IAC-23,C2,2,4,x77776

Unfolding methods of a two orders of magnitude mechanical volume reduced spheroid Tumbleweed Mobile Impactor

Nils Neumeister[a]*, Mikhail Maximchuk[a], Marco Zambolin[a], Ben Placke[a], Yara Eggenfellner[a], Arun Osman[a], Yasmine Mafoutsis[a], Sabin Ilegitim[a], Michael Sandrieser[a], Julian Rothenbuchner[a]

[a] *Team Tumbleweed, Delft, The Netherlands*

* Corresponding Author, nils@teamtumbleweed.eu

Abstract

Despite the increasing interest in planetary exploration, the cost of space missions makes it prohibitively expensive for most of the research community to have an active part in research. Team Tumbleweed aims to address this issue by developing a low-cost Mars mission based on a swarm of wind-driven mobile impactors. One of the main development challenges is the volume and mass restrictions imposed by current launchers. They severely limit the maximum size of the swarm due to the large volume taken up by the spheroid Tumbleweed Rovers, which are approximately five meters in diameter.

To solve this, the structure of a Tumbleweed Rover must be foldable, which reduces overall mission mass and volume to guarantee compatibility with current launch vehicles and decreases mission costs. The volume-efficient folding structure for wind-driven mobile impactors, presented in this paper, is designed to unfold during atmospheric entry, providing the necessary drag and impact resistance in order to land on Mars. Such a landing procedure presents fewer risks by landing on the Martian surface at terminal velocity, thereby removing the need for complex control sequences. The same structure also functions as the locomotion system, a control mechanism for the trajectory of the rover, and a framework for the deployment of the payload instruments into the operational configuration. The main design challenges of this system relate to the unfolding procedure, structural integrity, and the transition between mobile and stationary states.

In this paper, we focus on the Tumbleweed Rover's unfolding mechanism, which consists of a flexible carbon-fiber structure with a spring-loaded deployment system. We use several structural analysis tools to size the structure and iteratively develop the unfolding system through a series of prototypes. We then validate our design against its key requirements of unfolding, structural integrity, control, and deployment of payload instruments with a sub-scale prototype, along with a series of lab and field tests. Additionally, we show how the Tumbleweed Rover could be folded into a flat disk shape in order for the structure to be transported as a swarm mission on a single launch.

Keywords: Mars exploration, Tumbleweed rover, unfolding mechanism, volume reduction

1 Introduction

In the past decades, significant advancements in space exploration and technology have significantly reduced the costs of launching space missions, paving the way for an increasing number of ambitious missions to expand our understanding of the universe.

Traditionally, interplanetary missions are usually characterized by probes or space structures, such as NASA's Perseverance Rover, that can carry a limited amount of scientific payload on board due to the high mass fraction occupied by traditional electrically powered locomotion systems. Similarly, the hazardous environments on these planets demand immense levels of precision in engineering and control to prevent potential failures during transportation, landing, and completion of scientific missions. The mobility range and controllability limitations due to the immense distance to our planet, reduce the extent of large-scale planetary research. As a result, a more robust and adaptive architecture is needed. In this context, the concept of swarm-based Mars exploration system architecture emerges as a promising solution that merits dedicated research and investigation.

Swarm robotics, inspired by the collective behavior of Tumbleweed plants, introduces a paradigm shift in space exploration. By deploying multiple, relatively simple autonomous agents to work collaboratively, swarm-based systems possess several inherent advantages over traditional methods [1].

The aim of this paper is to discuss different models for an innovative wind-driven rover structure architecture that has the ability to fold into a volume that could fit into a heavy-lift vehicle payload fairing, and unfold upon command at a later stage. If this technology is proven to be working, it will provide an alternative approach in order to deploy a high quantity of payload mass on the Martian surface at low cost, a feature that will be highly requested in the future of space exploration. Moreover, this paper will discuss how the structure's unfolding properties can be applied to generate an alternative solution to the critical process of landing on Mars.

In particular, the Tumbleweed mission, which is still in its infancy, is expected to significantly benefit from the results obtained. The Tumbleweed is a concept for spherical wind-driven Mars rovers that dates back to the 1990s [2] and is inspired by and named after the tumbleweed plant structure. Recently, a mission was proposed to release around 90 such Tumbleweed rovers on Mars to survey its surface [3].

To begin, a brief analysis of the extent of current payload capabilities in relation to modern rocket capabilities as well as the economic feasibility and required structure collapsibility ratio for a full-scale Tumbleweed mission that would be needed will be presented. In the next part, payload mass budgets will be analyzed to determine requirements for the Tumbleweed architecture.

Based on the first parts, several potential Tumbleweed structures will be investigated and compared to determine the most suitable structure that can most ideally meet the mission requirements. To do so, the complexity, mass and volume, and potential volume reduction capabilities of each are reviewed. The structure that is chosen for testing is then further analyzed and potential actuation methods for structure deployment are proposed. The following section presents the model for testing the chosen structure.

The primary results from initial simulations and then physical model testing can then be obtained. Finally, the results from testing the structure will allow conclusions about the structure architecture to be drawn and additionally provide recommendations for further technological advancements in the structure and further fields of testing that would allow more advanced demonstrator missions to be produced, and increase industry understanding and interest in the mission design implemented in this paper.

2 Methods

In this section, we introduce the initial discussions required to make decisions about developing the rover structure architecture, the generation and analysis of various potential design options, and the selection and development of a structure that meets the mission requirements the most.

2.1 Determining geometric requirements for the rover based on currently available launch vehicles

The geometric limitations of launch vehicles for space-bound structures are one of the first things that need to be considered when developing a new structure. Due to the fairly universal dimensions of most modern launch vehicles and due to this research's proximity to the organization, ESA's Ariane 6 was chosen as a model for determining the geometries of a Tumbleweed mission.

2.1.1 Overview of the required structural collapsibility ratio for a full-scale mission

A heavy-lift launch vehicle is defined by its capability to lift between 20,000 to 50,000 kilograms (NASA classification) or between 20,000 to 100,000 kilograms (Russian classification) into LEO [4]. In this case, the dimensions of Ariane 6 were used for the calculations [5]. The usable volume beneath the long payload fairing in a single launch, with a height of 18m and a diameter of 4.6 m, comes to $1196.57\,\mathrm{m}^3$. Assuming the payload fairing to be cylindrical and starting from the goal of having 90 rovers in a mission that get folded into a disc, the maximum height of one of the folded rovers is to be 0.2 m. Including some margin between the diameter of the payload fairing and the one of the folded rover, the maximum diameter of the folded rover, including any restraining components or mandrels, needs to be 3.6m. By aiming for a final outer diameter of the unfolded rover of 5 m, a ratio of 3.6/5=0.72 is given.

2.1.2 Overview of the payload mass budget

The Tumbleweed mission shall have a total mass of no more than 4000 kg in its transfer configuration. This constraint is applied to accommodate for the payload mass that the launch vehicle is able to carry as well as the total mass of all constituents of the mission which will be launched into low-earth orbit. While Ariane 6, whose data was used for these mass calculations of the launcher, has a higher payload than that, the mass results by taking into account the Mars transfer delta-V which limits the originally available mass significantly. By assuming 2200 kg for the entry vehicle and transfer stage, a total of 1800 kg for all rovers is left which results in a maximum of 20 kg per rover for a 90 rovers mission.

