

An Initial Concept for a JUMP Mating Mechanism

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Abstract— Lunar landers currently under development for crew and cargo missions to the Moon are limited by the available boosters to launch them from Earth. Most landers are being developed for commercial launch vehicles (CLVs) in the Falcon Heavy / Vulcan / New Glenn / Atlas V class, limiting their performance with many lunar surface studies consequently restricted to 5-10 metric ton payloads. The JUMP Lander (Joinable Undercarriage to Maximize Payload) attempts to overcome this limitation by performing an in-space mating, linking multiple landers together. This research provides an initial proof of concept demonstration that two or more CLV-launched lunar landers can be mated in-space to produce a larger lander with greater payload capacity. Multiple rockets have been connected hundreds if not thousands of times in spaceflight history. An example is the space shuttle. The External Tank-Orbiter interface is an example where the 100-ton Orbiter is bolted to the side of the External Tank. This example serves as a concept metaphor for JUMP where a system of bolts is used as the mating system. This paper performs a high-level sizing analysis of the bolt, including the structural connection to each lander and the physical dimensions of the bolt, given the projected lander and payload masses. It sizes the necessary motors to perform the in-space mating and describes the motor to bolt integration. It describes the mounting and translation for the bolt-motor assembly, including structural supports, physical stops, and range of travel. It discusses active-active and active-passive implementations for the mating system and post-mating options to jettison no-longer-needed components of the assembly, including a discussion of benefits of jettisoning or not jettisoning. Finally, forward work for the mating mechanism and overall JUMP Lander concept is described.

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1. INTRODUCTION

Landing cargo on the surface of the Moon has been a severe challenge dating back to the Apollo program, where engineers counted successes when they were able to shave ounces of mass from the Lunar Module. [1]

Cargo mass limits ultimately traces back to the Earth launch vehicle. It limits the size of the lunar lander that can be launched, and the lander size limits the size – both mass and dimensions – of the lander payload.

Most launch vehicles that are anticipated to both be operational during the Artemis program and able to launch lunar landers fall within the class of launchers represented by the Delta IV Heavy, Vulcan, New Glenn, Atlas V, and Falcon Heavy, referred to in this paper as Commercial Launch Vehicles (CLVs). Rockets in this class can generally only launch payloads in the vicinity of 12-16 tons to Cislunar space. Even if the lunar cargo and lander are launched on separate rockets and integrated in space, the upper limit for a monolithic cargo element falls in the 10-16-ton range. Many internal NASA studies use a smaller range of 5-10 tons, which allows for growth margin and includes options where the payload is integrated with the lander at launch.

Note that the Space Launch System and Starship are also expected to be operational, both with much greater payload capacity. Starship is a launch vehicle that is commercial, but in order to not confuse the payload capacities Starship will not be grouped in the CLV category in this paper and will only be referred to as Starship.

Limitations in CLV lunar cargo performance prompted the Joinable Undercarriage to Maximize Payload (JUMP) Lander study. The JUMP Lander is a lunar lander concept that increases payload capacity by mating multiple lunar landers at their sides in Cislunar space, such they effectively become core stages of a larger lander with a greater payload capacity.

One of the first to propose the idea of linking landers for increased payload capacity was Scott Howe of the Jet Propulsion Laboratory (JPL), who proposed the idea shortly after the cancellation of the NASA Constellation program. However, there was no opportunity to develop the idea beyond high level PowerPoint and illustrations, shown in Figures 1 and 2. [2]

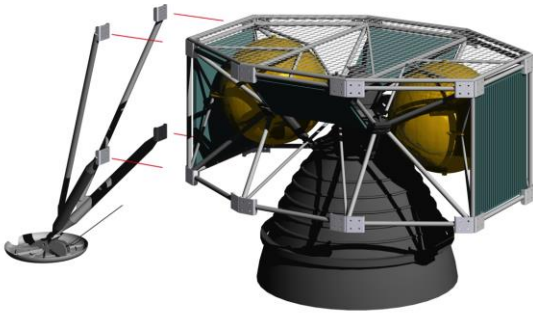


Figure 1. JPL Modular Lander Concept

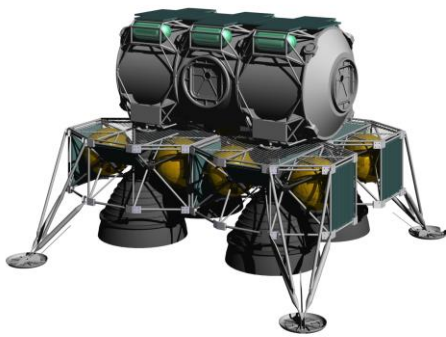


Figure 2. JPL Modular Lander Concept with Habitat

This research provides an initial proof of concept for a mating mechanism that enables two or more CLV-launched lunar landers to be mated in-space in such a manner.

