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A Review: ATHLETE—All-Terrain Hex-Limbed Extra-Terrestrial Explorer

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Abstract – *The ATHLETE (All–Terrain Hex–Limbed Extra–Terrestrial Explorer) is the first generation of wheel on limb Extra-Terrestrial vehicle developed for cargo handling, habitat transportation, and to explore different terrain where the human cannot reach. 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. There is a flexible platform which will provide a mobile base for pressurized lunar habitats allowing for long range surface exploration and crew transport. It is also capable of performing different types of functions as it equipped with a different tool on each of its limb. This paper contains the reviews of few papers which give idea of the of its construction, design of joint, design of structure, its electronics and software and will also be discussed the its capability of preparing outpost site.*

Keywords- *ATHLETE, Lunar Lander, Rover, Lunar Habitats, Extra-Terrestrial Explorer.*

I. INTRODUCTION

ATHLETE (All–Terrain Hex–Limbed Extra–Terrestrial Explorer) is a vehicle that can "walk" out of extreme terrain and use wheels to efficiently "roll" in nominal terrain will result in a vehicle that will be both more capable and lighter than a conventional wheeled all terrain vehicle. It has hexagon frame and has six limbs each having 6 DoF. All-terrain vehicle also needs to have substantial rim thrust available on each wheel to get out of bad situations, such as when one wheel drops into a hole, causing a body shift such that the center-of-mass projects largely onto the wheel down in the hole.

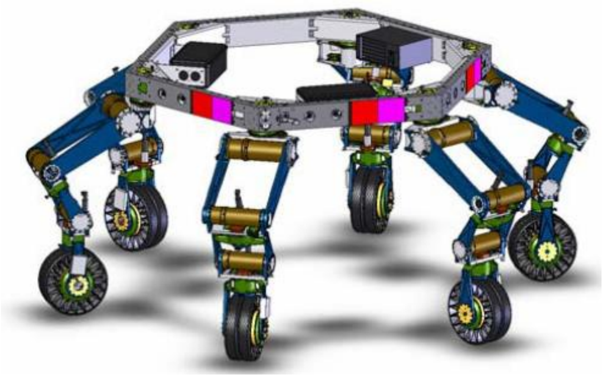

Fig. 1. ATHLETE Rover [1]

ATHLETE mainly consists following parts as shown in Fig. 1: (a)Hexagonal Frame, (b) Joint (Motor, Planetary gearbox, Encoders, Harmonic Drives, Bearings etc.), (c) Batteries, (d) Microcontrollers, (e) Cameras, (f) Rigid Links and Wheels.

ATHLETE is designed to travel at speeds of **5 km/h,** climb vertical steps of **1 m**, and carry payloads of up to **350 kg** in Earth gravity. Additionally, ATHLETE can fold into a flat ring, allowing for easier transport to the lunar surface, and is also capable of moving over extremely rough or steep terrain beyond the capability of any fielded vehicle. ATHLETE uses wheels on legs along with possible rappelling on a tether to accommodate this wide range of terrain. The vehicle uses wheels to roll over smooth terrain and also it can use the wheels as feet on the end of legs to achieve unprecedented mobility. One unique advantage of the wheel-on-leg ATHLETE concept is that it combines the high mobility of legged vehicles with the energy efficiency of wheeled vehicles. A second unique advantage of ATHLETE is that each of the limbs can be equipped with a quick disconnect tool adapter so that tools or general purpose manipulators can be affixed to the ends of the limbs.

For sensing its environment, ATHLETE has a number of stereo camera pairs. Each face of the hexagon has a pair (NavCams) that provides the long distance view required for tele operated driving. There are three more pairs (HazCams) mounted on the inner vertices of the hex that give visibility to the area below the robot and between the legs. Finally, some of the legs have cameras mounted above the wheels (ToolCams) that are designed to assist with the deployment and use of tools. For walking, they mainly rely on the HazCams because the NavCams do not see the ground within reach of the legs. Other sensors on the vehicle include an Inertial Measurement Unit (IMU) for pose measurement, and dual absolute and relative encoders on all the joints, which enable the calculation of torques.

