Candidate Mechanisms and Fabric Layup Materials for the Mars Surface Tunnel Concept

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Abstract—**The Mars Surface Tunnel (MST) concept presented herein potentially addresses the three interconnected problems of planetary protection, minimizing Mars Ascent Vehicle (MAV) ascent mass, and keeping surface systems free of Martian dust in a manned Mars mission. If the crew can enter the MAV wearing Intra-Vehicular Activity (IVA) suits which are considerably lighter than the Extra-Vehicular Activity (EVA) suits, the MAV ascent mass can be significantly reduced. Furthermore, for long term operations on the Martian surface, there will always be a need to conveniently and habitably connect various surface elements such as habitats, rovers and science labs to one another.**

The proposed MST concept is a habitable, inflatable-deployable enclosure that connects surface elements while addressing the primary prerequisites mentioned above. We propose, four candidate mechanisms for the deployment, operation and retraction of the tunnel: a rail-guided tunnel, an air bridge type tunnel, and two variants of a spring-based tunnel. All the mechanisms have an inflatable tunnel which is initially deflated and stowed, pressurized just before use, and if required, subsequently deflated and stowed for future use. Metrics for comparison are used to rank the candidate mechanisms, and to select appropriate concepts for MAV-to-rover and habitat-to-habitat connection.

A candidate fabric layup for the inflatable tunnel concept is proposed along with preliminary mass estimates based on prior experience in building inflatable space structures. The mass of the proposed tunnel concept connecting the MAV and the rover is estimated to be 219 kg. This lightweight, reusable system offers substantial benefits as a surface system in future human exploration, not only of Mars but also the Moon.

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1. INTRODUCTION

A variety of human Mars exploration architectures, particularly the ones which envisage a long-term stay on Mars leading to permanent residence, have multiple surface elements. Some of the example surface elements are: habitation systems (includes science outpost); Mars Ascent Vehicle (MAV); mobility systems (rovers); food production systems; in situ resource utilization (ISRU) systems; power generation and distribution systems; civil and construction engineering systems (such as cranes, robotic arms etc.). A retractable tunnel is a practical solution that facilitates the movement of crew and smaller cargo between two surface elements, such as between an MAV and a rover, or between two habitats.

Motivation for the Mars Surface Tunnel (MST) Concept

During the Apollo missions, lunar dust brought into the Lunar Module (LM) by astronauts after performing Extra Vehicular Activity (EVA) on the lunar surface presented significant challenges for the crew later in the mission [1]. After insertion into lunar orbit the cabin was filled with lunar dust causing nose and eye irritations, as well as making breathing difficult without helmets. Apollo 15, 16 and 17 crew also reported major dust related problems after lunar orbit insertion. As mankind prepares to embark on our maiden voyage to the Red Planet, manned systems such as the Mars Ascent Vehicle (MAV) as well as other exploration systems such as habitats and science labs are to be designed and operated in such a way that the crew does not encounter problems associated with Martian dust. Opening the MAV ingress hatch directly into the Martian environment would bring dust into the MAV, if crew directly board the MAV using their EVA suits contaminated with Martian dust. If the crew can enter the MAV using clean suits, i.e. devoid of Martian dust without opening the MAV hatch directly to the environment, the MAV interior can be kept clean and free of dust.

In addition to health hazards associated with the presence of dust in the cabin, missions to Mars are subject to stringent planetary protection requirements. When future Mars

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explorers return to Earth they must comply with NASA planetary protection policies as well as international agreements governing operations that involve returning material from an extra-terrestrial body [2]. The goal of planetary protection is to prevent forward contamination of Mars with Earth-based life forms as well as prevention of potential backward contamination of the Earth by extraterrestrial organisms through samples returned from Mars. If the MAV used by the crew to ascend to Mars orbit for their return journey to Earth has never seen prior usage and if the crew can furthermore enter the MAV wearing pristine Intra Vehicular Activity (IVA) suits, then planetary protection objectives can be more readily fulfilled.

Another fact which is of relevance in this context is that for the Mars Ascent Vehicle (MAV), propellant is the largest contributor to the MAV ascent mass. The required propellant mass depends on the ascended payload. Approximately seven kilograms of propellant is required for every kilogram of payload ascended to Mars orbit. Substantial MAV ascent mass savings can be had if the crew wears lighter IVA suits for the ascent instead of EVA suits [3]. For the crew to ingress the MAV using clean IVA suits, a controlled environment between the rover egress hatch and the MAV ingress hatch must be provided.

Keeping in mind these interconnected requirements of mitigating problems associated with Martian dust in the cabin, and conformance to planetary protection policies and MAV ascent mass savings, Rucker *et al.* have proposed an inflatable Mars Surface Tunnel (MST) connecting the MAV to the manned rover as a potential solution [4]. As shown in Figure 1, the basic concept of operations is that the crew drives from the habitat to the MAV launch site in a rover, discard their contaminated EVA suits in the rover, changes to clean IVA suits, and boards the MAV from the rover using a "tunnel" which provides a clean and controlled environment between the rover and the MAV. No comprehensive work has previously been done on aspects such as the deployment and retraction mechanism and fabric materials for the MST. In addition, aspects of hatch alignment, docking, and pressurization systems have not been studied in detail.

Therefore, we perform a preliminary study of candidate mechanisms for the deployment and retraction of the tunnel, as well as the fabric layup for the Mars Surface Tunnel (MST) concept. The proposed tunnel concept can connect not only rover and MAV, but can also be used for connecting other surface elements such as habitat to habitat, habitat to rover, and rover to science labs.