2. MATED SPACECRAFT IN DYNAMIC FLIGHT

The idea of side-mated rockets is not inherently new and has been used in the US launch vehicles since 1965. The Titan III and Titan IV rockets both consisted of a central liquid-fueled core and two large solid-fuel rocket boosters, operating from 1965 [3] to 2005. [4] The Delta IV Heavy [5] and Falcon Heavy [6] both use the approach of flying three near-identical core boosters. The Space Shuttle [7] mated two large Solid Rocket Boosters (SRBs) and the Orbiter to the External Tank (ET). The Falcon Heavy is shown lifting off from Kennedy Space Center in Figure 3.



Figure 3. Falcon Heavy Center Core with Two Strap-On Boosters at Launch

These launch vehicles illustrate the point that it is well within the realm of possibility for multiple lunar rockets to be joined together and maintain structural integrity during dynamic flight.

Extension to JUMP

The JUMP concept is inspired by the ET-Orbiter attachment. The ET is a large propellant tank that also is the structural backbone of the space shuttle system. [8] The Orbiter is bolted to the ET at three points, two aft and one forward, with the points on the ET shown in Figure 4.

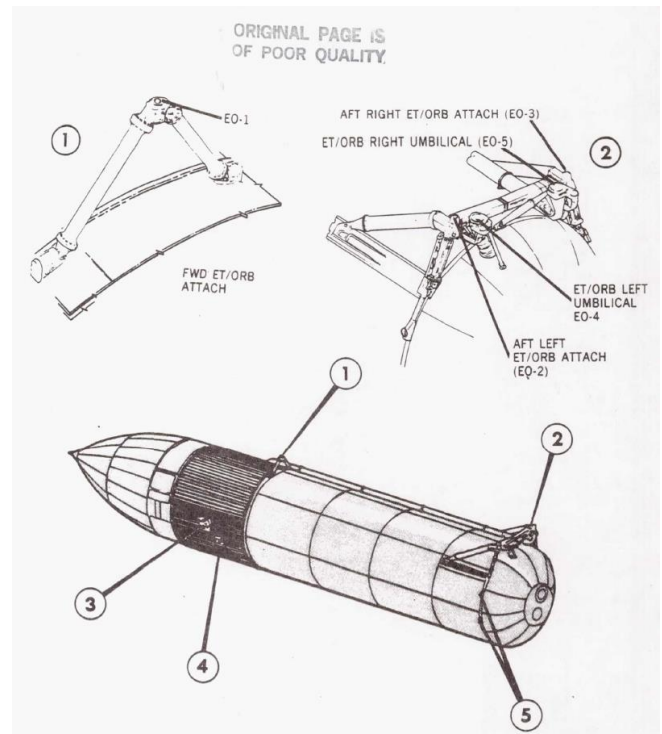


Figure 4. External Tank Orbiter Interfaces [8]

These three connection points enable the ET to carry the weight of the Orbiter prior to launch and support the complex stresses created by the two SRBs and three space shuttle main engines (SSMEs) during powered flight, shown in Figure 5. A JUMP Mating Mechanism (JMM) can be developed for the JUMP system that can similarly support the loads and stresses of the lander engines and attached payload.