2.2 Overview of the Tumbleweed architecture

The Tumbleweed rover is a structure that utilizes the winds on Mars to cover broad areas of the planetary surface in a fast and efficient manner. Tumbleweed vehicles need to be very durable to withstand bouncing and impact events when rolling across the Martian surface [6]. As previously mentioned, the Tumbleweed rover concept has been around for several decades and a diverse set of designs have been generated and tested. Most notably, NASA's LaRC Deployable Open-Structure Tumbleweed Concepts [7] are prominent designs that have repeatedly proven the functionality of these rovers. However, not a lot of next-generation prototypes with advanced scientific sensor payloads have been produced so far, due to numerous reasons.

With this research phase, Team Tumbleweed is interested to begin developing a newer generation of prototypes with the intention of also finding a new way to meet the geometric requirements just mentioned. This means also beginning to consider the implementation of advanced payload instruments and the way to safely support them in the Tumbleweed structure. For this reason, a double-structure system is proposed, with an outer structure that is in direct contact with the ground, and an independently rotating inner structure that remains upright while the rover is mobile. In doing so, we achieve trajectory control, improved power harvesting, simplified communications and payload integration, and overall higher system robustness due to preferable pointing stability.

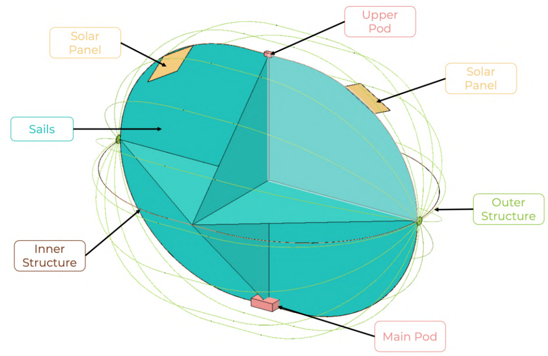

Figure 1: Simplified Tumbleweed Rover schematic

2.2.1 The Outer Structure

The Outer Structure (OS) will be the primary structure of this proposed generation of the Tumbleweed Rover and is also the primary focus of the paper. This structure will go through a diverse range of loads, fatigue cycles, and environmental influences, which could cause additional harm to the payload intended to be transported by a rover during a mission. As mentioned, this structure must be able to fold into a compact shape, in this case, an ideally flat disk shape. During design generation, covered in the later parts of this paper, these aspects are incredibly vital.

2.2.2 The Inner Structure

The second substructure of the proposed Tumbleweed Rover is the Inner Structure (IS), which is intended to house the sails used for propulsion, solar panels, the research instruments payload, and the mechanisms required for steering and braking. Due to its dependence on the design of the OS, the success of a structurally sound OS is necessary to make the functions of the IS possible. Decoupling the propulsion and research components of the rover from the OS will improve damping due to the forces exerted on the OS, and allow for an adjustable locomotion system. Depending on the payload limits and structural strength of the envisioned rover structure, a steering mechanism based on dynamic center-of-mass adjustments could be tested as well.

The development of the IS will not be heavily discussed in this paper, as its development is directly dependent on the functionality of the OS, but it is very significant when considering further development of the Tumbleweed Rover. As shown in Figure 1, the IS design shares similarities with that of the OS, but the volume it is able to fill is heavily dependent on the unfolding methods that will be used to deploy the OS.

The available space for an IS will be closely documented during the research period as maximizing the size of the final IS in relation to the size of the OS will have a notable impact on the rover's rolling behavior, namely in regards to the sizing of the sails and how much driving force they are able to provide.

2.3 Rover design concept generation

Multiple concepts were considered in developing a design for the Tumbleweed Rover. These concepts include a range of applications including, but not limited to, inflatables, coils, and rigidizable joints and arcs.

2.3.1 Rigidizable Joints-based Design

The use of rigidizable joints achieves a very low volume in the rover's packed configuration. One design idea making use of this concept works by adding a rigidizable composite section in the center of the structure of each pre-curved arc. This allows them to be folded in half from their initial shape, resulting in a minimization of the size by two.

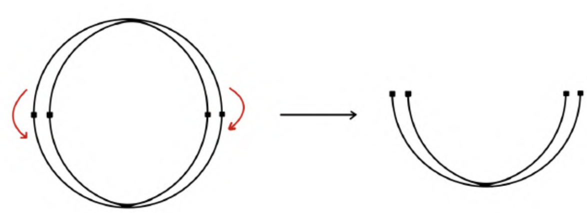

Figure 2: Rigidizable Joints Design

2.3.2 Inflatable-based Design

Inflatables can be used to achieve efficient folding configurations while maintaining structural integrity by enabling the rover to occupy a smaller volume. Inflatable booms, bodies, and canisters can be used to exert the required force to push the nodes and arcs to the unfolded shape. In order to further reduce the folded volume of the rover, inflatables can be combined with the use of rigidizable joints. Figure 3 illustrates one possible concept, utilizing inflatable members. Here, the inflatable booms give the rover its shape, and rigidity is added by internal cables. However, this concept was not further considered, due to the high risk of puncture, and difficulty in modelling the deployment of the design.

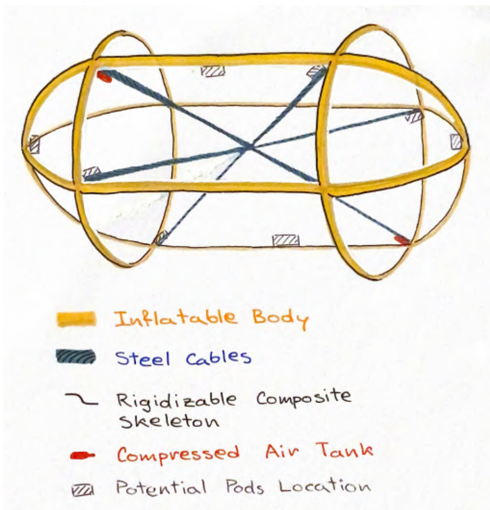

Figure 3: Inflatable-based Design

2.3.3 Coil-based Design

Coil-based designs use clockwise and counterclockwise coils to achieve a rigid structural shape while allowing the rover to obtain a low volume in the folded position. The coils are connected together at end nodes which present disks that can rotate in opposite directions. Connections along the main belt are needed to keep the rover in the correct unfolded configuration. The number of used coils and disks can vary in different sub-designs while maintaining the same original concept idea.

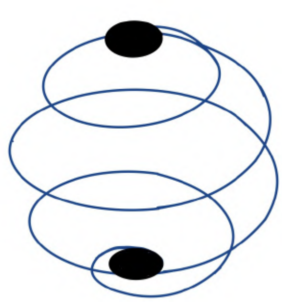

Figure 4: Coil Design

2.3.4 Stent Design

The stent concept is based on a mechanism used in the medical field that bends flexible members into a larger volumetric shape. In this case, the folded structure consists of a set of flexible rods arranged in a circular pattern. Each of the ends of these beams is connected to an end node. To deploy this rod-like shape into a spherical shape, the end nodes will be pushed or pulled closer together using guidewires or ropes that connect to each arc over an individual interface, making the beams deform into a quasi-spherical shape. After unfolding, a locking mechanism holds the rover in the unfolded position.

