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Suborbital flight demonstration for de-risking the entry, descent, and landing sequence of a Tumbleweed Mars rover

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Abstract

Many Mars exploration missions have failed during the entry, descent, and landing (EDL) phase, which commonly requires precise and time-critical operations executed autonomously by relatively unproven systems. The high risk associated with this mission phase also drives mission cost and timeline for Mars missions. An affordable way of testing such systems in realistic flight conditions creates opportunities for a significant reduction of the risks and costs associated with EDL. The current toolbox available to engineers is limited mainly to numerical simulation and ground testing. To improve this, Team Tumbleweed is preparing a representative demonstration flight using a scaled prototype flown on a sounding rocket with launch planned for 2026. This paper considers a Tumbleweed rover, which represents a promising new approach for lowering the cost of Mars exploration missions by implementing a novel EDL paradigm for reaching the Martian surface. Deployment of a Tumbleweed rover poses a unique challenge in the unfolding of compliant mechanisms during supersonic freefall, immediately following atmospheric entry. To increase the maturity of this solution towards TRL 6 and de-risk a future Mars mission, a flight prototype is designed to demonstrate rover deployment in realistic conditions. To achieve this, a study is conducted regarding the essential aerodynamic parameters that define the flight environment experienced by the Mars rover during deployment, such as Mach and Reynolds numbers. A demonstration-specific entry vehicle capable of being launched by a sounding rocket is then designed. The ballistics of this vehicle are tuned in order to carry a scaled rover prototype to a deployment point matching these conditions. The design of the entry vehicle is studied using numerical simulation, and takes into account uncertainties regarding the real trajectory of the rocket. The challenges brought up by scaling down the Tumbleweed rover itself to fit inside the demonstration entry vehicle are considered, as are the limits of reproducing Mars EDL in the Earth's atmosphere. Through this demonstration flight, Team Tumbleweed is seeking to verify and refine its understanding of the deployment dynamics of the rover. The team is also building organisational experience by executing the complete lifecycle of a space mission in preparation of future Mars missions. Such an approach may prove highly beneficial for the development of future radical solutions for Mars exploration, as well as demonstrating the viability of the Tumbleweed rover concept.

Keywords: Mars Exploration, Interplanetary Missions, Entry Descent and Landing, Sounding Rocket

Nomenclature

Re - Reynolds Number
M - Mach Number
Q - Dynamic pressure

Acronyms/Abbreviations
Centre of Gravity (CG)
Centre of Pressure (CP)
Computational Fluid Dynamics (CFD)
Deployment Demonstrator Mission (DDM)
Entry-descent Vehicle (EDV)
Entry, Descent and Landing (EDL)

1. Introduction

1.1 The Tumbleweed Mission

Team Tumbleweed has published several papers introducing its mission [1], technical work [2] [3] [4] and organisational concept [5]. This section provides a brief summary of this information to give the reader sufficient context.

1.1.1 Technology Gap

Mars exploration is one of the most active areas in space science, with several orbital, rover- and lander-based missions currently operating as well as plans for Human exploration in the near future. However, landing a scientific payload on Mars cannot be considered as a solved and technologically mature problem. Mars surface exploration is still characterised by high-stakes, expensive and infrequent missions with a significant risk of failure as demonstrated by the crash of ESA's Schiaparelli lander [6]. Team Tumbleweed aims to tackle this and fulfil its vision of opening deep space to everyone by designing and launching swarms of low-cost, wind-driven Mars rovers [1]. These so-called Tumbleweed rovers were studied at NASA in the 2000s [7] but never flown; Team Tumbleweed has operated since 2016 as an international volunteer organisation [5] to make this promising concept a reality.

1.1.2 Mission Concept

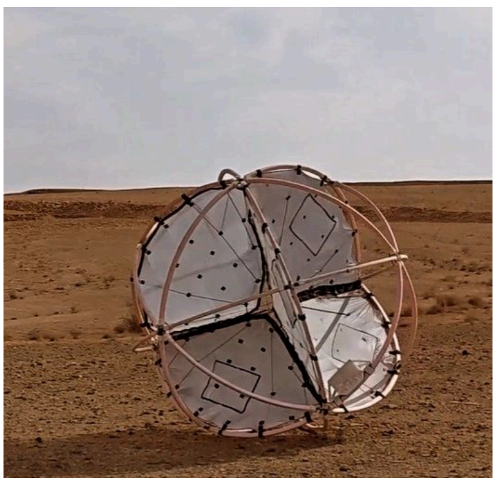

Fig. 1. Tumbleweed rover prototype in operation during the AMADEE20 Mars Analogous Mission.