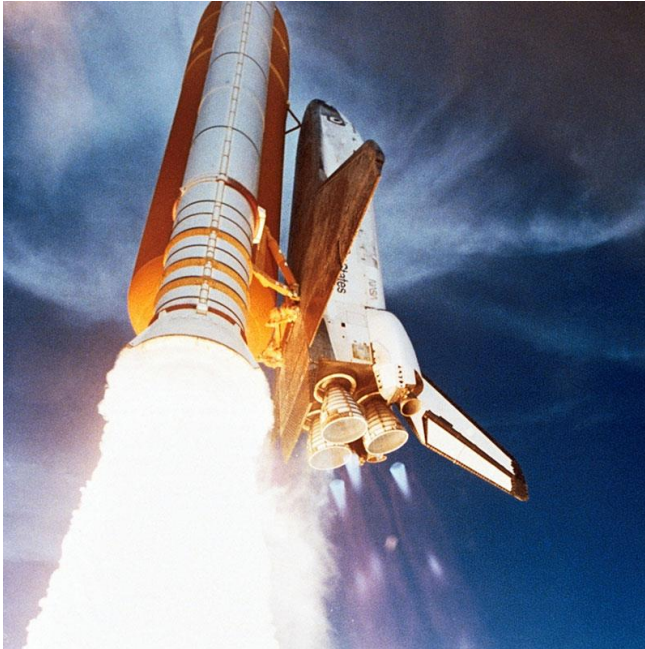


Figure 5. Space Shuttle Stack in Flight

3. JMM DESIGN

Overview

The JMM is an automated bolt system that drives a bolt from one spacecraft into the other, bolting the two together. The basic concept is illustrated in Figures 6 to 9. These images show the JMM next to cross-sectional views of two structural rings. These structural rings represent the outer structures, such as a ring frame or intertank, of two landers that have completed a rendezvous and alignment process.

The JMM consists of a motor whose shaft is a threaded bolt. The motor is mounted on a track assembly that allows it to translate in the horizontal direction, radially outward along the lander radius. The motor is fixed in place in all degrees of freedom except in the linear direction along the threaded shaft. The bolt is pre-loaded into a threaded hole in a structural ring of the lander, such that at its fully retracted position it is securely locked into the structural ring. This initial position is shown in Figure 6.

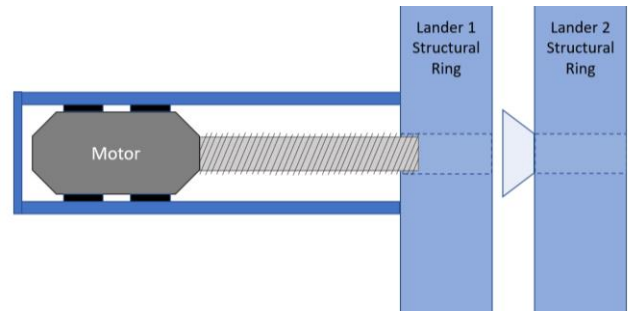


Figure 6. JMM Inactive Position

When the lander has rendezvoused with a second lander, and alignment and capture procedure is completed to secure the two landers in the proper position for the JMM to activate. (The alignment and capture will be discussed later.)

Once alignment and capture are complete, the JMM motor activates. As the bolt drives further into the structural ring, it pulls the motor along with it, shown in Figure 7. As the motor continues to drive the bolt, it emerges from the lander and follows a capture cone into a threaded structural ring of the second lander. Figure 8 shows the bolt entry into the second lander.

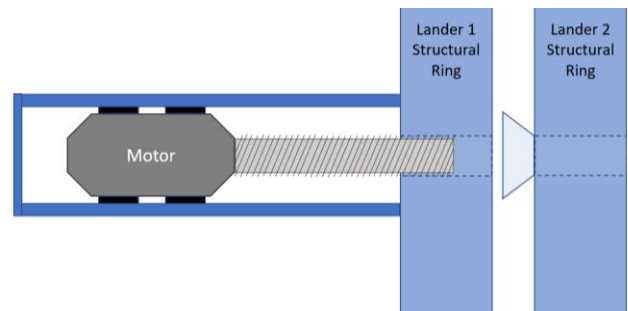


Figure 7. JMM Initial Activation

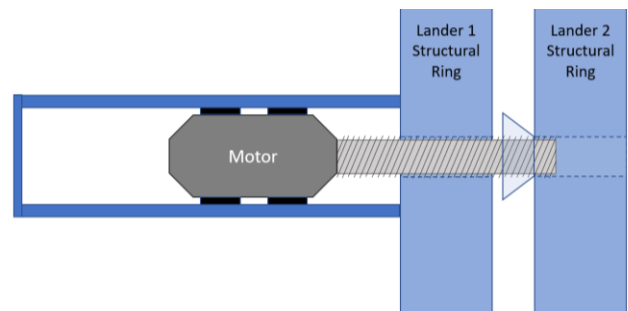


Figure 8. JMM Engages Second Lander

The motor continues to drive the bolt into the second lander's structural ring until the motor itself is driven into the inner surface of the first lander's structural ring. The motor is powered off at this point and the two landers are physically bolted to each other as shown in Figure 9.

