented. The technology readiness is addressed in terms of smaller missions. Finally, motivation for the prioritization of the Demonstrator Mission is established.

2.1 *Ultimate Tumbleweed Mission*

The Tumbleweed Mission Architecture was introduced earlier in [1]. For the convenience of the readers, we reintroduce this mission architecture briefly to describe the approach towards the development of the Demonstrator Mission.

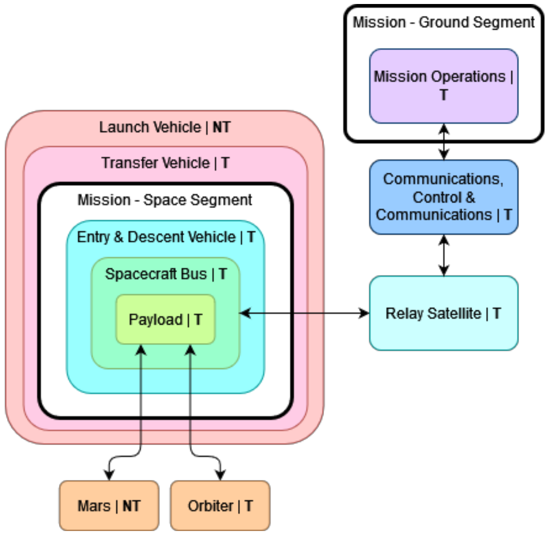

Figure 1: Tumbleweed Mission Architecture

The High-level architecture as shown in 1 of the mission is presented in terms of its logical constituents and their interactions – such that there is a clear scope of tradeability and decoupling based on Mission-level functions and capabilities. The following are the constituents of the mission :

- Mission Space segment :
  - Spacecraft bus
  - Payload
  - Launch Vehicle
  - Transfer Vehicle
  - Entry and Descent Vehicle
- Mission Ground Segment :
  - Mission Operations
  - Communications and Controls
  - Relay Satellites

The boundaries established in this diagram, serve as system boundaries and therefore, also stakeholder and Tumbleweed Mission responsibilities. Assumptions and conditions established in the Mission derivation presented in [1] will still hold valid for the subsequent derivations of missions in the next sections.

2.2 *Challenges with the Ultimate Tumbleweed Mission*

Whilst the Tumbleweed Mission concept has many properties that set it apart from the legacy Mars mission, as discussed in section 1, there are certain aspects that make it very challenging to realize as is. It is critical to map these challenges early and devise solutions for them to ensure a successful development program for the Tumbleweed Mission.

The Ultimate Mission can be divided into different phases as shown below:

- Pre-operational Phase: This phase includes mission conception, systems engineering, and research and development for the Tumbleweed Mission, emphasizing scientific data collection and dissemination. Unlike single-rover missions, this approach involves approximately 90 rovers, leading to differences in payload design, communication, and data processing.
- Operational Phase: In the Tumbleweed mission, the operational phase comprises two key parts. The first involves mobile operations with a swarm of about 90 rovers driven by Martian winds, spreading across the Martian surface during entry and descent. The second phase focuses on stationary operations, with rovers immobilized after achieving their desired distribution, forming a network of stations for unique scientific investigations.
- Post-operational Phase: After data collection and remote control duties, the stationary rovers undergo inerting and complete shutdown. Inerting disables ensures the rover will not move unintendedly and does not pose a hazard to future Mars activities. Then the rover can be shut down safely.

Tumbleweed Rover Operations

Tumbleweed rovers are released on the Martian surface near the north pole, with considerations of divergent wind patterns. With the wind, the Tumbleweed rovers collectively, characterize the terrain, and individually localize themselves. For this, each rover performs an attitude and location determination and communicates this information through the relay satellites to the ground segment.

Post the localization step, the rovers act independently. Each rover has a start-stop mechanism which provides the transition from a stationary to mobile phase and vice versa. To maintain a simple and lightweight rover design, this is the only control option the rovers poses.

In this manner, the rovers have a two-fold mode – stationary and mobile throughout its operational phase. during the stationairy phase, which due to durnial wind cycles are predominantly during the night, operations primairly consist of stationary science activities, communication and data processing.

In the mobile operations mode. the rover is generating and storing power, capturing scientific data and performing basic self-monitoring operations.

The random distribution of the tumbleweed ensures multiple sources of data covering a large area, as compared to a single rover. This mission concept, therefore, requires the possibility of utilizing a light-weight spherical rover which can house important scientific payload. Several structural, electro-mechanical as well as scientific requirements are introduced due to these desirable operational capabilities. These are discussed below :

Scale and Complexity

The systems engineering of the Tumbleweed Mission departs from the historically identified rovers in the following additional characteristics :

- Structural integrity : The structure of the Tumbleweed rovers, must be able to withstand the Martian atmosphere and ingress. Further, it must also be able to “tumble” for extended period of time on the Martian surface. Additionally, maintaining the mass and power budgets of the mission, is a parallel constraint to the structure.
- Payload diversity : Different rovers of the swarm, must house different payloads, with some repetition. Keeping all the other systems (sub-systems and components) of the rover similar, to achieve such a diversity, the payload instrumentation must be constrained to certain mass and power budgets. The interfaces to these payloads must therefore be simple and easy to integrate. Further, this implies that the quantum of data generated by different rovers at any given time is different.
- Processing of Data : With the diversity in payloads, the processing of data is another important factor of consideration. There is a need for the on-board systems of the rovers to process the captured information for a diverse set of payloads.
- Localization of Information : Due to the payload diversity and need to measure the same parameters at different locations, the mission requires harmonization and accurate localization of each of the parameters being measured. localization on Mars is challenging due to the lack of a navigation network. The dynamic tumbling motion and uncontrolled wind driven motion makes accurate location determination over an extended period of time.