In order to achieve the promised cost reduction, the team seeks to radically reduce the complexity of the rover compared to the state of the art. The Tumbleweed concept achieves this in two main ways: firstly, the spherical rover is wind-driven and has only a handful of moving parts once deployed, reducing power needs and technical risk. Secondly, the sails that the rover uses for propulsion double as parachutes, and the rover's structure is designed to absorb a terminal velocity impact on the Martian surface. This means that the rover does not need any special systems for landing and can be deployed in mid-air following atmospheric entry, with no further intervention needed. The complete rover is several metres in diameter, with 5 metres currently baselined for the final design.

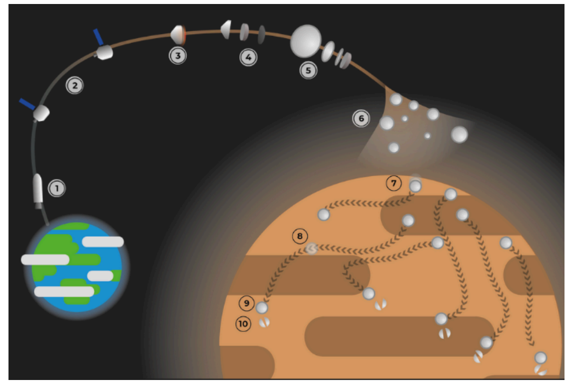

Fig. 2. Tumbleweed mission sequence.

This concept entails certain drawbacks such as limited freedom of movement, relatively small payload mass, and the risk of a rover becoming stuck in terrain. However, many of these drawbacks are addressed by the very low mass of an individual rover, currently projected to be approximately 8 kg [2]. Indeed, dozens of rovers can be packed on a single launch and deployed simultaneously as a swarm. By leveraging weather patterns on Mars, it is possible to cover an area of interest with rovers [7] and generate science returns that cannot be obtained by a single, more complex rover while investing only a fraction of that rover's budget.

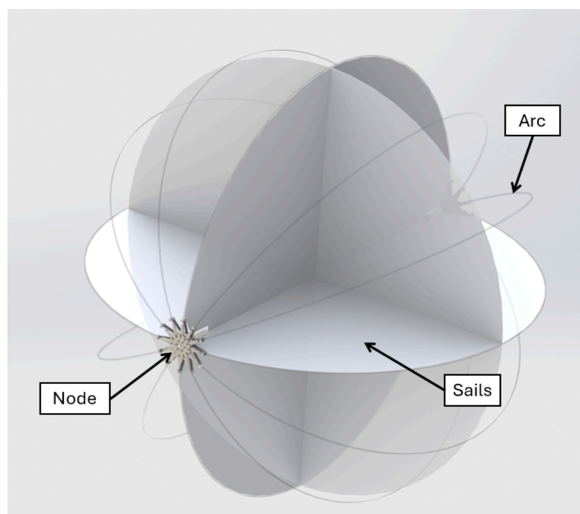

Fig. 3. Rover architecture with node, arcs and sails

1.1.3 Deployment Demonstration Mission

Given the large volume of a Tumbleweed rover, it must be folded during transit to Mars and unfold in mid-air at the moment of deployment. This critical step is one of the key technical hurdles that must be overcome to make this mission a reality; however, the combination of high-speed aerodynamics, compliant mechanisms design, and autonomous systems that must be understood to be successful is highly complex to model.

To verify the assumptions and raise the technological maturity of the proposed solution, the team elected to fly a suborbital Deployment Demonstration Mission (DDM) on Earth designed to put the rover through a representative Martian Entry, Descent, and Landing (EDL) sequence. This promises to reduce the risk associated with a Mars mission at a lower cost and a greater speed than with ground testing and analysis alone, as neither of these methods can accurately replicate the complex deployment environment. Team Tumbleweed believes that this hardware-rich testing approach for interplanetary systems could prove beneficial to other projects and help to bring down the costs of certain space exploration missions.

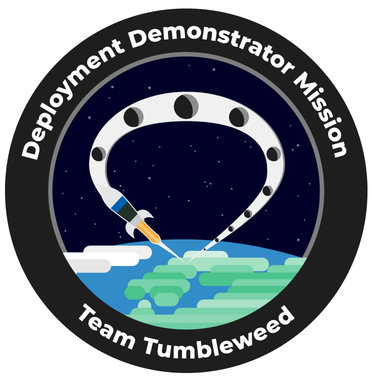

Fig. 4. Deployment Demonstrator Mission patch

1.2 DDM Mission objectives
The primary objective of the DDM is to demonstrate the mid-air deployment of the rover in conditions representative of a Mars entry, descent, and landing sequence. Three further secondary objectives have been identified:

- To demonstrate an impact landing and geolocation of the rover after landing
- To demonstrate scientific data collection during freefall and after landing
- To support Team Tumbleweed's outreach and educational activities as well as train new team members.

