# Design of a Robotic Ankle Joint for a Microspine-Based Robot

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# Design of a Robotic Ankle Joint for a Microspine-Based Robot

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**Successful robotic exploration of near-Earth asteroids necessitates a method of securely anchoring to the surface of these bodies without gravitational assistance. Microspine gripper arrays that can grasp rock faces are a potential solution to this problem. A key component of a future microspine-based rover will be the ankle used to attach each microspine gripper to the robot. The ankle's purpose is twofold: 1) to allow the gripper to conform to the rock so a higher percentage of microspines attach to the surface, and 2) to neutralize torques that may dislodge the grippers from the wall. Parts were developed using computer aided design and manufactured using a variety of methods including selective laser sintering, CNC milling, and traditional manual machining techniques. Upon completion of the final prototype, the gripper and ankle system was tested to demonstrate robotic engagement and disengagement of the gripper and to determine load bearing ability. The immediate application of this project is to outfit the Lemur IIb robot so it can climb and hang from rock walls.**

## I. Introduction

### A. Motivation

Near-Earth objects such as asteroids and comets are of increasing interest to scientists and space agencies as they may provide vital information about the origins of the solar system and life on planet Earth. Thus far, missions to near-Earth asteroids have been primarily limited to fly-bys and remote observation via satellites. Ground exploration of these bodies via landers and rovers will enable scientists to sample and study the rocks on their surface. This fundamental research will provide the necessary information regarding surface composition and environmental hazards to allow commencement of planning for future manned missions to these bodies.

The small mass of many near-Earth objects means that the gravitational force they produce can be millions of times smaller than that produced by Earth. Consequently, the escape velocities on these bodies can be less than 10 cm/s,[1] making traditional wheeled or legged mobility too risky. Therefore, robotic missions to asteroids and comets need a means of securely anchoring to surfaces in the presence of microgravity. This attachment device must produce anchoring forces of roughly 100N[1] in all directions in order to resist the inertial forces of a moving robot as well as provide the necessary weight-on-bit for a sampling drill.

Robots equipped with gripping end-effectors can potentially find use in a variety of situations other than the exploration of near-Earth objects. For example, they may also be used to explore steep cliffs and rock faces on Mars that wheeled robots cannot access. These rock faces often have exposed strata that can provide a geological record of the planet to scientists. Another potential use for rock-gripping robots is the exploration of caves, which often house unique and currently under-researched ecosystems.

### B. Microspine Grippers

Over the past year, the Robotics Platform Group at NASA/JPL has developed an omnidirectional micropsine gripper as a potential solution to the problem of anchoring to bodies in microgravity. The gripper consists of

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arrays of microspines arranged in a radially symmetric configuration that allows the gripper to resist forces in any direction. Microspine arrays consist of hundreds of compliant toes with embedded steel hooks. When these toes are dragged along a surface, the hooks engage with asperities on the surface, providing load bearing abilities.[2] Originally, these toes were designed for small lightweight robots, such as RISE and Spinybot, that climb vertical surfaces such as concrete or brick walls.[3,4] These robots featured a small number of toes all oriented in the same direction, which limited their mobility and load bearing ability. In contrast, the omnidirectional gripper developed by JPL can support much larger loads in a variety of directions, making it suitable for use on larger climbing robots.

Figure 1 shows an example the microspine toes used in the gripper. The creation of these toes is accomplished using a novel technique called Shape Deposition Manufacturing or SDM. SDM is an iterative manufacturing technique that enables the creation of multi-material parts with embedded components. Each toe features a rigid frame with embedded hooks, which engage with asperities in the rock, as well as flexures that allow each toe to individually comply to the surface.

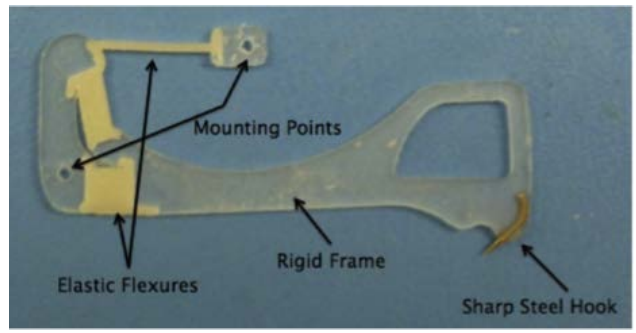



**Figure 1. Microspine gripper toe with labeled parts.**

At the start of this project, the microspine gripper had just entered its third iteration, which can be seen in figure 2. This version of the gripper was capable of lifting 107 N.[1] However, this iteration was hand-actuated, and thus not suitable for robotic use.