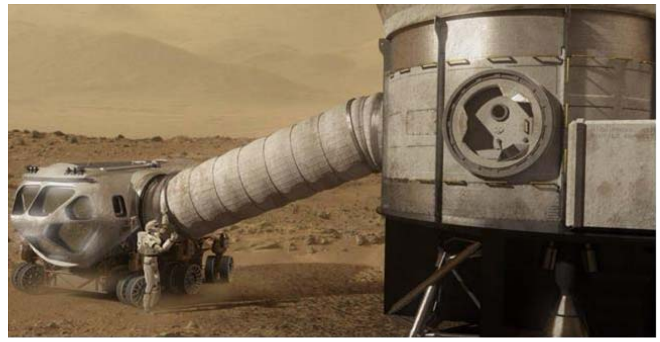

Figure 1. Artist's impression of the proposed inflatable Mars Surface Tunnel. Original work by NASA [4]**.**

In 1958, the International Council for Science, a non-governmental organization, established the Committee on Space Research (COSPAR) as an interdisciplinary scientific body "concerned with the progress on an international scale of all kinds of scientific investigations carried out with space vehicles, rockets and balloons." In 1967, the US, former USSR, and UK ratified the United Nations (UN) Outer Space Treaty, and has been signed and ratified by all the current space faring nations. Article IX of the Outer Space Treaty states, "States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary shall adopt appropriate measures for this purpose [5]."

One of the tasks carried out by the Committee on Space Research (COSPAR) is to develop guidelines for planetary protection depending on the type of the space mission and the celestial body under study. COSPAR has divided the missions into five categories ranging from I to V. The lowest Category I encompasses missions to locations such as Mercury which are not of direct interest from the perspective of chemical evolution or origins of life and has no planetary protection requirements, while the highest Restricted Category V encompasses missions which return samples from locations of significant interest to chemical evolution or origins of life such as Mars, Europa and Enceladus [5]. If the crew returns to Earth with Martian dust, it is classified as a Restricted Category V mission, which requires containment and quarantine of any sample returned to Earth. Inhalation and ingestion of Martian dust if present inside the Mars Ascent Vehicle (MAV) would make it challenging to conform to the strict containment guidelines for Category V missions. Using a concept such as MST to eliminate the possibility of dust entering the MAV is an attractive option thus, from the perspective of planetary protection requirements for a human mission to Mars [4].

Mars Ascent Vehicle (MAV) Mass Savings

The Mars Ascent Vehicle (MAV) is designed to carry a crew of six to a 1-sol Martian orbit. An Extra Vehicular

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Activity (EVA) suit is roughly 75 kg heavier than an Intra Vehicular Activity (IVA) suit, resulting in an ascended mass saving of 450 kg if the crew of six can ascend using IVA suits. With an estimated seven kilograms of propellant required for every kilogram of ascended mass, this results in an additional saving of 3150 kilograms for the MAV ascent mass. Also using IVA suits for the ascent would require a smaller cabin which could further reduce the structural mass of the MAV. MST enables the crew to transfer from the rover to the MAV by providing a pressurized and controlled environment which can be traversed wearing IVA suits and thus helps reduce the MAV ascent mass [3].

Connecting Other Surface Systems

In addition to the MAV-rover connection discussed earlier, the tunnel concept can also be used to connect two habitat modules as well as other surface elements such as rovers carrying samples to the science labs. Some of the possible habitat layouts for a Martian base involve the habitat units placed in a cyclic arrangement and a retractable tunnel can allow a rover to access the interior of the base for service or maintenance activities.

2. Functional Requirements

MAV-Rover Tunnel

The functional requirements of the Mars Surface Tunnel which connects the MAV to the rover are as follows [4].

1) The tunnel should provide a controlled environment between the MAV and the rover.
2) The tunnel should have a mechanism to provide environmental sealing at both the MAV and rover ends.
3) The tunnel should have a mechanism to align the hatches before docking.
4) The tunnel should provide sufficient volume for the passage of four crew members but not necessarily all at the same time.
5) The tunnel should provide mechanisms that aid in crew and cargo translation.
6) The tunnel should be capable of being detached from the MAV.
7) The tunnel should be capable of accommodating a relative elevation difference between the two ends.

Habitat-Habitat Tunnel

1) The tunnel should provide a controlled environment between the two habitats.
2) The tunnel should have a mechanism to provide environmental sealing at both the habitat ends.
3) The tunnel should have a mechanism to align the hatches before docking.
4) The tunnel should provide sufficient volume for the passage of at least one crew member in a walking position.
5) The tunnel should provide mechanisms that aid in crew and cargo translation.
6) The tunnel should be capable of being detached from at least one habitat, retracted to the habitat on the other side and then be reattached.
7) The tunnel should be capable of accommodating a relative elevation difference between the two ends.

3. Operational Assumptions

MAV-Rover Tunnel

1) The tunnel has docking hatches at both ends and the hatches are closed when stored on the MAV to prevent dust from entering the tunnel.
2) The tunnel does not have its own power source, life support or "active" thermal control systems. Either the MAV or the rover provides power and life support. The tunnel can have its own "passive" thermal control system such as Multi-Layer insulation (MLI).
3) The tunnel operates at the same internal pressure as that of the MAV and the rover which is 52.5 kPa [4].
4) The tunnel is not allowed to contact the Martian surface during deployment. The deployment mechanism must connect between the MAV and the rover hatches without the tunnel fabric contacting the ground. This assumption may be relaxed later if the effect of Martian regolith on the fabric material is adequately characterized.
5) The tunnel allows an incapacitated crew member to be winched in by another crew member.
6) The tunnel is either stored on the MAV before use or brought to the launch site stowed on the rover.
7) The tunnel is taken away from the launch site after use by the rover.