1.3 Paper structure
In this paper, section 2 covers the broad mission requirements and constraints driving the design. In section 3, the design process is presented including the analysis methodologies used. In section 4, the results of these studies and the present state of the DDM development process are presented.

2. Mission Requirements

2.1 Deployment sequence
In previous research published by Team Tumbleweed, a presumptive deployment point was defined at 10 km above the Martian surface [2]. According to the aforementioned trajectory simulation, that corresponds to a velocity of around 190 m/s or Mach 0.8. However, aerodynamic studies of sphere-cone capsules indicate that the vehicle may become unstable in the transonic regime [8]. If the EDV were to enter an unexpected spin or tumble before deployment, the nominal release of the rover may become impossible.

The classical answer to this problem is the use of a drogue parachute which is deployed around M = 2.0 to stabilise the EDV and slow it down to subsonic conditions [9] [10]. This solution was deemed suboptimal for the Tumbleweed mission concept as it would add a parachute system to the EDV with its associated risks which were not present before. In order to get around this, the EDV can release the folded rover while still in the supersonic regime at M=2.0. The rover remains folded around a spindle until it reaches its subsonic terminal velocity, where it is released from its spindle and unfolds.

2.2 Launch vehicle integration
For this suborbital mission, it is not practical to fly a full-scale rover as, even in the folded configuration, it would not fit on most sounding rockets. Therefore, the DDM consists of a single sub-scale rover, carried inside a bespoke entry vehicle designed to bring the rover to a deployment point that mimics the aerodynamic conditions experienced during a Mars landing (see Sec. 3.1.2 for a closer look at aerodynamic scaling). The rocket selected as a baseline for this flight is REXUS [11], with the payload hosted under the nose cone of the rocket. This immediately imposes some constraints on the design:

Table 1. Launch vehicle constraints

Apogee	80 +/- 20 km
Maximum EDV diameter	300 mm
Maximum EDV length	680mm
Maximum system weight	approx. 10 kg

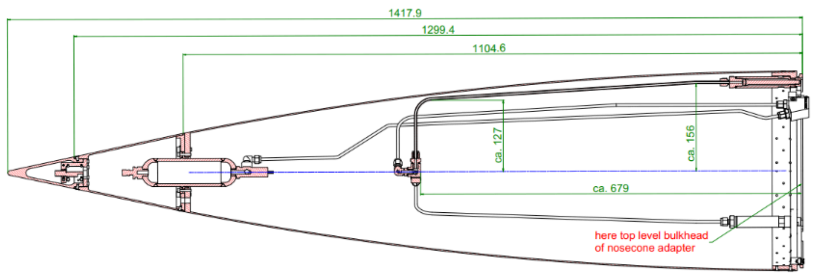

Fig.5. REXUS nose cone geometry, from [11]

2.3 Payload and data collection
To verify the successful mid-air deployment of the rover and study the dynamics of this event, the rover must carry a number of instruments. These can also be used to fulfil the secondary objective of demonstrating scientific data collection. The list of instruments to be carried is as follows:

- Inertial measurement unit
- Barometric altimeter
- Thermometer
- Miniaturised camera

In addition to this, equipment is carried to facilitate the recovery of the rover after landing. This includes a GPS receiver and a radio beacon. In the event that the rover is destroyed on landing or cannot be recovered, essential telemetry will be transmitted live during flight to verify if the unfolding was successful. The total capacity requirement for the onboard battery is 10 Wh.

2.4 Safety
The main safety concern raised by this mission is the risk of premature unfolding of the rover. The force exerted by the deployment mechanism on the structure during unfolding is in the order of hundreds of Newtons and the mechanism can cause injury if mishandled or in case of parts breakage. In addition, if the rover were to deploy while still onboard the launch vehicle, it could cause a sudden imbalance and take the rocket off course. These risks are mitigated by the use of redundant and fail-safe deployment triggers as well as a mechanical interlock to be left in place until ready to launch.

3. Design Methodology

3.1 Aerodynamic Representativity
To fulfil the primary objective of the mission, it is crucial to define a rover deployment point for the DDM where the aerodynamic conditions experienced by the rover are representative of those experienced during a deployment in the Martian atmosphere. Therefore, the team first had to define the trajectory of the Mars vehicle during entry, descent and landing, and model the corresponding aerodynamic conditions.

