A Wheel–on–limb rover for lunar operation*

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Abstract

The All–Terrain Hex–Limbed Extra–Terrestrial Explorer (ATHLETE) is a new mobility platform developed for potential lunar operations. This six limbed rover is designed to traverse quickly over benign terrain by rolling, traverse rough and steep terrain by walking, as well as perform general manipulation of tools and payloads. This flexible robotic platform will provide a mobile base for pressurized lunar habitats allowing for long range surface exploration and crew transport. It will also enable in-situ construction of lunar assets providing astronauts with the ability to assemble, maintain, and service a wide range of cargo. This paper presents the design details and capabilities of this wheel–on–limb platform.

1. Introduction

Beginning in 2020 the National Aeronautics and Space Administration (NASA) plans to return humans to the moon in an effort to build a permanent lunar outpost [1]. Astronauts will use the moon's natural resources to conduct scientific investigations and

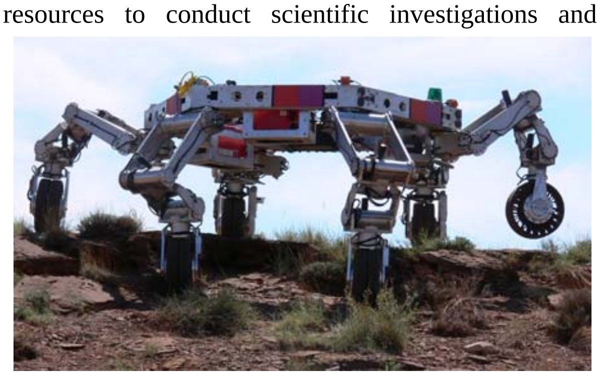

Figure 1, The ATHLETE rover as it climbs to the top of a hill.

prepare for a journey to Mars. Prior to human arrival, NASA plans to conduct robotic precursor missions for landing site reconnaissance, analysis of the natural resources, and technology risk reduction for the human lander. The All–Terrain Hex–Limbed Extra–Terrestrial Explorer (ATHLETE) was designed to aid in both the manned and unmanned portions of the return to the moon by providing versatile mobility and manipulation capabilities to be used via both remote operation from the earth and in cooperation with astronauts on the lunar surface.

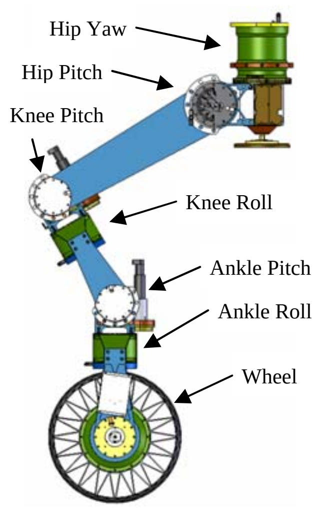

Figure 2, Kinematic layout of the limb.

The multipurpose ATHLETE vehicle is composed of six, six degree of freedom (DOF) limbs. Each of these limbs is identical and has a yaw, pitch, pitch, roll, pitch, roll kinematic structure as illustrated in Figure 2. The end effector of each limb is a powered wheel which can be used on gentle terrain to drive at speeds up to 10 kph. On rough and steep terrain the wheel can be locked allowing the vehicle to walk. Section 2 will describe the mechanical details of the limbs and the vehicle structure. The vehicle has 15 pairs of stereo cameras, a novel force sensing technique, as well as various other sensors allowing for a robust balance of on-board autonomy and teleoperation. Section 3 will discuss the sensing and command capabilities that will allow for safe vehicle operations over the expected lunar time delay. Section 4 will discuss the ability of the limbs to be used as general purpose manipulators and the

* This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology and was funded by the NASA Exploration Systems Mission Directorate

associated tools that allow for grasping, drilling, and moving of lunar regolith. Section 5 will discuss other capabilities such as rappelling down steep slopes and payloads such as a pressurized rover compartment (PRC) which will allow for the transport of unsuited astronauts. Finally Section 6 will discuss current and future work that will lead to a highly adaptable robotic platform able to support the upcoming return to the moon.

