Terminal Descent and Landing System Architectures for a Mars Precision Lander

TERMINAL DESCENT AND LANDING SYSTEM ARCHITECTURES FOR A MARS PRECISION LANDER
8TH INTERNATIONAL PLANETARY PROBE WORKSHOP
6-10 JUNE 2011, PORTSMOUTH, VIRGINIA

Lisa Peacocke[(1)], Marie-Claire Perkinson[(1)], Jaime Reed[(1)], Marco Wolf[(2)], Tobias Lutz[(2)], Christophe Balemboy[(2)]

[(1)] Astrium Ltd, Gunnels Wood Road, Stevenage, SG1 2AS, UK, Email: lisa.peacocke@astrium.eads.net
[(2)] Astrium GmbH, Airbus-Allee 1, 28199 Bremen, Germany, Email: marco.wolf@astrium.eads.net

ABSTRACT

Mars Precision Lander is a mission currently being studied within the ESA Mars Robotic Exploration Preparation (MREP) programme. A landing accuracy of better than 10 km is required for the precision lander, with a goal of 7.5 km. A potential mission scenario considered for the precision lander is the safe landing of a Sample Fetch Rover, as part of the Mars Sample Return programme. This rover would retrieve the sample cache obtained by the future NASA/ESA sample caching rover and place it in the Mars Ascent Vehicle, the first stage of its journey back to Earth. A precise landing is non-trivial, and requires a highly accurate guided entry and robust terminal descent and landing systems with potential hazard avoidance. This paper will summarise the various terminal descent, landing and egress architecture concepts investigated in the first half of the Mars Precision Lander contract.

1. BACKGROUND

The landing accuracy of past Mars missions has varied greatly, with landing ellipse major axes ranging from 280 km for Viking to 80 km for the Mars Exploration Rovers [1]. The upcoming Mars Science Laboratory will achieve a landing accuracy of 20 km, a significant improvement, but still greater precision will be needed for future missions.

The proposed Mars Sample Return (MSR) programme as currently envisioned [2] consists of three missions:

- 2018 Sample Caching mission – a sampling and caching rover will obtain a number of samples of Martian rocks and regolith over a two year period. These samples will then be cached in a sample container.
- 2022 MSR Orbiter mission – a communications relay orbiter for data transmission to Earth, and also the Earth return vehicle. The orbiter will detect and capture the sample container (launched into orbit by the 2024 lander mission) and transfer it to the Earth Re-entry Capsule (ERC). The orbiter will then return to Earth to release the ERC.
- Proposed 2024 MSR Lander mission – landing a Sample Fetching Rover (SFR) and Mars Ascent Vehicle (MAV) on the Martian surface. The SFR will locate and pick up the samples previously cached in the 2018 mission and return them to the MAV. The MAV will then launch into Mars orbit, and release the sample container into orbit near the MSR Orbiter for capture.

The Mars Precision Lander (MPL) could be used as a back-up mission to the current MSR programme, in the case that the MSR Lander mission encounters mass limitations. The SFR could be delivered separately by the MPL, requiring a very precise landing in close proximity to both the sample cache and the MAV.

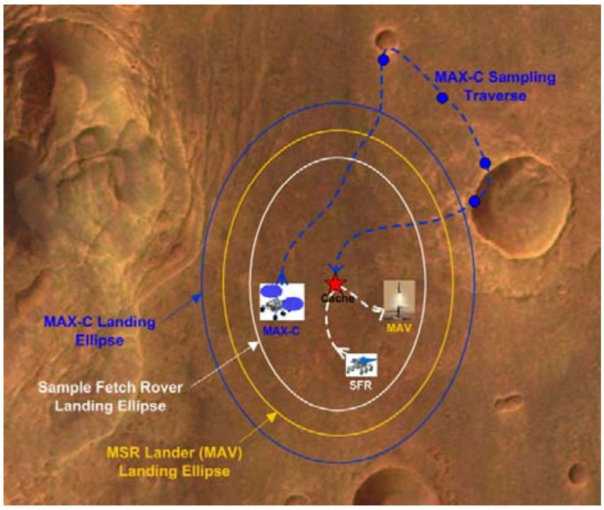


Fig. 1. The MPL could deliver the Sample Fetch Rover

A number of alternative mission scenarios could also make use of a Mars Precision Lander, such as: a larger rover that can sample, cache and return to the MAV; an element of a network science mission; and a stand-alone science rover mission providing technology demonstration for Europe. In all cases, the < 10 km precision landing capability would be a major step forward, and is a vital development for future Mars exploration.

2. MARS PRECISION LANDER MISSION

The Mars Precision Lander mission aims to launch on a Soyuz 2.1b/Fregat M from Kourou, with the Ariane 5 ECA as backup. The launch date will be 2022, 2024 or 2026, to be consistent with the MSR timeframe. Although a launch into a direct transfer is preferred for simplicity, mass constraints mean it is likely a launch into a Geostationary Transfer Orbiter (GTO) or an Earth Gravity Assist Manoeuvre (GAM) will be necessary. Both the direct transfer and launch into GTO lead to a mission duration of 1 year, with an Earth GAM increasing the mission duration to 2.5 years.