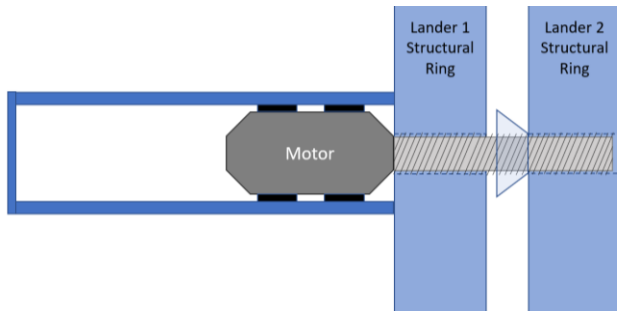


Figure 9. JMM Bolting Complete

A JUMP Lander will employ multiple JMMs as indicated in the following section to structurally mate lander core stages together.

JMM Sizing Analysis

As a proof of concept, a notional JMM is sized, partially using commercial off the shelf (COTS) equipment. The sizing analysis will assume a system of JMMs to join two landers together. Thus, the nomenclature in this paper is that a single JMM is one bolt mechanism. A JMM system is a series of JMMs that together bolt one lander to another.

Bolt Sizing

The driving load case for the JMM is shear. The load is the mass of the lander, which is estimated at 15,000 kg. For this analysis, a factor of safety of three is applied, resulting in a sizing load of 45,000 kg. The JMM system consists of six JMMs to carry this load, but with the stipulation that the JMM system must still carry the load if up to a third of the JMMs fail to mate. This means the JMMs must each be sized to carry one fourth of the load, or 11,250 kg each. Shear stress is approximately 58% of the tensile strength of a material, [9] thus a bolt with a tensile strength of 19,396.55 kg or 42,762.03 lbs. is needed. To add additional margin, the bolt selected will have a proof load of 43,000 lbs. or greater.

A COTS bolt of this type is selected from a commercial vendor chart lookup – an ASTM A307 carbon steel bolt with a diameter of 3.25 inches, a proof load of 68,400 lbs., and a tightening torque of 8976 in lbs. (galvanized and waxed). [10] The density is 7.85 g/cm³. The bolt length is 8.15 inches, which is driven by the frame mount, which in turn will be explained later in this paper. The bolt has a mass of approximately 8.7 kg.

Motor Selection

Rather than attempt to design a custom motor, an internet search was performed to identify a COTS motor with enough torque to overcome the bolt's tightening torque as a proof of concept. A motor was selected from the LSHT Torqmotors and Nichols Motors catalog. [11] There is no expectation that this would be the actual motor used in a flight configuration – it merely establishes a point of departure. This motor is a hydraulic motor merely to provide an initial point of analysis

and a future trade should compare electromechanical, hydraulic, and pneumatic options. Each carry implications that require additional analysis.

The selected motor is the motor series TG 0785, which can supply a maximum intermittent torque of 12,636 in lbs., a maximum continuous torque of 9239 in lbs., and a minimum starting torque of 8772 in lbs. continuous and 11,876 in lbs. intermittent. The vendor describes the intermittent operating rating as 10% of every minute. The motor has dimensions of 129.5 mm diameter and 267 mm length. It has a mass of 20.2 kg. It has a maximum supply pressure of 4350 psi and a maximum oil flow of 76 L/min continuous and 114 L/min intermittent. [11]

Motor Mount

As illustrated in Figures 6 through 9, the motor can move freely in one dimension. The Figures notionally illustrate a motor mount that holds the motor in place while allowing it to slide back and forth as the bolt drives into or out of the lander structural rings. This motor mount is a frame structure that carries the motor mass in conjunction with the portion of the bolt that remains inside the structural ring. This prevents the motor/bolt assembly from becoming a cantilever at any point in time. Rails, wheels, skids, or telescoping mechanisms can enable the one-dimensional sliding motion. No detailed sizing is performed on this box-like or cylindrical frame structure in this paper, but a mass placeholder of 10 kg for the entire motor mount is assumed. It is designed to form a hard stop to prevent the motor from backing the bolt all the way out of the lander structural ring. The inactive position in Figure 6 represents a nominal ring penetration of 0.89 inches and the hard stop position involves a ring penetration of 0.39 inches. Thus, the motor mount has an internal length of 18.27 inches.