Habitat-Habitat Tunnel

1) The tunnel has docking hatches at both ends and the hatches are closed when stored on the MAV to prevent dust from entering the tunnel.
2) The habitats to which the tunnel is connected provides the power and life support.
3) The tunnel operates at the same pressure as that of the habitats which is 101 kPa [4].
4) Ground support structures allow deployment and retraction of the tunnel between the two habitats without the tunnel contacting the ground.
5) The tunnel allows an incapacitated crew member to be winched in by another crew member.
6) The tunnel is stored on either of the habitats connected using the tunnel before use.
7) The tunnel is assumed to have an operational life of 20 years in the Martian environment.

4. Subsystems and Trade Studies

Trade Options for Tunnel Subsystems

Trade options considered for some of the tunnel subsystems are listed in Table 1, which are discussed under each of the

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corresponding subsections. Some of the trades options are presented in Table 1 and have been adapted from the previous work on the MST concept [4].

Pressurization System

The tunnel needs to be pressurized so that it is rigid while deployed for the crew to transit the tunnel using IVA suits. Both the manned rover and the MAV operate at 52.5 kPa, hence the tunnel's operational pressure is chosen as 52.5 kPa. For the habitat-habitat tunnel, the operational pressure is 101 kPa, since all habitats are pressurized to 101 kPa. Since the tunnel itself does not have a source of air, it is required that either the rover or the MAV provide this air volume from its Environmental Control and Life Support System (ECLSS). Between the rover and the MAV, we choose to draw air from the rover's ECLSS, as this allows the crew to use all of the MAV's ECLSS supplies in case of an in-orbit contingency, while the rover's ECLSS system is unused after the departure of the crew. However, since the tunnel is initially stored on the MAV, the tunnel must begin to be inflated using an air source at the MAV end. A stored high-pressure gas cylinder on the MAV is used to begin inflating the tunnel. Practical experience with inflatable structures show that even a small pressure such as 0.8 kilopascals (kPa) is enough to fully inflate and deploy the tunnel to its full length. Once docked to the rover, air from the rover's ECLSS system is used to fully pressurize the tunnel to its operational pressure of 52.5 kPa. For the habitat-habitat tunnel, the habitat's ECLSS system is used to pressurize the tunnel to 101 kPa.

Hatch Alignment Mechanism

The tunnel which is initially stored on the MAV is extended toward the rover side hatch when inflated. To allow docking with the rover's hatch, the rover side tunnel hatch needs to be aligned with the rover hatch. For concepts such as the rail-guided tunnel, the hatch alignment problem is taken care of entirely by the guide wires as explained in Section 5. However, for the other concepts, the rover's robotic arm or the crew manually adjusting the tunnel is used to perform the hatch alignment.

Crew Translation

For the MAV-rover tunnel, between walking, crawling and sliding, we choose the crew to have to slide through the tunnel since this allows the tunnel diameter to be minimized and hence the mass and storage volume of the tunnel to be minimized as well. Both the MAV and the rover hatches are 1.4-meter diameter and we accordingly size the tunnel to be of like dimension—allowing the crew to slide or crawl through, but precluding walking. The rationale hereby is that the MAV-rover tunnel would only be used when a crew of six embarks every synodic period, i.e. approximately once every two years. For the more frequently used habitat-habitat tunnel, it is a requirement that the crew should be able to walk through the tunnel, therefore presupposing a larger 2.0-meter diameter.

Table 1. Trade Options for various tunnel subsystems

Subsystem	Trade Options
Pressurization	Rover ECLSS, MAV ECLSS, Lander descent stage, Stored high pressure gas, combination.
Hatch Alignment	Guide wires, rover's robotic arm
Crew Translation	Walk, Crawl, Slide
Cargo Translation	Winch, carried by crew, slide
Docking System	Standards (International, US)
Deployment	Rail Guided Tunnel, Air Bridge Type, Spring Type

Docking System

To allow for both the MAV-rover tunnel and the habitat-habitat tunnels to be re-used, a likewise re-usable docking and undocking system is required. To ensure compatibility with systems built by the private space industry as well as international partners, a variant of the International Docking System Standard (IDSS) adapted for operation on the Martian surface is incorporated in both ends of the tunnel [6]. A schematic showing the concept of operations for the IDSS is shown in Figure 2 [7].

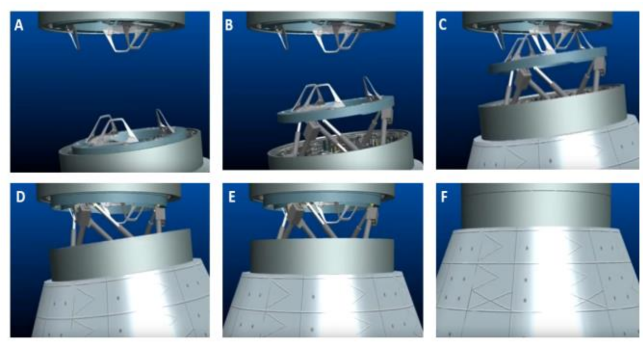

Figure 2. Schematic illustrating the concept of operations for the International Docking System Standard (IDSS) [7]**.**

A: The hatch on the tunnel approaches the docking port on the rover from below to dock with the rover, B: The docking mechanism on the tunnel extends outwards, C: The petals are coarse centering devices which ensure a lock even if the two are not perfectly lined up, D: The two halves are in contact. E: The mechanisms on the tunnel docking port adjust to line up perfectly. F: Lock in place, docking complete. A similar docking standard can be used at both ends of the MST for connecting various surface elements on the surface of Mars.