The MPL spacecraft composite will consist of a Carrier and a Guided Entry Module (GEM). The GEM will contain the Powered Surface Lander (PSL) and the Sample Fetch Rover (SFR). The safe accommodation and deployment of the 85 kg SFR is critical, particularly with the high potential of hazardous terrain.

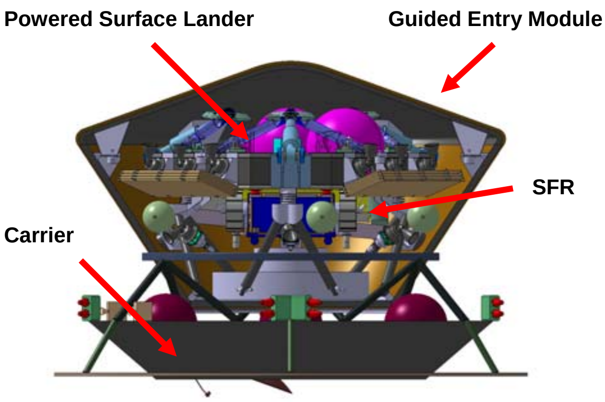


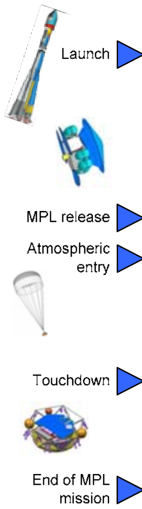
Fig. 2. MPL reference solution composite (design not yet fixed)

When approaching Mars, the hyperbolic entry will be limited to less than 4 km/s. A GEM mass greater than 1000 kg needs to be delivered to the Entry Interface Point (EIP). Arrival will occur outside the main dust storm season and away from solar conjunction periods.

The GEM will be released from the Carrier from the Mars hyperbolic arrival trajectory, so no Mars orbit insertion manoeuvre is required. Early and late release of the GEM is possible, with early release allowing for the Carrier to perform a Mars avoidance manoeuvre, but resulting in error propagation. Late release removes errors, but may lead to the Carrier impacting on Mars or an increased Δv requirement for avoidance.

The landing site co-ordinates will be within a latitude range of 5 degrees south to 25 degrees north, and at any longitude. The landing altitude will be lower than -1 km MOLA, with a goal of 0 km MOLA.

The overall mission timeline is illustrated below:



PHASE	ACTIVITIES
Pre-launch	• Composite in fairing / baby-sitting
LEOP	• Launch & Fregat burns • ESOC listening • Separation, first acquisition and s/c check-out • Dispersion correction manoeuvres
Cruise	• Perform correction manoeuvres • Comms with Earth: Housekeeping / Spacecraft & rover checks / Software patches • Maintain MPL / Rover environments • Accurate ranging for targetting • Initialize and release MPL onto stable trajectory
Coast	• MPL on battery power, communications to Orbiters / Earth • Final correction manoeuvres
Entry & Descent	• Stabilization and guidance during entry • Deploy back-shell and parachute • Release heat shield, deploy lander, jettison parachute • Send TM to Orbiters and Earth
Landing	• Thrusters firing and final guidance; transmit TM • Deploy landing system • Hazard avoidance turned on, search for landing spot
On-Surface	• Perform health checks & transmit EDL data • Deploy ramps / egress system • Transmit TM during deployments • Possible SFR hibernation for 2 weeks (TBC/TBD)
Egress	• Rover egress

Fig. 3. MPL mission timeline

The sequence after EIP is split into:

- Hypersonic Entry Phase: EIP to Mach 2-5.
- Descent Phase: end of hypersonic phase to start of terminal descent phase, including any parachutes.
- Terminal Descent Phase: slow-down of lander to just before touchdown, typically starting with parachute release.
- Touchdown Phase: from first point of touching the surface, including any required initialisation or bouncing, to cancellation of all velocities.
- Egress Phase: from being on the surface with to velocity to the rover being on the surface in a free state ready to start its mission.

The baseline GEM shape selected is a rigid Viking blunt capsule shape of 2.8 m diameter. The lift/drag coefficient expected is 0.2-0.25 with a maximum heat flux of 1600 W/m^2. The ballistic coefficient is expected to be near 100 kg/m^2. Norcoat-Liège is the nominal ablative material, with ASTERM as a back-up mid-density material.

A direct guided entry with lift modulation will be performed, although a skip entry is possible to enlarge the entry corridor. A single stage supersonic parachute of 14-16 m diameter is preferred to minimise mass and appears feasible at present. Frontshield separation will occur at Mach 0.4 and the powered surface lander will separate from the backshell when its velocity relative to the ground is less than 90 m/s. This is expected to be between 1.2 and 1.7 km altitude.