Pump Selection

As this is a hydraulic motor, it also requires a pump. A COTS pump was selected based on the supply pressure and oil flow specifications of the motor. The SH6V 75 variable displacement axial piston pump for closed circuit [12] was identified as capable of supplying hydraulic fluid at or greater than the needs specified by the motor.

The SH6V 75 has a continuous pressure of 5800 psi and a peak pressure of 6525. It has a maximum flow of 220 L/min continuous, 255 L/min peak. Overall dimensions are 12.8 inches length, 9.4 inches width, and 10.9 inches height. It has a mass of 51 kg. [12]

Reservoir Selection

A reservoir is also required to contain the hydraulic fluid. Conventional practices for a closed-circuit system [13] suggest a capacity roughly 0.6 times the mean flow rate of the variable displacement pump, resulting in 132 liters of hydraulic fluid. A COTS reservoir tank of this size was

identified [14] with dimensions of 24 inches in diameter and 19.2 inches in width and a mass of 33.18 kg.

For this analysis it is assumed that fluid lines and valves can connect all JMMs on a lander with a single reservoir tank. Additionally, one pump can supply fluid to all six motors. It is not necessary for all JMMs to act in parallel – they can be activated one at a time, perhaps cycling through each in sequence much the same way that one cycles through tightening or loosening lug nuts when changing the tire on a car.

Lander Structural Ring Modification

Figures 6 through 9 indicate that the bolt is driven into a threaded hole in the lander structural ring. This implies some modification to the lander structure. For illustration, Figures 13 and 14 illustrate common portions of propellant tanks relevant to this discussion.



Figure 10. Space Shuttle External Tank Exploded View

Figure 10 shows the External Tank of the Space Shuttle. The structural element of significance is the intertank – the ribbed structure in the image that connects the liquid oxygen tank and the liquid hydrogen tank.



Figure 11. SLS Dual Use Upper Stage Liquid Hydrogen Tank

Figure 11 provides an exploded view of the liquid hydrogen tank of the SLS Dual Use Upper Stage. The forward and aft skirts are similar to the intertank, a structural element that connects a propellant tank to other rocket structures. The Y-rings (also called T-wings in other tanks) are structural

elements that connect the barrel segment(s) of a propellant tank to the dome segments.

The intertank, skirts, and rings are all candidate locations on a lander for mounting the JMM. The selected location on any of these structural elements, which will be referred to in this paper as the Threaded Frame Mount, will require modification. The Threaded Frame Mount is a threaded block of this structure and it is what the JMM bolts itself to.

First, it is assumed in this paper that the structure is composed of AL-2219. This is the same aluminum alloy used in the Standard Weight Tank and Lightweight Tank versions of the Space Shuttle External Tank [15] and is also used in the liquid oxygen and liquid hydrogen tanks of the SLS. [16]

The Threaded Frame Mount has a thickness of 3.575 inches, and it has both a height and width of 10.725 inches (three times its thickness). The 3.25-inch threaded hole runs through the center of the Threaded Frame Mount. The Motor Mount is welded to the interior of the Threaded Frame Mount, holding the motor in place with the bolt partially inserted into the Threaded Frame Mount.

The Threaded Frame Mount on the target lander does not have a Motor Mount, but instead has a conical guide welded to the exterior, notionally indicated in Figures 6 to 9. The conical guide has an inner diameter of 3.25 inches, an outer diameter of 6.5 inches, and a height of 0.94 inches. The Threaded Frame Mount has a mass of approximately 39.15 kg.

Active-Passive vs. Active-Active JMM

The JMM as described thus far is an active-passive system. The initial thought for the JMM was that there would be separate active and passive mechanisms. Assuming a three-core configuration, each lander would have one active JMM system and one passive JMM system. The active in one core would connect to the passive in another core.