5. Candidate Deployment Mechanisms

Several candidate mechanisms are proposed for the deployment and use of the MST, each having its own advantages and disadvantages. The concepts are described for the MAV-rover connection, but are also relevant for nodes connecting other architectural elements such as habitats-to-habitats, habitats-to-rovers and other landed

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assets to rovers. Each of the presented concept mechanisms have been chosen keeping in mind the functional requirements presented in Section 2.

Rail-Guided Tunnel

The concept of operations for the rail-guided tunnel is shown in Figure 3. In this concept, the crew exit the rover in their EVA suits and connect the rover to the MAV with guide wires after which the wires are subsequently tensioned. The tunnel is assumed to be made of three key components, the MAV side hatch, an inflatable fabric as the main tunnel body, and the rover side hatch. The tunnel is initially assumed to be deflated and stowed outside the MAV hatch, with the MAV side hatch secured to the MAV. The rover side docking hatch of the tunnel is then unlocked and secured to the guide wires by a translational mechanism such as a pulley or a slider that allows that hatch to translate along the guide wires. The crew then initiates least inflation of the tunnel to instigate the tunnel's rover end hatch to move towards the rover. Once the rover end hatch of the tunnel reaches the rover, the crew manually docks it to the rover. The crew then attaches a second set of translational devices (same as those used earlier to move the rover side hatch) on to the MAV side hatch. These devices are used later to move the MAV side hatch to the rover. With both ends of the tunnel secured in place, the tunnel is pressurized to its operating pressure of 52.5 kPa.

After inspecting the inflated tunnel, the crew return to the rover, change from their EVA to IVA suits and crawl into the MAV through the tunnel, winching across the returning cargo (or potentially an incapacitated crew member). Once all crew and cargo are inside the MAV, the MAV side tunnel hatch and the MAV hatch are closed and the tunnel partially deflated. The MAV side tunnel hatch is then detached from the MAV. The translational devices attached to the MAV side tunnel hatch are now used to pull it towards the rover along the guide wires. As the MAV side hatch comes close to the rover end, the tunnel is completely deflated and stowed on the rover side hatch as it was stowed earlier on the MAV side hatch before use. This allows for the tunnel to be used again for future missions. The crew then releases the MAV side guide wires from inside and the tunnel is drawn to the rover. The rover is then programmed to exit the MAV launch area, after which the MAV launches the crew into Martian orbit for the return trip home.

Air Bridge Type Tunnel

As shown in Figure 4, the concept of operations for the air bridge type tunnel is similar to that of a retractable air bridge used at airports to connect the terminals to the aircraft doors. The bridge is initially stored in the habitation zone and is brought to the MAV launch site by the rover, pre-attached to the rover hatch. After appropriately positioning the rover relative to the MAV, the crew initiates minimal tunnel inflation to extend the tunnel towards the MAV hatch. Rover-based inflatable or composite booms support the tunnel while it extends towards the MAV. Once the MAV end of the tunnel reaches the MAV hatch and is docked, the tunnel is fully pressurized. After the crew and cargo transfer through the tunnel, the MAV side of the tunnel is undocked and automatically retracted towards the rover, which is then commanded to drive away from the launch site.

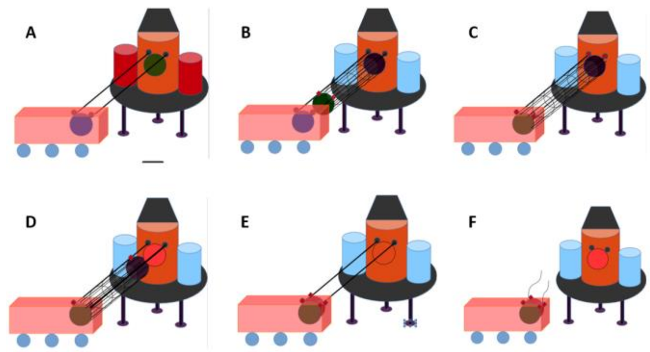

Figure 3. Schematic showing the concept of operations for the rail-guided tunnel. A: Tunnel stowed on the MAV, guide wires attached, B: Tunnel begins to inflate and the rover side hatch moves towards the rover, C: Rover end hatch docked to the rover, tunnel fully inflated, D: Tunnel partially deflated, MAV side hatch moves towards the rover, E: Tunnel fully deflated and stowed on the rover, F: Guide wires detach, rover drives away.