Technology Readiness Level

Technology readiness represents one of the other challenges associated with the Ultimate Mission. The specific deviances of the Tumbleweed Mission from the conventional rovers pose novel technical challenges with respect to the rover design. These technical challenges can be broken down from systems's perspective down to component and element specific levels.

- Systems Engineering – The complexity of the Tumbleweed Mission is solved with model based systems engineering, specifically through system-level analysis. The first of the mission's most critical elements are Entry Descent and Landing.
- Structural, Mechanical, and Thermal Engineering: The rovers should be able to withstand the acceleration forces during the entry descent and landing phases. To house many such rovers, would then also pose the need for some form of unfolding mechanism for each of the rovers. Thus, the mechanical and structural properties and limits of operation must be endured during the different expected states that the rover goes through. .
- Power Systems : The source of power for the tumbleweed is another critical design challenge. Solar power and nuclear power are trusted modes of powering deep space vehicles, and satellites. But, these come with a bottleneck of mass and weight considerations. Especially the high mass of nuclear power makes it incompatible with the Tumbleweed Rover architecture. While limiting the payload to be selective and dispersed, already relieves the power budget of individual tumbleweed rovers, the weight of the solar panels is still a concern. This is addressed in our research work later.
- Onboard Systems: Processing systems for the deep space rovers, are designed for high degrees of radiation tolerance and failures which can increase the costs of fabrication and manufacturing and make it non-scalable for commercial purposes. Tumbleweed rover processing systems must be able to handle the routine operations of the rover in stationary and mobile states of the rover, without such costs using commercial off-the-shelf components. The mass and power budget constraints add to the design challenges as well. Team Tumbleweed also aims at addressing this in later research.

Mission Cost and Timeline

The technical and non-technical challenges as well as the development needs of the Tumbleweed Mission pose a difficult problem from the financial perspective. There are many technologies that are intended to be used in their commercial form, however, these must be operational in an environment in which they have not been tested before. Further, such niche development and testing come with a huge cost. Therefore, the multitude of risks associated with the ultimate mission are monumental. Not to mention, the development of such a full-fledged mission would involve multiple parties, co-development and interfacing with numerous stakeholders.

Due to various factors explained so far, there is a need for a development strategy of the Tumbleweed Mission Concept that significantly reduces the scope of the short-term activities whilst still contributing significantly to the technology maturation of all key technologies. Additionally, it is critical that at any given time the activity-costs, -risks and -timeline remain within an acceptable and manageable domain.

2.3 Deriving a Demonstrator Mission framework

Given the challenges and risks which are discussed so far, there is definitely a need to formulate an ultimate mission in a more organized manner. It is also important that the potential challenges are addressed correctly and fulfil the objectives laid out concretely. In order to break the goals and demonstrate the capabilities of the ultimate mission more realistically, a systems engineering approach of de-risking the mission into several constituent de-scoped version of the mission is taken. This is explained below.

The concept of demonstrator missions is not new to the space domain. This is nominally used to de-couple risks while still performing qualifier testing and validation on a mission. This way, a low-risk but highly informative test setup is achieved and the rover's capabilities are tested.

Mars Demonstrator Mission

We start with discussing the first demonstrator that is a minimum viable product of the Tumbleweed Mission. As a Mars Mission, the Tumbleweed should be able to prove its capabilities on mars. And this is to identify and qualify one tumbleweed's characteristics before the full-scale mission can be deployed. This is because the functional capability of a swarm-like Mars mission can be guaranteed if one single tumbleweed demonstrates its capabilities well enough. The risks associated with the ultimate mission are also minimized by such a demonstrator mission, as it provides a test of the rover design in its desired environment.

The major goals of this demonstrator mission would be the following :

- Quantify rover dynamics in a Martian environment as well as identify design features of the rover
- Validate and Verify functional and operational capabilities of the rover and its sub-systems.
- Validate functionality of scientific equipment from within a Tumbleweed structure
- Quantify performance and efficiency of the system in terms of the Tumbleweed's ability to travel and collect information across distances
- Rover durability and lifetime – to test long-term effects of harsh Martian environment on the rover, and the components
- validate EDL system concept – and quantify the landing parameters of the rover.

As seen from its major objectives, it is clear that the Mars Demonstrator Mission is the closest representative candidate for the Ultimate mission, and therefore also provides a reliable prototype to depend on the Ultimate mission design on.

In-Orbit Demonstrator Mission

The In-Orbit Demonstrator Mission is a demonstrator mission that is specifically meant to test only some critical subsystems of the rover. Particularly, this demonstrator acts as a measure of the certainty of the radiation tolerance and thermal sensitivity of the rover and its constituents.

In order to actively decouple the risks associated with Martian radiation and its impact on the Tumbleweed rover, the In-orbit demonstrator must exhibit functional capabilities in a deep-space environment. To simplify this problem, it is identified that the demonstration of functions can be decoupled as well. Therefore, an In-Orbit Demonstrator Mission needs to only prove the ability of rover subsystems to operate in deep space. This problem can be further simplified by replacing a full-sized rover and its components to a test sample of each of the subsystems or even less, which are sufficiently unique and require such proof.

While this mission does not aim at reducing the mission system's level risks associated with its functions and operational routines, it does significantly help in quantifying the constituent components. The primary objectives to be tested here would be on-board computing and payload electronics, cost, materials of use for the structure and the communications systems. The payload electronics shall demonstrate the ability to perform fail-safe compute and command operations in a deep space environment. The materials to be used in Tumbleweed, shall demonstrate thermal and radiation tolerance from the structural perspective. And the communications systems must adjacently demonstrate packet transmit and receive, albeit a full two-way communication in a fail-safe manner without loss of critical information.