3.1.1 Mars Entry Trajectory
The Mars entry vehicle used as a reference in this project was defined according to previous work performed by D.Tjokrosetio [12]. It is a 45° sphere-cone design with a diameter of 0.8m, sized to house a single Tumbleweed rover for a Mars demonstration mission. The entry interface is defined with the following parameters:

Table 2. Mars entry trajectory parameters

Entry interface altitude	125 km
Flight path angle	-11.916°
Entry velocity	7.25 km/s

Based on this information, an entry trajectory simulation was computed using NASA Glenn's Martian atmosphere model [13].

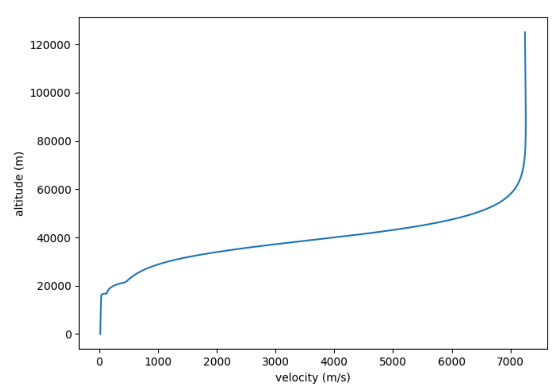

Fig. 6. Plot of altitude versus velocity for Mars entry

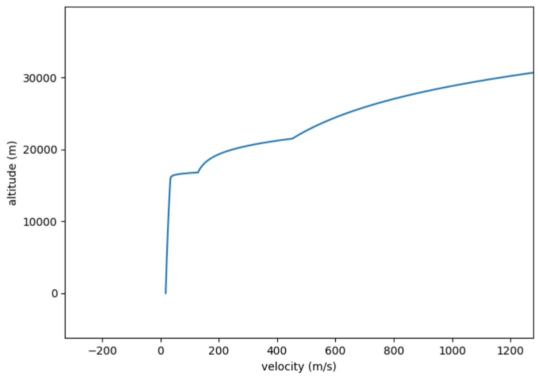

Fig. 7. Plot of altitude versus velocity for Mars entry, detail

3.1.2 Aerodynamic scaling

Given the reduced scale of the DDM rover compared to the Mars rover, one must choose which aerodynamic parameters are the most relevant to conserve for this test. Three key parameters were identified: Mach number (M) , Reynolds number (Re) and dynamic pressure (Q). The conservation of the Mach and Reynolds numbers ensures that the airflow behaves in a representative way for the environment expected during deployment on Mars [14] [15]. Furthermore, the conservation of dynamic pressure means that a representative amount of force will be exerted on the rover structure during deployment, which significantly affects the unfolding of the flexible structure. The target values for these numbers are as follows:

Table 3. Aerodynamic targets

	M	Re	Q (Pa)
Rover release	2.0	81270	310
Unfolding	0.56	102780	36.7

3.2 Trajectory Simulation

In order to translate these targets into design parameters for the rover and EDV, a monte-carlo method was used by varying the rover and EDV masses, EDV drag coefficient and launcher apogee. The variation of the EDV's drag coefficient depending on Mach number was accounted for by evaluating prospective EDV concepts in Computational Fluid Dynamics (CFD). For each set of design parameters, the flight trajectory is computed and compared to the reference Mars mission.

In the following plots, the Mars trajectory in brown is overlaid with possible EDV trajectories in colour. The key steps of deployment (EDV opening - rover in folded configuration - unfolding triggered-unfolding complete) are shown with black boxes including a 25% margin.

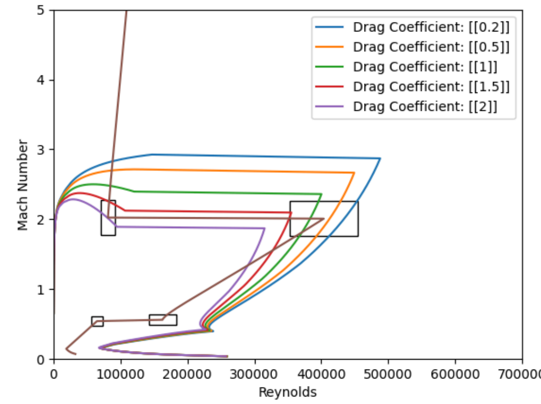

Fig. 8. Plot of M versus Re for the reference Mars trajectory (brown) and the DDM EDV with a range of drag coefficients (defined at M=2.0) and a mass of 5.5kg