A modification of the original stent with a simpler unfolding mechanism involves pre-curved rods with a default unfolded configuration. A string could go through each rod pulling them together which is cut during deployment.

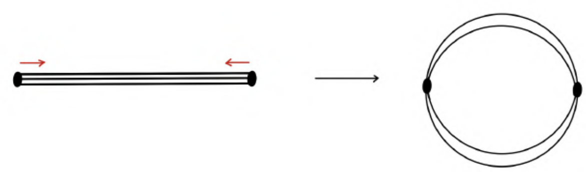

Figure 5: Stent Design

2.3.5 Design selection

The Tumbleweed rover must exhibit characteristics of foldability, reliability, precise control, seamless deployment, robust structural integrity, and have the capability to change from mobile to stationary states, all while demonstrating practical feasibility. The stent design has emerged as the prevailing choice in the design selection process, effectively meeting all requisite criteria and demonstrating superior performance among the competing designs.

The stent design's lightweight structure minimizes the complexity of the deployment mechanism, as its actuation system can be designed with high reliability and low mass, compared to some competitors using inflatable actuation for instance. Moreover, it is also advantageous for the planned 90-rover Tumbleweed mission, efficiently accommodating the inherent constraints of limited payload mass capacity. Furthermore, its flexibility and possible 2-stage deployment method facilitate good foldability and compact stowage, enabling the transport of a larger number of rover payloads during the mission, whereas systems like the coil design struggle to achieve such a high collapsibility ratio. The stent design's deployed shape approximating perfect spherical conditions maximizes the internal volume for additional mechanisms like the Inner Structure which constitutes to be another big advantage. Additionally, the reliability is demonstrated by the stent design's proven track record in medical applications [8].

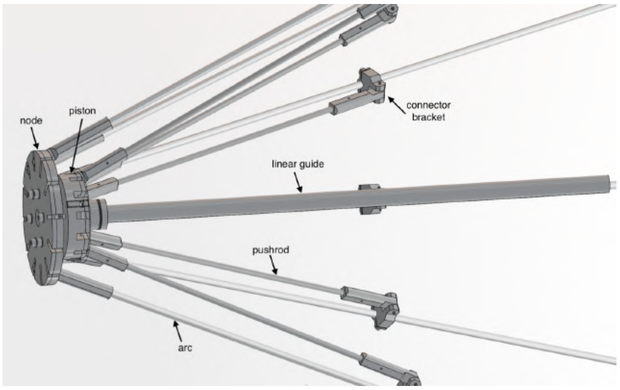

Figure 6: Parts of the Stent Design

Note that for enhanced visibility some of the arcs in Figure 6 have been made transparent.

2.4 Structure Collapsibility

As with most past planetary surface exploration missions, entry, descent, and landing (EDL) is arguably the most critical phase of the Tumbleweed mission. In this stage, the rover shall execute an accurately-timed deployment sequence, as well as absorb the impact at landing, while protecting the delicate payload onboard.

2.4.1 Folding steps of the stent model

As mentioned in Section 2.1.1, the rover shall be able to fold into a compact shape for transportation within the launch vehicle and aeroshell. The stent design concept is therefore envisioned to take on a cylindrical shape when unactuated, wherein the arcs are straightened and therefore relaxed. However, the length of the stent in this configuration can be problematic, which is why an additional folding step is proposed. In this step, the straight stent is bent into a coiled shape with a relatively small diameter and thickness. See Figure 7.

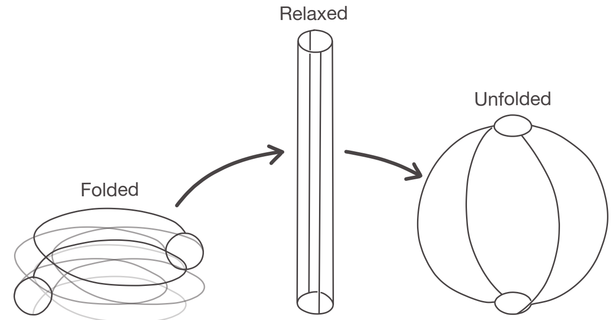

Figure 7: Stent configurations

Bending the stent structure into the coiled shape presents one of the highest strains that shall be endured by the structure, due to the small radius of curvature. This sets a limit on the maximum diameter of the arc section, which can be calculated using Equation (1).

$$d_{max} = D_{coil} \cdot \|\varepsilon_{fail}\| \tag{1}$$

Here, d_{max} is the maximum diameter of the arc section, D_{coil} is the diameter of the above-mentioned coil, and ε_{fail} is the failure strain of the arc material. This formula has been derived assuming that the central axis of the arc remains under zero stress and strain in bending. Assuming a normal-modulus CFRP rod, the failure strain can be roughly approximated as $1\,\%$, or 0.01 [9]. Considering a coil diameter of $1.5\,\mathrm{m}$ (target $30\,\%$ of the deployed diameter of $5\,\mathrm{m}$), the maximum cross-section diameter then is $15\,\mathrm{mm}$. This, however, is merely a first-order estimate, as safety factors and landing impact loads must also be taken into account.

After the rover has been released from the aeroshell and uncoiled into a straight rod, an additional unfolding step is needed in order to enable safe landing and locomotion. In this step, all rover arcs are simultaneously bent into an approximately semi-circular shape, such that the sails can fully deploy, and the rover is able to roll and absorb impact, thanks to its quasi-spherical shape. This bending will be enabled by an active deployment mechanism, presented in Section 2.7. Said sequence is shown in Figure 7.

2.5 Locomotion of the Tumbleweed Rover

As previously mentioned, the stent design needs to be able to roll through the Martian surface by using the Martian winds [10], which will generate drag on its sails. As a result, when it comes down to locomotion, there are four critical subsystems: the Outer Structure (OS), the Inner Structure (IS), the pods, and the sails. The first two will be able to rotate independently from one another and will have slightly different designs due to the differences in functions and requirements they have to comply with.

The rover's OS will drive the overall shape of the rover and therefore will determine the rolling capabilities of the structure. It could present multiple geometries when it achieves the unfolded configuration. These can range from a perfect spherical to an ellipsoid and they can highly influence the rolling behaviour, the controllability, and the speed of the rover. If the Tumbleweed Rover's OS is designed as a sphere, it will allow the sail to have the maximum surface area, generating the highest amount of drag which would lead to higher speeds and bigger distances covered during the dynamic operations of the mission. Nevertheless, the spherical shape will reduce the predictability of the rover's trajectory when rolling and also will strongly limit the possibility of maneuvering the structure with any type of mechanism because the rover will be induced into motion by any type of disturbance yaw moment. On the other hand, if a more elliptical shape is selected, the rover will be able to have a main axis of rotation which will constrain the motion of the rover only to winds coming with the correct flow orientation. Moreover, through the use of an appropriate sail architecture, the side winds could be channeled and deflected in order to create a drag force exactly in the main direction of motion. The negative side of this geometry is the lower surface area which will generate a lower drag force, consequently decreasing the speed and distance traveled by the rover. From the description of the concept in Section 2.1.1, the final OS shape achieved by the Tumbleweed Rover can change based on how close the nodes are pulled together during unfolding, which is strictly dependent on the applied unfolding force.