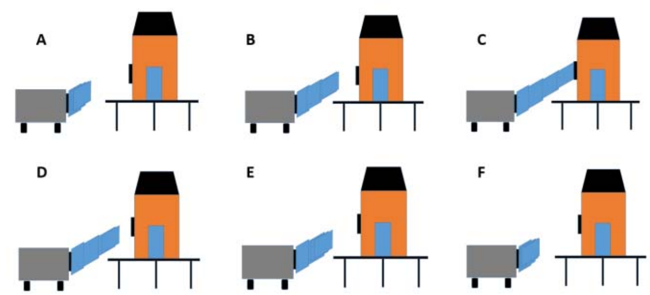

Figure 4. Schematic showing the concept of operations for the air bridge type tunnel. A: Tunnel arrives stowed on the rover, B: Tunnel begins to inflate and the MAV side hatch moves towards the MAV, C: MAV side hatch of the tunnel docked to the MAV ingress hatch, tunnel fully inflated, D: MAV side hatch detaches and moves away, E: Tunnel moves towards the rover, F: Tunnel is stowed on the rover, and the rover is commanded to drive away.

Helical Spring Tunnels

In the first spring tunnel concept, the tunnel incorporates a helical spring embedded within the tunnel's soft goods walls, and running axially throughout the length of the tunnel. The concept of operations for this design approach is shown in Figure 5. The helical spring tunnel is stored on the MAV in its nominal retracted configuration. As the crew begins to inflate the tunnel, the lowest possible pressure is used to extend the spring towards the rover. Similar to the preceding concepts, a support structure such as guide wires or boom prevents the tunnel from contacting the Martian surface during deployment. Once the tunnel reaches the

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rover and docks to the rover hatch, the crew fully pressurizes the tunnel. After the crew and cargo transfer to the MAV, the tunnel is partially deflated and then undocked from the MAV while remaining docked to the rover. The restoring force from the stretched spring causes the tunnel to substantially retract towards the rover. An objective of using a spring is to let the tunnel move towards the rover for storage after use while reducing the requirement for additional mechanical systems or power. A possible drawback of this concept is spring mass and spring fatigue.

We also consider an alternative to the concept presented in the preceding subsection, whereby the spring is nominally extended rather than retracted. When the tunnel is initially stored on the MAV before use, the tunnel is locked in its retracted position. As the crew unlocks the tunnel and commences pressurization, the restoring force of the spring aids the pressure force to inflate the tunnel and move the rover side hatch towards the rover. After docking and transfer as mentioned in the earlier concepts, the MAV side of the tunnel is undocked. An external mechanical power source must be used to move the MAV side hatch towards the rover for storage. Compared to the earlier concept, this concept is likely easier to deploy, but clearly more difficult to retract to the rover after use.

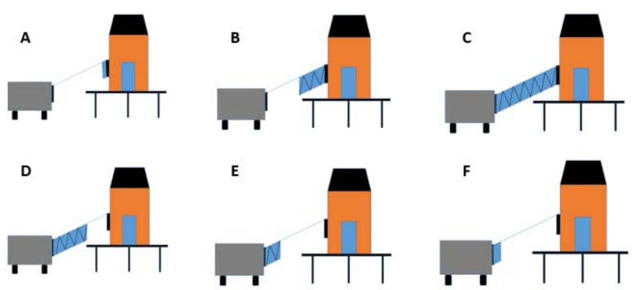

Figure 5. Schematic showing the concept of operations for the first variant of the helical spring tunnel. A: Tunnel stowed on the MAV, guide wires attached, B: Tunnel begins to inflate and the rover side hatch moves towards the rover extending the spring, C: Rover end hatch docked to the rover, tunnel fully inflated, D,E: Tunnel partially deflated, the restoring force of the spring moves the MAV side hatch moves towards the rover F: Tunnel stowed on the rover, guide wires detach, rover drives away.

6. TUNNEL DESIGN METRICS

Several candidate mechanisms for the MST have been proposed in Section 5, namely the rail-guided tunnel concept, the air bridge type tunnel concept, and two variants of the helical spring type tunnel. In this section, a merit-based comparison of the candidate concepts is presented to identify a preferred mechanism(s) for the MAV-rover tunnel and the habitat-habitat tunnel. A brief overview of the rationale behind the ranking of each of the concepts is presented in the following subsections with specific reference to each of the metrics listed in Table 2. Each of the tunnel concepts is given a relative score for each metric that is presented in Table 3.

Rail-Guided Tunnel

The rail guided tunnel is a relatively simple mechanical system in which the tunnel body is composed of inflatable fabric and has metallic hatches to connect to the rover and the MAV hatches. The rails guide the movement of the tunnel during the deployment towards the rover end and for storage on the rover after use. Since no other system is required for aligning the tunnel hatch with the rover hatch, this concept gets a high score for ease of hatch alignment. Unless the robotic arm or another rover can connect the guide wires, this step needs to be done manually and hence the crew needs to perform Extra Vehicular Activity (EVA) to connect the guide wires and thus gets a low score for the criterion. Other than connecting the guide wires, the sliding mechanisms make the tunnel deployment as well as retraction easy and is ranked high on ease of tunnel operations. Due to its construction from inflatable fabric and metallic frames at both ends, when deployed the full length of the tunnel needs to be used and hence scores low on the adjustability of tunnel length. One advantage of this type of construction is that it allows for the tunnel to be made of relatively soft fabric which is flexible when deflated but can be made sufficiently rigid by pressurization. As such, the tunnel body potentially weighs less and requires reduced storage volume, which gives it a high score on low mass and low storage footprint. The concept also ranks high on re-usability since the sliding mechanisms can be used to deflate and store the tunnel on the rover after use. The fact that, when inflated, the tunnel expands to its full length makes it difficult to be used for connecting other elements which need a different length and hence scores low on adaptability to other connections. The sliding mechanisms and guide wires add mass to the system and the sliders need mechanical power from a device such as an electrical motor.