Earth Demonstrator Mission

The Earth Demonstrator, as the name suggests, aims to demonstrate the Tumbleweed mission capabilities on the terrestrial environment on Earth. This is done with the goal to de-couple Tumbleweed mission operational and functional capabilities from the surrounding environment.

The goal of this mission is to identify whether the desirable Tumbleweed rover can achieve the desired performance in a terrain similar to that of Mars but tested on Earth. This provides a fairly low-cost test of the rover and the mission as a whole. Further, it also provides a realistic test of the rover structural and mechanical integrity in an identical environment. The purpose of such a Mission would be qualifying the rover dynamics in a 1g environment. Additionally, this would also help in testing performance of some of the sub-systems such as location and attitude determination, on-board computing system, payload computing systems as well as rover actuation and maneuverability in the presence of Wind. It also aims at demonstrating the general utility of the concept using simulated earth science goals.

This Mission together with the In-Orbit Demonstrator can be used to extrapolate the risks associated with the Mars Demonstrator Mission in terms of technology readiness, maturity of design and verification of functional capabilities to a much accurate degree.

Deployment Demonstrator Mission

The Deployment Demonstrator Mission serves the purpose of testing deployment strategies of the Tumbleweed rover. This is a critical step in all the historically deployed Martian rovers and has been touted as the "seven minutes of terror" - which determine the future of the mission. Since this involves a parent mission (to carry the rover and the EDV vehicle), it has the highest risk of all the Mission states.

The purpose of this mission is to quantify risks and costs associated with the rover loss in the EDL process of the mission. The key parameters to collect and identify would be the aerodynamic forces. Some aspects of EDL testing cannot be fully replicated on Earth due to the differences in Martian atmospheric conditions. Therefore, mission planners conduct tests in Martian-like environments on Earth, such as high-altitude drop tests in thin atmospheres or testing in vacuum chambers to mimic Mars' lack of atmosphere.

2.4 Mars Demonstrator prioritisation

The culmination of the EDL testing process is the rover's actual landing on Mars. During the real entry, descent, and landing on Mars, the mission team closely monitors telemetry data and compares it to predictions made during testing to ensure a safe and successful landing.

The Mars Demonstrator Mission, maintains the goals closest to the ultimate mission. This is because this mission is a single sample of the ultimate mission with a swarm of rovers. Therefore, proof of technology readiness on one such rover in this mission, would prove, the readiness of technologies and would factor out all the associated risks that the ultimate mission quantified, except for that of a swarm behaviour. Further, this mission is driven with a martian environment as a target an hence accurately quantifies the actual performance qualifications of the desired rover.

A successful Mars Demonstrator Mission would therefore, solidify the design and mission concepts. It provides a comprehensive platform for developing and demonstrating all mission phases and technologies. This is the reason, the MDM is chosen as the desired mission to be engineered.

3 Demonstrator Mission Design

This section will discuss the design of the Mars Demonstration mission, the needs of which were laid out in section 2.3, in more detail. Here the high level design of the Mars Demonstrator Mission is summarised. A previous initial Mission baseline design of A Tumbleweed Mars demonstrator mission has been released in a report in May of 2022 [2]. In this paper, we aim to summarize some results presented there, whilst also updating and expanding on it using the system engineering work that has been done since.

3.1 Stakeholder Analysis

To identify stakeholders for Team Tumbleweed, a comprehensive assessment was conducted, taking into account individuals, investors, organizations, employees, customers, suppliers, and regulatory bodies that could influence the project. Subsequently, each stakeholder was categorized based on their level of influence and interest in the project, resulting in classifications such as Key Players, those whose needs require attention, individuals or entities deserving of consideration, or those with comparatively lower significance in terms of impact and interest.

Key Player stakeholders:

- Space Agencies: They enable the mission to be flown and are the primary customer.
- Mission scientists: The direct customer of the science return from the mission.
- Science Objectives: The scientific investigations required to meet the mission's science goals.
- Team Tumbleweed: The organization is responsible for the overall mission.

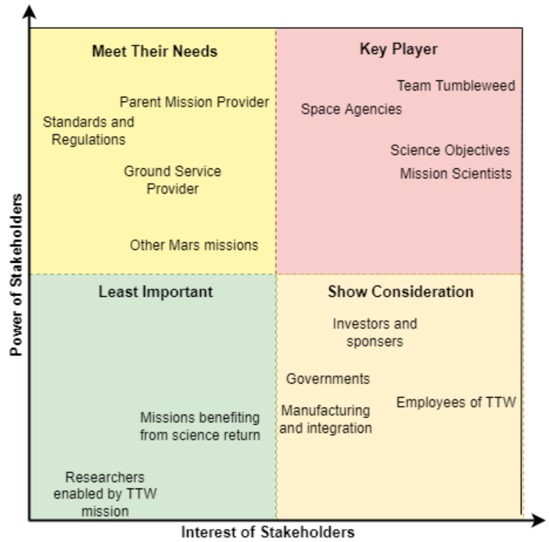

Figure 2: Stakeholder Matrix

Moreover, stakeholders underwent a comprehensive brainstorming and iterative process, in conjunction with the delineation of the mission's scientific objectives, to delineate the mission's capabilities. As a result, stakeholder-related requirements were incorporated into the mission framework. We present a brief stakeholder analysis in 2. The detailed requirements captured with the Stakeholders are beyond the cope of the discussion here and therefore have been left out for brevity.

3.2 Operational Capabilities

Deriving the operational capabilities of a Mars rover involves a balance between mission objectives, engineering constraints, and available technology. It requires a multidisciplinary approach involving scientists, engineers, and mission planners to ensure that the rover can successfully achieve its scientific goals while operating in the challenging Martian environment.