The remainder of this paper will focus on the Terminal Descent, Touchdown, and Egress Phases. Working sessions involving the MPL team and assorted Astrium experts were held early in the contract to brainstorm and identify the full range of options for each EDL phase, and a variety of concepts were investigated.

The surface rocks and slopes strongly drive the architecture design. A hazard avoidance system is one option, otherwise the system must be able to land safely in the worst case scenario – a combination of a 60 cm rock and 22.5° slope.

3. TERMINAL DESCENT ARCHITECTURES

Terminal descent begins at parachute release. Six promising options were identified during the brainstorming workshop and are described here:

1. Parafoil
2. Auto-rotor
3. Balloon/Zeppelin
4. Rocket Rotor
5. Retro Propulsion
6. No Terminal Descent Phase

3.1 Parafoil

A steerable sub-sonic parafoil would combine the functionality of a parachute and a wing to provide the deployable system with a very high lift-to-drag ratio (>3) with the additional capability of aerodynamic controllability. A parafoil is attractive for a precision landing as both deceleration in the subsonic regime and precise manoeuvring can be obtained. This concept has been proved under Earth environmental conditions with NASA's X-28 Crew Return Vehicle project and the German SLGSys project conducted in 1996 with four free-flights.

Fig. 4. X-38 lifting body concept with parafoil used for landing (credit: NASA)

The use of parafoils for a Mars landing would allow some cross-range corrections but has a very large impact on the mass due to the additional subsystems needed to fly and steer the parafoil itself (winches, ropes, motors etc.). Another major issue is that the lift generated is proportional to atmospheric density so that to generate the same lift force on Mars requires about 100 times the planform area as on Earth. This large size would be very complex to deploy and control reliably, and would be extremely expensive to develop. Additionally, wind drift would decrease precision significantly, so the parafoil is not considered promising for the MPL mission.

3.2 Auto-rotor

The auto-rotation principle is based on the aerodynamic lift generated by freely-rotating (i.e. unpowered) rotor blades in forward and vertically-descending flights [3]. Vehicles using this principle are termed autogyros. Unlike helicopter rotor systems, the autogyro rotor is mechanically simple and the blades do not necessarily require cyclic pitch control. Auto-rotational landings of various types of vehicle have been conducted in terrestrial free flight trials and wind tunnel tests.

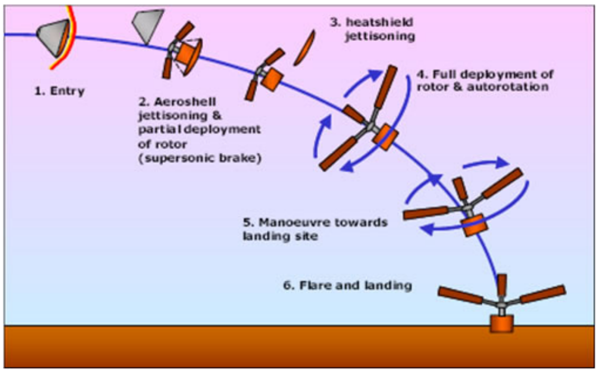


Fig. 5. Autorotation principle

After deployment, the velocity would decrease until a steady state descent is achieved, and a vertical or flare terminal descent manoeuvre is possible. This is a high mass concept, however, with a risky and complex deployment and operation and a low technology readiness level (TRL).

3.3 Balloon/Zeppelin

Balloons, including Montgolfieres, can be used on Mars to soft land relatively large payloads at under 3 m/s. Following a parachute descent, the balloon would be deployed and filled by ambient gas flowing in through a hole at the base, and rapid heating of the balloon to provide buoyancy. Balloons are far more stable than parafoils/parachutes for the terminal descent phase.

Fig. 6. TANDEM Titan balloon (credit: ESA)

Much work has been performed on balloons for Mars, following the successful use of balloons during the Vega mission to Venus. NASA has performed both wind tunnel and stratospheric tests. However, they have the same issue with reduced lift due to the reduced Mars atmospheric density. This greatly increases the volume and thus mass of the balloon required. A long duration Mars aerobot would be a preferable application for this technology, but it is considered overly massive and complex for a terminal descent. The lack of landing accuracy due to extensive wind drift also means this is not a promising candidate for the Mars Precision Lander.

3.4 Rocket Rotor

A rocket rotor lander would build on the autorotation principles described earlier, but with the addition of small rocket motors mounted at the tips of the blades. These rocket motors would spin-up the rotor to provide increased deceleration and more control of the landing. Such a system has been investigated by Rotary Rocket Inc. who were developing an actual flight system before closing down. The TRL is very low for a Mars application, with many issues related to operation.

3.5 Retro Propulsion

Retro propulsion is the traditional form of Mars terminal descent. NASA's Viking landers used monopropellant hydrazine thusters, with the Mars Pathfinder and Mars Exploration Rover missions using solid rocket motors to decelerate the entry module prior to touchdown on airbags.

A huge variety of potential retro propulsion solutions exists, based upon the types of propellant and the configuration of the thrusters and propulsion system architecture. This is considered the most advanced technology for an MPL terminal descent. Disadvantages include plume effects when near the ground, generation of dust and thermal fluxes, and pollution of the landing site.