## II. Objectives

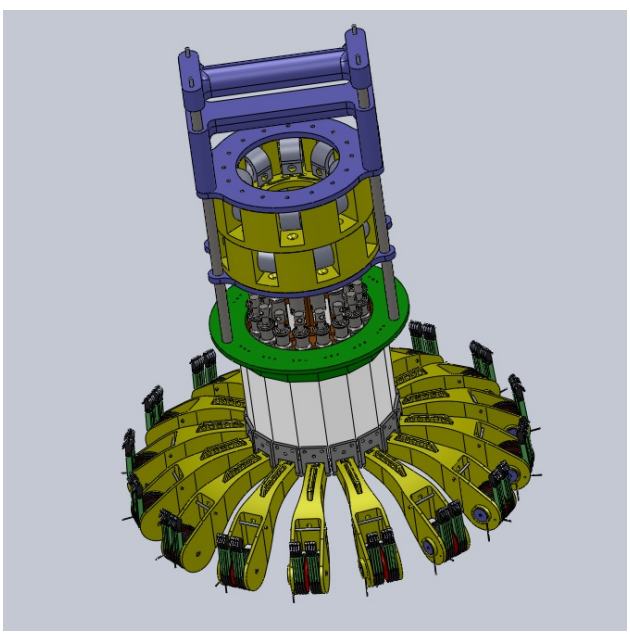


**Figure 2. CAD model of hand-actuated microspine array system**

The goal of the work carried out during the Summer months at JPL was to design, manufacture, and test an ankle joint for a microspine gripping robot. This joint allows the micrcospine gripper to interface with the Lemur IIb robot, which can be seen in figure 3, and also contains actuation mechanisms to robotically engage and disengage the gripper. Another major requirement for the ankle is that it allow the gripper to passively comply to the rock surface to improve attachment strength. Finally, the ankle must neutralize torques and moments that can disrupt microspine attachment. The ultimate goal of this project is to equip the Lemur IIb robot with four microspine grippers so it can climb rock walls and inverted faces.

### A. Actuation

The ankle must house both the engagement and disengagement actuation devices. The previous-generation gripper, shown in figure 2, was actuated manually using cables attached to a handle. These cables pull the microspine arrays radially inward. As they drag along the surface, the toes engage with asperities providing the gripper with its load bearing ability. Disengagement is accomplished by pulling another set of cables that rotate the arrays up and away from the rock surface. These two modes must be actuated using electric motors and linear actuators so they can be controlled robotically.

### B. Compliance

A difficult issue for microspine grippers is that the success rate of a toe engaging with a surface can be quite low, thereby necessitating the need for many hundreds of toes on a practical gripper system. An ankle mechanism that can conform to the macro-scale orientation of the rock increases the probability that microspines will find suitable asperities. Additionally, passive compliance is needed because the orientation of the rock surface directly under the gripper is unknown. Passive compliance to the wall will allow Lemur to climb rock faces without having to visually analyze the topography of the climbing surface. Finally, the ankle must have elastic components to bring the gripper back to a neutral position between steps.

### C. Torque Neutralization

While the microspine gripper can support large loads normal to the wall and in the plane of the wall, it has trouble handling torques or moments. Applying torque to a microspine gripper tends to twist the toes and the array housings causing the hooks to disengage with the surface. Therefore, in order to minimize the chance of this occurring while a robot attempts to walk using grippers, torques must not pass through the ankle to the gripper. Of special importance is the ability of the ankle to spin freely about the normal axis to the wall. When the Lemur takes a step using a gripping foot, the robot will attach to the rock surface and then rotate its arm, pushing itself up. However, the gripper will remain at a fixed orientation with respect to the wall while the ankle and limb rotate upwards. Therefore, the gripper needs the ability to spin within the ankle while imparting minimal torque on the microspine toes.