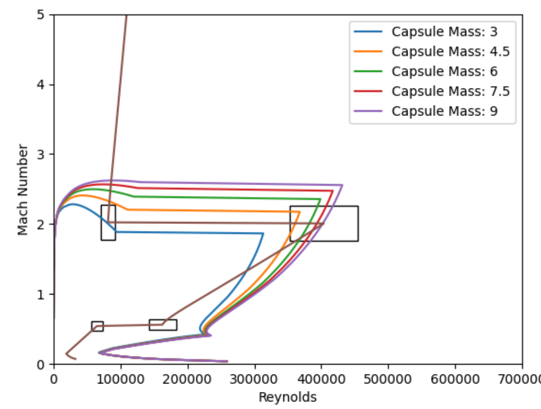

Fig. 9. Plot of M versus Re for the reference Mars trajectory (brown) and the DDM EDV with a range of masses and a drag coefficient at M=2.0 of 1.1

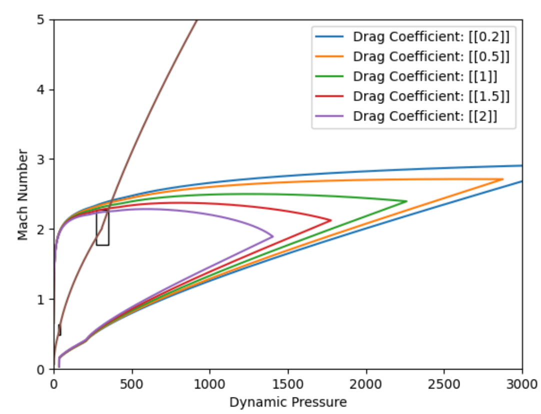

Fig. 10. Plot of M versus Q for the reference Mars trajectory (brown) and the DDM EDV with a range of drag coefficients (defined at M=2.0) and a mass of 5.5kg

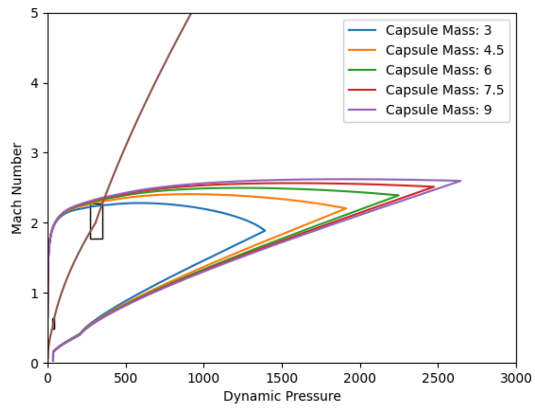

Fig. 11. Plot of M versus Q for the reference Mars trajectory (brown) and the DDM EDV with a range of masses and a drag coefficient at M=2.0 of 1.1

As can be seen in Fig.8 to Fig.11, it is possible to accurately reproduce the Mach and Reynolds numbers at the critical stages of deployment with a suborbital trajectory. However, in all cases the dynamic pressure at these steps is larger by a factor of up to 10 for the DDM compared to the Mars trajectory. While such a large factor is not desirable, an overestimation of the dynamic pressure is not deemed critical as it provides a conservative load case for testing the rover structure.

The launcher apogee cannot be known precisely at this stage, as it depends on the total mass of experiments carried and the performance of the rocket on the day. Therefore, tolerance bands of 25% are defined for the scaling parameters and the risk of missing the deployment target for a given EDV design is considered.

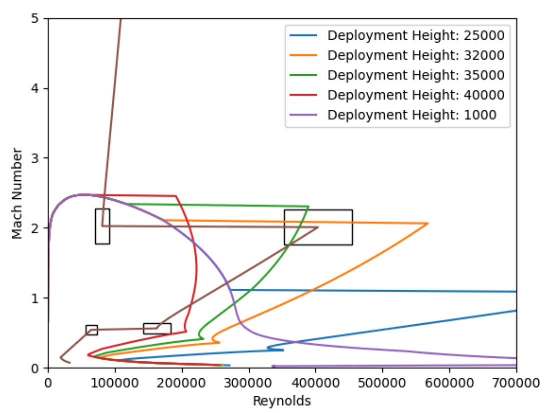

Fig. 12. Plot of M versus Re for the reference Mars trajectory (brown) and the DDM EDV with a range of deployment altitudes, a mass of 5.5kg and a drag coefficient at M=2.0 of 1.1

3.3 Aerodynamic stability

To follow the expected trajectory and release the rover in good order, the EDV must maintain aerodynamic stability throughout its flight. Given the tight trajectory and integration constraints driving the design of the EDV, this is not trivial and requires careful consideration. Several EDV shapes are considered, including a cone, a teardrop, a PARES capsule [16] and variations on these.