For the Mars Precision Lander, the Ariane 5 SCA hydrazine thrusters are considered promising for the powered descent stage, along with throttleable bipropellant engines. Solids have higher performance, and could be used in conjunction with a monopropellant system to optimise the descent.

3.6 No Terminal Descent Phase

The option of landing directly on airbags or performing a hard landing was briefly considered and ruled out. A hard landing would transmit extreme and unendurable shock loads to the rover payload. A hard landing on airbags at very high speeds would require significantly more robust airbag materials and configurations than are available currently, and would still transmit very high shock loads to the rover, which it is not likely to survive.

4. LANDING/TOUCHDOWN ARCHITECTURES

Eight touchdown options were identified in the brainstorming sessions:

1. Legs
2. Airbags
3. Crushable Structures
4. Dropship
5. Shell Lander
6. Penetrator
7. Under-Carriage/Skids
8. Pre-prepared Landing Structures

A number of concepts where the rover had additional elements incorporated on it directly, such as airbags or crushable structures, were considered, but ruled out due to concerns with the separation/fouling after landing

4.1 Legs

Various types of landing legs have been used on past planetary landers, such as Surveyor, Apollo, Viking and Phoenix, so significant heritage exists for this option. The legs can be fixed, flexible or crushable to absorb the landing impact load.

Two types of landing legs can be distinguished. *Cantilever* legs have secondary struts connected via ball joints to the outer tube of the main leg, and aim to maximise ground clearance beneath the lander. In the *Inverted Tripod* configuration, the secondary support structure is connected directly to the footpad, aiding in shock absorption but reducing ground clearance. The reference legged solution for MPL was an inverted tripod configuration, as shown in the figure below.

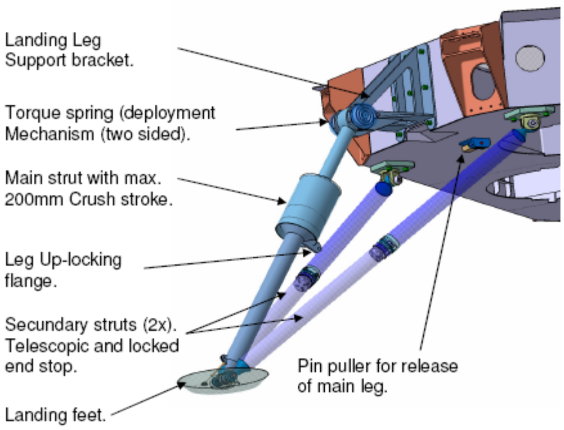


Fig. 7. Landing leg touchdown concept

Deployable legs would be required to fit within the entry module, with deployment mechanisms necessary. The primary shock absorber is typically plastically deformable aluminium honeycomb cylinders that absorb the kinetic energy at touchdown by deformation.

Landing legs must be robust to the landing impact, and are a heavy concept. If hazard avoidance is not used, the landing legs must be designed to withstand the worst case slope (22.5°) and rock (60 cm) combination, a very high total slope requiring many levelling and lowering joints to enable safe rover egress. This would increase mass drastically. Relatively simple and lightweight legs are only possible if hazard avoidance is incorporated into the design.

4.2 Airbags

Two types of airbag solutions are possible – unvented (bouncy ball) and vented.

Unvented airbags have been used on the Mars Pathfinder and MER missions, and the principle consists of completely surrounding the payload with a protective cocoon of airbags which are compressed during landing impact. Since the gas is not vented, there is little energy dissipation, and the impact kinetic energy is almost all returned, resulting in typically twenty or more bounces before coming to rest. To provide all-round protection and abrasion resistance results in heavy airbags and also requires a substantial lander structure with self-righting capability. The large distances that can be covered by unvented airbags during bouncing mean this concept is unlikely to be considered a precision lander.

Vented airbags, however, have an airbag set only on the base of the surface platform, and the airbag gas is released through small vents as soon as compression occurs on the surface. This concept requires less volume and mass for the airbags, but it is also very sensitive to slopes, winds and toppling.

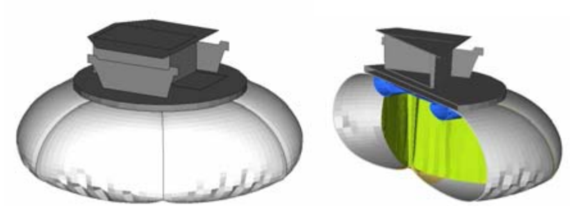


Fig. 8. Vented airbag touchdown concept

With both airbag designs, egress is challenging. The rover must pass over the deflated airbags, and the egress path could be blocked by obstacles and slopes from the airbag material. Past Mars missions have encountered blocked egress paths and this is difficult to avoid without additional retraction mechanisms.