II. LITERATURE REVIEW

M. Bibuli, M. Caccia, and L. Lapierre et al. (2007) In this paper author have discussed initial results of field tests of two prototype vehicles. This vehicle concept is capable of efficient rolling mobility on moderate terrain and walking mobility on extreme terrain. Each limb has a quick-disconnect tool adapter so that it can perform general-purpose handling, assembly, maintenance, and servicing tasks using any or all of the limbs.

These limbs can be used to pose the body while driving, walk as a secondary method of mobility, or interact with the vehicle's surroundings as manipulators. Each of the limbs is identical and is composed of the hip yaw, hip pitch, knee pitch, knee roll, ankle pitch, and ankle roll joints as illustrated in Fig. 2. (with dimensions in meters). At the end of each limb is a powered wheel that is used either for driving or for actuating tools during manipulation tasks.

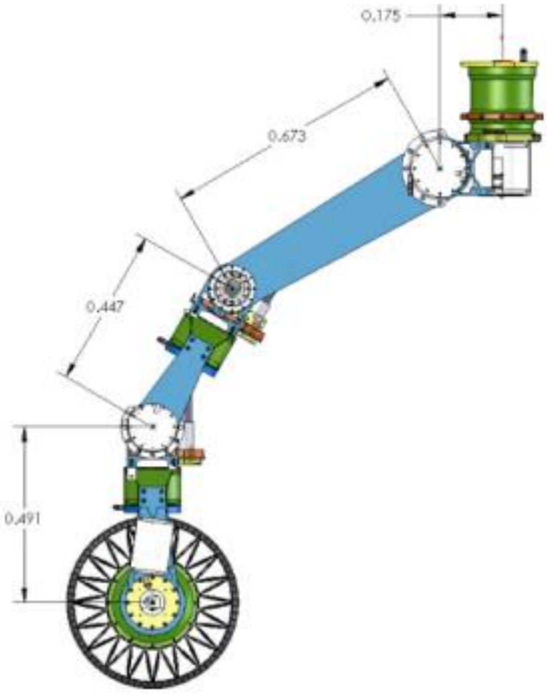

Fig. 2. ATHLETE Limb

Here each joint in the limb is composed of Maxon® "EC-max 40" 120 W (mechanical output) brushless dc motor with planetary gearbox as well as a power-off safety brake. This motor is then connected, through a coupling, to a harmonic drive gear to provide the high output torque necessary for each joint. The hip yaw and hip pitch joints both use a harmonic gear reduction providing 3060 Nm of torque before ratcheting. The knee pitch joint uses a harmonic gear providing 1476 Nm of torque. The knee roll, ankle pitch, and ankle roll joints all provide 994 Nm of torque. Fig. 3. shows a cross section of the hip pitch actuator of the joint design.

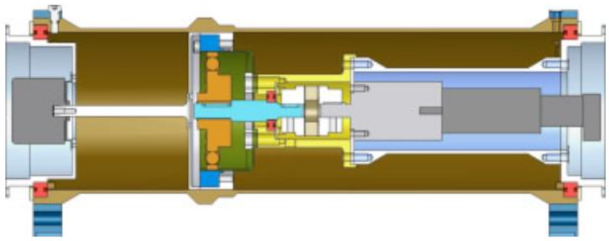

Fig. 3. Cross-Section of Hip Pitch Actuator

At the end of each limb, a quick disconnect tool adapter has been developed that allows the wheel motor to power any tool. Drill and gripper have been developed including many others. These tools have been extracted automatically from the "tool belt" and used for the different tasks, such as drilling holes in terrain, picking up moderate sized payloads, unspooling umbilicals etc.

One attractive implication of this is that landers could be made mobile by using ATHLETE limbs to stabilize them during landing while using airbags or crushable material under the launch adapter ring to absorb the primary impact energy. If landers are mobile, then there may be no reason to have separation interfaces to their payloads, because those payloads can be moved by the ATHLETE lander mobility system to wherever those payloads are needed.

M. Heverly and J. Matthews at al. (2008) This paper presents the design details and capabilities of this wheel–on–limb platform.

A. 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 size of the vehicle is limited by the inner diameter of the launch vehicle that will be used to transport it to the moon. As the length of the thigh is slightly less than the length of the hexagon face, which allows the thigh to be positioned directly under the face of the hexagon as show in Fig 3 the stowed configuration of the Vehicle.