An MBSE approach is taken here. Model-Based Systems Engineering (MBSE) is a comprehensive approach used in the design, development, and operation of Mars rovers to ensure the success of complex missions. Here's how MBSE is applied in the context of a Mars rover as described in this section:

- Conceptualization and Requirements Analysis
- System Architecture Modeling
- Subsystem Design and Integration

For this purpose, we implement our MBSE model using the Capella Tool which follows the ARCADIA methodology. From our stakeholder objectives and conceptualisation of the Demonstrator Mission is derived. The key operational capabilities as seen from the ARCADIA methodology are shown in the list below. Three specific capabilities represent the key goals of the mission, which can be further broken down into more granular sub-capabilities.

- A. Travel to Mars
  - Launch into space
  - Depart From Earth
  - Transfer to Mars
  - Approach Mars
- B. Demonstrate TRL 9 of Tumbleweed Technologies
  - EDL
  - Reach Deployment Altitude in Martian Atmosphere
  - Unfold in Martian Atmosphere
  - Land on Mars
  - Transmit Data
  - Locate System in atmosphere
  - EOPS
  - Locate System On Mars
  - Sustain system in martian Daytime environment
  - Sustain system in Martian nighttime environment
  - Communicate with Earth ground station
  - Tumble system over surface
  - Arest system from tumble
  - MOPS
  - Collect science data whilst arrested
  - Perform controlled traversal of Martian surface
  - Collect science data whilst tumbling
  - SOPS
  - Disable system mobility
  - Collect science data whilst mobility disabled
  - EOL
  - Decommission system
  - C. Demonstrate utility of Tumbleweed Mission
  - Collect science data whilst arrested
  - Collect science data whilst tumbling
  - Collect science data whilst mobility disabled
- C. Demonstrate utility of Tumbleweed Mission
  - Collect science data whilst arrested
  - Collect science data whilst tumbling
  - Collect science data whilst mobility disabled

3.3 Architecture, Concept Operations & Function Mission Phases

The architecture of the demonstrator mission is defined to enable the realisation of the previously discussed ca-

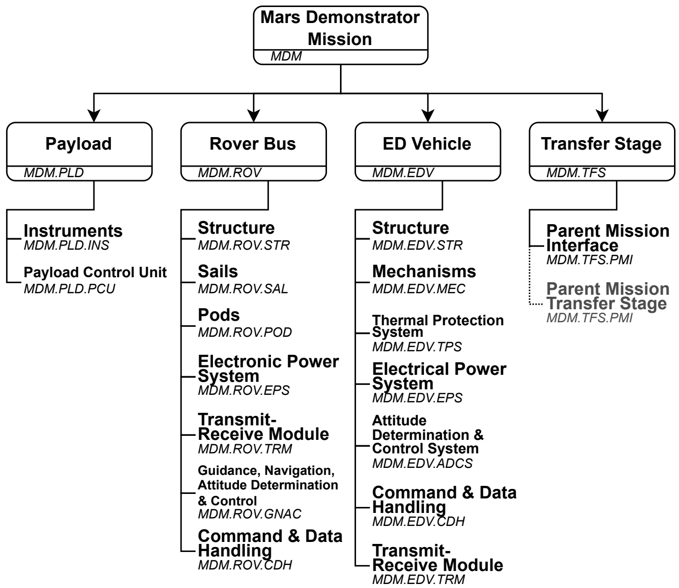

Figure 3: Product Tree of the Space Segment of the Mars Demonstrator Mission

pabilities whilst minimising the system complexity. As a demonstrator mission for the Tumbleweed Mission it is unsurprising that the outline of the demonstrator mission architecture is similar to that of the Tumbleweed Mission architecture presented at the IAC last year[1]. As can be derived the desired capabilities presented in subsection 3.2, the demonstrator mission has a few key architecture freedoms that the Tumbleweed mission does not have.

Firstly the demonstrator mission has no explicit need for multiple rovers, and therefore also has less need for autonomy. Swarm based performance can be understood in independently from the in-situ demonstration of the relevant systems. There are no dedicated systems required for enabling swarm functionality on top of the rovers systems already in place for the operations of the rover itself.

Secondly, the demonstrator mission rover does not need to cover as much distance as a rover in the tumbleweed mission. In the Tumbleweed mission the distance covered needs to be sufficient to reach a desirable spread of rovers to perform the proposed swarm-based scientific objectives. For the demonstrator mission, however, the distance needs to be sufficient to understand the behaviour and degradation of the motion systems of the rover as it traverses the surface, which can be achieved in significantly less distance. Additionally the regions explored on Mars have a reduced relevance, as the scientific return of the Demonstrator Mission Payload instruments is of secondary importance. Lower travel performance requirements also relax the sizing requirements of the rover, as it is acceptable if it travels less fast or far within a given timeframe.

As a result, the architecture of the demonstrator can be simplified whilst retaining the demonstrative relevance and power of the mission when compared to the Tumbleweed Mission: the demonstrator mission can be much less massive. With a singular, reduced preferment rover, the existing Mars orbiters can support the demonstrator for communication and with that the need for dedicated communication relays is also removed. These aspects together make it possible to design the Demonstrator mission as a Payload of Opportunity: The rover could be a lightweight payload carried by another mission. This 'parent mission' can support the Demonstrator Mission's space systems during the launch and transfer to Mars, where it can be deployed to start the demonstration activities for the demonstration mission.