4.3 Crushable Structures

A crushable structure on the base of the surface platform is an alternative touchdown concept. Layers of crushable aluminium honeycomb are the likely material. Different shapes of the crushable structure and densities of the core cause different behaviour of the honeycomb layers, particularly in lateral loading.

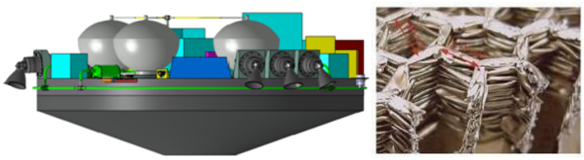


Fig. 9. Crushable structure concept with crushable honeycomb (credit: ESA)

Tilted impacts of up to 18 degrees are feasible for a crushable landing, and minimal bounce occurs.

Crushable material is, however, sensitive to shear forces, so the design is susceptible to rocks and obstacles where toppling can occur. Sharp rocks can drastically reduce the effectiveness of the impact attenuation, so hazard avoidance would be necessary. The egress of the rover is likely to be simplified in this design as the surface platform is very close to the Mars surface after crushing. This design is being used for the 2016 ExoMars landing demonstrator.

4.4 Dropship

The Dropship is based on NASA's Skycrane approach. After the parachute has significantly slowed the vehicle and the heatshield has separated, a powered descent stage with retro propulsion thrusters (the Dropship) will slow the nested rover/payload even further. When the vehicle has been slowed to nearly zero velocity, the rover will be released from the descent stage. A set of cables and an umbilical (sometimes called a bridle) will lower the deployed rover/payload to the surface.

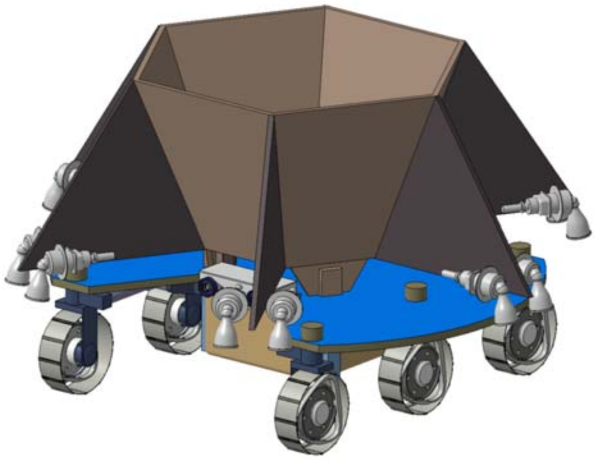


Fig. 10. Potential Dropship configuration

When the onboard computer detects a successful and persistent touchdown, the cables and umbilical will be cut. The Dropship descent stage will pitch away from the rover and power away at full throttle to crash-land at some distance from the rover.

This type of touchdown is soft, but does require the rover to attenuate the landing shocks itself, potentially adding mass and changing the rover locomotion system configuration. Landing the rover on its wheels, however, will remove the need for any other touchdown system such as landing legs, and the egress system will be a relatively simple cable and winch mechanism, also reducing mass. An alternative concept involves incorporating the Dropship subsystems into the entry module backshell, which would further reduce mass and enable much greater payload masses.

A significant advantage of this design is its flexibility to different payloads and missions. A network science element can just as easily be delivered via Dropship as the sample fetch rover. This is not necessarily true for a number of the alternative touchdown concepts.

4.5 Shell Lander

Shell landers deal with payloads totally encapsulated by a protective shell. The shell can incorporate a crushable structure (honeycomb layer or metallic foam), airbags , or a combination of both. The target with this type of landing is to guarantee maximum protection of the payload, while reducing touchdown complexity.

The shell lander would follow a long parachute phase, which reduces the descent velocity to a suitable minimum to keep the impact load within an adequate limit. As the payload is completely surrounded by the shell, no particular landing orientation is required, so the shell can be released by the parachute to impact on the ground. After touchdown, the shell would open up and the payload would be in the correct orientation ready for egress. The Beagle 2 lander was this type of design, but with the aid of external airbags to attenuate the impact loads.

Fig. 11. Beagle 2 shell lander design

Survival of the hard landing is a challenge for the rover, and the egress would be complex. This type of lander is more suited to static payloads or small rovers. An 85 kg sample fetch rover would need significant redesign and additional mass to enable survival. The shell lander concept is therefore not considered promising.

4.6 Penetrator

A penetrator is a touchdown concept where no attempt at a soft-landing is performed. After entry, the penetrator containing the payload would plummet through the atmosphere, hitting the Martian surface at over 400 km/h. The impact would partly shatter the external shell, with the forebody penetrating through the soil as far as 0.6 metres. The aftbody would remain on the surface containing the payload.