Another possible issue with the described arc-based design is the smoothness of the rolling motion, which may be impacted by the spaces between individual arcs. This can be compared to gear backlash and can increase vibrations and fatigue experienced by the rover. To mitigate this, it is possible to mount the arcs in a counter-rotating fashion such that, at any point in time, at least two arcs are in contact with the ground.

The rover's IS will be placed inside the OS and it will present an additional connection with the sails. The first interface will drive the overall geometry of the IS arcs, while the sails will determine the number of arcs required for optimal rolling conditions. In the stent rover design, the IS will be connected to the OS through their nodes as explained in Section 2.8. This link between the two subsystems is designed in order to allow an independent rotation of the two structures and, most importantly, to utilize only one single mechanism to unfold both structures. This last aspect is very critical in order to minimize the mass, size, and complexity of the rover which allows an easier folding of the overall structure.

Lastly, the pods depicted in Figure 1, which house the major instrument components, are envisioned to function as a major component for steering maneuverability. By shifting the position of the Main Pod about the IS, the center of mass of the Tumbleweed Rover can be altered, and therefore the direction in which the rover is rolling.

2.6 Main design challenges

As previously mentioned, the current design has a few challenges, mainly regarding the unfolding mechanism, structural integrity and the transition between mobile and stationary states.

In unfolded form, the volume of the Tumbleweed is large. Thus, it needs to fold into a more compact form so multiple rovers can fit into the transport vehicle to Mars. The challenge is therefore developing a structure that can take the form of a sphere (operation), a stent (transition), and a curved stent (during transport). It is complicated to fit all of the structures and subsystems in the compact curved stent form.

The unfolding system, the most vital component of the rover, requires the actuators to always work in optimal conditions. Any underload can hinder the structure from deploying, while an overload may affect the integrity of the main structure. The main challenge will emerge during pre-launch loading, where the proper loading has to be ensured in the spring-actioned actuators. Considering the choice to use a spring-loaded actuator, plastic deformations can drastically influence the reliability of the subsystem. This effect has to be thoroughly studied as the expected travel times exceed 8 months.

One of the main challenges is the brittleness of the unfolding locking system (we need further design choices).

A particular challenge the team ran into regards the improper positioning of the arcs during deployment, hence the need of the rods, as briefly shown in Figure 6. However, due to weight and volume requirements, they cannot be designed to ensure the proper bending of the arcs. Even though the OS is designed to include push rods, the IS does not have a sufficient volume to incorporate such a feature. Therefore, pre-bending has to be ensured in all arcs to allow the sails to properly function. This may turn out to be both a manufacturing and a transportation challenge.

One of the main issues with the concept of the Tumbleweed Rover is the level of stress the arcs must encounter. From landing to simply rolling on the ground, the arcs, which already are in constant bending while deployed, have to endure the further pressure generated by the impact with any surface. This can ultimately irreversibly damage the OS. The arcs need to be stiff enough to not bend under the rover's own weight, but also flexible enough to absorb shocks from surface irregularities.

One of the requirements of the rover is the ability to transition between a mobile and a stationary state. While in the mobile state, the center of mass of the Tumbleweed is in its center, on the axis of the two nodes. The transition to the stationary state consists of the center of mass moving lower and closer to the ground so there is a resistance to motion even if the sails are open. The challenge with this is that the entire IS has to be lowered.

2.7 Analysis of potential actuation methods

In order for the Tumbleweed Rover to transition from the cylindrical shape to the deployed rover structure, as mentioned in Section 2.4.1, an automated actuation system is needed for this structural transition. A number of concepts were considered for this. After analyzing and comparing their characteristics to the requirements determined in Section 2.1, a system was chosen to be pursued for this research study.

Pyro Actuation An actuation system using pyros would rely on the exhaust gasses from the combustion of a solid substance, to provide enough pressure for the stent unfolding. For example, gunpowder could be used. This substance was considered for the estimation, as it has the advantages of being relatively easy to store, not sublimating in a vacuum, and being a low explosive, which means it would only produce minor shock waves.

For a pyro-based actuation system to properly work, the necessary mass of combustible material needs to be calculated to fine-tune the force exerted by the system. To estimate the mass required for an actuation system using pyros, the necessary mass of the gunpowder was first calculated using four methods: based on the work provided by the gas, considering isothermal and adiabatic expansions, and based on the force provided by the gas pressure, also with isothermal and adiabatic expansions.

For storing the gunpowder, a piston shell would be needed. Here, the material properties of AL7075T6 were assumed, as it is a commonly used lightweight aerospace alloy. The shell would have a cylindrical shape, with a spherical bulkhead, in order to better endure the high pressure of the explosion.

Given these considerations, pyro-actuation would be a reasonably reliable system as the required forces needed for actuation are fairly easy to adjust. It's also relatively cost-effective, the materials required are very accessible, and mechanically, there are few moving parts. However, given the explosive nature of this system, the storage and implementation are substantially more difficult than the other considered concepts. Reliability and accuracy of the combustion would require an immense amount of additional research and engineering, which was deemed unachievable during this research phase. The safety aspect of dealing with this sort of actuation is also a concern, as limited accessibility to the required equipment, makes the development of this system difficult. Furthermore, the reusability of this system is also problematic. In the consideration of wanting to repeatedly fold and unfold the mobile-impactor, single-use combustible materials can't be used.

Gas bladder actuation Similarly to the pyro actuation mechanism a gas bladder actuation can be used to perform the unfolding procedure. In this consideration, the actuation force to push the umbrella mechanism and unfold the rover is generated by the use of pressurized gas. This will be released when the unfolding procedure is initialized during entry and the change of pressure will result in a force on the unfolding structure. In order to make an analytical estimation of the pressure and the size of the gas bladder required for the system to function, the assumption of an isentropic change of state based on Boyle-Mariotte's law was made [11]. Using this, as well as the force required by the unfolding structure analysis, and the piston dimensions of the actuation system can be used to backtrack the pressure that has to be provided in the gas bladder in its closed state.

Adjacent to many of the mentioned advantages and disadvantages of the pyro actuation system, the gas bladder actuation also lacks the ability to be reused easily, making repeated folding and unfolding sequences troublesome. Although the mechanism itself can present good reliability the very specific application makes the usage of off-the-shelf products difficult, increasing the production costs of this system.

Motorized Actuation The third concept considered proposes the use of a servo motor or linear actuation motor to deploy the arcs. Several options can be considered including linear motors, DC (brushless or brushed), or servo drives.

Linear motors have the advantage of being a relatively simple design, where the actuator is attached to both the connector and the umbrella mechanism. The main disadvantage of linear actuation is the weight-to-performance ratio, which can increase significantly for the concept design. For DC motors, the issue is the comparably low torque output. This can be counteracted by using a gear motor, which increases the torque and reduces the speed. This then poses the problem of yet again heavy assemblies. The last option to use is a servo drive, which in comparison to the DC motors, has a higher torque rating, although the cost factor is generally higher for the servo motor.