The resulting architecture is shown in the form of System Boundary or Context Diagram in Figure 4, showing all relevant logical constituents of the Demonstration Mission. Note the thick black line denoting the edge of the Mars Demonstrator Mission. inside the boundary is part of the Demonstrator. Outside is considered the environment it interacts with which including Mars itself, the parent mission transfer vehicle, relay satellites and other Orbiters. The abstract trajectory segments for launch-, transfer-, approach-, entry decent & landing- and rolling-trajectories have not been illustrated for clarity, as they are not relevant for this discussion.

based on the architecture, a preliminary product tree is defined and can be seen in Figure 3. This three only shows the space segment and does not show any products part of the ground segments or products that primarily interact with the parent mission, such as the Launch Vehicle, as they are outside the scope of this paper.

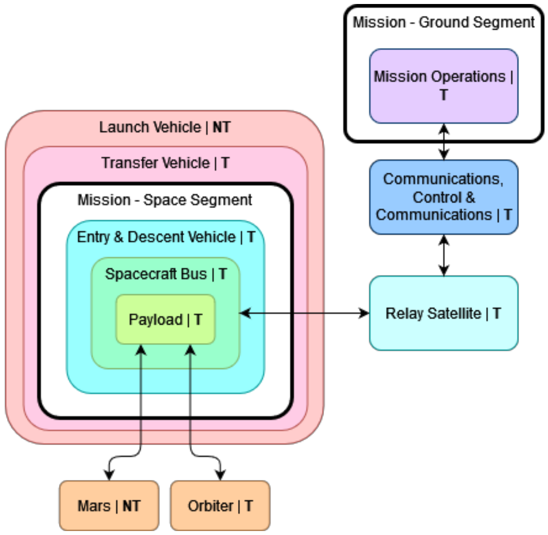

Figure 4: Mars Demonstrator Mission Architecture

With this Architecture derived from the top-level freedoms and constraints, a concept for the phases and operations of the demonstrator mission can be created. As a demonstrator, these operations will once again be similar to the operations presented for the Tumbleweed Mission [1].

in Figure 5 the concept operations are visualized graphically. There are several key steps along the mission timeline that can be identified and numbered:

1. **Launch**: The Demonstrator is launched as a Payload of Opportunity aboard a parent mission
2. **Transfer**: The Parent mission and demonstrator complete a heliocentric trajectory to Mars.
3. **Separation & Approach**: The Demonstrator Mission space segment is deployed from the parent mission and approaches the Martian atmosphere.
4. **Entry & Decent**: the EDV of the demonstrator enters and descents through the Martian atmosphere.
5. **Deployment**: The Demonstrator Rover is deployed from the EDV and unfolds.
6. **Landing**: The Demonstrator rover lands on the Martian Surface.
7. **Mobile Operations**: The Demonstrator Rover performs technology demonstration experiments whilst mobile on the Martian surface.
8. **Stationary Operations**: The mobility of the Demonstrator Rover is disabled and it performs technology demonstration experiments whilst stationary on the Martian surface.
9. **Decommissioning**: The Demonstrator Mission systems are safely disabled and disposed for planetary protection.

The functional design of the Demonstrator Mission is defined to consist of 9 top-level functions. Functions are used to define the desired functionality of the mission and map them onto the logical constituents (or systems) of the mission. As these top-level functions also follow the timeline of the mission, they are also referred to as the functional phases of the mission. They are defined as followed:

F1 Development
F2 Manufacturing & AIT
F3 Launch
F4 Transfer
F5 Approach
F6 Entry, Decent & Landing
F7 Mobile Operations
F8 Stationary Operations
F9 Decommissioning

A noteworthy aspects of the definition of these element are the fact that the transfer and approach are treated as separate functional phases. This is justified by understanding the difference in the relation and dependencies existing between the demonstrator systems and the parent mission systems across these phases. The transition between transfer and approach phase is defined by the separation of the demonstrator from the parent. These functions are fundamental to the analyses and trade studies that will be presented in subsection 3.4.

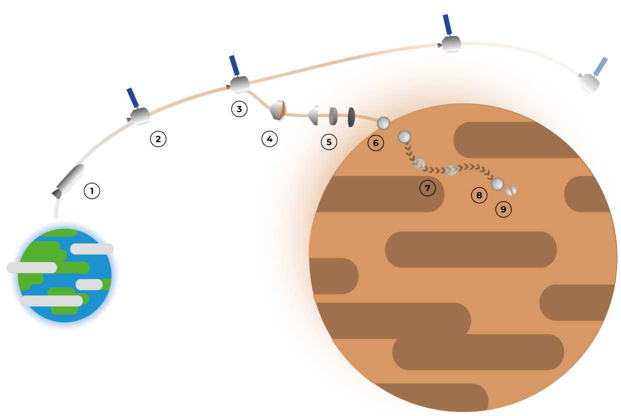

Figure 5: Concept Operations Diagram of the Demonstrator Mission

3.4 *Design Trades*

This section discusses key design trades of the Mars Demonstrator Mission. First the approach phase will explored, where the impact of the Mars-trajectory of the parent mission on the demonstrator is investigated. The Entry, Descent, and Landing design space is explored next. After that, the design aspects of the Mobile Operation phase are discussed. Finally some design considerations for the decommissioning of the system are given.