2. Vehicle design

The 850 kg ATHLETE vehicle is designed with an open hexagonal frame, as shown in Figure 3, that measures 2.75 m tip to tip with a six degree of freedom limb located at each vertex of the hexagon. This axisymmetric robot was designed as a prototype vehicle to test the wheel–on–limb mobility concept as well as provide a platform for software development. The research nature of the project demands spaceflight design principles without requiring the use of spaceflight hardware. This allowed for the rapid design, build, and test cycle of the vehicle which began in March of 2005. Hardware development started two months later in May, and the first of two fully functional vehicles was operational at the beginning of October of that same year. Since that time the vehicles have been on numerous desert field tests as well as engaged in constant laboratory testing.

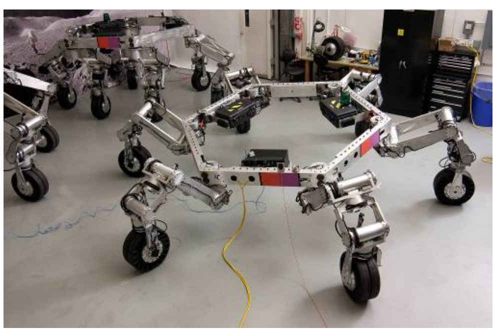

Figure 3, The hexagonal body of the ATHLETE vehicle with limbs at each vertex

2.1. Joint design

The 36 joints share several common design elements. To reduce the overall vehicle complexity, identical actuators are used as the first stage to all of the joints. A common 120 watt brushless DC motor with an integral 81:1 planetary gearhead, optical encoder, and brake are used in every joint. This actuator is then used in combination with various size harmonic drive gears resulting in overall gear ratios ranging from 3,640:1 to 13,100:1 for the various joints. Each joint also incorporates a high precision absolute encoder at the output of the actuator.

The joint actuators all use distributed motion control with the motor controllers co-located with the actuators. This controller architecture significantly reduces the cable harness necessary to traverse the 6 DOF limb as communication with all motor controllers occurs over a common RS485 bus. A main processor is located at the rover body and directs the motion of all the joints and limbs allowing for coordinated limb motion as well as closed chain body posing.

2.2. Structural design

The current ATHLETE prototype is approximately 1/3 scale of the potential flight vehicle that will have a hexagonal frame 8.8 m in diameter and have 6 m long limbs. The vehicle size is limited by the inner diameter of the launch vehicle that will be used to transport it to the moon. To allow the vehicle to stow for launch, the length of the thigh is slightly less than the length of the hexagon face. This allows the thigh to be positioned directly under the face of the hexagon, minimizing the stowed volume as shown in Figure 4. The open frame structure of the links allows the lower portion of the limb, including the wheel, to pass through the thigh. This increases the work volume of the limb and allows the shin to be stowed inside of the thigh for launch, further reducing the stowed vehicle size. This geometric configuration results in a 1.8 m limb length for the current vehicle from the hip yaw axis to the rotation axis of the 0.5 m diameter wheel.

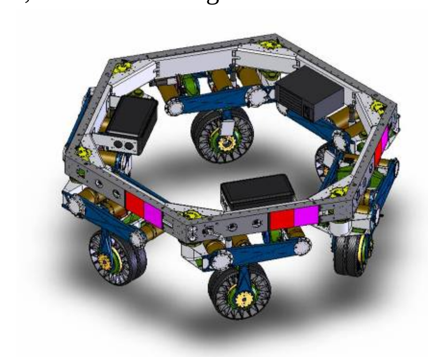

Figure 4, The stowed configuration of the vehicle

2.3. Wheel design

Each wheel consists of a 746 watt brushless DC motor with an integral 36:1 planetary gearbox, optical encoder, and brake. This high power wheel allows the vehicle to drive up significant slopes as well as travel at a top speed of 10 kph. This motor also serves as the mechanical power input to the end effector tools that will be discussed in Section 4.

The wheel of the vehicle is made with the Michelin Tweel® shown in Figure 5. The Tweel® is a non-pneumatic wheel which mimics the performance and advantages of pneumatic tires without the disadvantages of an integral pressure vessel.

Figure 5, An ATHLETE Tweel® shown deforming over uneven terrain

The Tweel adds passive compliance over undulating terrain and deforms to increase the contact area between the wheel and the ground. This increased contact patch aids in reducing the vehicle ground pressure for flotation on loosely compacted regolith. The mechanics of the tweel are such that a uniform pressure profile is created across the length of the area in contact.