For this paper, calculations solely serve as a rough estimate in what range the torque/force requirements, needed for each mechanism, are derived. Furthermore, the peak force to push the rods outwards is used for the estimate. The team opted to investigate three possible designs using a motor actuation, which include pulling the umbrella mechanism by ropes, utilizing a linear motor, or using a spindle drive to achieve the pulling force.

For the forces and the torque required for each system, the number of arcs and the diameter of the motor shaft are used and a mechanical equilibrium calculation can be produced.

Spring unfolding This design involves the use of the elastic energy and force provided by a spring to unfold the rover. Using this principle, the spring mechanism will be initiated at the desired time, driving a piston in a translatory motion. This basic model of actuating the unfolding mechanism presents a cost-effective and comparably low complexity system, which due to its mechanical simplicity will also make achieving the mass requirements easier. Although due to the spring's capability of compressing back together this system by itself lacks the guarantee of keeping the rover fully unfolded during rolling. Therefore, a locking mechanism is necessary. To calculate the needed spring constant and the necessary displacement a simple conservation of energy can be applied between the fully compressed and the fully unfolded state of the spring. The optimal spring constant and minimum displacement can then be chosen in a trade-off, based on the requirements set by the geometrical shape of the unfolding structure.

For the purpose of choosing amongst the four options for the actuation method, a trade between certain criteria was performed. This trade included mass, mechanical simplicity, expected reliability, feasibility, cost, and material availability. Altogether, the spring performed more highly than all characteristics that were considered. In four of those categories (mass, ease of implementation, cost, material availability), the spring design met the requirements and for the other two, only minor correctable deficiencies were found. With these results, the spring proved to be an optimal actuation mechanism.

2.8 Development and testing of the stent design

In this section, the design development of the stent model is described as well as the testing architecture that was used to facilitate these developments.

2.8.1 2D design iteration of the unfolding mechanism

An important determining factor for the performance of the unfolding mechanism is its well-designed geometrical shape. To visualize this the decision was made to create simple sketches in CAD to act as simulations for the kinetics of the main points of the unfolding structure. Using this, different concepts for the unfolding can be analyzed and its geometrical dependencies can be optimized to reach a maximum deflection angle of the arcs at the nodes of the rover, as this is a crucial factor in determining the unfolded shape of the arcs.

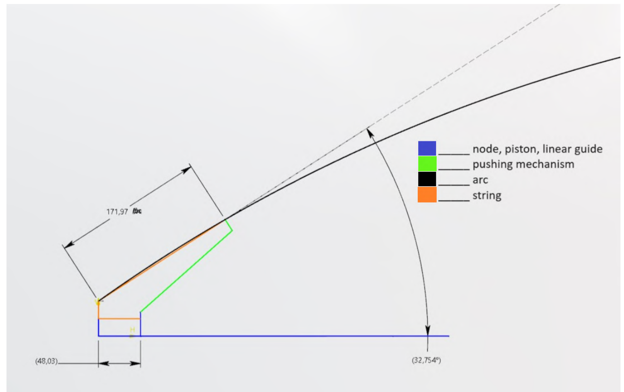

Figure 8: 2D-visualization using sketches in CAD software

2.8.2 Converting 2D designs to 3D models for real-world testing

To be able to prove the functionality of the unfolding mechanism, CAD software was used to design parts and assemblies of the rover structure. Utilizing the knowledge that was given by the optimized geometrical visualizations, the major points of the 2D model were embedded in these parts with their respective dimensions to best resemble their kinematic behavior in the actual rover model. All CAD parts were designed on the premise of being 3D-printed, as this was chosen to be the main manufacturing process for the prototypes, due to the simplicity in design choices and the accessibility of 3D-printers. As shown in Figure 9 and Figure 10, the 3D parts were designed, so that the assembly can be attached to the testing architecture described in Section 2.8.4.

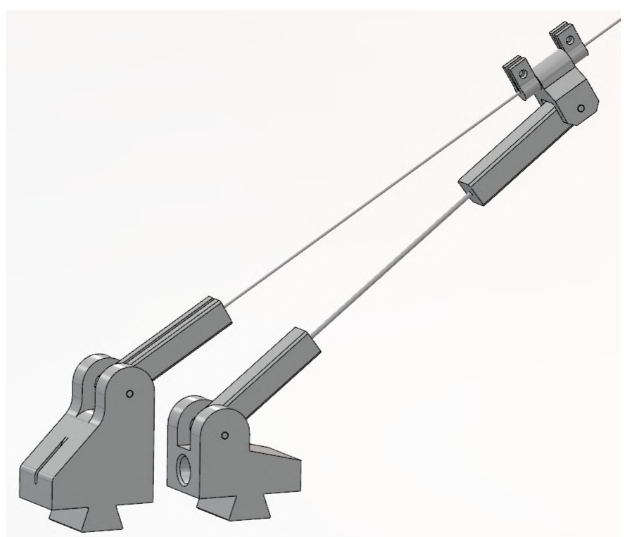

Figure 9: Unfolding mechanism without rope

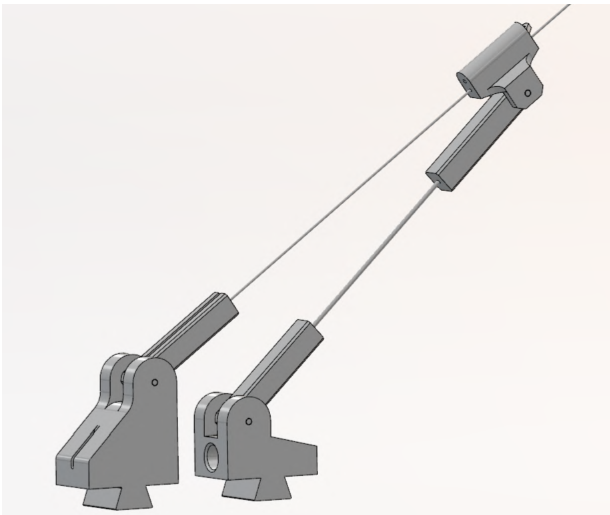

Figure 10: Unfolding mechanism with rope

2.8.3 Analyzing arc bending behaviour using FEM

To gain more insight into the bending behaviour of the arcs without requiring more testing, Finite Element Analysis was conducted. This allowed us to predict the shape, reaction forces, and internal stresses in the arc, for different deflection angles. The model used 1D quadratic beam elements, with a hybrid formulation to account for the nonlinearities caused by the large deflection of the arc. The simulation results were then validated by comparing the resulting shapes with a bench test, where arcs were mounted on a linear guide under different deflection angles. An example simulation can be seen in Figure 11, where a deflection angle of 60° was applied. Its corresponding validation test is shown in Figure 12, where a similar bent shape is obtained.