Mars Approach

An import step for the Demonstrator Mission Design is to analyse the different parent mission transfer trajectories that could carry the demonstrator to Mars. Whilst the trajectory is not something that is likely to be controllable as part of the design of the Demonstrator Mission, it is critical to asses what kind of parent mission designs are compatible with the mission. Since the Demonstrator is a Mars mission, a parent mission with a trajectory along or to Mars is required. There are three options:

- **Parent Lander**: The parent mission is a lander that lands on the surface. As a consequence the trajectory of the parent mission will bring it into the Martian atmosphere (and to the surface) at some point. The Demonstrator has to separate shortly before atmospheric entry and get out of the way for the parent mission to demonstrate the entry capabilities.
- **Parent Orbiter**: The parent mission is an Mars orbiter that will go into an orbit around Mars. If the parent mission uses aerobraking or even aerocapture the trajectory might pass trough the Martian Atmosphere, but most likely the trajectory simply brings the mission in an orbit around Mars. The demonstrator will have to perform some manoeuvre to ensure it enters the atmosphere directly or slows down enough the enter from orbit for separation before or after Martian capture, respectively.
- **Parent Flyby**: The Parent mission is only performing a flyby or gravity assist manoeuvre, and will not remain in the Martian sphere of influence. The demonstrator needs to separate early enough to correct its course compared to the parent to enable it to enter the martian atmosphere and land.

Since the phase between the separation from the parent and entry of the atmosphere is defined to be the approach phase, the approach phase can be very different based on what the parents mission design is. However, the majority of the variability is contained within the approach phase. Regardless of the parent mission type, the trans-Mars trajectory will ensure that the Mission enters the Martian sphere of influence on a hyperbolic trajectory. As a result, an baseline trajectory can be modelled. Then depending on the parent missions actually trajectory, a separation time and correction manoeuvre can be designed and optimised to put the demonstrator back on the baseline trajectory.

in reality the baseline design should be optimised for the specifics of a parent mission, instead of always reverting to the same design regardless of the parent mission transfer & approach trajectory. however, for this paper we will only focus on an initial baseline trajectory design and work from there.

To find the atmospheric entry conditions for the baseline trajectory the transfer is modelled as a patched conic trajectory on a simplified case. there are a few key assumptions: Earth and Mars orbits are considered circular with their orbital period to determine their mean orbital radii. The planets orbits are planar, meaning that the 1.8 degrees inclination difference is ignored [3]. Finally, the mission is assumed to depart from earth at the pericenter of the transfer orbit. within each of the patches, only the closest body (Earth, Sun, and Mars) is considered while the other celestial bodies are ignored. the spheres of influence are the patch points.

To compute the trajectories along the conic sections we utilize the Kepler and vis-viva equations. The Kepler equation relates the orbital radius r to a given true anomaly θ, given the orbits semi-major axis a and the eccentricity e,

$$r(\theta) = \frac{a(1-e^2)}{1+e\cos{(\theta-\omega)}},$$

where ω is the argument of pericenter: the angle between the pericenter and the reference datum. The vis-viva relates orbital energies:

$$V^2 = \mu\left(\frac{2}{r} - \frac{1}{a}\right)$$

with μ the gravitational parameter of the central body.

These relations, and some of their derived properties are used to propagate initial conditions trough the trajectory.

For this baseline case we assume the parent mission leaves Earth from a 400km altitude orbit. The arrival hyperbolic trajectory assumes a initial Martian pericenter of 300km for the parent mission. When the Demonstrator is assumed to aim for a 100km pericenter (thus within the atmosphere) for entry and separates from the parent at martian sphere of influence, the entry conditions can be computed.

In This case a manoeuvre of 415 m/s is required, end gives entry condition velocity V_e of 7246 m/s, entry flight path angle γ_e of -11.916 degrees, at the atmospheric interface altitude h of 125km.

Whilst these preliminary results rely on a lot of assumptions and do not account for different parent missions. it shows that separating from an Orbiter or Flyby mission needs to be done before reaching the martian sphere of influence, as currently the delta-V is to high. To analyse the other cases and earlier releases a more detailed model is to be constructed.

Entry, Descent, and Landing

To lower costs, reduce system components, and simplify swarm deployment for large-scale missions, a novel approach to entry, descent, and landing on mars was investigated. Entering and landing on planetary bodies with earth-like atmospheres from orbit presents three primary challenges: protecting against high heat loads caused by hypersonic flows; resisting high mechanical loads due to aerodynamic drag; and sufficiently decelerating from the high circular velocities to a safe landing speed. The first two problems are conventionally handled in Mars missions by way of an aeroshell. Ensuring a survivable final velocity for a safe landing is, however, a unique challenge due to Mars's thin atmosphere. Different payload configurations require highly specialised systems. Heavier systems, such as MSL [4], made use of a rocket-powered retropropulsive descent stage to achieve sufficient deceleration and precision landing. Lighter missions, such as MER, used fewer landing rockets but required airbags to cushion the landing [5]. All successful Mars landers so far have deployed parachutes during descent. The design and integration of these systems add significant costs and complexity to the mission. A substantial engineering effort is required and the presence of new subsystems and mechanisms brings more failure modes [6]. To ensure a cheaper, more cost-efficient system, the tumbleweed mission exploits the lightweight nature of the rover to simplify entry, descent, and landing.

We investigated an entry, descent, and landing concept consisting of an aeroshell for thermal protection and deceleration during initial descent, which deploys the tumbleweed rover for independent free fall during the last portion of the trajectory. The primary objective of this investigation is to verify safe conditions for rover deployment and landing are achievable.

Our Mars entry trajectory simulation, written in Python, was adapted from an Earth re-entry MATLAB model provided by the TU Delft course AE4870B Re-Entry Systems [7]. This simulation models a 2D ballistic entry trajectory, including all phases specific to the Mars demonstrator mission, i.e. capsule descent, deployment, and rover descent.

We assume entry conditions, derived from the mars approach analysis discussed above, are; an initial velocity V_e of 7246 m/s, entry flight path angle γ_e of -11.916 degrees, at an altitude h of 125km. The total mass of the entry capsule was estimated to be m = 18.18kg.