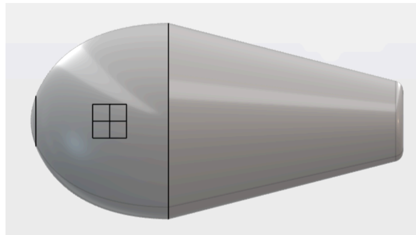

Fig. 13. Truncated teardrop capsule concept

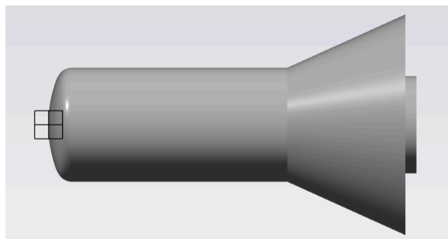

Fig. 14. PARES capsule concept [16]

The analysis of EDV stability is segmented into two parts: static stability and dynamic stability, which can be described as the tendency to produce a righting moment when displaced from the nominal angle of attack of the flight, and the tendency to dampen pitching oscillations respectively.

In terms of static stability, the relative position of the Centre of Pressure (CP) to the Centre of Gravity (CG) is critical for maintaining balance. The CG is the point where the total weight of the object acts, while the CP is the point where the sum of all aerodynamic pressure forces is concentrated. The following formula was used to calculate the centre of pressure:

$$Cp = \frac{\int x \cdot p(x) \cdot dx}{\int p(x) \cdot dx} \qquad (1)$$

Here x represents the position coordinate and $p(x)$ denotes pressure that varies with location. The position of the CG can only be estimated at this stage as the final rover mass and packaging concept are not known. As a baseline, the CG is set at ⅓ of the EDV length.

The dynamic stability can be described by an encompassing parameter known as the pitch damping sum (PDS) [17] [18] shown in equation (2). Various methods to obtain the PDS using CFD have been developed, using either steady-state or unsteady models.

$$C_{m_{\dot{\alpha}}} + C_{m_q} = \frac{\int C_m d\theta}{\int \dot{\theta}^2 dt} \quad \frac{2U}{D} \qquad (2)$$

A negative pitch damping sum indicates stability. Generally, the value is desired to be as low as possible. By calculating the PDS for a range of Mach numbers, a good estimate of the dynamic stability of a vehicle over the course of its trajectory can be obtained.

In the end, the Forced Oscillation Technique was employed, in which a simulation of a vehicle being rotated around its centre of mass in a single-degree-of-freedom sinusoidal motion is performed while the moments acting about the pitch axis are recorded [17].

After obtaining the moments for different positions in time, the moment coefficients are calculated and plotted against the corresponding angle of attack. Examples of these plots for the Mushroom and the Dart at Mach 0.25 are shown in figures 15 and 17 respectively. With these plots the dynamic stability can be visualised and the PDS can be calculated using equation (2).