Figure 11: FEM Bending Simulation with 60° Deflection (Abaqus CAE)

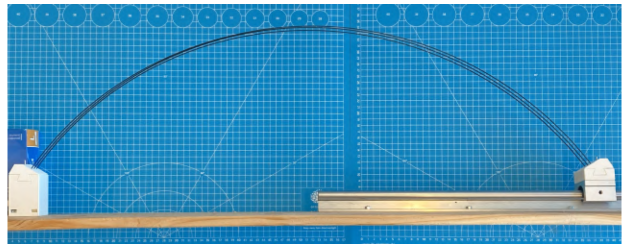

Figure 12: Bending Bench Test with 60° Deflection Angle

2.8.4 Testing architecture for arc bending

To verify the expected structural performance, the material bending capabilities, the load resistance of the arcs, and the achievable deployed shape need to be tested. Therefore, various methods are implemented to optimize the arc structure and the mechanism used to deploy it. A testing architecture to test the bending behavior of the arcs is first introduced to simulate the deflection curve of the arcs as well as calculate the necessary dimensions of a mechanism to achieve the deployed shape. The testing rig includes a linear rail with adjustable attachment points for the arcs which is used to bend the arcs into the deployed positions. With additional adjustments, deployment mechanisms can be attached to the rig to test their feasibility.

Figure 13: Testing Rig

The previously described testing rig was used to simulate the unfolding conditions of the rover. A section of the Tumbleweed (1 of the 12 arcs) was used for simplicity.

This way, the deflection of a single arc could be observed. Considering the final dimensions of the rover have not been set, a 2-meter-long arc was chosen for performing the tests. The outer node was fixed and the inner node was mounted onto the linear slide. There was a fixed-length string tied in between the inner node and the arc slider that also passed through the outer node. This way, as the inner node moves towards the center of the Tumbleweed, the arc slider moves more towards the outer node, further bending the arc. To simulate the unfolding, the inner node was initially in the folded position (next to the outer node, at the left end of the linear slide (Figure 13). The inner node was then pulled to the right along the linear slide to simulate the unfolding forces to be used. The second end of the arc was kept fixed in the plane of the wooden plank and was allowed to move only on the axis of the linear slide. During this process, the arc began to bend due to its two ends coming closer while also maintaining the right curvature due to the push rod connector.

The testing phase proved that the arcs can successfully bend to a 90-degree position, which is the desired angle needed to produce a spherical rover shape. During the numerous attempts, no malfunctions occurred, showing the effectiveness of the push-rods and the interfaces. The most significant result of the testing procedure is the determination of the optimal extension angle of both the arc node and the push rod. By allowing the interfaces to move along the rod and the testing rig (which simulated the linear guide), it was possible to determine the position in which the arc was best extended (constant bending) and least stressed. Another discovery consisted of determining the range of angles in which the design would function within expected parameters. Also, the design proved to have a natural intent to return to its initial position, which disproves the need for further design features to limit the degrees and range of freedom of movement. However, a design flaw made itself shown. The great friction between the arc and the arc slider can sometimes block the movement of the push rod, destabilizing the load application on the nodes and damaging the structural integrity of the rover. Additionally, the blockage of a slider can result in the failure of the respective rod by either not allowing it to fully deploy or by causing it to fracture.

Following the above-mentioned tests, the design was proven to be functional and behaved as predicted. A few improvement opportunities were observed as well. Firstly, the arc bent into its final curvature depending on the length of the push rod. So further testing should include multiple push rod lengths and a detailed analysis of this parameter would be beneficial. Secondly, the non-fixed end of the arc (the rightmost one) was hard to keep in place, so for further testing, a second linear slide could be used to limit the movement of the node to a single axis. Thirdly, different string lengths could be experimented with. This way, the optimal value for the sum of the two distances, one from the inner to the outer node and the second from the outer node to the arc slider, could be found.

3 Results

In this section, the results from the testing methods previously mentioned will be described.

3.1 Building and testing a half-model of the most rudimentary version of the umbrella mechanism

The first test of the umbrella mechanism is intended to test its first iteration and see whether the proposed design works in the least complex version of the system with the desired outcome of the mechanism allowing the folded rover to unfold smoothly into the deployed position. For the sake of simplicity, only one node with four arcs was tested while making sure that this simplification did not lead to any reduction in the significance of the test results.

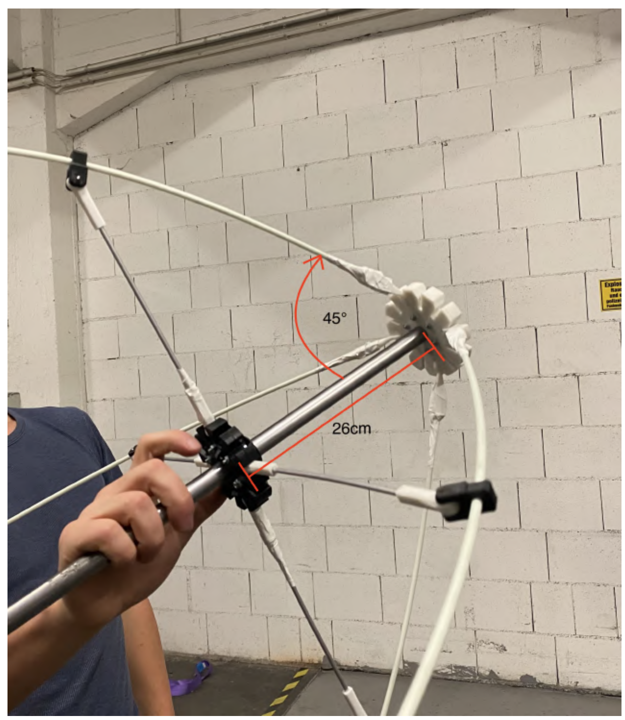

Figure 14: Umbrella Mechanism

The assembled mechanism allowed the arcs to be brought into a bent position and thus deploy the rover. A problem occurred as the arcs did not fully reach the desired position, meaning the angle between the linear guide and each deployed arc did not exceed 45 degrees (see Figure 14). In order for the rover to take the shape of a sphere, the angle is required to be close to 90 degrees, requiring an adaptation of the geometry of the pushing mechanism in the next iteration. As a result of the reached angle, the displacement of the piston was 26 cm (see Figure 14) which changes as the angle increases.

3.2 The complete model assembly

The second assembly test was carried out with six arcs and two nodes, to test if a spherical shape would still be possible with a fully assembled rover model. When unfolding the Tumbleweed rover, the piston ran along the linear guide without friction forces impacting the deployment of the structure. The shape of the arcs in the center adopted the desired bend, however, closer to the nodes the necessary 90 degrees were still not reached. Trying to extend the length of the push rods as an attempt for troubleshooting did not achieve a significant change in the arc deflection. See Figure 15.

Another objective of the second test was to bend the unfolded rover into an annular shape, which will play an important role in transportation and storage in the launcher. The linear guide did not create any issues and little force had to be applied to attain the desired shape. However, with the Tumbleweed rover aiming to have a final outer diameter of five meters in the deployed position, it will have to be coiled into a spring-like shape to have a proper size to be able to fit in the launcher in the folded position.