For instance, the active JMM system on lander A contains a series of six JMMs. The JMM system on lander B is passive, with no JMMs but conical guides on each of six Threaded Frame Mounts. When properly aligned, the active JMM system on lander A mates to the passive JMM system on lander B. Initially, this was intended to be the JMM concept, but there is value in considering an active-active approach.

An active-active JMM system will enable either lander A or lander B to serve as the active mating element but can even implement a hybrid approach where some JMMs on lander A are active while other JMMs on lander B are active. There is of course a mass penalty, but an active-active system provides several advantages.

With an active-active JMM system, a single motor failure does not result in the failure to mate – the motor on the other core stage can perform the mating. Also, because any two JMMs can mate, the extensibility potential for JMM use

beyond lunar landers is significantly expanded. Additionally, with only one JMM type (no longer separate active and passive configurations), design and manufacturing are simpler, especially if the JMM has multiple applications (e.g. uses other than landers or different types of landers with different numbers of cores). For these reasons, the Active-Active is the baseline configuration for the JUMP Lander.

Figures 12, 13, and 14 illustrate the changes that convert the JMM to an active-active system.

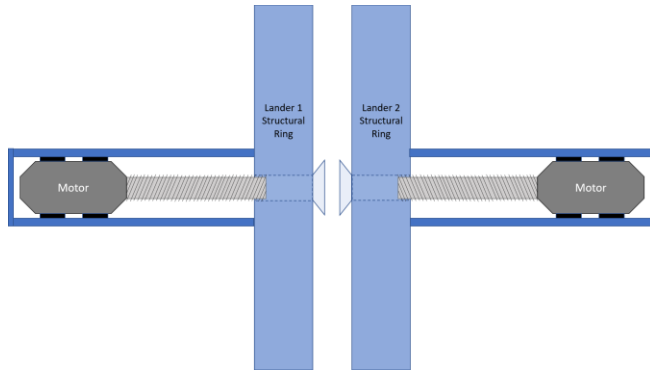


Figure 12. Active-Active JMM in Inactive Position

Instead of different configurations for landers A and B, both vehicles have the identical JMM construction. There is a motor, bolt, and motor mount attached to the Threaded Frame Mounts on both vehicles. And both Threaded Frame Mounts have conical guides. In the inactive positions, both motors are fully retracted, with each bolt only penetrating 0.89 inches into their respective Threaded Frame Mounts.

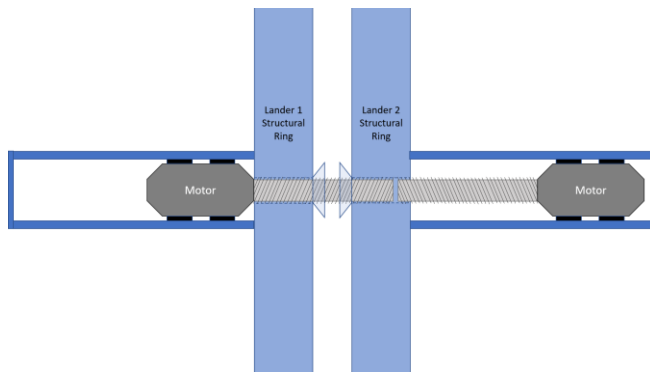


Figure 13. Active-Active JMM with Mating Performed by Lander A

In Figure 13, lander A is serving in the active role and its motor has driven its bolt into the Threaded Frame Mount of lander B. When its motor has reached its hard stop against the lander A Threaded Frame Mount, the bolt has penetrated sufficiently far into the lander B Threaded Frame Mount to reach another hard stop against the lander B bolt.

