

FINAL DESIGN REPORT
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Two-way Interplanetary Geological Guidance with an Exploration Robot



Final Design Report

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Extra-Terrestrial Sample Return Utilizing a Hopping and Drilling Robot

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ABSTRACT

In accordance with President Bush's vision for the United States' Space Program, NASA has developed space-based mission architectures for returning humans to the Moon while providing both additional capabilities for further exploration of the solar system and maintaining a permanent space presence. Key features of these new architectures will be in-situ resource utilization, revolutionary surface transportation, and state-of-the-art exploration techniques. The Two-way Interplanetary Geological Guidance with an Exploration Robot (TIGGER) mission proposes feasible and cost-effective solutions to some of the challenges that NASA has encountered in its continued expansion of space exploration. Establishing lunar outposts and further exploration of the Martian surface requires more capable rovers than current technology allows. TIGGER will employ a revolutionary hopping robot to explore the vast expanses of varying lunar terrain, autonomously analyzing the subsurface composition and searching for evidence of water. Utilizing an ultrasonic drill, samples will be collected and stored from each location that TIGGER explores. In addition, the discovery of water on the moon would lead to the possibility of constructing an outpost there, promoting future missions where the water could be used in fuel-synthesis processes or for life support. The presence of a fuel outpost significantly increases both the quantity and variety of opportunities for space exploration. TIGGER also addresses NASA's goal of returning samples from outside of Earth's sphere of influence. This can be accomplished by utilizing recent innovations in space transportation architectures. The proposed transportation architecture design for sample return is adaptable to future interplanetary exploration missions, including missions to Mars and the moons of outer planets. The successful autonomous return of samples will be a significant step towards the future of space exploration. In addition, it will expedite the creation of a space transportation highway, enabling the construction of safe and sustainable outposts on the Moon and beyond.

MISSION STATEMENT

The TIGGER mission implements a hopping system aboard a robot exposed to an environment with extreme conditions. The hopping system will be able to cover long distances in a relatively short period of time. During each hopping maneuver, synthetic aperture radar will be used to map the surface of the moon. TIGGER will have the capability to collect and analyze samples by drilling through the surface of the moon, acquiring core samples at various depths during the drilling process. These samples will then be transported back to Earth's orbit for further analysis. The revolutionary transportation architecture used in this mission is adaptable for interplanetary exploration missions to Mars and the moons of outer planets, such as Enceladus.

INTRODUCTION

The TIGGER mission has been developed by a team of undergraduate Engineering Physics students studying at Embry-Riddle Aeronautical University. Its purpose is to explore the revolutionary concept of a "hopping robot," and to develop a revolutionary transportation architecture to return samples back from an interplanetary mission. In essence, TIGGER has been designed to use a single hemispherical leg to propel itself from one location to another. TIGGER is a three part system: a spacecraft, an explorer robot, and a sample return module. Its rounded bottom allows the robot to always achieve proper stability in an upright position. This quality is greatly beneficial because it allows TIGGER to explore more locations than an ordinary rover with all-terrain maneuvering capabilities.

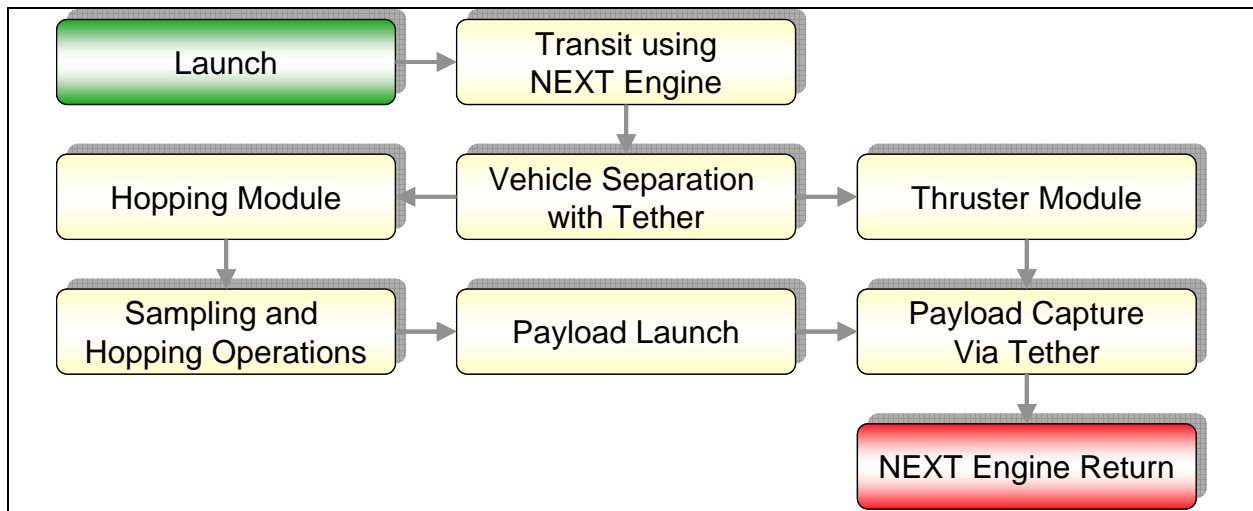


Figure 1. Mission Architecture

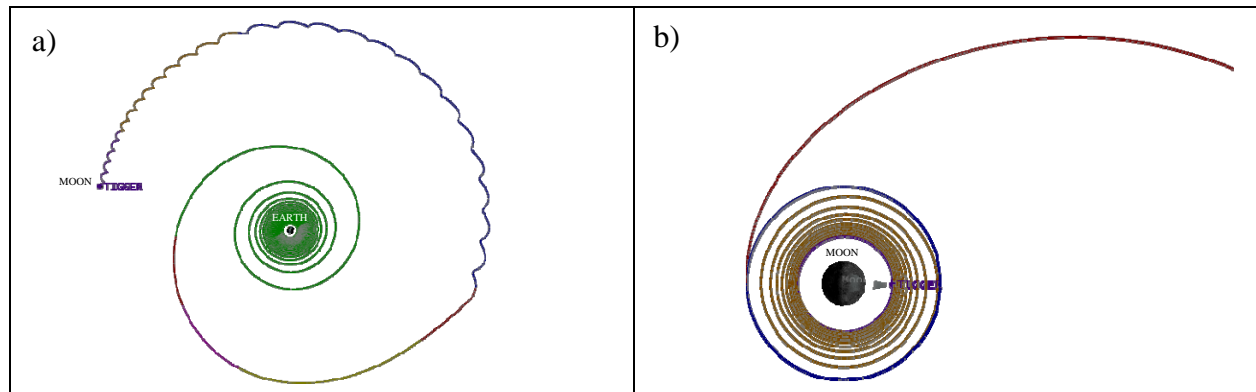


Figure 2. a) Spiral Orbit from Earth to Moon b) Lunar Rendezvous

Because TIGGER also weighs significantly less than any exploration vehicles currently in use, transportation costs, including launch and its transit to the Moon, would be greatly reduced. TIGGER will be using revolutionary propulsion technology, Xenon Ion Propulsion System (XIPS), which uses continuous low thrust. Once TIGGER reaches the moon, it will separate from the tether assembly and initiate a soft-landing trajectory to the Moon. The TIGGER spacecraft will descend to the surface of the Moon with a Cold Hibernating Elastic Memory (CHEM) foam landing system, offering both precision landing and thermal insulation. TIGGER has been programmed to use its spherical monopod leg to propel itself both upward and in any desired direction to reach its intended location. On each hopping maneuver, as TIGGER is traveling upward towards its maximum vertical altitude, it will use synthetic aperture radar to map the surrounding terrain for navigation purposes. Upon reaching a suitable destination, TIGGER will stabilize by using the spherical monopod leg and attitude control system. The ultrasonic drill

will then deploy from the base of TIGGER and drill into the surface of the moon, collecting samples from different depths beneath the robot using the hollow drill stem. These samples will then be placed in a thermal flask for storage. TIGGER will continue on to other sites, taking samples and photographs of the terrain at each location it hops to. Once the maximum sample storage capacity has been reached, TIGGER will launch the samples into orbit around the Moon using a mortar system. The samples will dock with the tether assembly and then be returned using the XIPS engine. Figure 1 summarizes the mission architecture.