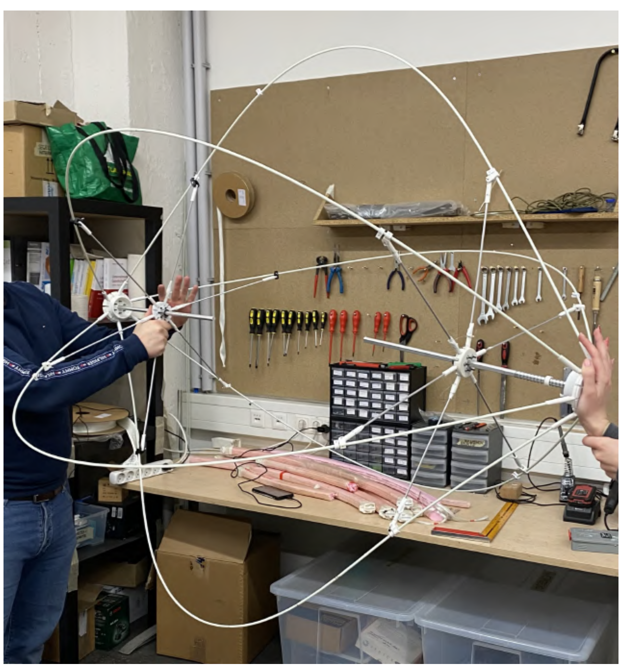

Figure 15: Unfolded Rover

3.3 Actuation mechanism testing on a singular arc using the testing rig

Following testing of a half-assembly rover led to the team's decision that the behavior of the umbrella mechanism needs to be studied further to better understand how the mechanism works and where the main problems lie. This is why the linear testing rig setup was implemented. Limiting the analysis of the mechanism's behavior to a singular arc allows for more precise development of the overall mechanism by starting development with singular mechanism components before moving on to all the components fitting together in the entire mechanism as a whole. The first test which tested the most simple variation of the umbrella mechanism Section 2.8.4 verified that the maximum arc deflection possible with this design does not meet the requirements for the shape of the OS. The deflection angle did not exceed 70° even with increased push-rod lengths. Due to this design's triangular nature, an angle improvement is not possible, even if the piston were to move past the point where the push rod sits precisely perpendicular to the linear guide. See Figure 16.

Figure 16: Push rod perpendicular to the linear guide

Only allowing the connection point between the pushrod and the arc to move along the length of the arc would make a higher deflection angle possible; this being a focal point of the next variation of the mechanism design. Adding the rope that pulls the arc interface closer to the nodes further assisted with distributing the forces being applied to the arcs, meaning deployment required much less force.

Furthermore, due to the rope pulling the arc interface closer to the node, an almost 90° arc deflection angle is achieved. See Figure 17.

Figure 17: The arc to linear guide angle reaching 90°

This is a promising result that is expected to translate well for a spherical shape for a complete rover. In order to make accurate interpretations of how much volume within the OS is available for an IS, the displacement of the pistons during deployment, and the distance between the two nodes were reviewed. The displacement of the piston to maximum arc deflection was approximately 13.5 cm as shown in Figure 18.

Figure 18: Displacement of the piston

While only one node was used during this test, by manually moving the free end to the fully deployed position, it was possible to determine that the distance between the two nodes was reduced by approximately 94 cm from folded to the deployed position. See Figure 19.

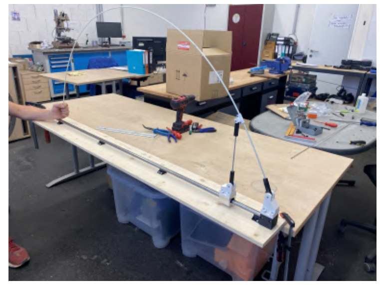

Figure 19: Holding one end of the arc to simulate the fully deployed arc

This means, as shown in Equation (2), there would be room for an IS with a maximum diameter of approximately 78 cm including 1 cm of margin.

$$d_{max} = 200cm - 94cm - (13.5cm * 2) = 79cm \quad (2)$$

As these results stem from tests conducted on 2 m long arcs, scaling up to the desired 5 m total diameter for the OS would require consideration of increased arc diameters, push-rod lengths, and maximum piston displacement with increased structure geometries. These results proved that there is promising potential with an umbrella mechanism using the rope design, but to ensure that deploying both ends of the rover structure would be achievable if each deployment ensued simultaneously, an additional test with two nodes attached to the testing rig was necessary.

3.4 Testing both actuation systems on a single arc

With the second test conducted on the testing rig, the second node was attached to a linear bearing so that the end of the arc was able to move to the position in which maximum deflection was possible. As the two umbrella mechanisms function in opposing directions, examining the behavior of the loose-end node and the piston on that end moving in the same direction was necessary. This test proved that deployment is achievable with both ends.

Moreover, the test further confirmed that geometrically, it is possible to achieve a near-perfect half-circle deployed arc with the umbrella mechanism with the rope component as shown in Figure 20. Given an equal amount of deployment force applied to either end of the arc assembly, both umbrella mechanism assemblies are able to deploy the arcs equally as well.

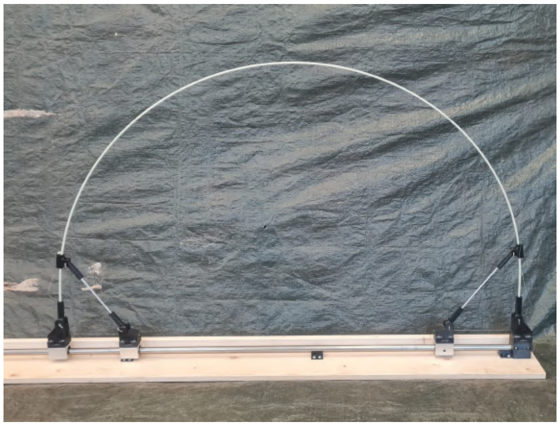

Figure 20: Arc shape following actuation of both mechanisms

While the test provides further notable successes with the development of the umbrella mechanism, several matters continue to arise that will require further research and potential alterations to the structure design. Namely, in order for the umbrella mechanism to push the arcs outward, a slight pre-tension to the arcs was applied during the assembly of the testing rig so that the arcs were slightly already bent outwards. This raises an issue with the envisioned stowed position of the rover, as mentioned in Section 2.4.1, as slightly bent arcs make it difficult to bend the rover into either an annular or even spiral shape. If this proves too difficult, either the stowed position or the umbrella mechanism will require revision. Furthermore, an issue that was already seen previously during the assembly tests, the stability of the arcs needs to be investigated and prevention of lateral movement needs to be implemented to ensure the OS is stable and no interference with the IS is possible. The connection points between the arcs and node need to limit this lateral movement otherwise structural rigidity can't be ensured.

4 Discussion

This section elaborates on the research study analyzing unfolding mechanisms that are to be integrated into the Tumbleweed rover by discussing the learnings from the testing phases, the suitability and the expected challenges of the mechanism's integration to the Tumbleweed rover, as well as necessary points of further research for the unfolding methods.

4.1 Statements about the testing results

Based on the results gathered through testing a model of the stent actuation system, it can be interpreted that converting the spring actuated mechanism to a full-scale rover prototype will potentially allow the structure to take on a spherical geometric shape. Such a prototype could not be built during this research phase due to budgetary and time constraints, so more definite statements cannot be made. However, the additional simulations using CAD modeling and FEM provided considerable proof for the possibility of the envisioned geometry, so it is expected that similar results are achievable in a rover demonstrator model.