The lunar rover vehicle (LRV) developed for the Apollo missions used a woven metallic mesh in the design of a deformable wheel to provide approximately 7 kPa of ground pressure [2]. This wire mesh, however, had limited life due to fatigue induced by rolling over rocks resulting in sharp bends in the woven wires. Since then, planetary rovers such as the Mars Exploration Rovers have used non-deformable wheels and depended upon traversing over relatively solid ground [3]. The Tweel® concept shows promise as a long life, deformable planetary wheel and the design of such is an active task.

The risk of outgassing, UV and atomic oxygen degradation, and hardening/brittleness at cryogenic temperatures make elastomers unsuitable for use in the lunar environment. As the current terrestrial Tweels used on ATHLETE are mostly comprised of elastomers, they are ultimately inappropriate. However, work was recently completed on two variants of the Tweel that are comprised of lunar-appropriate materials. The first (shown in Figure 6) of these is a 4kg wheel consisting of thin titanium bands separated by a wire rope shear structure and supported by flexible Betacloth spokes. The second prototype wheel (also 4kgs) recently constructed is made from a proprietary composite material invented by Michelin. This composite material's mechanical properties actually improve at cryogenic temperatures and provide sufficient performance over the entire lunar temperature range (40-400K). Both variants have a load carrying capacity of approximately 200kgs on earth. This load carrying efficiency (weight of wheel/weight carried) is already several times better than that of the Apollo wheels. In addition, the composite structure has been subjected to more than 600,000 representative load cycles, which equates to some 1000 km of driving (Apollo wheels were designed for 120km of life). Because the Tweel design is easily scalable to virtually any size, loading requirements, or desired ground pressure, it will have immediate applicability to any number of planned extra-terrestrial missions involving surface mobility.

Figure 6: The Lunar Tweel Prototype and the resulting uniform contact patch in soft soil after applying 100kgs.

Since the ATHLETE vehicle can walk as well as roll over the lunar terrain it does not have the same ground pressure requirements as a purely wheeled rover. If the ATHLETE wheel sinks in extremely soft terrain, it can simply transition to walking to extricate itself and continue walking in the soft soil. Thus the wheel ground pressure can be increased to the range of 20-45 kPa without sacrificing the rover's ability to traverse over soft soil. This results in a smaller and less massive wheel than would be required of a purely wheeled design capable of traversing the same terrain.

3. Sensing and autonomy

The operational scenario for the vehicle includes both command by astronauts on the moon as well as remote operation from the earth's surface over a 4 – 10 second time delay. In either of these situations the vehicle must have a certain level of autonomy to keep itself safe, but is not required to make strategic decisions since it will always have human supervisory control.

3.1. Visual Sensing

To facilitate remote operations the vehicle will have 15 sets of stereo cameras. A pair of stereo navigation cameras is located in the face of each side of the hexagonal frame. This gives the operator a simultaneous 360 degree view around the vehicle. Three sets of stereo haz-cams are located on the interior faces of the hexagonal frame located 120 degrees apart. These cameras are pointed down at a 45 degree angle to view the terrain directly under the vehicle. A pair of stereo tool-cams is located at the end of each of the limbs which gives a tool frame view for manipulation. The tool-cams also allow for vehicle inspection, payload inspection, as well as viewing terrain occluded in the nav-cam or haz-cam images.

The images returned by the stereo cameras are used to reconstruct the 3-D geometry of the terrain around the vehicle. This data is used to build a terrain mesh, as shown in Figure 7, creating a virtual environment from which the operator can plan the motions of the vehicle [4]. The operator can then send high level commands to the vehicle such as drive *X* meters at *Y* heading or move a certain limb *X* meters in a given coordinate frame.