Air Bridge Type Tunnel

The air bridge type concept using inflatable materials is likely to be a more complex mechanical design than the rail-guided concept which requires sealing of the various extendable inflatable elements, be completely deflatable when stored and also be rigid enough when pressurized and deployed. Due to the above factors, the concept ranks low on overall simplicity of mechanical design. To the concept's credit, the crew need not exit the rover or perform EVA to deploy and operate the tunnel, hence the concept scores high in that aspect. One of the most challenging practical problems associated with this concept is supporting the overhanging structure during deployment before it is attached to the MAV. For the various sections to maintain rigidity during deployment while they are still partially inflated, it is likely that the tunnel fabric is made of thicker and stronger materials than the wire guided tunnel and hence is heavier. One of the unique advantages of the air bridge type tunnel is the fact the tunnel length can be adjusted as required and hence scores high in tunnel length

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adjustability for connecting different surface elements. Despite the larger mass, the air bridge type tunnel can be stored elsewhere before use and is given a high score for ease of storage. The tunnel after storage on the rover can be reused for other connections such as habitat to rover and scores high on reusability and adaptability for uses other than the rover-MAV connection. Actuation of the tunnel requires an external power source and the crew must manually align and dock the tunnel with the MAV.

Table 2. List of metrics for comparison of candidate tunnel concepts

No.	Tunnel Metric
1	Simplicity of overall mechanical system
2	Ease of hatch alignment
3	Ease of hatch detachment from MAV
4	Ease of tunnel storage on the rover after use
5	Adjustability of deployed tunnel length
6	Mass of tunnel body
7	Use of relatively soft fabric for tunnel body
8	Re-usability of the tunnel
9	Adaptability to connect habitat-rover etc.
10	Minimal use of external power for operations
11	Storage footprint on the MAV/rover
12	Crew EVA not required for tunnel deployment
13	Ease of manufacture

Helical Spring Tunnel

The first variant of the helical spring tunnel is very similar to the rail guided tunnel concept, with the addition of a helical spring embedded inside the body fabric and runs along the length of the tunnel. The concept scores high on ease of tunnel deployment and hatch alignment, while the crew needs to perform EVA to connect the guide wires and start the deployment process. The pressure forces inflate and deploy the tunnel while also extending the spring and thus storing potential energy which is used later to retract the tunnel and store it on the rover. The deployment mechanism is simple and hence the concept gets a high score for ease of operation but less that the rail guided concept since the spring adds some complexity to the overall system. The restoring force of the spring eliminates the need for an external sliding mechanism and associated power source to move the MAV side tunnel hatch to the rover end after use and hence ranks high on ease of tunnel retraction and re-usability. However, embedding a spring inside the fabric increases the system mass and likely increases the storage volume required, hence the concept gets a lower score for mass savings and storage footprint than the rail guided tunnel but still higher than the air bridge concept. The concept is given the highest score for re-usability since the spring forces automatically move the tunnel towards the rover for storage and the tunnel can be inflated and deflated for later use. The tunnel can be employed for applications requiring a different length by locking a portion of the spring and only allowing the rest of the spring and the fabric to be pressurized, thus scoring high on other potential applications such as rover-to-habitat connections and habitat-to-habitat connections.

The second variant of the helical spring tunnel differs from the first variant only by the fact that the spring is initially compressed while stored on board the MAV. When the crew unlocks the tunnel, the restoring forces from the spring causes the tunnel to deploy automatically along with the pressure forces thus scoring higher on ease of tunnel deployment. Note that external mechanical power is required to compress the spring and move the MAV side hatch to the rover end during retraction and hence scores lower for ease of tunnel retraction. The concept scores high on re-usability as well as adaptability to other applications.

Ranking Candidate Mechanisms

A number of criteria are listed and each tunnel concept is given a score from 1 to 5 in Table 3 in the light of the discussion presented in the earlier sections. A score of 1 is the lowest and is least desirable while a score of 5 is the highest and most desirable. A sum of the weighted scores for each criterion is used to compute an aggregate score for each of the tunnel concepts. It is observed that with the above set of scores of each of the metrics and weights, the helical spring type tunnel and the rail guided tunnel appear to be the most attractive candidates while the air bridge tunnel is the less favored choice.

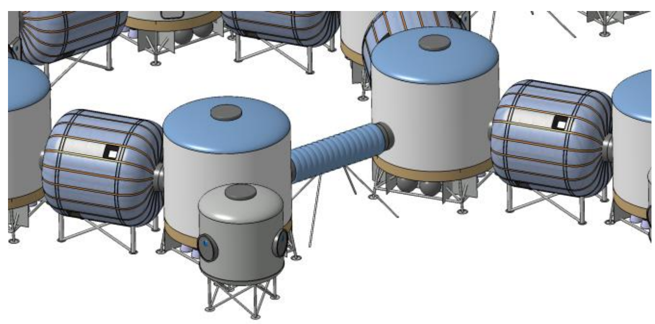

Figure 6. Schematic of the inflatable tunnel connecting two habitats. The tunnel allows crew to walk between the habitats, and when retracted allows a rover to access the inside of the habitat layout for service or maintenance activities [8].

We emphasize that the entries for each of the metrics and the weights are subjective and some of the metrics may not be applicable for some connections. The rail guided concept in our opinion for example, is better suited for the MAV-rover connection and the habitat-habitat connection, while the air bridge type tunnel is better suited for a habitat-rover or a science lab-rover connection.