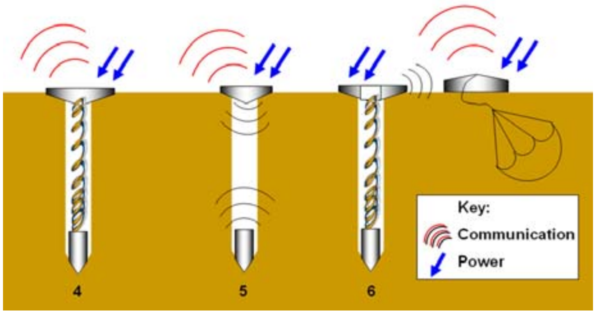


Fig. 12. Penetrator touchdown concepts

The major problem with this design is the extreme impact shock loads and the high g-level of deceleration. Although a candidate for small static payloads, this was considered an impossible touchdown concept for a rover and the Mars Precision lander.

4.7 Under-carriage/Skids

An under-carriage or skids could be used for terminal descents with high horizontal velocity, such as the parafoil or balloon/aerobot concepts. Such a concept requires a landing in an area of flat terrain with minimal rocks – not common on Mars. It is also a very high risk concept, with significant likelihood of toppling or catching on rocks, and at a very low TRL with no space heritage. This concept was therefore eliminated early in the investigations.

4.8 Pre-prepared Landing Structures

A novel touchdown design was briefly considered, where either a previous mission would have prepared a landing surface, or the lander would have ejected a suitable surface (such as an airbag or crushable structure) ahead of itself. It is very unlikely that any previous mission to Mars could place a landing structure on the surface, and even if this was possible, the landing accuracy required would be extremely stringent, on the order of metres. Also, there appears to be no advantage in ejecting a structure ahead compared to having it attached to the lander. Thus, this concept was eliminated for the Mars Precision Lander.

5. EGRESS ARCHITECTURES

The safe egress of the rover is highly interlinked with the terminal descent and landing architecture. Six egress options were considered in detail in the first half of the MPL contract:

1. Mechanical Ramps (folded, inflatable, rolled)
2. Cables and Winch
3. Crane
4. Folding Legs
5. Drop onto Surface
6. Flip Rover

A concept where a highly capable robot arm on the rover lifts itself down from the surface platform was briefly considered but ruled out as the sample fetch rover design is out of the MPL study scope.

5.1 Mechanical Ramps

Three subsets of mechanical ramps have been investigated – folded ramps, inflatable ramps, and rolled ramps. In all cases, it is assumed that two ramps on opposite sides are necessary to give two egress paths, and the maximum slope of the ramp is 20°.

Folded Ramps
Fan folded ramps and scissor ramps would deploy a number of sections that lock into place to provide a rigid structure. The number of sections is highly dependent on the volume available inside the entry module. The deployment can be driven by either springs or motors. One concept for a scissor-mechanism deployed ramp is illustrated below.

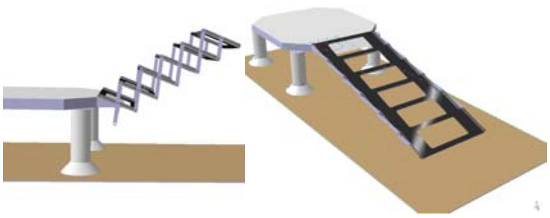


Fig. 13. Scissor ramp egress concept

The ramp sections will be made of carbon-fibre reinforced plastic laminate. For a fan folded ramp, locking mechanisms at each fold will be required to prevent collapse and provide rigidity. These could be simple blocks/stoppers or hook locking mechanisms. To minimise the number of mechanisms required for deployment and locking, the number of ramp sections should also be minimised.

A preliminary sizing was performed for a 2 section fan folded ramp deployed by motors. Each ramp section was 1 x 1 m in size, with cutouts used to reduce mass. The approximate calculated mass was 6 kg per ramp.

Inflatable Ramps
An inflatable ramp would consist of material filled with nitrogen by a gas inflation system comprising a

tank and topping head. This concept has the potential for stowed volume savings. However, it includes a complex gas inflation system with high pressure gas and a number of mechanisms.

The material used is silicon-coated Vectran, which has significant space heritage from airbag applications. The ramp structure is similar to an aircraft escape slide, comprising 5 longitudinally connected beams of 0.3 m diameter each, as shown in the figure below.

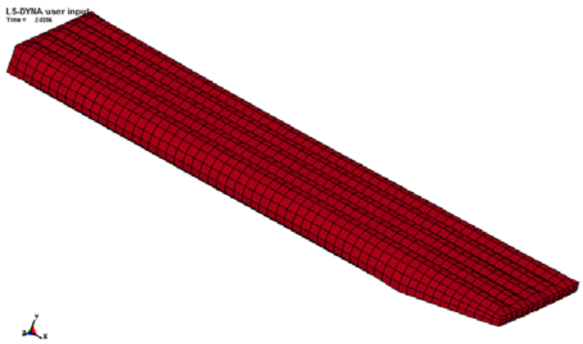


Fig. 14. Inflatable ramp egress concept (credit: AeroSekur)

An inflation pressure of 6 kPa is sufficient to support the 85 kg rover during egress. Each ramp has a mass of approximately 10 kg, including the inflation system.

Rolled Ramps

Two rolled ramps were considered – a rolled slat ramp deployed by tape springs, and a rolled tube ramp using Bi-stable Reeled Composites (BRCs), a new technology under development.