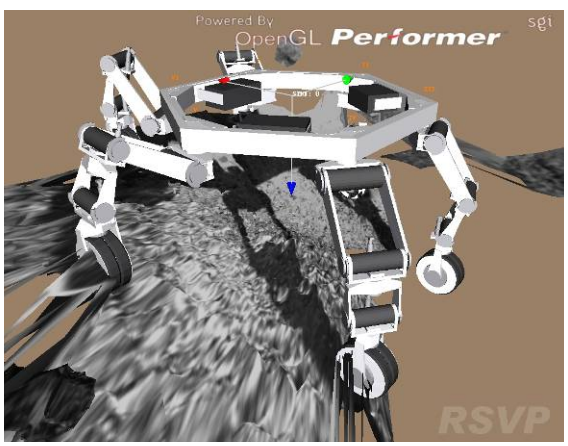

Figure 7, Terrain mesh showing 3-D environment around the vehicle constructed from stereo imagery

3.2. Force Sensing

During the high level motion commands, the operator is no longer actively commanding the vehicle, and the rover must ensure its own safety. One way it does this by monitoring the torques at each of the six limb joints. This force sensing is done using a novel technique based on the motor encoder, the actuator output encoder, and a characterization of the joint stiffness [5]. As discussed in Section 2.1, the input of the actuator has a relative encoder at the motor, a planetary and harmonic gear reduction, and an absolute encoder at the output of the joint. The torsionsal stiffness of the gearbox can be characterized by applying a known load to the joint and measuring the difference between the input and output encoders. Subsequent difference measurements of the output and input encoders can be used with the joint stiffness to infer the applied torque. This joint torque sensing on all six axes, combined with the kinematic information of the limb, can be used to resolve the three force and three torque components of the wrench applied at the wheel. Recalibration of the incremental encoders can be performed by simply lifting the limb off of the ground. The kinematic information given by the absolute encoders combined with a mass model of the limb and the gravity vector given by an onboard inertial measurement unit (IMU) results in a known torque at all of the joints for the limb in free space. This combined with the joint stiffness model can be used to re-calibrate the incremental encoder in the case that motor position knowledge is lost.

While driving, joint torque monitoring can be used to ensure that variations in the terrain do not result in unsafe torque levels at any of the joints. Resolved forces at the wheels can also be used in active suspension to servo the position of the limbs conforming to the terrain. In this way, the vehicle can drive over uneven terrain while maintaining an equal distribution of forces across all the wheels and a level body. This aids in floatation on soft terrain by distributing the vehicle ground pressure across all the wheels. It will also help with crew transportation on the moon by maintaining a level rover deck while driving over undulating terrain.

4. Tool Use

The six degree of freedom limbs can be used as legs for walking on rough terrain, but can also be used as arms for general purpose manipulation. To facilitate these manipulation tasks, a tool attachment is incorporated at the end effector of each limb. This tool mechanism holds both the stereo tool-cams as well as an actuated clamp to enable the use of an interchangeable suite of tools.

4.1. Tool Clamp

The tool clamp mechanism, shown in Figure 8, is a single actuator system that performs both the function of deploying and aiming the tool cameras as well as securing the various tools to the end of the limb. The cameras pivot through a 90 degree range from fully stowed, pointing along the axis of the ankle roll joint, to fully deployed, pointing along the wheel rotation axis. This allows the tool-cams to be pointed at the tip of any length tool. Coupled with the deployment of the cameras is the linear motion of a two jaw, V-shaped clamp. As the cameras deploy, the jaws open to accept a tool. The limb can then move to secure one of several tools from a rover mounted tool belt. The clamp rigidly connects the tool to the end of the limb and the distance between the jaws of the clamp sets the pointing angle of the cameras. Therefore each tool can have a unique sized mating interface to set the pointing angle of the tool-cams for that tool's use.

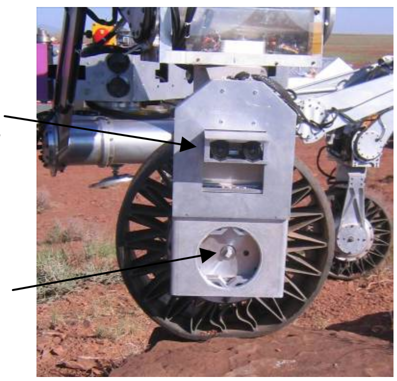

Figure 8. Tool mechanism located at the end of each ATHLETE limb

In the center of the tool clamp is a 12.7 mm (½ inch) square key. This key is coupled to the output rotation of the wheel and provides 746 watts of rotational mechanical power to the tools. This wheel rotation is a seventh degree of freedom on each limb that can be used to actuate the end-effector mounted tools.

4.2. Tools

Any number of tools are potentially useful for lunar operations. The tool clamp mechanism allows for tools to be easily changed for various tasks. Tool development is an ongoing task for ATHLETE based upon the anticipated needs such as scientific exploration, in-situ construction, and collection of potentially useful resources such as ice in the permanently shaded floor of the lunar polar craters.