ORBITS AND CONSTELLATION DESIGN

It was determined through a simulation using Satellite Tool Kit that the ideal launch date for TIGGER to go to the Moon is June 12, 2012. TIGGER will be launched on that day at 4:54:15 Universal Time into LEO. Once the spacecraft is in orbit, it will begin its slow spiral to the Moon using the XIPS engine. TIGGER will arrive in the vicinity of the Moon in 47 days. At this point, the

spacecraft will begin to thrust in the direction opposite to its velocity vector, allowing it to slow down and match the velocity of the Moon in its orbit around Earth. After a series of short coasting maneuvers and thrusting maneuvers, TIGGER will be in a circular orbit around the Moon on August 16, 2012, 48 days after launch. Figure 2a shows the entire orbital path of TIGGER from launch to lunar orbit. Table 1 contains a brief summary of the orbital data.

Table 1. Final Orbital Data for the Moon

Eccentricity of Orbit	0
Inclination of Orbit (Lunar Frame)	60-deg
Total Delta V	4.63-km/s
Total Fuel Consumed	23.50-kg

LAUNCH SYSTEM

The Taurus rocket was chosen as the launch vehicle for the TIGGER mission. The specifications on the Taurus Rocket are listed in Table 2. TIGGER's payload is substantially smaller than the capacity of the payload fairing, at 395-kg. This allows TIGGER to be able to share a payload with another company sending up a satellite to LEO, thus splitting the cost of launch and optimizing the overall cost of the launch.

Table 2. Taurus Rocket Specifications^{i,ii}

Design Constraints	Parameters
Transportation mass to Low Earth Orbit (kg)	1400
Payload Max diameter(m)	1.4
Payload Max Length (m)	2.8
Reliability	~ 90%

SPACE PROPULSION SYSTEM

A XIPS was chosen for TIGGER's engine. The NASA Evolutionary Xenon Thruster (NEXT) engine was evaluated to be the most compatible engine for TIGGER because of its high thrust for an ion engine at its achievable power levelsⁱⁱⁱ. The engine will start up after the upper and final stages of the integrated space transport system separate from its launching vehicle. After startup, the NEXT engine will burn nearly continuously except for a few short instances when the engine will turn itself off and then back on. This will be done to correct errors and perform maintenance. The NEXT engine will be gimballed, allowing the engine to accelerate or decelerate the vehicle, as well as allowing TIGGER to enter a stable orbit around the

Moon. In addition, the NEXT engine will be used to return the samples back from the Moon after the samples rendezvous with the transfer stage. The propellant requirements are listed in Table 3.

Table 3. Propulsion System Requirements

Transfer Stage	To the Moon	From the Moon
Delta V (km/s)	4.63	4.63
Final Mass (kg)	318.5	98.31
Mass of Propellant (kg)	58.07	17.92
Wet mass (kg)	~ 395	~117

POWER SYSTEM

The power subsystem defines the modes of the mission and also provides approximate durations of each mode. The power generation system's requirement is to provide adequate power with acceptable regulation during all modes. The results from a preliminary analysis have indicated that the optimal power generation system is a combination of nuclear and solar power, with batteries as an energy storage system. Table 4 lists the characteristics of the power system.^{iv}

Table 4. Solar Arrays Characteristics

Characteristic	Value
Cell Type	Triple junction (InGaP/GaAs/Ge)
Cell Efficiency	28%
Support Architecture	Square Rigger
Array Specific Power	250-W/kg
Number of Solar Array	2
Dimensions	6.75-m x 2.00-m
Estimated solar array mass	156.29-kg
Power Capacity at BOL	7372-W
Power Capacity at EOL	6000-W

The power generation system supporting the XIPS is the PowerSails Technology System. Developed by the Air Force Research Lab, the solar power generation system is estimated to provide approximately 6 kW to the XIPS. Since size and weight are important drivers in the technology selection, triple junction (InGaP/GaAs/Ge) photovoltaic cells were chosen for their higher power-to-area ratio and inexpensive cost per watt-of-power-generated. The n-p multi-junction cells are less susceptible to damage from charged particle radiation than p-n junctions, such as silicon cells.^{iv}

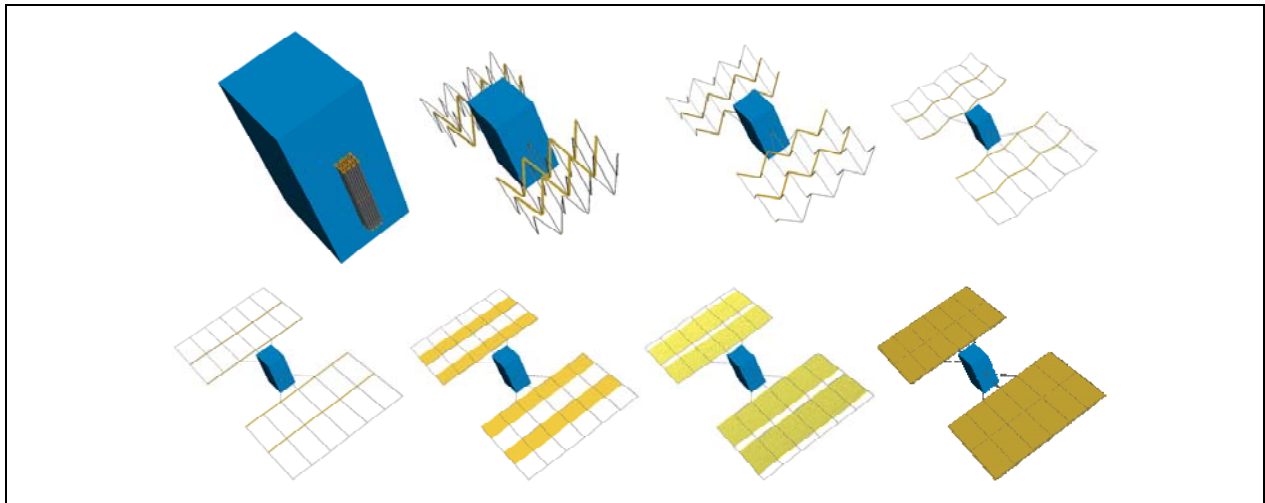


Figure 3. Solar Array Deployment

The mass benefits of the multi-junction arrays are further increased when an advanced array support architecture is used. This support architecture, which is under development by AEC-Able, is referred to as the SquareRigger. The SquareRigger Array is capable of being compacted down to nearly a fraction of its deployment dimensions during launch. During deployment, the SquareRigger structure is slowly controlled by a motor until it latches into place. These same motors will then raise the photovoltaic blankets (see Figure 3).