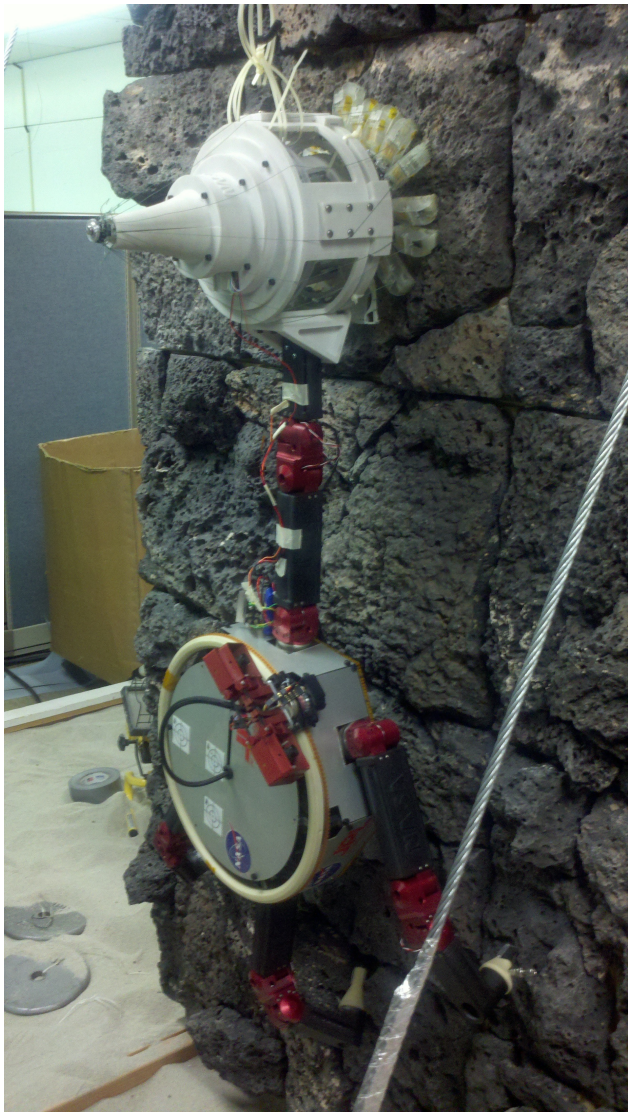


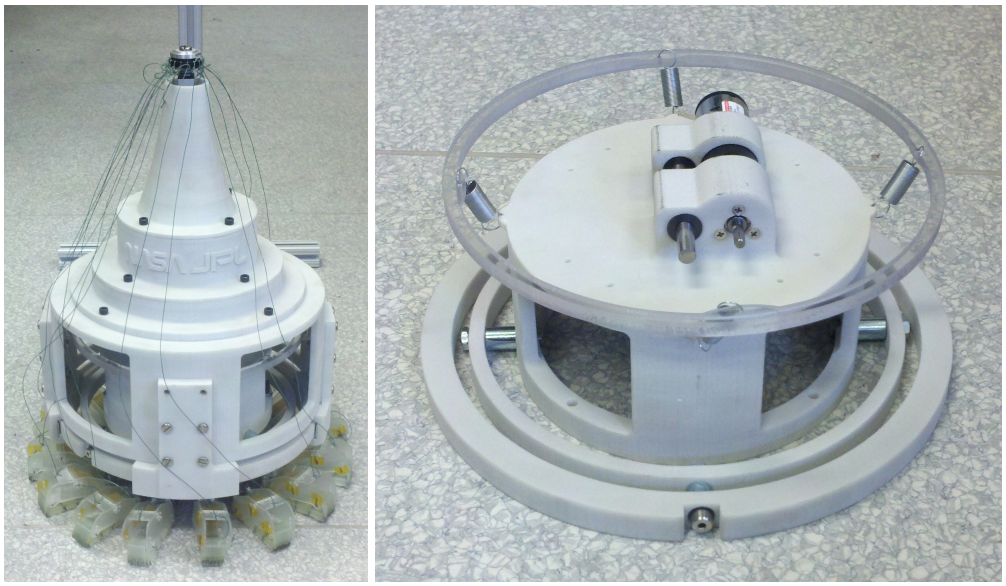
**Figure 3. The Lemur IIb robot with ankle and microspine gripper hanging from a vertical rock wall.**

## III. Current State of Research

Significant progress towards the goal of outfitting the Lemur IIb with microspine grippers has been made in the last 10 weeks. Two mock-ups of the ankle mechanism were fabricated to test the proposed mechanical solutions to the problems outlined above. Then, a final prototype, which can be seen in figure 4(a), was manufactured and tested.