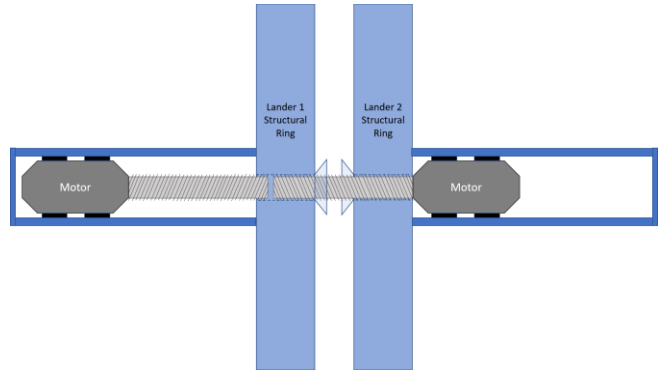


Figure 14. Active-Active JMM with Mating Performed by Lander B

Figure 14 is the reverse of Figure 13. In this case, lander B is serving in the active role and its bolt has penetrated into the lander A Threaded Frame Mount, reaching a hard stop against the lander A bolt.

4. CAPTURE AND ALIGNMENT SYSTEM

It is not likely that the JUMP lander Reaction Control System (RCS) thrusters will be able to maneuver precisely enough to align the JMM for actuation and hold the two landers together while the mating is completed. A capture and alignment system (CAS) will be needed to stabilize the spacecraft.

NASA already has made significant investment in automated rendezvous and capture of spacecraft [17], which has enabled current commercial logistics contracts for ISS and Gateway. [18]

This technology can be used to enable one lander to rendezvous and align with the second lander. The CAS system would then make physical contact with the second lander and hold it in a fixed position relative to the first lander. They will hold the two landers stable while the JMMs engage, forming the structural connection. A variety of options exist to perform the capture and alignment function.

CAS Options

Two immediately obvious, but potentially mass prohibitive, options are the NASA Docking System (NDS) [19] and the Low Impact Docking System (LIDS). [20] In both cases, the complete docking system is not needed. Instead, the approach, alignment, capture, and attenuation, and retraction phases of either system would be needed.

Another obvious option is the Remote Manipulator System (RMS) employed on the Space Shuttle Orbiter and the International Space Station. [21] The RMS has been used for decades in space to maneuver payloads of similar and greater masses within very tight maneuvering corridors, though this has always been a manual action performed by an onboard astronaut.

Another option that takes a task that has previously been performed in space and transfers it to a robot is the use of Robonaut arms. One of the more famous spacewalks of the Space Shuttle program occurred on STS-49, where three astronauts performed a hand capture of the stranded INTELSAT VI satellite. [22] Robonaut is a dexterous humanoid robot currently aboard the International Space Station. [23] Arms derived from the current Robonaut could be attached to the landers and used in a similar fashion to the action performed by the STS-49 crew.

An option that combines cubesat capabilities with naval history is a free flyer with cable and winch. Even going back as far as the tenth century, Vikings would sometimes tie their ships together in battle. [24] Rope is the oldest fastener in human history and could play a role in the CAS. A set of cubesats could be released from a lander, each carrying a cable attached on the other end to a winch on the lander. The cubesats could maneuver to the second lander and attach the cables at an anchor point. The winch retraction will then draw the two landers together. However, because cables can only exert force in tension a cable system will be inherently complex.

CAS Baseline.

The point of departure approach for the CAS is to use dexterous, humanoid arms – potentially but not necessarily Robonaut derived, one arm near each JMM. Capture and alignment will be performed autonomously with ground supervision.

A key advantage of dexterous arms is they have many degrees of freedom and the twelve arms (six per lander) can work as a unit to manipulate the landers. Hand holds will also be included in nearby locations on each lander.

CAS Post-mating jettison options

Once the mating is complete, the CAS serves no further purpose to the JMM. Thus, the option exists to jettison the CAS. Doing so will remove the mass of the CAS from the system and enable the lander to deliver more cargo to the lunar surface.

The jettison can be a multi-step process. The arms can first remove the hand rails and toss them away from the stack. Half of the arms can then remove an adjacent arm, tossing them away as well. For the remaining arms, there is no other manipulator to remove them. Thus, they will need to be separated via explosive bolts, springs, or some other system that can impart an ejection force to them.

The only compelling reason to leave the CAS attached would be if there was an architectural plan to reuse the CAS on the lunar surface. There presently is no such plan.

5. POTENTIAL SPACEFLIGHT APPLICATIONS

The JMM as described in this paper can potentially be applied in numerous other spaceflight applications.

The most immediate application is to implement the JMM in the same fashion it is employed in the JUMP Lander concept study, using it with HLS or CLPS landers to increase their payload capacity. CLPS landers as small as the Astrobotic Peregrine lander could be augmented, such that five or six Peregrines linked with JMMs could land a 500 kg payload.