The power required on the hopper is estimated at approximately 100-W for a mission lifetime of two years. Since the robot must be able to operate during both daytime and eclipses, a multi-coupled Radioisotope Thermoelectric Generator (RTG) was found to be most suitable. For a successful hopping mission, a Sr-90 isotope fuel was chosen to fulfill the mass constraint.^v

Table 5. Energy Storage Batteries

Parameter	NiCd	NiH2	Li-Ion
Energy Density (W-hr/kg)	30	60	150
Energy Efficiency %	72	70	96
Self Discharge %/day	1	10	0.3
Temperature Range (deg C)	0 to 40	-20 to 30	10 to 30
Memory Effect	Yes	Yes	No

In order to maintain continuous power output to all subsystems, it is necessary to implement an energy storage system that is capable of being recharged. This energy storage system will be

used as part of the main power system to supply the load during an eclipse, or whenever the load exceeds the solar array or RTG capabilities. A Lithium Ion battery was chosen for this system because of its small mass, long shelf-life, wide range of operating temperature, and high discharge voltage when compared to NiCd and NiH2 (see Table 5).^{iv}

While operation at this high voltage is aggressive, it is necessary to keep the mass of the power cabling at an acceptable level. Within the Electrical Power System, there are two buses. One provides 30-V of regulated power to the subsystems, including the battery and charge control unit. A Power Distribution Unit is used to distribute the proper amount of power to all the subsystems. The second bus provides 100-V of regulated power for the electric propulsion system. There is one Power Processing Unit and one thruster; the switchbox handles the connections in case of failures.

MOMENTUM EXCHANGE TETHER

A Momentum Exchange Tether (MET) will be used for the Lunar mission to decelerate the hopping robot and the spacecraft before landing on the Moon's surface. The MET will also be used to catch the sample return capsule in a sub-orbital trajectory. Once the payload is captured, it will be slowed down to approximately zero velocity, then retracted into the spacecraft and returned back to Earth. As in Hoyt^{vi}, the tether system is composed of a long tether, a counterbalance mass at one end (mother spacecraft), and a central facility with the ability to climb up and down along the tether. This movement will let the system rotate around a desired center of mass, located approximately

halfway between the counterbalance mass and the central facility, while the sample return capsule will attach to the other end.

The MET will be made of Spectra 2000, a material that is 100 stronger than aluminum in tension, but three times lighter^{vii}. The tether will be 10-km long, and will be left in a circular parking orbit at an altitude of 20-km above the Moon's surface. The tether will weigh 27-kg, the service satellite 205-kg, and the sample return capsule approximately 6.6-kg.

ATTITUDE DETERMINATION AND CONTROL

TIGGER will employ both a sun sensor and a star-tracker for attitude determination. The use of both systems is for redundancy. TIGGER will gain three-axis control using the gimbal on the Xenon propulsion engine. This gimballed thruster will allow TIGGER to steer in any desirable direction. The control of TIGGER will be completely autonomous. This will be accomplished with closed-loop feedback and a Proportional Integral Controller (PIC)^{viii}. Figure 4 and Figure 5 are the results of a model of the designed control algorithm implemented in MATLAB. Figure 4 demonstrates that a disturbance can be dampened using the corresponding thruster angle in Figure 5.

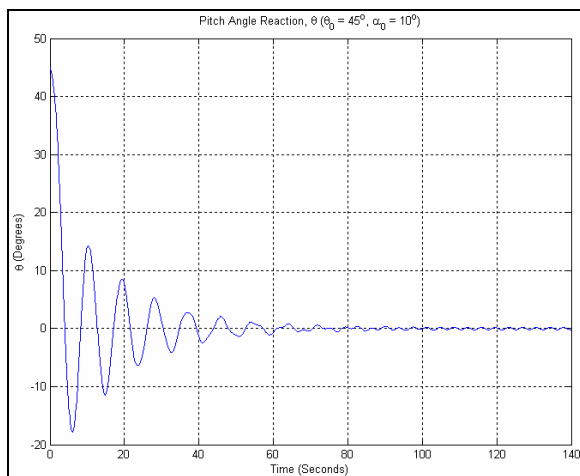


Figure 4. Pitch angle reaction (disturbance)^{viii}

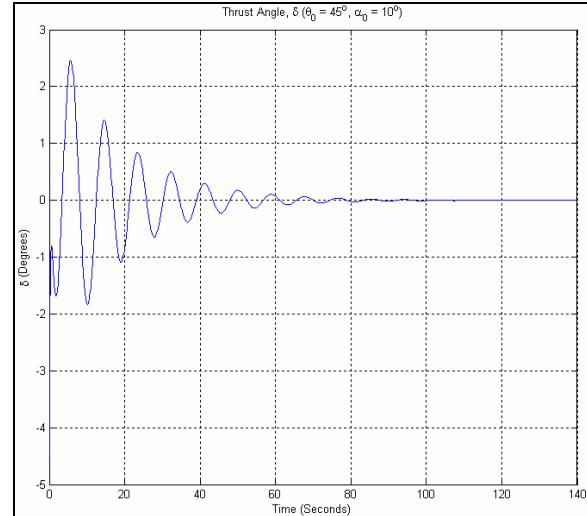


Figure 5. Thruster angle to counteract disturbance^{viii}

LANDING SYSTEM

The entry velocity at the Moon will be roughly 2.4-km/s. For that reason, all rovers of the past have used active propulsion systems onboard such as SRB's, retro-rockets, or monopropellant engines. Instead, TIGGER is utilizing the tether can also be used to decelerate and lower the vehicle down onto the moon before impact. This will reduce the entry velocity of TIGGER from 2.4-km/s to under 100-m/s. The base of TIGGER will be able to absorb impacts of approximately 10 m/s due to its hopping ability. To absorb the remaining velocity TIGGER will use Cold Hibernating Elastic Memory (CHEM) foam for landing. CHEM foams are composed of combinations of polyurethane and polyurethane-urea thermoplastic polymers, which have shape memory polymer (SMP) characteristics^{ix x}. The size, shape, and volume of CHEM foam can be vastly compacted and changed depending on whether the foam has reached its thermal transition point. At temperatures above the transition point the foam can be compacted into a rubbery state, and below the transition temperature the foam can be unconstrained in a glassy state. This technology would work by first applying the foam onto the spacecraft and then compressing the foam by over 90% of its original volume. The spacecraft can be launched without active control over the landing system. Before impacting the Moon, the foam will be deployed to its original state. The foam will then act as an inelastic collision as the ground crushes the foam. It is certified as a space radiation resistant material. Since the foam is only needed at the point of landing, there is no need

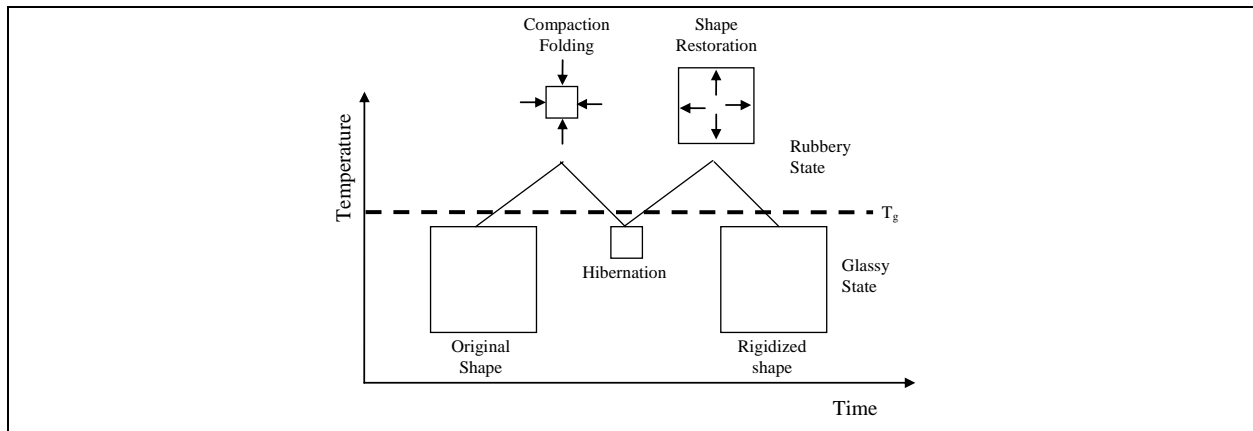


Figure 6. CHEM foam processing cycle.^{xi xii}

to encapsulate the rover in a structure. This eliminates a large amount of mass normally required by all other landing systems and is why a CHEM foam landing system is anticipated to be two orders of magnitudes less massive than any other current landing system^{xi xii}.