Initially, several tools have been developed to demonstrate the vehicle's capabilities. A gripper, shown in Figure 9, can be used for grasping, carrying, and manipulating objects. An auger drill has been used to collect deep soil samples, secure payloads, as well as provide an anchor for rappelling. A 1 m long dual limb scoop, held between the tool clamps of adjacent limbs, has also been used to perform bulldozer type tasks such as moving large quantities of dirt and leveling ground.

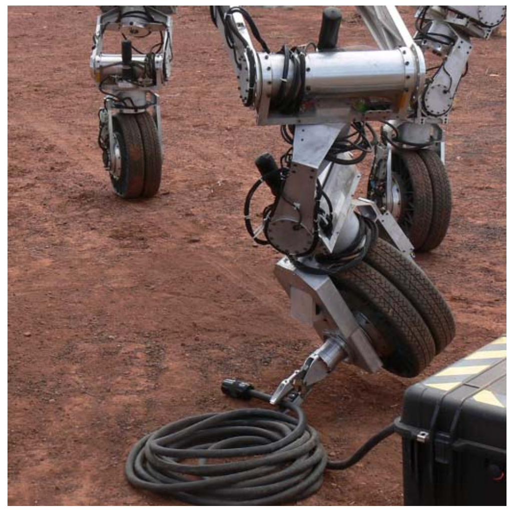

Figure 9. Gripper attached to ATHLETE limb shown manipulating a cable

5. Payloads and capabilities

The ATHLETE rover is designed to be both a multi-purpose robotic exploration/work vehicle as well as a crew transportation vehicle. The flexibility and adaptability of the robot allows it to simultaneously meet the requirements of these disparate tasks.

5.1. Pressurized rover compartment

For lunar operations, astronauts may have an unpressurized rover, similar to the Apollo lunar roving vehicle, for short excursions in addition to a pressurized habitat where spacesuits are not required. The ATHLETE vehicle can provide a mobile base to the pressurized habitat allowing for long range traverses as well as transport of the landed crew module from the landing site to an outpost location. The current prototype vehicle has a payload capacity of 250 kg, but the flight vehicle will have a lunar payload capacity upwards of 14 metric tons. This will allow the entire landed mass of a potential manned exploration mission to be mobile.

The body posing capability of the vehicle allows the rover frame to be placed on the ground as shown in Figure 10. This allows for easy ingress and egress of a pressurized rover compartment on the ATHLETE deck as the top of the rover frame is approximately 0.5 m above the surface in this configuration.

Figure 10, Suited astronauts entering a simulated pressurized rover compartment on the deck of a squatted ATHLETE vehicle

5.2. Rappelling

To explore extremely rough and steep terrain, such as the base of an impact crater, safety lines are required to ensure the stability of the vehicle. For use on steep slopes (> 20 deg) a rappelling winch has been incorporated into a face of the rover as shown in Figure 11.

Figure 11. ATHLETE rover rappelling down steep slope

This winch uses a brushless DC motor with a safety brake and a 16:1 planetary gearbox. At the top of the hill, the ATHLETE vehicle can secure an anchor using a 2 m long auger bit driven into the ground by the tool mechanism. The rappelling line is attached to the auger and as the vehicle descends down the hill a cable spool that is carried on the vehicle is paid out. When the vehicle is stationary, the winch brake is engaged and power is not required on the winch to hold the vehicle. As the vehicle moves, the brake is released and a constant current controller on the winch motor delivers approximately constant tension on the line as additional cable is released. The rappelling line offloads the downslope weight of the vehicle and allows the rover to safely drive and/or walk down steep slopes without additional demand from the wheel or joint actuators.

5.2. Multi-robot cooperation

To develop a continual human presence on the moon requires a great deal of infrastructure. In-situ construction of these permanent assets will involve manipulation of large structures. The heavy payload capability of the ATHLETE vehicle, combined with the ability to manipulate large objects with two adjacent limbs allows the vehicle to move large objects. For payloads too large for a single vehicle to manipulate, multiple ATHLETE vehicles can be used in concert to manipulate and transport extremely large structures as shown in Figure 12.