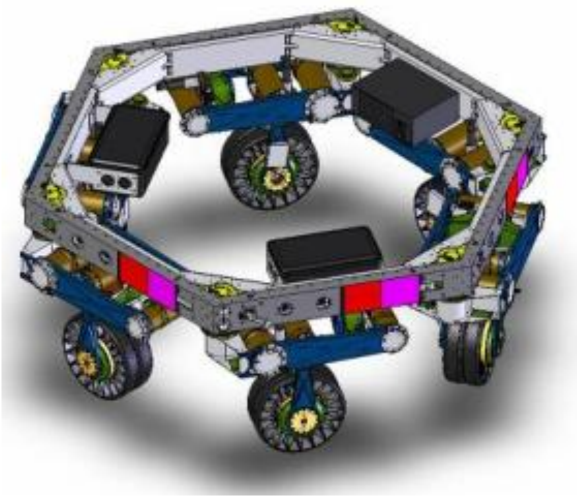

Fig. 4. The Stowed Configuration of the Vehicle

Now if we talk about the main structure of the vehicle is hexagonal ring with the hip joints attached at each of the six corners, here the hexagonal structure is welded aluminium c-channel with removable interior close outs.

B. 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. The wheel of the vehicle is made with the Michelin Tweel® shown in Fig 4. The Tweel® is a non-pneumatic wheel which mimics the performance and advantages of pneumatic tires without the disadvantages of an integral pressure vessel. 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.

Fig. 5. An ATHLETE Tweel Shown Deforming Over Uneven Terrain

C. 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 decisions since it will always have human supervisory control. Here for the visual sensing 15 set of stereo camera 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. 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.

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.

B. H. Wilcox et al (2010) In this paper an application of ATHLETE as Cargo Unloading from high deck is discussed, heavy compressive structures used to transport cargo in terrestrial mobile gantries Current analysis indicates that the structure mass of ATHLETE is only ~30% greater than a theoretically-optimal configuration such as SPIDER, but the ATHLETE configuration enables walking. Having seen the mass benefits that accrue to walking vehicles by virtue of their lighter wheels and wheel-drive assemblies, it is not surprising that the small mass penalty associated with putting structural members in bending instead of pure compression is overwhelmed by the mass advantages of walking over pure rolling. This is a special case of a more general result that human intuition, developed as it is in one Earth-gravity, can lead to preconceptions about lunar gravity that are simply not valid.

In ATHLETE is used for the Cargo unloading from High deck, here the system consists of two "Tri-ATHLETE" which is the second generation of the ATHLETE so these vehicles are docked together with a modular cargo pallet sandwiched between them. The Tri-ATHLETE concept allows ATHLETE to pick up and set down cargo pallets without needing to limbo out from under them. It will be done by splitting the hexagonal frame of ATHLETE into three pieces, a center rectangular interchangeable cargo pallet, and two triangular "wings" that each have three of the limbs attached. Here the main objective is to develop the system to the point where a cargo offloading demonstration could be conducted from a half scale Altair lander mock-up as shown in Fig. 6