MECHANICAL SYSTEM

In the mission requirements for this project, a new locomotive system is to be developed based on the principle that small animals, like insects, use a hopping system as opposed to crawling to move large distances. Right now, most robotic exploration is done with wheels or walking robots, but both methods of locomotion have drawbacks. Rolling on wheels requires the rover to stay on a prepared, or very limited, surface. Roving robots are also very slow-moving. Because of this they must choose paths that do not exceed limitations. Walking robots are also very slow moving and although they can cover more versatile terrain than rovers, they are still limited by elevation gradients and increased complexity in the controls system to ensure stability.

Hopping robots can cover large distances quickly and can deal well with elevation

changes. There are several methods considered for a hopping system, such as a legged system, similar to a grasshopper, or a rocket thruster, which is analogous to a jelly fish. Although thrusters allow greater performance, they have limited use for long-term mission because of the need to store propellants. Because of this, TIGGER will have a legged-hopping system.

There are two groups of hopping robots: a multi-legged system and a single-legged system. A multi-legged system has the advantage of an easier mode of stability, while a one-legged system might "lose its balance." Despite this drawback to a monopod, a monopod greatly reduces the mechanical complexity. For example, in a monopod system, it is easy to correct for a delayed fire of a piston to propel the robot, while a multi-legged robot might topple due to this minor malfunction. Also a multi-legged robot would require more actuators and moving components, therefore to reduce complexity and increase the robustness of the robot, a monopod design will be used.

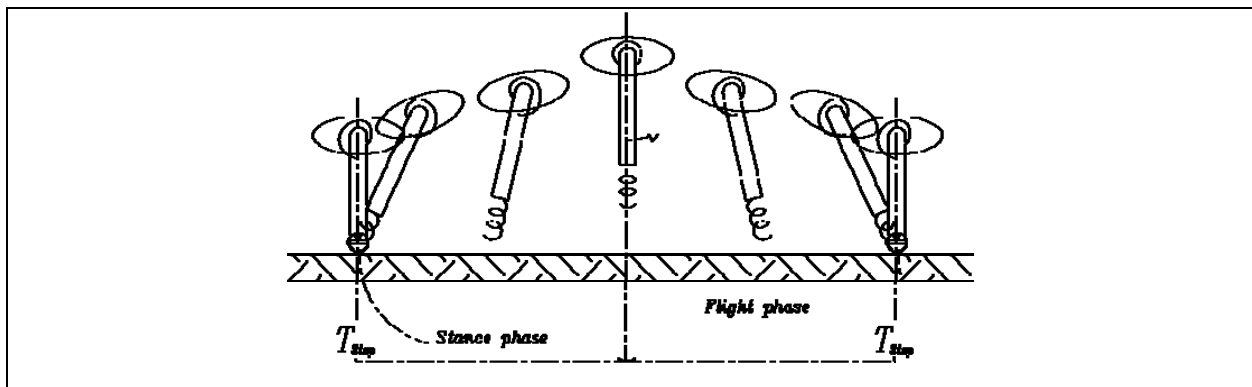


Figure 7. Basic concept of hopping robot system^{xii}

The monopod hopper will store energy in a spring, because after analysis of a gas cylinder, a cylinder would have to be too massive to make TIGGER feasible. Also, if a gas cylinder is used, a compressor would be needed to add energy to the system and also an extra gas cylinder to supply the compressor. The robot would use this spring like a pogo stick to hop around. A linear type motor will be used to add energy to the system. This motor will be a screw-type, worm gear motor to crank the spring tighter and add energy. The method of adding energy is a requirement to counter losses of energy from a gain in potential energy by climbing up hill, friction internally in the spring, deformation of the Moon's surface on impact, and most importantly, by the inelastic collision between the foot and the surface. The foot of the spacecraft has a mass of approximately 9-kg. This results in a loss of 9% of the hopper's energy per hop.

The hopping robot will be controlled using mechanical stops to limit the velocity of the robot leaving the surface in each jump and motors to control the location of the center of mass of the hopper with respect to the hopper's contact point with the surface. The force of the spring will run through the center of mass from the point of contact, making the motion of the robot controllable (Figure 8). The hopping robot will jump 25-m high on the Moon, requiring a spring with spring constant greater than 56-kN/m. A wave-type spring will be used because it provides up to 50% more deflection than a coil type spring in the same space. The leg height is 0.8-m extended, while the compressed size is 0.4-m to give a large throw and reduce impact loading. A steel spring can be used, if necessary, but this will be based solely on cost. One requirement for the hopping robot on this mission is that it must transport a drilling platform and the drill to different locations on the surface for sample collection. For the drill to function, the hopping robot must be able to remain stable on the surface.

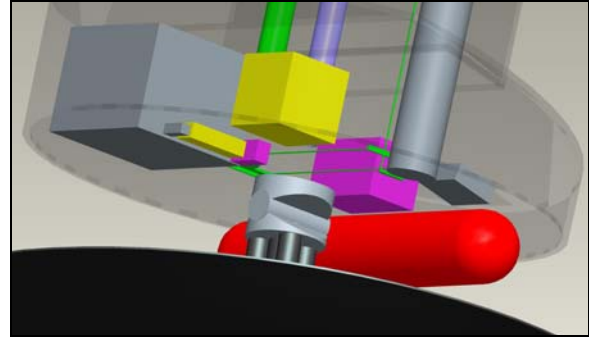


Figure 8. Gimbals for control system

Jet Propulsion Laboratory designed a hopping robot that uses a bowl-like foot on the end of the leg, allowing the robot to stand upright. The size of this foot is determined by the moment of inertia of the entire robot and the ratio of how far the robot can jump to how high it must jump.

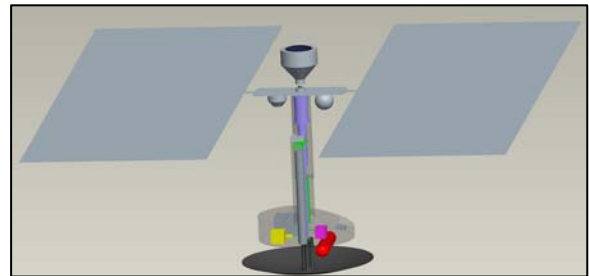


Figure 9. Spacecraft structure

STRUCTURAL SYSTEM

TIGGER (Figure 9) is designed to be a three part system: a spacecraft (Figure 10b), an explorer robot (Figure 10a), and a sample return module. The spacecraft module will consist of the ion propulsion system with its power system, the tether system, and components required for the return capsule to reach Earth that will not land on the Moon. The explorer robot will consist of all scientific payloads, the hopping system, the sampling system, and any parts of the return module that are not stored in orbit on the spacecraft module. The return module refers to the parts of the spacecraft that are returned to Earth and the components used to get there that are not otherwise used.