### A. Gimbal System

To address the issues of compliance and torque neutralization the ankle system contains a set of gimbals, which can be seen in figure 4(b). The gimbals are composed of two concentric rings mounted on orthogonal axes. They allow the gripper to rotate around all axes so that when pushed against the rock wall, the gripper can passively comply to the surface. Additionally, the gimbals do not transmit torques through their axes, which helps prevent the microspine toes from dislodging from the walls. Rotation about the normal axis to the wall is accomplished by allowing the outer ring to slide within C-shaped clamps that attach the gimbals to the outer housing of the ankle. These clamps fit loosely around the outer ring and are lined with Teflon



(a) Completed ankle mechanism. (b) The interior of the ankle, showcasing the gimbal system, springs, and actuation device for the engagement wires.

**Figure 4. Completed ankle mechanism and interior housing with gimbal rings**

in order to generate the lowest possible coefficient of friction. This ensures that the gripper can spin freely when the robot takes a step, while generating minimal torques on the microspine toes.

Figure 4(b) also shows the springs used in the ankle to bring the gripper back to a neutral position between steps. These extension springs are mounted at the top of the housing in a radial configuration. They are mounted at an upwards angle so that their line of action roughly intersects the axes of both gimbals. This ensures that no matter which direction the gripper rotates, the springs always extend rather than compress. The springs also need to have a low spring constant so they do not induce large torques on the microspine toes. The springs have only enough stiffness to keep the gripper relatively close to horizontal when the ankle is horizontal. Through experimentation, it was found that springs with a constant of .78 lbs./in provide the necessary restoring force on the gripper.

During testing of the mock-up versions of the ankle, it was found that the springs must be decoupled from rotation about the normal axis. The reason for this is that when the springs are rigidly mounted on both ends they need to extend too much to allow the gripper to rotate the approximately 90° required for the robot to take a step. Having the springs rigidly mounted would impart a large torque on the microspines and twist them off the wall during a step by the robot. To decouple the springs from this axis of rotation, one side of each spring is attached to a rotating ring. This ring is mounted to the outer housing of the ankle through low-friction, Teflon-lined, C-shaped clamps. Mounting the springs in this fashion allows the springs to rotate with the gripper about the axis normal to the wall, but still bring the gripper back to its neutral position with respect to the wall

## B. Disengagement Actuation

For the disengagement of the microspines, A linear actuator was mounted at the top of the ankle. This linear actuator pulls on strings mounted to each individual microspine array to pull them up and away from the wall. Tests of previous generation microspine grippers show that the linear actuator needs to provide roughly 5 pounds of force over a 2 inch distance in order to disengage the microspines from a rock surface. Using these requirements, the Firgelli L12 linear actuator was selected, as it can provide the necessary force and throw in a well-packaged and inexpensive design.

### C. Engagement Actuation

A brushed DC motor was chosen as the second actuator to provide engagement of the microspines. Tests on previous generation microspine grippers show that a total of about 40 pounds of tension is created in the engagement wires during the gripping process. In order to ensure that the motor can reliably provide this force and to reduce the chance of the motor stalling and drawing a dangerously large current, a safety factor of 1.5 was chosen for the motor. This necessitates that the motor provide 60 lbs of pulling force on the engagement wires before stalling. Given the diameter of the shaft used for spooling the engagement wire, one can find that the motor needs to provide at least 7.5 lbf-in of torque. The motor selected for this application, when coupled to a gearbox, can provide 13.02 lbf-in of torque, roughly double the requirement. This ensures that the motor will be able to provide the necessary force to engage the gripper under virtually all conditions.

### D. Materials and Manufacturing

The majority of the parts for the ankle were rapid prototyped using a procedure called selective laser sintering or SLS. The SLS process uses a laser to fuse together cross-sections of the model in layers plastic powder. The layers of plastic are added and sintered together iteratively until the finished model is made. A major advantage of the SLS method over other rapid prototyping techniques is that the unsintered portions of plastic powder act as a support structure for the layers above. Therefore, no specific support structures need to be printed with the SLS procedure, allowing the method to produce highly complex three-dimensional parts. The material chosen for the rapid prototyped parts was glass-filled nylon 12, which is stiffer and less expensive than regular nylon 12.