Gravity at any point along the trajectory is calculated using the following equation:

$$g = g_0 \frac{R_m^2}{(R_m + h)^2}$$

where the average martian gravitational acceleration g_0 is 3.72 ms^{-2}, the radius of mars R_m is 3389.5 km, and h is the altitude at the current time-step.

A three-layer exponential fit is used to model the density of the Martian atmosphere. The form of the exponential fit for all three layers is:

$$\rho = \rho_0 e^{\frac{-h}{H_s}}$$

where ρ_0 is assumed to be the average atmospheric density of the bottom of the layer, H_s is the scale height of the layer, and h is the current altitude.

We assume a fully ballistic aeroshell entry with no lift. A constant drag Coefficient C_d of 1.1 is assumed for the aeroshell throughout the entire trajectory. The reference area A of the aeroshell was taken to be the base area and determined to be 0.287 m^2.

Standard equations of motion for 2-D ballistic flight are obtained from the literature [7]. These equations of motion are numerically solved using a Runge-Kutta integrator of order four to find the velocity, flight path angle, and altitude at every time step.

The g-load for a ballistic flight can be found by normalising the drag force by the weight of the capsule as follows:

$$gload = \frac{\sqrt{C_D^2} P_d A}{m g_0}$$

Here P_d refers to dynamic pressure, given by:

$$P_d = \frac{1}{2} \rho V^2$$

Heat flux calculations will not be discussed in this report. The focus remains on validating the feasibility of rover deployment, free-fall, and independent landing. This deployment takes place well after significant aerodynamic heating ceases.

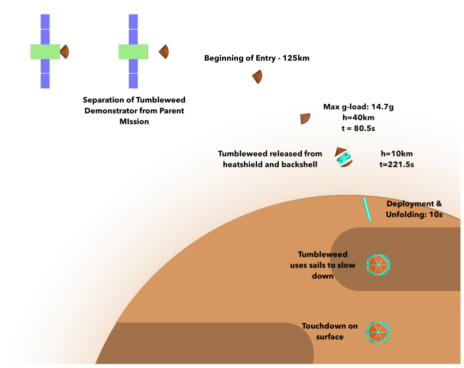

Figure 6: Entry, descent, and landing sequence for the Mars demonstrator mission

Rover deployment takes place at an altitude of 10 km. The mass of the descent module post-deployment is solely that of the rover, m = 8.0 kg. The rover unfolds from its coiled state initially into a cylinder, with a reference surface area A of 0.8 m^2, and a drag coefficient C_d of 1.17 [8]. This simulation models the rover as a cylinder for 10 seconds, after which it further unfolds into its spherical shape with open sails. In its spherical unfolded form, the rover has a C_d of 1.28 and an A of 8.55 m^2.

	Aeroshell	Folded Rover	Un-folded rover
C_d	1.1	1.17	1.28
$A(m^2)$	0.29	0.80	8.55
$m(kg)$	18.2	8.0	8.0

Table 1: (Vehicle) Parameters of EDL configurations for each phase

As can be seen in figure 7 the entry capsule decelerates conventionally, from its velocity at entry of 7246 m/s to a deployment velocity of 292 m/s at h = 10 km. Over the next 10 seconds, the cylindrical rover decelerates at a higher rate to 136 m/s at h = 8.7 km. Thereafter, the rover unfolds further into its spherical form, further increasing deceleration. Velocity decreases rapidly within the next 450m of descent, reaching V = 25 m/s at an altitude of 8.25 km. Figure 8 shows that the rover decelerates minimally for the rest of the trajectory, reaching a final impact velocity of 17 m/s.

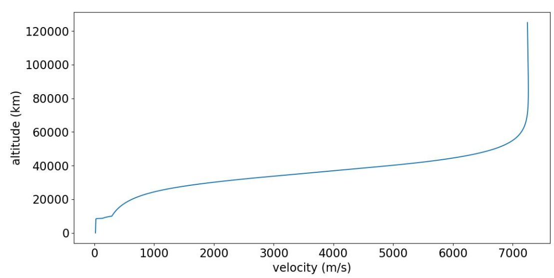

Figure 7: Altitude vs Velocity (full trajectory)

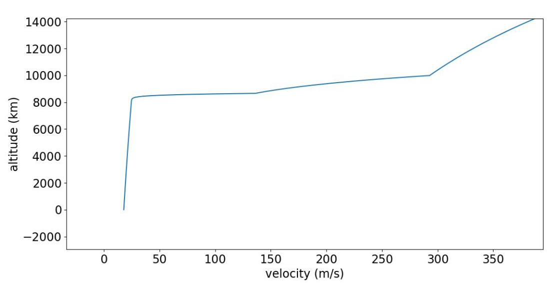

Figure 8: Altitude vs velocity (deployment sequence)

The mechanical loading response from the simulation is shown in figure 9. Up to the deployment point at h = 10 km, we see a typical g-load curve for atmospheric entry of a conventional aeroshell. At deployment, the graph shows an instantaneous spike in the mechanical loading, increasing from 1.5 to 9.2 martian g's. Over the next 10 seconds, the load decreases to 2.5 g's at 8.67km. The rover unfolds completely and we see another, larger, instantaneous g-load spike, increasing to 15.2 Martian g's. As seen in figure 10, both spikes occur in 0.5s, i.e. one step of the simulation. It takes a final 10s for the g-load to settle down to a value of 1g (i.e. terminal velocity is achieved), at which it remains for the last 8.2km of descent.