The entire spacecraft structure is covered in thermal protection except for the foot of the hopping robot. Since the spacecraft system will be deployed from the launch vehicle and never lands on the Moon, the largest force exerted on it will be that of liftoff from Earth (6g's). The ion engine's thrust is negligible compared to that of the launch vehicle; however, it does affect the

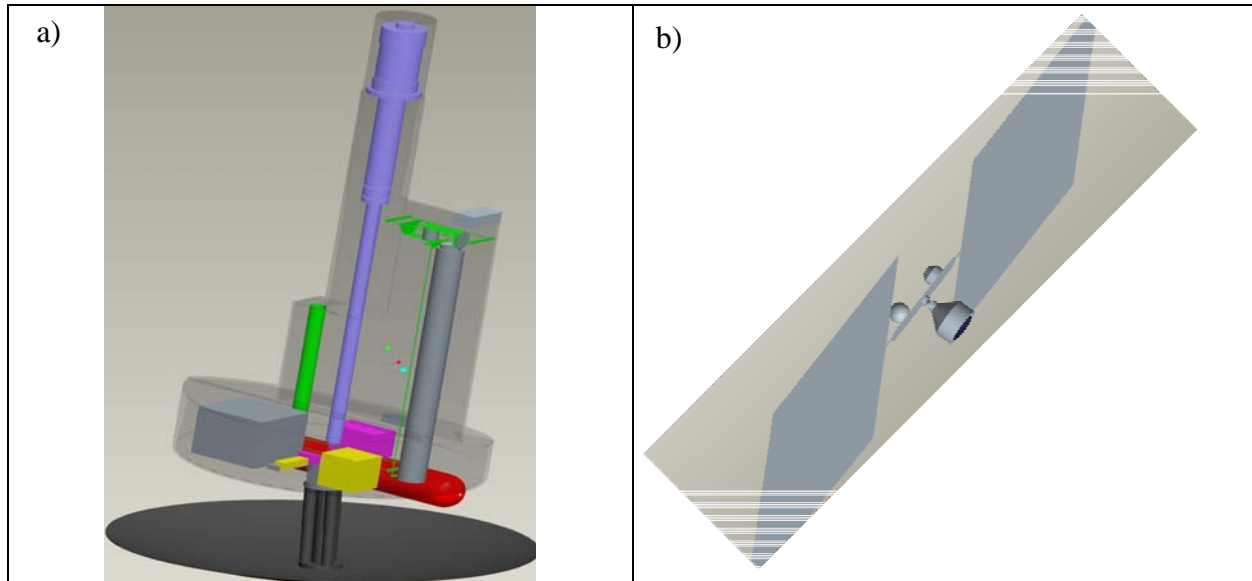


Figure 10. a) Spacecraft components b) Spacecraft without the hopping system

deployable solar arrays. Part of the structure will constantly be in contact with the RTGs, which have an operational temperature of approximately 1,500-K. Similar to most space missions, the framework of the spacecraft is made of aluminum.

The foot will serve as a shield for the missions to Mars and Enceladus, and will be covered in AQ60. This material has excellent thermal protective properties and also is the best material available to protect against micrometeorites.

Due to method of drilling, the structure must withstand oscillations in the 60-Hz to 1000-Hz range. Also due to the vast temperature range, between 65-K (in the shade) and 1,500-K (the RTG), the material properties of the structure must hold up to avoid a mission failure. Aluminum satisfies these conditions. Analysis of the hopping system shows that the largest loading of any component is due to the launch system and that based on the curves for cyclic loading fatigue (see below), a structure that can withstand the single 6g loading of launch can easily survive the cyclic loads of the hopping system. The structure plays a major role in determining the moment of inertia of the explorer robot.

Another major factor in determining the moment of inertia is the changing mass distribution due to the sampling system and the launch of the return capsule. In the sampling system, the

canisters to contain samples are moved from one side of the hopper to the other and at the same time they are filled with ice and rock. Later, the entire return capsule is launched from inside the robot which again changes the mass of the robot.

The return canister itself is contained within a pipe similar to that of a mortar tube. The tube will be thermally insulated to protect the internal components of the hopping robot. The canister itself will be made of a soft aluminum with one end covered in AQ60 to not only protect from debris on the return journey, but also to protect the ice samples from the explosive blast inside the mortar-like tube. The aluminum will be made ductile to increase the probability that it will return to Earth without puncturing. Inside of this aluminum, thermal insulation will encapsulate the samples to isolate them from the rest of the structure.

THERMAL CONTROL SYSTEM

A thermal control system (TCS) will maintain all the components of the spacecraft and hopping robot at operating temperatures at all times. Only a passive thermal subsystem has been considered since they are lighter, cheaper, and do not require any power. Radiators will be used to dissipate excess heat that enters the spacecraft and into the hopping robot. In addition, multilayer insulation (MLI) blankets will be used on all external surfaces, except for the areas reserved for radiators, in order to minimize

heat inputs/outputs where heat transfer is not needed or beneficial.

The radiator that will be used for the hopping robot and for the spacecraft is a 1.6-mm thin aluminum foil with a 5-mm silvered Teflon coating. This radiator has the exceptional emissivity over absorptivity ratio of 15.6. About 0.4-m² of radiator material is needed to dissipate 3,000-W of heat. It weighs about 3.3-kg per square meter. The same kind of radiator will be used for all the alternative missions.

The spacecraft and the hopping robot will also need to be covered by a multi-layer insulation system (MLI) anywhere else but on the radiators. This special insulation blankets will minimize the heat transfer (in and out of the spacecraft), and will ensure that the temperature inside the vehicle is within the operational range of each single subsystem. MLI are made of many thin mylar layers of carbon/aluminum (0.25-mm thick each), and weights about 0.73-kg per squared meter. The MLI must have a very low effective emissivity ε^* , so that the heat lost by the spacecraft is a minimum. The MLI emissivity is proportional to $1/(n+1)$, where n is the number of layers. However if the number of layers exceed 15-20, there is a sudden decrease in efficiency. Therefore, only 15 layers will be used for the TIGGER mission.

Both radiators and MLI will guarantee that, on average, the equilibrium temperature inside the spacecraft and the hopping robot will never exceed 210-K or go below 110-K. All the electronics and the instrumentation will be specifically placed in warmer areas, while the rock samples will be stored in the colder sections, so that the temperature for the ice phase change will not be reached at any time.

COMMUNICATION ARCHITECTURE

The communication system will consist of a ground based station, the orbiting spacecraft and the hopping robot. Data and images that are collected on the surface of the Moon will be sent to the orbiting spacecraft and then to the ground station at a rate of 2.6-kbps, using 20-W of power. The ground station will have a 0.7-m parabolic dish antenna with encoding/decoding capabilities. The orbiting spacecraft must be able to receive/demodulate uplink signals from the hopping robot and send/modulate signals to the Earth-based station. The ground-based

system and hopping robot must be able to receive/demodulate and send/modulate signals to and from the orbiting spacecraft. This will be accomplished using monopole antennas with conducting ground planes. Both the hopping robot and orbiting spacecraft will have two antennas for redundancy. An integrated transponder that includes the exciter, receiver, Command Data Unit (CDU), Telemetry Modulation Unit (TMU) and temperature sensors will be used to reduce the mass and size of the system.

Communication Architecture for Mars Mission

The same architecture will be used for a mission to Mars but, because the distance is so much greater, a parabolic dish antenna will replace one of the monopole antennas on the orbiting spacecraft. The other monopole antenna will remain for redundancy.