In order to reduce the manufacturing cost of the ankle, several parts were manufactured on-site using a 3-axis CNC mill. Unlike parts produced by the SLS process, parts made using a 3-axis CNC mill must be manufactured using milling and drilling operations in only one direction, as the drill bit can only move straight up and down. Therefore, the design of these these parts is often referred to as 2.5 dimensional design, since it does not fully take advantage of three dimensions of the stock material. The ankle design featured two such parts that were made on the mill, saving considerable money.

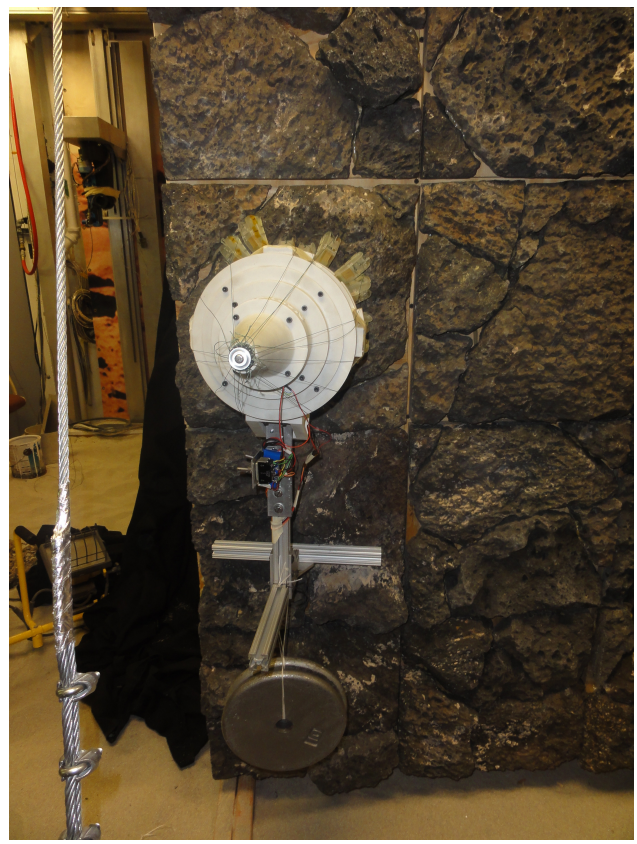


**Figure 5. Gripper supporting 29 lb total load.**

### E. Testing

Testing of the final prototype revealed the design's promise for use on a microspine climbing robot, as well as problems that should be addressed by the next iteration. To test the ankle and gripper system, the ankle was mounted to an arm that extends down and then towards the wall. The arm counteracts the pitch-back moment created by the distance between the wall and the center of gravity of the ankle. On a full robot with multiple grippers, the pitch-back moment would be balanced by the other grippers in contact with the wall. In addition, two different attachment points for the arm were tested. The first attachment point is the center of the top of the outer housing. This attachment point is quite far away from the wall and therefore creates a large pitch-back moment. The advantage of this attachment point is that when the robot is on horizontal ground, the force is applied axially through the ankle and gripper. The second attachment point is on the side of the ankle and closer to the wall than the first attachment point. This attachment point produces a smaller pitch-back moment but does not load the ankle axially on horizontal ground. Tests show

that the microspine gripper and ankle system can support 19 lbs (84.52 N) in the shear direction to a rock wall when the arm is mounted at the upper attachment point and 29 lbs (129N) when the arm is mounted on the side of the ankle (figure 5).

Additionally, the ankle's ability to neutralize torques about all its axes was tested by manually rotating the arm. When the arm was turned and torques were applied to the ankle, they did not seem to pass through to the gripper, as microspine disengagement was minimal. The ability of the ankle to rotate about the normal axis to the wall without compromising load bearing ability is especially important, as a climbing robot will need this capability while taking a step. To test this feature, the arm attached to the ankle was rotated roughly 90 degrees, during which only a few microspines detached from the wall, but quickly regained grip. Even after undergoing a 90 degree simulated step, the ankle and gripper were still able to support 29 lbs, showing that rotation does not compromise load bearing ability.