4.2 Challenges and limitations

The stent design and the unfolding mechanism that was developed in parallel are attractive for developing a full-scale demonstrator Tumbleweed prototype, as the volume reduction achievable with this method is within the bounds of the geometric requirements that were based on the dimensions of current launch vehicles [5]. There remain, however, issues with the current design that won't make integration into a demonstrator rover fully possible yet. For starters, converting the unfolding mechanism from one built around a singular arc to one that must deploy 12 arcs will remain a significant challenge. This is because, with the increased number of arcs, the spring system will need to produce more force but with the same amount of available displacement. Here, scaling of the spring values for deployment will be an important factor to consider for successful arc deployment.

Additionally, the stability of the stent model is also a major concern. The location of structural supports is currently limited to the ends of each arc, which raises concerns about the range of external forces such a structure is able to withstand. Forces being applied to the peaks of each arc (which is guaranteed during rolling) can cause the arcs to bend away from their initial orientation if the structural supports aren't responsive enough. This can lead to catastrophic structural failure if the external forces are frequent and powerful enough. The material and the dimension selection for the arcs, as well as the rigidness of the node and unfolding mechanism system, are elemental for the success of constructing a functional rover. This also applies to the linear guide system along which the pistons travel during deployment. As the linear guides aren't directly connected to one another, the alignment of the two can be problematic. In order for the OS to maintain its spherical shape, the linear guides must remain parallel to one another so as to not disrupt the angle at which each push rod approaches the correlating arc. The length of the linear guide and the overall dimensions of the subsystem it is part of are considerable challenges for developing an IS, as well, as it is expected that the node system (or others if deemed necessary) of the IS will be attached to the inner ends of the linear guide as a way to also prevent the unfolding mechanism from detaching from the linear guide.

4.3 Points for further research

As already previously mentioned, the stability of the Tumbleweed stent model will require further testing. During the construction of a further fully assembled prototype, the arc stability must be analyzed and if necessary, alterations to the design will be required. A potential design choice that was considered and could be implemented if further research phases, is the intertwining of the OS arcs. With arcs overlapping one another, increased structural stability could be expected. By slightly altering how the arcs are attached to the node system, the arcs would approach the opposite node at an angle, causing them to overlap with neighboring arcs. Implementing this is predicted to also affect the overall rolling behavior of the Tumbleweed rover. As the primary rotation of the OS is about the longitudinal axis of the stent, lateral forces being applied to the arcs could have a major impact on stability. Here the intertwining arcs could have benefits that are worth researching. However, this design change could prove challenging when considering the folded position it must be able to achieve; the overlapping arcs can prove twisting the stent into an annular shape far more difficult.

Overall, the primary takeaway from this research phase is that a Tumbleweed rover based on a stent model does have tremendous potential. However, to determine its suitability for a full-scale demonstrator prototype, an important next step is to construct another full assembly model and observe the structural behavior of the system. If the unfolding mechanism is able to function fully, further prototype development is encouraged.

Ultimately, it continues to remain of interest for the Tumbleweed mission, to continue analyzing further structure models as well as other options for the unfolding methods. The rover designs mentioned previously, as well as the potential actuation methods, are still very notable design options that should still be considered for more advanced rover development stages, however, for this research phase, the umbrella stent model was deemed the most promising given the structural aspects discussed in Section 2.8.

5 Conclusion

An overview of a scientific study concerning the selection and development of an unfolding mechanism for a spheroid Tumbleweed Mobile Impactor has been portrayed in this paper. The use of Tumbleweed rovers has been frequently proven as a highly practical approach to conducting research on Mars [10] yet methods for transporting a larger swarm of such rovers still face technological restraints due to the volume and weight limitations of modern-day launch vehicles. Through the assessment of possible volume reduction mechanisms and numerous stages of design iterations, several conclusions could be drawn from the development of the stent-based rover design.

After weighing the primary requirements of a Tumbleweed mission, the stent design emerged as the most satisfactory design choice. Complemented with a spring actuation method, the rover transitioned from an annular shape to a fully unfolded spherical shape achieving a volume minimization that fulfills the payload size requirement with respect to the mission objective of sending 90 rovers to Mars. Initial testing, which included a single arc bending test confirmed the effectiveness of the push rods and interfaces of the unfolding mechanism. Further assembly tests demonstrated the feasibility of putting the unfolded rover into an annular shape which is vital for transportation purposes. Half model assemblies increased the angle of deflection bringing it close to 90 degrees and confirmed that the maximum deflection angle achieves a fairly spherical shape.

However, it must be noted that the research and preliminary design process of the Tumbleweed Rover did not allow for further verification of the potential of a stent design Tumbleweed Rover, additional complete model assemblies are required to make quantifiable conclusions about this design. In addition, a fully assembled prototype will be vital for the next steps of turning this concept into a finalized design, which will carry an inner structure and validate the structure architecture of the Tumbleweed mission.

References

[1] C. Rouff, "Intelligence in future nasa swarm-based missions," *AAAI Fall Symposium: Regarding the Intelligence in Distributed Intelligent Systems*, 2007.

[2] J. L. Wilson, A. P. Mazzoleni, F. R. DeJarnette, J. Antol, G. A. Hajos, and C. V. Strickland, "Design, analysis and testing of mars tumbleweed rover concepts," *Journal of Spacecraft and Rockets*, vol. 45, no. 2, 2008.

[3] J. Rothenbuchner, L. Cohen, F. Abel, D. Buryaka, K. Cuervo, J. Kingsnorth, O. Mikulskytė, A. Phillips, M. Renoldner, and M. Sandrieser, "The tumbleweed mission: Enabling novel mars data sets through low-cost rover swarms, iac-22,a3,ip,x72458," in *73rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022.*

[4] I. Vorbach, "The launch landscape: Medium/heavy lift vehicles," Mar. 2021, accessed September 14, 2023. https://spacedotbiz.substack.com/p/the-launch-landscape-mediumheavy.

[5] R. Lagier, "Ariane 6 user's manual," pp. 5–8, Feb. 2021.

[6] J. Antol, "A new vehicle for planetary surface exploration - the mars tumbleweed rover," *AIAA 2005-2520*, January 2005.

[7] ——, "The nasa langley mars tumbleweed rover prototype," *AIAA 2006-64*, January 2006.

[8] D. Stoeckel, C. Bonsignore, and S. Duda, "A survey of stent designs," *Minimally Invasive Therapy Allied Technologies*, vol. 11, pp. 137–147, 2002.

[9] A. Al-Mosawe, R. Al-Mahaidi, and X.-L. Zhao, "Engineering properties of CFRP laminate under high strain rates," *Composite Structures*, vol. 180, pp. 9–15, Nov. 2017.

[10] D. Tjokrosetio, J. Kingsnorth, A. Shanbag, Pikulić, H. Manelski, J. Rothenbuchner, O. Mikulskytė, G. Cozzolongo, and A. Westenberg, "Identification of human landing sites on mars with a swarm of wind-driven mobile impactors, ac-23,a5,2,2,x77773," in *74th International Astronautical Congress (IAC), Baku, Azerbaijan, 2-6 October 2023.*

[11] T. E. of Encyclopaedia, "Boyle's law," n.d., accessed September 14, 2023. https://www.britannica.com/science/Boyles-law.