Communication Architecture for Enceladus Mission

The signal will be sent directly to the Deep Space Network (DSN) 70-m parabolic dish antennas from the hopping robot. A phased array antenna will be used in order to accommodate the hopping motion. Phased array antennas also have the benefit of graceful degradation. A monopole antenna will be placed on the opposite side in case the hopper gets stuck with the primary antenna facing away from the Earth. This will allow emergency override or repositioning commands to be sent to the hopper.

COMMAND AND DATA HANDLING

The command and data handling subsystem downloads code size, data rate and throughput from other subsystems while it outputs mainly mass and power. Data from the camera and the synthetic aperture radar system will be stored in two solid state data recorders. The use of two recorders increases the maximum capacity of TIGGER, but also creates redundancy in the event of large-scale data corruption.

TIGGER will use two X-2000 Flight computers to control the data handling process. This computer is the best choice for high radiation and fault tolerance. The primary computer will be connected to the Solid State Memory and Hi Speed I/O through the VME Backplane. The secondary computer will be connected to the

Telecommunication systems through fire wire, resolution, up to about 10-cm. Furthermore, this

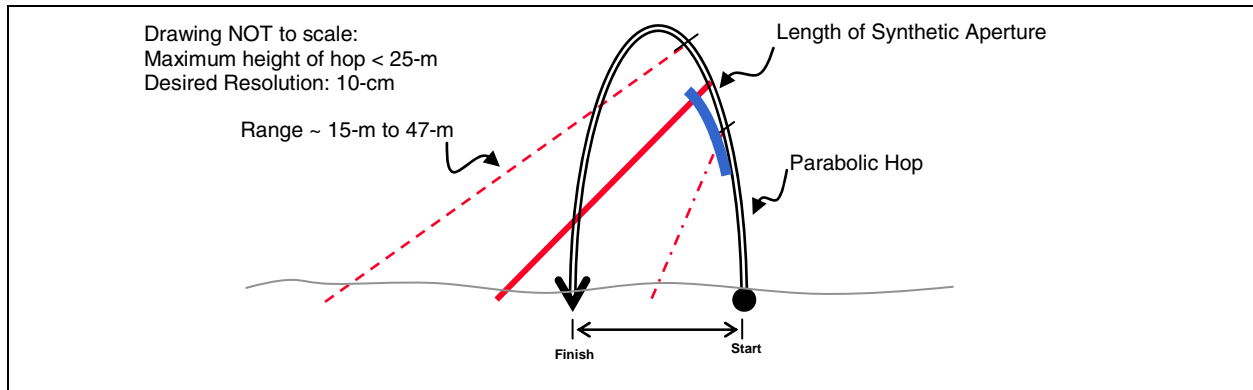


Figure 11. Diagram of Navigation Process

for maximum data transfer rate.ⁱ

Both the flight computer and the mass storage device will provide uplink and downlink support for communications among the Orbiter, hopper, and ground station. These two devices will also have control of spacecraft pointing and thrusting, power distribution, system temperatures, and subsystem communications.ⁱ

NAVIGATION SYSTEM

TIGGER's hopper must be able to autonomously guide its way across the surface of the Moon. However, the hopper must be able to move large distances with each hop while avoiding obstacles that could either damage or destroy components within the hopper. TIGGER has no ability to change its landing location mid-flight, so it will always scan one step ahead of itself. It was determined that a rock that is on the order of 15-cm tall could possibly cause the hopper to fall over. Even if the rock is relatively wide, for example, 10-m, but TIGGER landed on the edge of the rock, the hopper would slide off, possibly toppling in the process. This means that TIGGER requires a high resolution, approximately 10-cm, for its navigation system. Initially, TIGGER had three options for navigation: Visual photography, infrared photography, and Synthetic Aperture Radar (SAR). However, due to the long range needed and the limited data storage space available, SAR is the only feasible option for TIGGER.

SAR is a radar method in which the antenna is attached to a moving object. When the object moves it causes the antenna to scan a large area on the ground, thus "synthesizing" a large antenna aperture. This method has many advantages^{xiv}. First, SAR allows very high

high resolution is carried over to a very large coverage area. With SAR, TIGGER would be able to map an area at least 50-m wide and 47-m long on the Moon. This allows TIGGER to choose the best landing site possible in its path. Also, SAR is not inhibited by a lack of light, so it would be operational at anytime, anywhere on the Moon.

TIGGER will use a phased array antenna in conjunction with a processing unit to produce the map. This antenna will be attached to the side of the hopper on a two-axis gimbal, which would allow the antenna to be pointed^{xv}. Initially, TIGGER will begin a hop towards a pre-determined location. Once TIGGER is a few meters off of the surface, the antenna will begin transmitting waves with a frequency of 16.8-GHz (see Figure 11). This frequency was chosen because it is ideal for high-resolution imaging^{xiv}. As TIGGER gains altitude, the antenna will be synthesizing a larger antenna and scanning an area in front of the hopper from between 15-m and 47-m away. As TIGGER reaches the top of its hop, the antenna will finish imaging and TIGGER will land in its pre-determined location. From here, the process will repeat again when TIGGER is ready to move to a new location. Table 6 summarizes the SAR specifications.

Table 6. Navigation Specifications

Specifications	Values
Hop Height	25-m
Frequency	16.8-GHz
Range	15-m to 47-m
Length of Synthetic Aperture	8.37-m
Swath	50-m
Resolution	10-cm
Bandwidth	3-GHz

Power	24.72-W
Mass	10-kg

compared with TIGGER's overall system requirements so other scientific payload

Table 7. Scientific Instrumentation Characteristics

Instrument	Power Usage (W)	Dimensions (cm)	Data Requirements	Mass (kg)
Radiation Detector ^{xv}	4.1	11.1 x 10.9 x 17.7	10.7 bps	0.882
Radar Altimeter ^{xvi}	10.0	15 x 8 x 5	240 bps	0.6
Accelerometer ^{xvii}	0.1	2 x 2 x 5	200 bps	0.150
Panoramic Cameras ^{xviii}	3.8	N/A	12.98 Mb/image	0.534
Microscopic Imager ^{xix}	2.0	N/A	12.98 Mb/image	0.4
Sun Sensor ^{xx}	0.1	9.5 x 10.7 x 3.5	Nominal	0.3
Mass Spectrometer ^{xxi}	3.0	7 x 3 x 4	1.024 Mb/sample	0.28

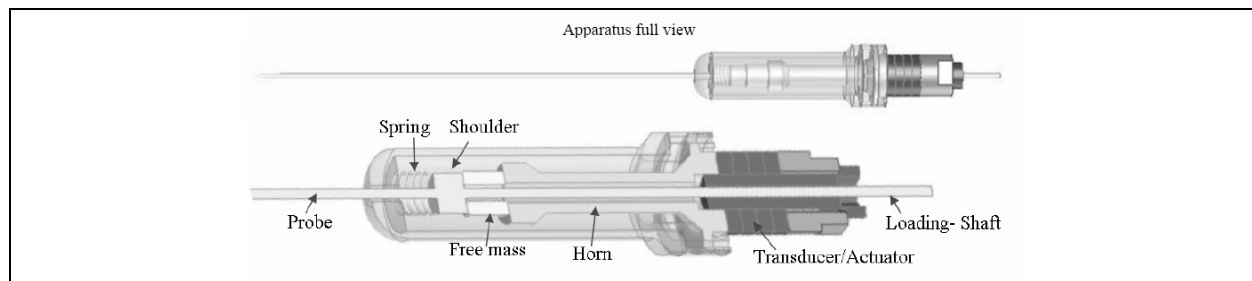


Figure 12. Two isometric views of a prototype of USDC

Dimensions	30-cm by 30-cm by 30-cm
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SCIENTIFIC PAYLOAD