During the above testing, the behavior of the actuation devices could also be observed. The torque for both the engagement and disengagement actuators was more than adequate. However, the motor lacked a brake, and therefore could be backdriven by the tension in the wires.

### F. Proposed Changes

Several problems with the ankle and potential improvements that can be made presented themselves during testing of the ankle and gripper mechanisms. The first problem encountered while testing the ankle is that the tension in the engagement wires when the gripper was fully actuated was large enough to backdrive the motor. This causes a relaxation of tension in the engagement wires and a loss of gripping force. During testing, this problem was remedied by inserting a pin into the gears to prevent them from backdriving. On future versions of the gripper, the engagement actuation motor should be equipped with a brake to stop the motor from rotating when the wires are fully tensioned.

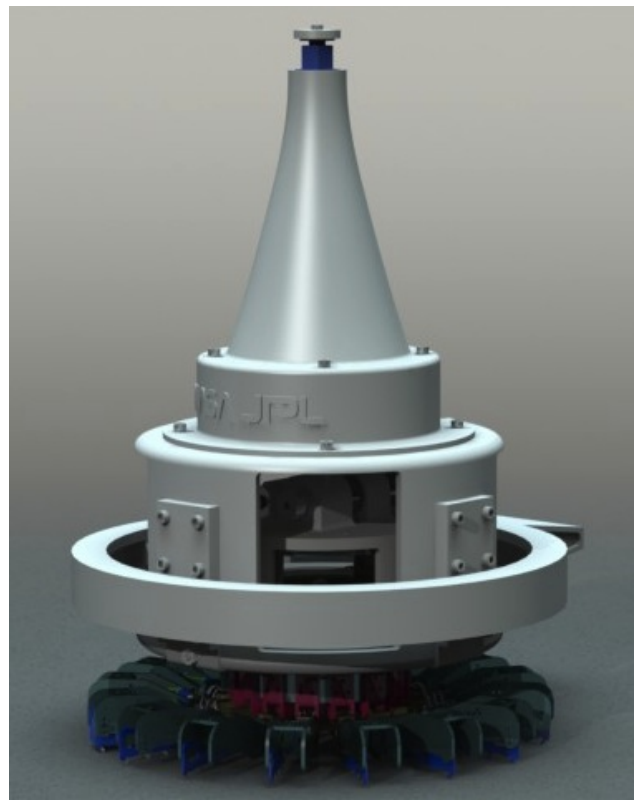


**Figure 6. Render of second version of ankle.**

Another problem encountered during testing of the prototype ankle was that the disengagement wires tended to get caught on various parts of the ankle. This became especially troublesome when attempting to rotate the ankle, as the tension in the caught wires would oppose the rotation. To alleviate this problem in future versions, the position of the sliding ring that provides rotation about the normal axis to the wall was changed from underneath the outer housing to the exterior of the outer housing as shown in figure 6. This change allows the entire ankle assembly to spin as one unit and prevents the disengagement wires from having to travel around the outer housing, thereby decreasing the likelihood that they will get caught on parts of the ankle as they now only travel along their length.

The final major change made to the ankle's design addresses problems raised by the length of throw provided by the linear actuator. Initial estimations of the required throw proved to be too short, as the lack of extra slack in the disengagement wires occasionally pulled the toes off the wall. This issue becomes even more problematic when the gripper has rotated significantly in the ankle to conform to the wall, because the rotation of the ankle can add several inches to the distance between the toes and the linear actuator. To address this problem, the new ankle design will feature a linear actuator that doubles the throw from the 50mm provided by the current actuator to 100mm.

## IV. Conclusion

Work towards the goal of outfitting the Lemur IIb robot with microspine grippers will continue in the near future. A second iteration of the ankle with the changes outlined above will be designed, tested, and attached to the robot. Additionally, control algorithms to command the movement of Lemur's limbs and the gripper's actuation devices as the robot climbs will be developed. Future work will allow robotic platforms to climb rock surfaces other than walls and make transitions from flat ground to vertical and inverted surfaces. This ongoing research brings NASA one step closer to a mission to send rovers to near-Earth objects, paving the way for future manned missions to these bodies.

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