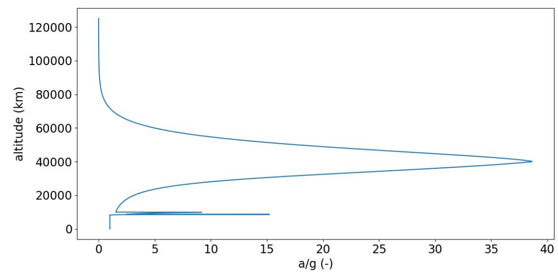

Figure 9: G-load vs altitude (Martian g's)

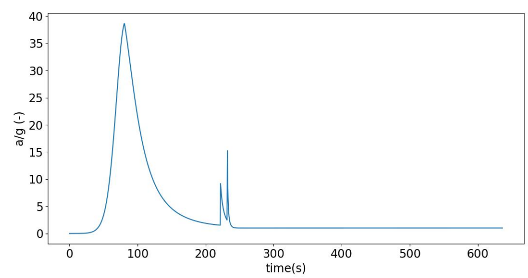

Figure 10: G-load vs time (Martian g's)

Our preliminary entry, descent, and landing analysis of a novel, parachute-less, descent stage-less, free-fall landing concept for the tumbleweed rover shows promising results. As seen in figure 8, a final impact velocity of 17 m/s is estimated by the simulation. Although still too high for a safe landing, with further optimisation of the trajectory, deployment point, and parameters of the capsule (mass, size, aerodynamics) may lead to lower impact velocities. Additionally, the use of an airbag system, or similar impact-reducing systems, can be investigated to further cushion impact.

Further work is needed to identify optimal entry trajectory, deployment point, capsule and rover aerodynamics, and the benefits/disadvantages of adding impact cushioning mechanisms. More work is needed to produce a more reliable and accurate simulation of rover deployment. The current model assumes discrete, instantaneous unfolding. A more continuous modelling of the unfolding dynamics must be investigated. Furthermore, the durability and structural integrity of the rover against mechanical loading during deployment must be analysed to determine whether the rover is able to survive the deployment process.

4 Discussion

In this section we discuss the results presented in this paper. First the demonstration framework and the demonstration missions are discussed. Finally we discuss future works.

4.1 Demonstration framework and prioritisation of missions

In section 2 a demonstration framework for the Tumbleweed mission was derived and several demonstration missions needs defined. We show that it is possible to use these demonstration missions to de-risk the development of the Tumbleweed mission, whilst retaining technical and operational feasibility at any time in the development. Our framework enables the development of novel, miniaturised deep-space science mission trough a set of precursor missions. Each of these missions tackles a subset of the required critical technical advancements to make the following missions feasible.

In terms of the prioritisation of development of the demonstrator missions, as discussed in subsection 2.4, the Mars Demonstrator mission was prioritised for baseline generation. Even though other efforts, such as the Deployment Demonstrator and Earth Demonstrator are directly achievable from the current design state, establishing a baseline design for the Mars Demonstrator first is crucial. With a (initial) baseline design available for both the Mars Demonstrator and the Tumbleweed Mission itself, targets for the development of space hardware and software have been set.

This prioritisation strategy enables the paper design of the Martian Missions (Demonstration and Tumbleweed) to continue whilst the critical technologies mature trough the development and completion of the precursor missions. That allows concurrent engineering to take place on multiple scales. First within each of the missions, but also company-wide concurrent engineer trough the separate mission developments happening in parallel. To make efficient use of the framework, it is important that the engineering can be done efficiently and without large managerial overheads. Segmenting the engineering efforts too much can cause resources to be spread to thin, causing all projects to suffer in terms of time, cost and technical quality.

4.2 Mars Demonstrator Design

The initial analyses presented in this paper were conducted to further quantify the feasibility of selected concepts for different phases of the Mars demonstrator mission. The preliminary results of each analysis substantiate the overall concept of the mission and the constituent systems and subsystems. However, these preliminary analyses do not guarantee feasibility but serve as stepping stones for deeper investigations into system performance. Most importantly, the tools developed can be further augmented and integrated into a global, end-end mission optimisation software, which can serve better quantify feasibility as well as improve the achievability of mission objectives and key results.

4.3 Future work

With an (initial) baseline design available for both the Tumbleweed mission and the Mars Demonstrator mission, it is important to look forward to next steps within the presented development framework. It is clear that there are several items that should be addressed.

- The baseline and directly following detailed design of the Earth Demonstrator Mission and Deployment Demonstrator Mission need to be established in more detail. With the mission needs established and technological development goals set for each of them, the details can be worked out. Similar to what has been done on a high level for the Mars Demonstrator Mission in this paper, a high level design can be established first. Since the requirements and constraints are significantly relaxed for these earth application missions and the scope is reduced, such a study can be completed in a much shorter time frame. As a result even detailed design and hardware development can start soon after a detailed design is established for the missions. For the EDM the largest issue is the definition of the environment in which the system will operate, and for the DDM the early acquisition of allocated system space on sub-orbital launch is vital.
- The continued development of the demonstrator mission. There are many aspects of the mission that are not yet quantifiable or understood completely. Therefor continuing development on the Transfer and Approach trajectory analysis, Entry Decent & landing Vehicle design, Mobile operations and stationary operations performance modelling and safe decommissioning methods is essential.
- Continuing the investigations into the Tumbleweed mission, especially focusing on the scientific return and mission utility estimations.

5 Conclusion

The Demonstrator framework provides a structured method to de-risking the Tumbleweed mission development through the precursing execution of several demonstration missions. The analysis shown on the Mars Demonstrator Mission corroborates the feasibility of concepts and technologies required for the large-scale exploration of Mars with low-cost wind-driven rovers and an in-situ demonstration mission. From this analysis, further requirements, specifications and capabilities for additional precursor missions can be derived. This work will support and cultivate design and development across all technical departments to push the respective critical technologies further and mature the mission concepts.

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