A greater benefit is seen with the HLS class of landers, where the Blue Federation (formerly known as the National Team) currently advertises an ability to land 14 tons of cargo on the lunar surface. [25] Three Blue Federation landers joined by JMMs could land as much as 38-40 tons on the surface.

Additionally, all three HLS providers rely on some fashion of in-space docking and/or assembly and thus the JMM is a potential option to trade against their baseline docking or berthing solutions.

The All-Terrain Hex-Legged Extra-Terrestrial Explorer (ATHLETE) cargo handling and transportation robot could also potentially use a variant of the JMM. The ATHLETE can carry large payloads as shown in Figure 15 by splitting in half and using each half to grapple one side of the payload. The JMM could serve as that attachment system.



Figure 15. ATHLETE Carrying Habitat Element

The JMM can also be used for assembly of large spacecraft, such as Mars transit vehicles. A 2016 nuclear thermal propulsion study [26] proposed the spacecraft shown in Figure 16. While it is not the current NASA reference concept, the structural interface between the propellant tanks and the pressurized crew habitat does illustrate that there are likely to be structural interfaces where a NASA Docking System is not the most effective solution.



Figure 16. Former Mars Transit Vehicle Concept

The JMM may also find utility on the surfaces of the Moon and Mars. Figure 17 was taken during the NASA Desert RATS field tests and shows the cabin of the Small Pressurized Rover (SPR) being mated to its chassis, the two elements having been separated for transport from Johnson Space Center to the Arizona desert. Using JMMs to connect the cabin to the chassis could enable the Moon or Mars flight configurations of the rover to more easily assemble or disassemble the vehicle to serve operational needs – for instance replacing a failed chassis or repurposing a rover cabin to serve as an airlock or assembling a field station from multiple cabins.



Figure 17. SPR Attachment to Chassis

The JMM can also be used to attach various work packages to both pressurized and unpressurized rover chassis. This may include bulldozer blades, remote communications or power stations, drills, science instruments, cranes and manipulators, etc.

6. SUMMARY AND FORWARD WORK

The JUMP Mating Mechanism is a scalable, high strength solution to enable assembly of large spacecraft elements. Intended to join lunar lander descent stages, it is extensible to a wide variety of in-space, ascent/entry, and surface applications. Many spacecraft concepts have shown large elements that require mating and the JMM provides a solution that supports dynamic flight environments not suitable to more traditional docking systems. The JMM is the key technology that enables CLV-launched lunar landers to land lunar payloads in excess of 30-40 tons on the lunar surface.

Forward work includes integration of the JMM into the JUMP Lander Concept Illustration Vehicles, which will provide a more complete assessment of the overall JUMP concept. A reference mission based on the JUMP Lander can then be developed and assessed.

Significant forward work also involves design refinement of the point of departure JMM. The current JMM carries load primarily in shear. It would be worthwhile to explore a design solution that carries load in tension or compression instead. Also, extensive conservatism was built into the JMM design that may have unfair mass penalties. More detailed structural and mechanisms analysis is needed to refine the current design concept.

The JMM motor should also be traded, specifically trading electromechanical and pneumatic motors against hydraulic baseline.

An electromechanical motor is heavier than an equivalent hydraulic motor, but the hydraulic motor requires additional mass in the form of pump, reservoir, hydraulic fluid and connecting fluid lines and valves. It is possible that the total system mass of an electromechanical system may be less than a hydraulic or pneumatic system.

A pneumatic system, however, may be able to share its working fluid with the propulsion system. For instance, in a LOX-Methane system, liquid methane could be heated to gas and circulated through the pneumatic system before being routed to the rocket engine.

For hydraulic option, consider methods to jettison the hydraulic fluid after the mating is performed. This mass is no longer needed unless it is integrated into another vehicle function (e.g. common fluid between hydraulic and thermal control systems). If it is not needed, then jettisoning prior to additional flight maneuvers will increase payload capacity. It may also be worth considering placing the pumps in locations where they may also be jettisoned as they are not needed once

mating has been completed. It will likely be difficult to jettison the motors as their functionality requires placing them in interior locations that lack a clear path to space.

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BIOGRAPHY



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