The most important instrument on TIGGER will be the mass spectrometer. The mass spectrometer will be used for two purposes: To analyze core samples before they are placed in storage containers and to accurately analyze the chemical composition of the lunar soil in search for water. TIGGER will use a radiation assessment detector (RAD), which will be able to fully characterize the radiation in the local environment around TIGGER. By being able to map out the radiation on the Moon, Mars, and Enceladus it is possible to determine the hazardous radiation levels that would be incurred by human presence as well as determining how the radiation has influenced the presence of life on and beneath each of the surfaces analyzed. Sun sensors will be used for attitude control and radar altimeters as well as accelerometers will be used on both the space transfer vehicle as well as the hopping robot in order to land safely. Panoramic and microscopic imager cameras will be used to receive valuable visible information as to the landscape of the Moon, Mars, and Enceladus as well as to see the fine structure of the drilled samples from beneath the surface. Scientific instrument data is listed in Table 7. The requirements for all the instruments are nominal

accommodations can be easily made to scale the mission up to suit other possible scientific investigations.

PAYLOAD DRILL SYSTEM

Planetary sampling using conventional drilling and coring techniques has always been limited by the presence of high axial forces and torque that made it necessary to have heavy robots and rovers with complex anchoring systems. In the past few years, JPL recently developed a new drilling mechanism called USDC (Ultrasonic/Sonic Driller/Corer) to overcome the limitations of the conventional spinning drill system. The USDC has a free-mass that operates as a frequency transformer to convert 20-kHz ultrasonic waves to 60-Hz – 1000-Hz sonic hammering action applied onto the drill bit. The actuator of the USDC consists of a stack of piezoelectric ceramics with a backing material that focuses the emission of the acoustic energy forward, and a horn that amplifies the displacements generated by the stack. The tip of the ultrasonic horn impacts the free-mass creating a sonic resonance between the horn and the bit. The drill bit will finally impact the rock, and when its strain limit is reached, the drill bit will start penetrating the surface. Therefore, the three main components of the USDC are the actuator/horn, the free mass, and the drill bit, shown in Figure 12.

The USDC has been tested to be successful at extreme temperatures, and at low gravity^{xvi}. The drill for TIGGER mission will be about 2-m in height, with a drill bit of about 1-m. The collected sample will have a 5-cm x 5-cm cylindrical shape. It will take about 10 hours to drill one hole, with a peak power of 25-W.

SAMPLING SYSTEM

Ten samples will be collected from the northern polar region of the moon and returned to Earth's parking orbit to be collected. In order to maximize the possibility of discovering ice, samples will be collected from the deepest and most shadowed craters in the northern polar region. The return capsule will be radiation hardened and thermally protected. Each sample will be stored individually in order to avoid contamination. Each sample container will be cylindrical with a length of 5.25-cm and a diameter of 5.12-cm. The bottom of the container will be tapered in order to fit securely with the next container. The actual sample will be 4.9-cm in diameter and height, which will provide a clearance.

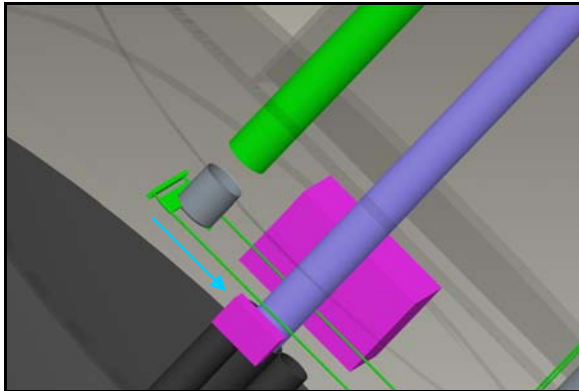


Figure 13. Empty Sample Container

Once the drill has extracted the sample, an empty sample container will be dropped onto a holding tray that is on the screw rails (see Figure 12). A small tab, controlled by a micro-switch, will prevent the next container from dropping until the tray is back in place. Then, the container will be moved horizontally under the drill where a microswitch will ensure that the container stops in the correct position. The sample will be dropped from the drill into the empty container (see Figure 14) and moved to a vertical screw rail system.

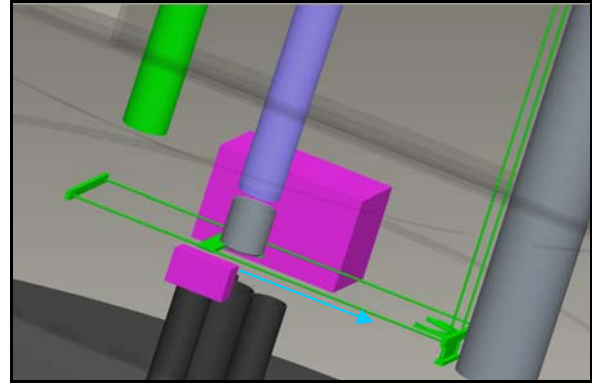


Figure 14. Sample from Drill to the Container

The holding trays will fit together so that the sample is picked up when the vertical rail moves up. This vertical rail will lift the sample to the top of the return capsule where it will be picked up by another horizontal rail system (see Figure 15). This will place the container in the return capsule.

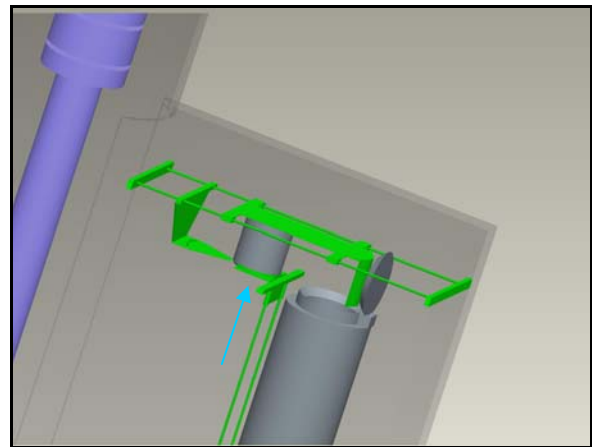


Figure 15. Second Horizontal Rail

There is a computer-controlled pressure cylinder in the capsule to prevent the samples from dropping to the bottom. The motors will then reverse and return the rails and trays to their initial position to start the process over when the next sample is obtained. After all 10 samples are in the return capsule, the horizontal rail will retract. This will allow the spring-loaded top of the return capsule to close. It will seal with a pin lock upon snapping shut.

SAMPLE RETURN SYSTEM

A combustion-based projectile launcher will be used for the Moon and Enceladus missions for putting the sample capsule into a suborbital trajectory to rendezvous with the orbiting spacecraft. The velocities required are low for

this stage of the mission, so a projectile launcher is a feasible option. This type of launch device is advantageous because it does not require energy to be diverted into accelerating fuel, which is the case in any rocket.

The propellant that will be used is M30 (see Table 8). The barrel will be made out of Aluminum 7178.