Figure 12, Two ATHLETE vehicles shown lifting a mock pressurized crew compartment from a mock lander.

To facilitate multi-vehicle cooperation, commands are sent to both vehicles and queued until the vehicles receive a command to simultaneously start the coordinated motion. Forces at the end effector and torques at the joints are constantly monitored and if any forces or torques extend outside the specified bounds all motion on all the robots is immediately stopped. This basic mode of multi-robot coordination works well for simple tasks such as pure Cartesian lifting motion. More sophisticated force sharing algorithms, however, are currently under development for more complex coordinated motions.

6. Future Work

The thrust of the future work for ATHLETE is focused on developing capabilities necessary for a return mission to the moon. NASA convened an Inter-center group called the Lunar Architecture Team, whose final phase-two report presented at the AIAA Space 2007 Conference in Long Beach, CA included prominent use of ATHLETE vehicles for habitat and cargo mobility [6]. An Illustration of full sized vehicles (8.8 m in diameter with 6 m long limbs) carrying pressurized crew compartments is shown in Figure 13.

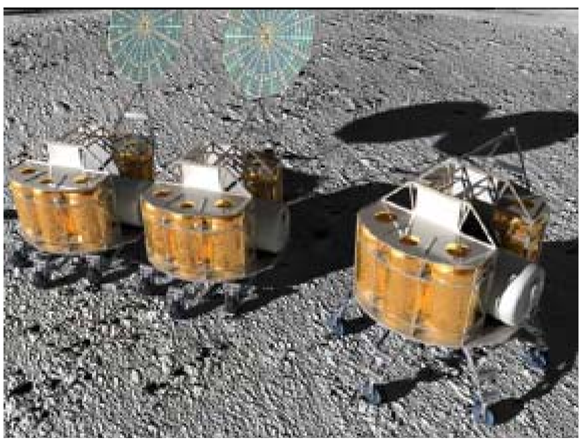

Figure 13, ATHLETE vehicles shown carrying pressurized crew compartments in an artist's concept. Image courtesy of NASA Langley Research Center.

The move from a prototype vehicle using off-the-shelf hardware to a flight-ready vehicle capable of supporting the new lunar architecture is the focus of the ATHLETE team. This effort includes tasks such as the development of actuators and control electronics that can operate for long periods of time in the harsh lunar environment, the development of a lunar fuel cell power system, and the refinement of the flight software. Work constantly continues on the current vehicles, maturing control algorithms and operational scenarios which will be directly applicable to the flight vehicle.

Developing tools to allow for accurate and safe control of the vehicles from Earth over a lunar time delay is also an active area of research. Remote operation of vehicles on Mars entails a single downlink of data and uplink of commands per day. This allows the user to carefully construct a set of commands to perform a given task without feedback. With direct teleoperation, the user has immediate feedback and very little extended planning is required. Operation over a lunar (4 – 10 second) time delay is a combination of these two modes. Giving the operator the right feedback and visualization tools to allow swift yet safe supervisory control is also a focus of current and future work.

7. Conclusions

The ATHLETE vehicle is a complex robot with more degrees of freedom than any other planetary rover. This complexity, however, comes with the benefits of capability and flexibility. The ATHLETE rover can traverse terrain that no other planetary rover can traverse. It can negotiate a step nearly equal to its fully extended limb length and more than three times its wheel diameter. It can act as an exploration rover, a crew transport vehicle, and a construction asset on the lunar surface. This wheel-on-limb rover is highly adaptable and will potentially play a key role in man's return to the moon.

8. Acknowledgments

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology and was funded by the NASA Exploration Systems Mission Directorate. The author would also like to acknowledge the hard work of the entire ATHLETE team in the development of these vehicles (Brian Wilcox, Jaret Matthews, Norman Ahmad, Jeff Biesiadecki, Todd Litwin, Jack Morrison, Curtis Collins, Julie Townsend, David Mittman, Al Sirota, Michael McHenry, Mike Garrett, Jeff Norris, Larry Broms, Chuck Morris, Lien Pham, Susan Ung, Beverly St. Ange, Kobie Boykins, Brian Cooper, John Wright, Frank Hartman, Scott Maxwell, Chet Joswig, and Tom Crockett).

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A copy of the presentation can be downloaded at http://www.spaceref.com/news/viewsr.html?pid=25506.