The rolled slat ramp consists of a number of carbon-fibre slats deployed by tape springs based on carpenter's tape measures. Tape springs have been developed by Astrium for deployable space structures, and significant energy can be stored when two tape springs are folded together. Pairs of short tape spring sections will run in rows between the ramp sections in a similar fashion to Fig. 15 below.

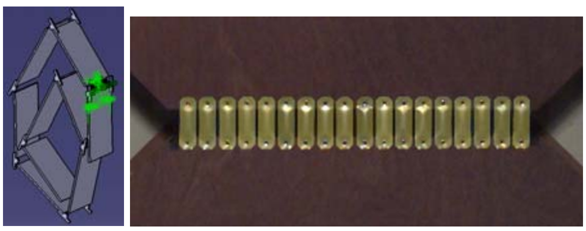


Fig. 15. Rolled slat ramp egress concept and tape spring breadboard

This is a high mass concept, and requires a large volume when stowed. Deployment must be upwards to prevent the ramp being obstructed by surface obstacles. A preliminary mass estimate of 9 kg per ramp was calculated.

Alternatively, a rolled tube ramp using BRCs is a lighter mass solution. BRCs are stored in a squat coiled form, and deploy into a long thin tubular form. They are stronger than the stainless steel Storable Tubular Extendible Members (STEM) used in the Mars Pathfinder egress ramps, and are extremely light and stiff. BRCs also have the advantage that they are stable in any configuration, so do not need to be held down to prevent deployment.

A variety of materials can be used in the BRCs, with glass/propylene being common, and carbon-fibre/cyano-ester currently undergoing space qualification. The deployment mechanism is a simple pair of rollers and an electric motor, with the small number of moving parts providing good reliability.

Fig. 16. RolaTube BRCs form the ramp's outer struts (credit: RolaTube)

The rolled tube ramp would have two BRCs as the outer struts deployed from the small volume deployment mechanisms. Aluminium bracing struts run between the two main tube struts, with Kevlar mesh cross films used to prevent obstruction from the rocks. A preliminary sizing estimates that each ramp is 3 kg, a very lightweight egress solution.

5.2 Cables and Winch

A cable and winch mechanism is applicable for the Dropship touchdown concept. It would lower the rover to the surface using a set of cables. A design similar to that used by NASA's Skycrane system is proposed, using a rotating spool with a gear set and braking and retracting elements to ensure the rover is released at a continuous rate [4].

The three cables will be comprised of Vectran fibre, and an umbilical will provide an electrical link to the rover. Pyro cutters are necessary either on the cables or on the rover, with the

This is a low mass egress solution, with a preliminary mass estimate giving 6 kg total for the single mechanism.

5.3 Crane

A crane concept would lift the rover by a hard latching point, rotate 180 degrees, then lower the rover to the surface on a cable and pulley system. The crane must be pre-attached to the rover prior to launch, and the major mechanism is the rotational joint at the base of the crane.

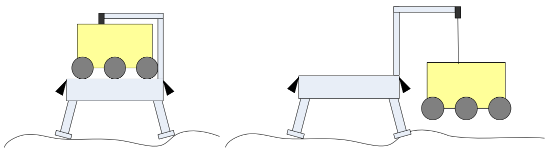


Fig. 17. Crane egress concept

This concept is unlikely to provide multiple egress paths, which is a major reliability issue. Two egress paths are necessary for the Mars Precision Lander, to ensure a clear surface location is found. An extendable top bar would allow the crane to reach further to different points around the lander, but greatly complicates the design. Alternatively, two cranes could be incorporated on opposite sides of the lander, with both pre-attached to the rover. A separate camera system would be required on the surface platform to determine which crane to use, and the unwanted crane would then be released and moved out of the way. This is a highly complex design.

The preliminary sizing assumed aluminium alloy 2024 bars, and calculated a mass of approximately 8 kg per crane. However, the high complexity of the solutions required to provide two egress paths means this concept is considered unfeasible for the Mars Precision Lander.

5.4 Folding Legs

If landing legs are used for the touchdown phase, additional rotational joints can be added to allow the leg to 'fold' and lower the surface platform fully to the surface. This is an extension of past research activities into the levelling of legged landers carried out by Astrium.

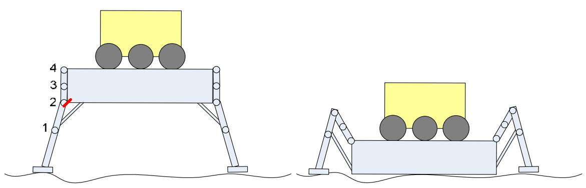


Fig. 18. Folding leg egress concept

In this concept, three rotating joints at the top of the landing legs (joints 2, 3 and 4 in the figure above) would be locked to the side of the surface platform during landing to survive the impact shock load. Once landed, the hold-down and release mechanism at joint 2 would release the joints and the folding and lowering process would be performed. Dependent on the height of the surface platform, the rover could simply drive straight off onto the surface, or simple egress aids could be used to assist the rover egress.