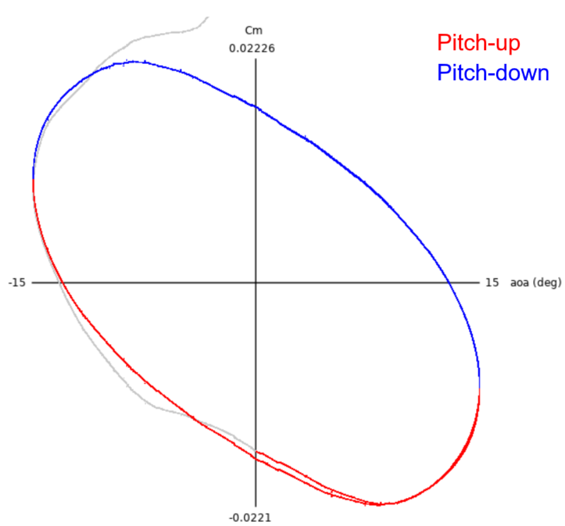

Fig. 15. "Dart" design stable moment coefficient plot at Mach 0.25

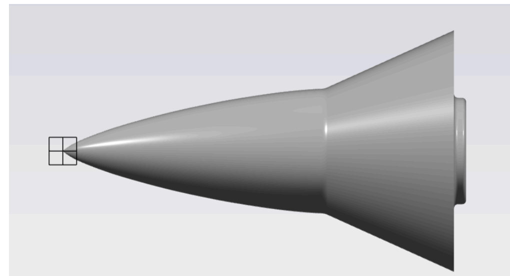

Fig. 16. Dart capsule concept

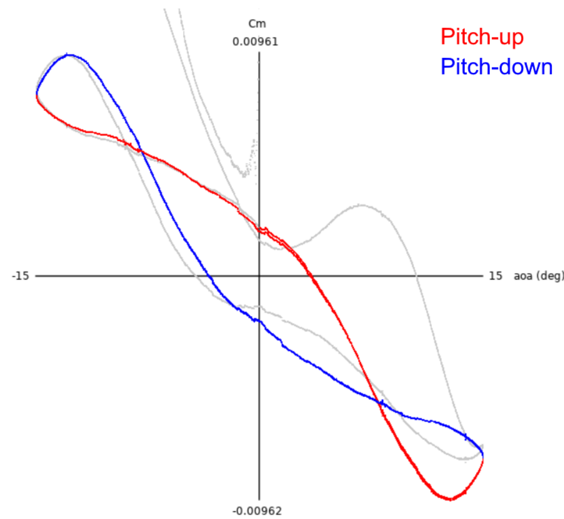

Fig. 17. "Mushroom" design unstable moment coefficient plot at Mach 0.25

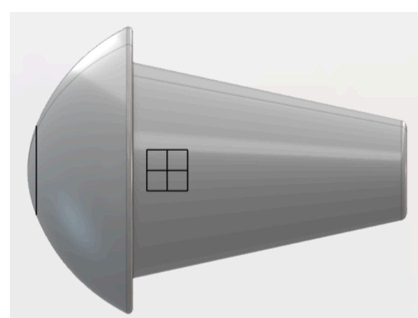

Fig. 18. Mushroom capsule concept

3.4 Rover design

The mechanical design of the rover used in DDM is focused on producing a structure that is able to deploy autonomously while withstanding the significant aerodynamic forces exerted on it, and still fit within the EDV which is itself constrained by the launch vehicle. The baseline material chosen for the structural arcs is carbon fibre composite, as it offers attractive strength-to-weight characteristics and a high potential for elastic deformation. However, this is subject to change for the flight article. Analytical and experimental studies were performed to relate the diameter of the rods used to form the structure with the minimum bending radius. This sets an upper bound on the size of rods that can be used while still allowing the folded rover to fit inside the EDV.

Furthermore, design efforts focused on producing a reliable deployment mechanism that would be compatible with packaging inside the EDV. The mechanism is composed of an actuator fitting in a cylindrical form factor, surrounded by lever arms which pry the arcs open to achieve deployment.

Several actuator designs were considered and prototyped. In the node mechanism, internal springs are preloaded in the folded configuration, and released via an electronic trigger at the moment of deployment.

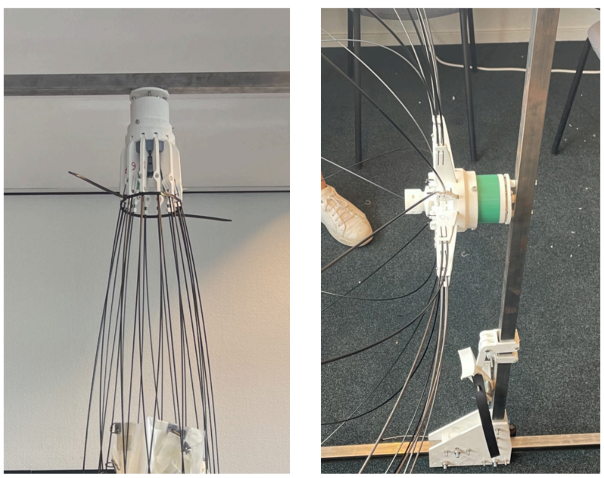

Fig. 19. Folded (left) and Deployed (right) Mechanism

4. Results

4.1 EDV Sizing

As a result of the study presented in section 3.2, the target design characteristics are defined as follows, with a nominal launcher apogee of 80 km:

Table 4. EDV design targets

Deployment altitude	35km
EDV mass	5.5 kg
EDV drag coefficient	1.1

The EDV concept retained for further development is the “dart” shown in Fig.16. This is an adaptation of the PARES concept shown in Fig.14 which trades some volume efficiency for reduced drag, needed in order to reach the nominal deployment target while maintaining a comfortable stability margin. The drag coefficient at M=2.0 of the dart variant shown is 1.3, with a significant margin to adjust this value by tuning the size of the flared skirt section.