Table 3. Comparison of tunnel concepts using tunnel metrics

Metric	Weight Factor	Rail Guided Tunnel	Air Bridge Type Tunnel	Helical Spring Type
Simplicity of overall mechanical system	3	5	3	4
Ease of hatch alignment	2	5	3	5
Ease of hatch detachment from MAV	1	5	3	5
Ease of tunnel storage on the rover after use	1	4	2	5
Adjustability of deployed tunnel length	2	2	5	4
Mass of tunnel body	2	5	3	4
Use of relatively soft fabric for tunnel body	1	5	2	4
Re-usability of the tunnel	3	5	5	5
Adaptability to connect habitat-rover etc.	2	3	5	4
Minimal use of external power for operations	1	4	2	5
Storage footprint on the MAV/rover	1	4	4	3
Crew EVA not required for tunnel deployment	1	3	5	3
Ease of manufacturability	3	5	3	3
Total Score		**100**	**83**	**95**

7. Proposed Tunnel Concept

We propose the rail-guided concept for the MAV-rover connection for its mechanical simplicity, ease of hatch alignment, re-usability, ease of manufacturability, and ease of tunnel storage on the rover after use. We also choose the rail guided concept for the habitat-habitat connection. A schematic showing the tunnel connecting two habitats is shown in Figure 6. It is not yet known if the inflated tunnel would be able to support the weight of crew and equipment on its own, since structural analysis to answer this question has not been performed within the scope of this work. Ground support structures may be considered for this function.

8. Tunnel Sizing

The MAV-rover tunnel has a length of 7 meters and a diameter of 1.4 meters when fully inflated. The length is based on the distance between the MAV ingress hatch and the rover hatch presented in previous work on the MST [4]. The tunnel connecting the two habitats has a length of 9 meters with 2-meter diameter. The larger diameter allows crew to walk through the tunnels connecting the habitats. The length of the tunnel is based on the distance between the two habitats in a candidate Martian base layout [8].

9. Fabric Layup

Based on Thin Red Line Aerospace's experience in design of inflatable structures for space applications, we choose the fabric layup to consist of an internal scuff layer, redundant gas barriers, a flame retardant layer, a pressure restraint layer comprising braided tendons, and an outer protective layer as shown in Figure 7. The layers starting from the innermost to the outermost with the corresponding materials for each of the layers is presented in Table 4.

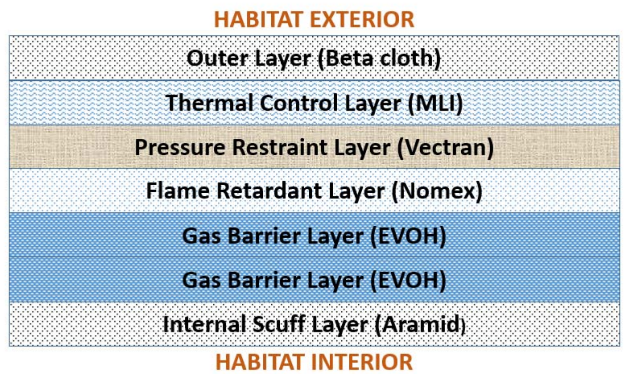

Figure 7. Baseline fabric layup for the Mars Surface Tunnel concept. Layer thicknesses are not to scale.

The fabric layup conceptualized for the NASA TransHab inflatable habitat project can be seen as a functional baseline for the MST fabric layers [9]. The thickness for each of the layers, unless otherwise marked, is based on Thin Red Line's experience in manufacturing inflatable structures for space application [10]. The requirements for thermal control and the outer protective layers are heavily mission specific, and hence simple baseline values were incorporated for comparative purposes only. All tunnel layers present a predominantly uniform cylindrical geometry except for the pressure restraint layer, which comprises meridional and circumferential arrays of spaced tendons. For the pressure restraint layer, a conservative estimate of an equivalent continuous is taken for ease of computation of the overall fabric mass. The thickness of each layer is given in mil-inches (thousandth of an inch). Material properties were taken from publicly available manufacturers' data sheets.

The internal scuff layer is made from puncture-resistant aramid. Ethylene Vinyl Alcohol Copolymer (EVOH) is incorporated as primary barrier constituent in the redundant

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life support atmosphere retaining bladder layers. Nomex® is used for flame retardancy. Multi-Layer Insulation (MLI) blanket acreage is used for thermal control, and the outermost protective layer tentatively consists of beta cloth. The previous study on the MST considered an exterior micrometeorite/debris protection layer, however we do not include it here assuming the probability of being hit by a micrometeorite is low during the very limited time the MAV-rover tunnel is operational. Conversely, the habitat-habitat tunnel will require debris shielding if left operational for several years in the Martian environment. A discussion of micrometeoroid protection layer is not included in the present study.

Table 4. Proposed fabric layup for the Mars Surface Tunnel (MST)

No.	Layer	Material	Density (kg/cubic meter)	Thickness (mil-inches)
1	Internal Scuff Layer	Aramid	1440	2
2,3	Redundant Gas Barriers	EVOH	1200	7 (each)
4	Flame Retardant Layer	Nomex®	950	7
5	Pressure Restraint	Vectran®	1400	7
6	Thermal Control	MLI	~1200	7
7	Outer layers	Beta cloth	~1400	4

10. Mass Estimation

The mass of the fabric layup for the MAV-rover tunnel is estimated considering each of the layers to be a cylindrical shell of radius 0.7 m, length 7.0 m, and thickness as listed in Table 4.