Large and robust joints of around 2 kg each are required to carry the full surface platform and rover mass, with numerous integrated sensors to determine the height and angle of the surface platform. With 3 joints required per leg, this is a highly complex option with many mechanisms and thus potential for single point failure.

The preliminary mass estimate for the egress system (the joints and support structure only, not including the remainder of the legs) was calculated to be 23 kg for a 3-legged lander. This is the highest mass egress concept, and is thus less preferred, except in the case that hazard avoidance is not incorporated. The folding legs are the only touchdown/egress system that allows landing on the worst case slope and rock combination.

5.5 Drop onto Surface

This is a simple concept applicable only if the rover is suspended below the surface platform. The rover is simply released from the surface platform by a set of hold-down and release mechanisms. The rover must be initialised before being released.

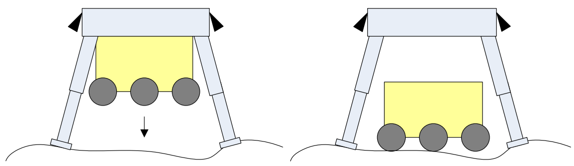


Fig. 19. Drop onto surface egress concept

Assuming that the rover wheels are initially 0.7 m above the surface, the impact velocity will be 2.28 m/s. The shock load applied to the rover is dependent on the surface material and compression distance, with a compression of 1 cm giving a shock load of 26.5 g. The rover could be designed to withstand such conditions.

Dropping onto the surface is a very low mass egress system (around 0.5 kg) with simple operation, but requires a specific configuration that prevents solar array deployment during rover initialisation. It is therefore not promising for the current MPL scenario.

5.6 Flip Rover

In this novel concept, the rover is stowed in an inverted position and flipped 180 degrees by a simple robot arm. The rover would then be placed ready to go on the Martian surface.

Bipod support struts and hold-down and release mechanisms would support the rover on the surface platform, and the arm would attach to the rover at a hard latching point. The rotational joint at the base of the arm would need to be robust and likely heavy. A frame could be utilised instead of an arm to improve the support of the rover.

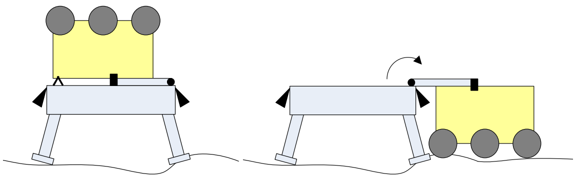


Fig. 20. Flip rover egress concept

Flipping the rover has the same major issue as the crane concept, with only a single egress path being available. Two opposing arms/frames could be used, both pre-latched and one later released, but this is also highly complex with relatively high potential for failure. The design also limits the height of the surface platform, making it inflexible to changes unless greater complexity is added. Additionally, the entry module would have a higher centre of gravity due to the heavy locomotion system being near the back of the module, which increases instability during entry.

The preliminary sizing assuming the use of aluminium alloy 2024 gave a mass of 8 kg per flipping arm, but the significant negative consequences mean this concept is considered unlikely for the Mars Precision Lander.

6. SUMMARY AND CONCLUSION

A large number of terminal descent, touchdown and egress architectures are possible for the Mars Precision Lander mission, although a certain technology readiness is necessary to enable selection.

The most promising terminal descent system is considered to be a retro propulsion powered descent. This option has significantly more heritage than any other and is the most reliable design.

Four of the touchdown systems are still considered promising for the MPL: landing legs, airbags, crushable structure and the Dropship. Further analysis will be performed on these four prior to down-selection.

The preferred egress system is highly dependent on the touchdown system selected. For a legged lander, airbags and crushable structure, the rolled tube ramp using RolaTube technology appears promising with its low mass and volume requirements. For a Dropship design, the cable and winch mechanism is considered necessary.

Selection of the preferred options via trade-off analysis is forthcoming, in conjunction with ESA. The second phase of the Mars Precision Lander contract will then focus on the detailed design of the selected mission architecture, to prove the feasibility of a precise and safe delivery system for Mars.

7. ACKNOWLEDGEMENTS

The work described here is part of an on-going study being conducted under ESA Contract No. 4000102983/11/NL/EK.

REFERENCES

1. Braun R. D. and Manning R. M., Mars Exploration Entry, Descent and Landing Challenges, *Journal of Spacecraft and Rockets*, Vol.44.2, 10-323, 2007
2. Mattingly R., *Mars Sample Return: Proposed MSR Campaign Description*, NASA Document D-66014, Initial Release, 2010
3. Lutz T. et al., *Application of Auto-rotation for Entry, Descent and Landing on Mars*, 7th International Planetary Probe Workshop, Barcelona, June 12-18, 2010
4. Stelzner A. et al., *Mars Science Laboratory Entry, Descent and Landing System*, IEEEAC #1497, IEEE Aerospace Conference, Big Sky, MT, March 4-11, 2006