Table 8. Mortar Specifications

	Moon	Enceladus
Length (m)	1.00	1.00
Mass (kg)	3.82	3.82
Mass of Capsule (kg)	4.80	3.20
Altitude of Orbit for Rendezvous (km)	20	100
Mass of M30 Propellant (kg)	4.46	4.06
Muzzle velocity (m/s)	254.7	150.3

MOMENTUM EXCHANGE TETHER FOR THE MARS MISSION

A MET will be used for a mission to Mars. However, for the Mars mission the MET will not just capture the payload and retract it into the spacecraft, but it will swing it via momentum transfer, and deliver the payload back to LEO with the needed delta-v. In order to increase the speed of the payload, the central facility will use energy from solar cells to climb up towards the mother spacecraft to keep the center of mass of the system at the same altitude. The distance from the tether tip to the center of mass will increase and conservation of angular momentum will raise the angular velocity of the system as the facility moves closer to the center of mass.

The MET for this alternative mission will be made of Spectra 2000, as well. The tether will be 100-km long (to maximize the momentum arm), and will be left on a circular parking orbit at an altitude of 200-km over the Martian surface. The tether will weigh just 71-kg, the service satellite 310-kg, and the sample return capsule approximately 6.6-kg. This tether is able to produce a delta-v of about 7-km/sec.

ELECTRODYNAMIC TETHER FOR THE ENCELADUS MISSION

Saturn has a magnetic field that is about 580 times stronger than that of the Earth, which makes the use of an Electro-Dynamic Tether (EDT) for orbital maneuvers very feasible. This

system allows the spacecraft to decelerate without the use of a propellant in the magnetic field of Saturn. It will also act as a momentum exchange tether at the end of mission, when it will capture the sample return capsule coming from Enceladus, and will swing it back to LEO.

The EDT system has two plasma contractors at either ends of the tether, which enables (low) current to flow through it by closing the circuit using the ambient plasma^{xvii}. The tether then produces a Lorentz force with the interaction between the current and the magnetic field of Saturn. Nevertheless, the generated thrust is very low, and it strongly depends on the local magnetic field of the planet, and on the orientation of the tether. Therefore, the current will need to be tightly controlled during any orbital maneuver in order to achieve the desired effect.

The tether will be left on a circular orbit around Enceladus at an altitude of 100-km (230,000-km from Saturn). It will be 10-km in length, and weighs about 85-kg. The service satellite of the EDT will weigh about 320kg, while the sample return capsule was estimated to weigh not more than 9.34-kg. The tether cable has an aluminum core, and a thin layer of Spectra 2000 around it to increase its tensile strength. This EDT is able to produce a maximum of 30-N of Lorentz drag (or thrust).

SOLAR SAILS

Solar sails will be used to complete the return mission back to Earth for the Mars and Enceladus missions, after the capsule is accelerated by the tether. The sails will be used to decelerate the sample return capsule so that it can reach Earth. A spinning sail, Figure 17, is the type of sail that will be used. The sail material will be CP-1, which has an areal density of 6-g/m², a reflectivity of 85%, and a thickness of 5 microns. Table 9 gives the area and mass of the solar sail for both missions.

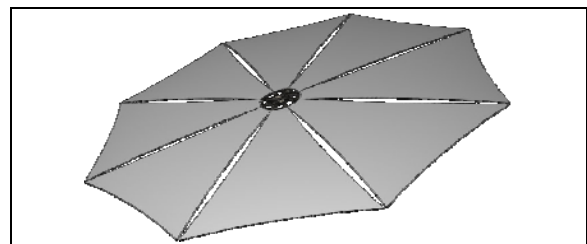


Figure 17. Spinning Sail^{xviii}

Table 9. Solar sails characteristics

	Mars	Enceladus
Area (m ²)	294.3	1025.1
Mass (kg)	1.77	6.15

OUTREACH

In order to encourage interest in space, TIGGER was presented to Ray Grimard’s Advanced Aerospace Technology class at Seabreeze High School (2700 N. Oleander Ave. Daytona Beach, FL (386) 258-4674). The students showed their enthusiasm by being involved in the presentation and asking many informed questions.

CONCLUSION

TIGGER will be the first mission of its kind and will revolutionize the exploration of the environment on celestial bodies. By employing a hopping system on the surface of the moon, the robot will be able to cover large distances and harsh terrain which would have been impossible for previous rovers to reach. TIGGER will successfully serve as an integrated space transfer vehicle, entry vehicle, landing vehicle, exploring robot, and sample-return vehicle. The space transfer phase of TIGGER uses a XIPS engine to propel the spacecraft to a parking orbit around the moon. The exploring robot phase of TIGGER involves hopping, drilling and collecting samples. For the return phase of TIGGER, the hopping robot will deploy

a mortar which will propel the return capsule into an orbit around the Moon where it will be captured by the tether. The XIPS engine will be used to return the samples back to Earth for further analysis. This trade study covered a broad overview of the entire mission and mission alternatives.



Figure 18. Photo from the outreach presentation

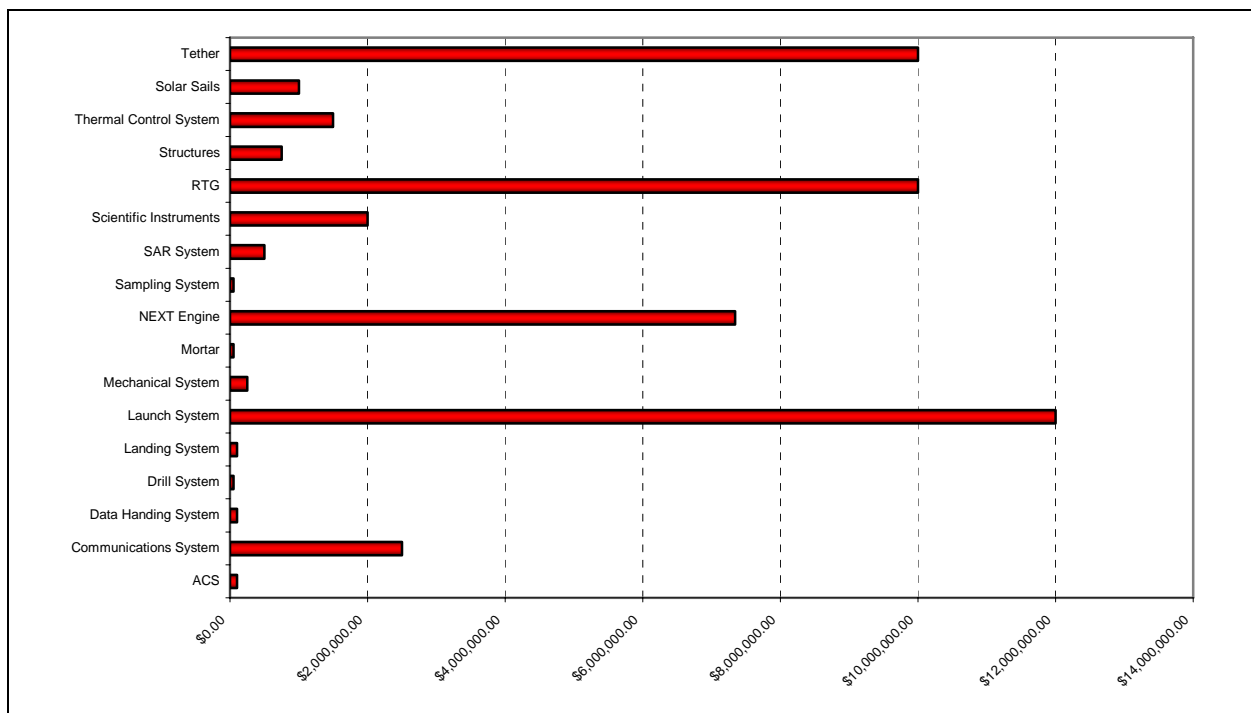


Figure 16. Mission Cost Analysis

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