4.2 Rover prototyping

Several scale rover prototypes as well as a bespoke test bench were assembled to verify the deployment kinematics and test successive mechanism concepts. Once a satisfactory design was reached, the test campaign progressed to initial freefall deployment testing from a low altitude. At this stage, the rover is entirely passive and the nodes actuate as soon as it is released.

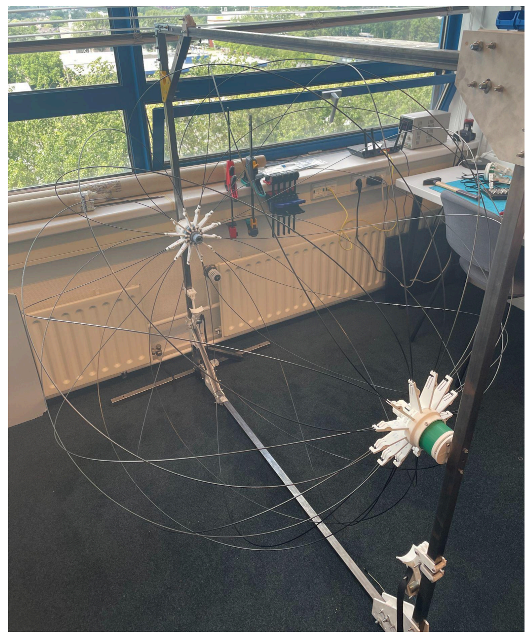

Fig. 20. Deployed Rover inside the Test Bench

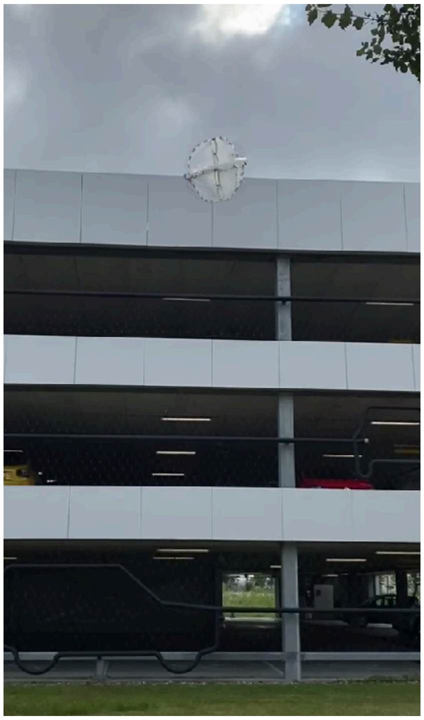

Fig. 21. Rover in freefall during a low altitude manual drop test

4.3 Embedded systems

In parallel with the rover development and EDV design efforts, prototype embedded electronics systems were developed for the DDM. Three key capabilities were demonstrated:

- Remote triggering of the deployment mechanism
- Sensor data acquisition
- Wireless data transmission

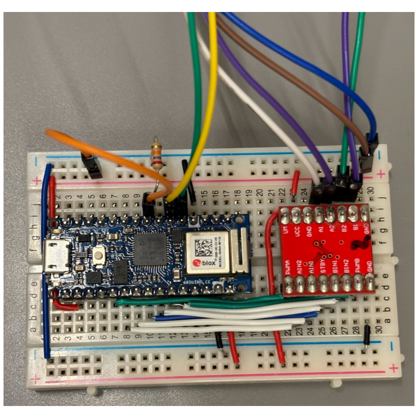

Fig. 22. Breadboarded prototype of the remote deployment triggering mechanism

These systems will be integrated into the prototype rover for further testing.

5. Discussion

5.1 Next steps

The next key milestone in the DDM development cycle is an integrated low-altitude deployment test, where the rover is released in a folded configuration and the unfolding is remotely triggered.

Furthermore, a representative EDV prototype will be produced to demonstrate rover packaging in the folded configuration and a complete deployment sequence from a medium altitude, by releasing the EDV from a light aircraft.

A definitive launch solution for DDM has not been confirmed at this stage due to organisational and financial constraints, but it is expected to be ready for flight in 2025. Several options for securing a launch service are under consideration.

5.3 Conclusion

This paper demonstrates that a representative suborbital demonstration of the Mars EDL sequence for a Tumbleweed rover can be achieved using existing launch services and technology. Furthermore, rapid progress was made towards producing a functional Tumbleweed rover prototype capable of autonomous deployment and landing. This was achieved using a rapid prototyping approach with negligible costs compared to traditional aerospace technology projects.

The flight demonstration paradigm developed for DDM is proving highly successful in developing a radical new technology for interplanetary flight. This paradigm could prove beneficial for other mission concepts under consideration, as it offers a cost-effective way to increase technology readiness level and demonstrate feasibility.

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