Table 5. Mass of the fabric layers used for the MAV-rover tunnel and the habitat-habitat tunnel

No.	Layer	MAV-Rover Tunnel (kg)	Habitat-Habitat Tunnel (kg)
1	Internal Scuff Layer	2.2	4.0
2,3	Redundant Gas Barriers	12.9	23.7
4	Flame Retardant Layer	5.1	9.4
5	Pressure Restraint	7.5	13.8
6	Thermal Control Layer	6.1	11.3
7	Outer layer	4.4	7.9
	Total Fabric Mass	**38.2**	**70.1**

For the habitat-habitat tunnel, the mass of the fabric layup is estimated considering each of the layers to be a cylindrical shell of radius 1.0 m, length 9.0 m and thickness as listed inTable 4. The computed mass for each fabric layer for the MAV-rover tunnel and the habitat-habitat connection is shown in Table 5.

The mass of tunnel components other than the fabric has been adapted from the previous work on the MST concept and are listed in Table 6 [4]. The total mass of the MAV-rover tunnel is estimated to be 214 kg and the mass of the habitat-habitat tunnel is 247 kg. These mass estimates are clearly approximate since the thicknesses and masses of the various soft goods layers is based on experience applicable to work on other mission concepts and legacy architectures.

11. Comparison with Past Work

The Mars Surface Tunnel (MST) concept was studied by M. Rucker *et al* [4]. However, the study did not analyze the deployment or retraction mechanisms for the tunnel, or the details of the fabric (soft goods) layup for the inflatable tunnel.

Table 6. Mass of MAV-rover tunnel components from previous work on MST

No.	Component	MAV-Rover Tunnel Component Mass (kg)	Habitat-Habitat Tunnel Component Mass (kg)
1	MAV-Side Latches	17.3	17.3
2	MAV-Side End Frame	28.3	28.3
3	MAV-Side Winch	9.5	9.5
4	Winch Motor	10.0	10.0
5	Tunnel Body (Fabric)	38.4	70.4
6	Tunnel Straps	2.7	3.47
7	Rover-Side Hatch Frame	28.3	28.3
8	Ground Support Structure	30.0	30.0
9	Rover-Side Pressure Hatch	30.0	30.0
10	Mating Mechanisms	13.0	13.0
11	Crew Translation Devices	1.4	1.8
12	Tunnel Maintenance Kit	5.0	5.0
	Total	**213.9**	**247.0**

One of the major unanswered questions in the earlier work was how the inflatable tunnel could be deployed and then aligned with the rover hatch. The present work addresses initial aspects of the potential deployment, hatch alignment and retraction mechanisms for an inflatable tunnel. The minimum functional tunnel considered in the past work does not consider re-usability for the MST. In the present work, we have incorporated storage and re-usability of the MST as a key feature in all the candidate mechanisms. This allows the MAV-rover tunnel to be re-used for connecting other surface systems, or additionally for MAV-rover connections in later phases of the manned missions. A candidate fabric layup along with the functionality of each of the fabric layers is also presented, and is used to obtain a refined estimate for the mass of the tunnel body. The various mechanisms presented in this study also allows a designer to choose appropriate concepts for connecting surface systems such as habitats to rovers and rovers to science labs.

12. Conclusions and Future Work

The Mars Surface Tunnel (MST) concept helps to mitigate problems associated with Martian dust in the Mars Ascent Vehicle (MAV), simplifies planetary protection protocols for returning crew and enables the crew to ingress the vehicle using lighter IVA suits which helps reduce the MAV ascent mass. Besides connecting the MAV to the rover, the tunnel concept can also be used to connect other surface elements such as habitats to habitats and habitats to rovers. The functional requirements for the MAV-rover tunnel and the habitat-habitat tunnel have been identified, and trade studies have been done for some of the tunnel subsystems. Four candidate mechanisms—a rail-guided tunnel, an air bridge type tunnel, and two variants of a helical spring tunnel have been proposed for the MST and compared using a list of tunnel metrics. For the MAV-rover connection we propose the rail-guided tunnel concept for its overall simplicity, ease of hatch alignment and ease of storage on the rover after use. We also choose the rail-guided tunnel for the habitat-habitat connection. We propose the tunnel soft goods to comprise an internal scuff layer, redundant life support bladders, a flame retardant layer, pressure restraint structure, thermal insulation, and an outer protective layer.

We have identified potential areas for future work to advance the MST concept. Such areas include analytical structural models for the tunnel, manufacturability issues for various tunnel concepts, inflation/pressurization systems, and variables associated with long term storage in the Martian environment. In essence, structures such as the MST belong to a class of structures known as inflatable beams, whose structural models have not been fully developed, however some analytical solutions for cantilevered inflatable beams are known [11]. More recently, new analytical and numerical solutions for deflections of highly pressurized fabric tubes have been studied by Wielgosz [12]. A comprehensive variety of design and analysis methodologies for inflatable structures has been studied by Veldman [13], while the potential of incorporating pressure restraint articulation is being investigated by one of the authors. Standards for determination of micrometeoroid protection requirement must be investigated, as well as the local environmental effect of Martian regolith on the outer layer of the MST. While this study focused solely on the use of a tunnel as a solution to the problems identified in Section 1, there are intriguing design alternatives to the tunnel, for example, incorporating inflatable airlocks or suit ports, which remain to be investigated.

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