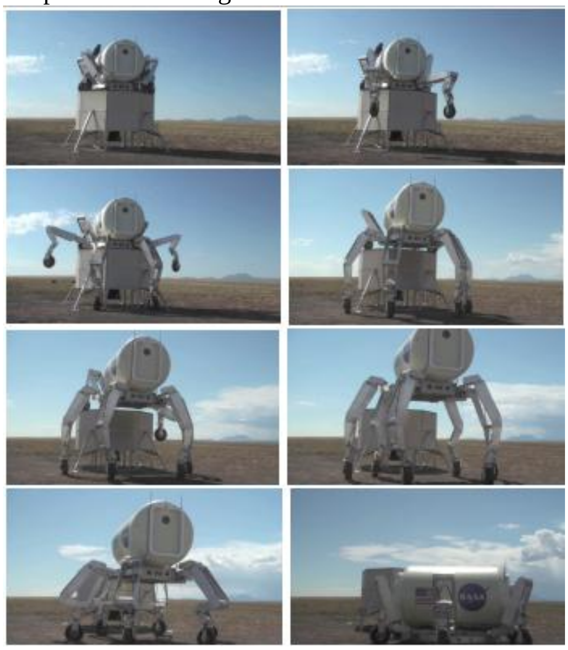

Fig. 6. ATHLETE Cargo Unloading Sequence

ATHLETE was conceived to be able to provide extreme terrain cargo mobility at very low mass. This mass savings results from having wheels and wheel drive actuators that are sized for nominal terrain instead of the worst terrain that will ever be encountered. If the rolling vehicle gets stuck (roughly once-per-day), it simply locks the wheels and uses them as feet in walking out of the extreme terrain. The resulting wheels and drive actuators are much lighter than those needed for a conventional vehicle. This mass savings more than makes up for the mass of the limb actuators, the "Tri-ATHLETE" concept allows ATHLETE to "embrace" a payload and "walk" it off the high deck of the Altair cargo lander, and to provide low-mass, extended range mobility for that payload, even over extreme terrain.

J. Townsend, J. Biesiadecki, and C. Collins (2010) here the author discussed ATHLETE's Mobility performance with active Terrence compliance The algorithm for active compliance uses onboard sensing to calculate updates in leg position to be applied during the drive. The algorithm makes use of joint position data from relative and absolute encoders, rate data from the wheel encoders, and the gravity vector reported by a deck mounted inertial measurement unit (IMU). Relative and absolute encoder data is used to estimate joint torques and wheel contact forces. Several aspects of vehicle state are evaluated independently for deviations from the desired nominal state and corrections are calculated to restore the nominal state for each case, that cases are Force Distribution, Deck Leveling, Deck Centering, Deck Height Management, Wheel Fork Orientation, Transverse Load Reduction, Wheel Speed Synchronization.

ATHLETE's onboard active compliance algorithm was first characterized in the JPL Mars Yard in late 2007. Fig 7. and Fig. 8 illustrate how the active compliance algorithm affects wheel reaction forces during driving activities. Fig. 7 displays the magnitude of reaction forces along each wheel's Z-axis as SDM-A drives 27 meters across flat, obstacle-free natural terrain in the JPL Mars Yard. In this test, the active compliance algorithm was not used.

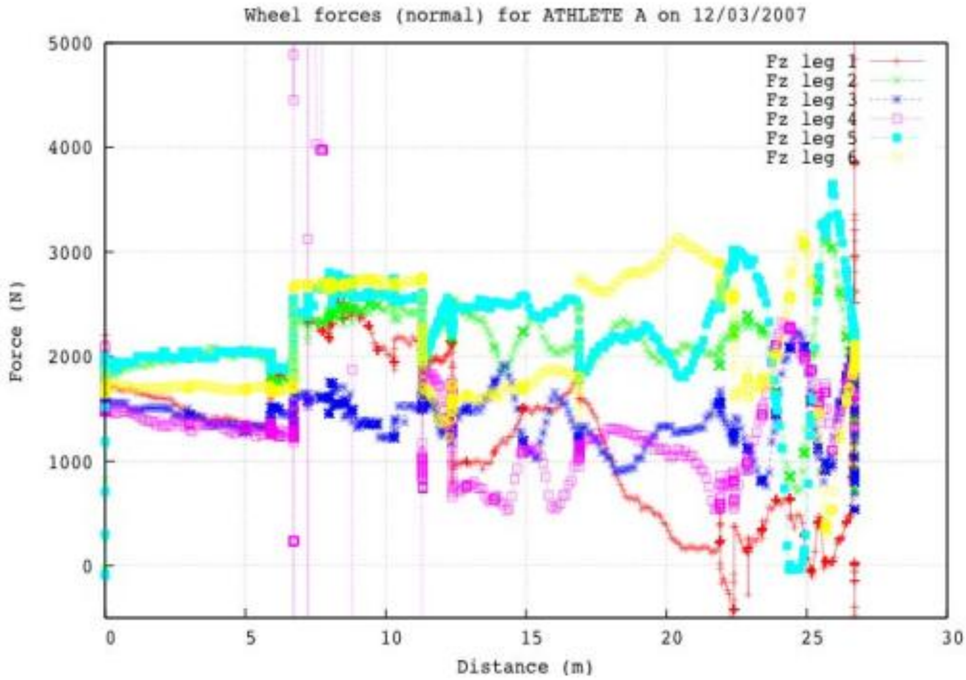

Fig. 7. Force distribution while driving without Active Compliance

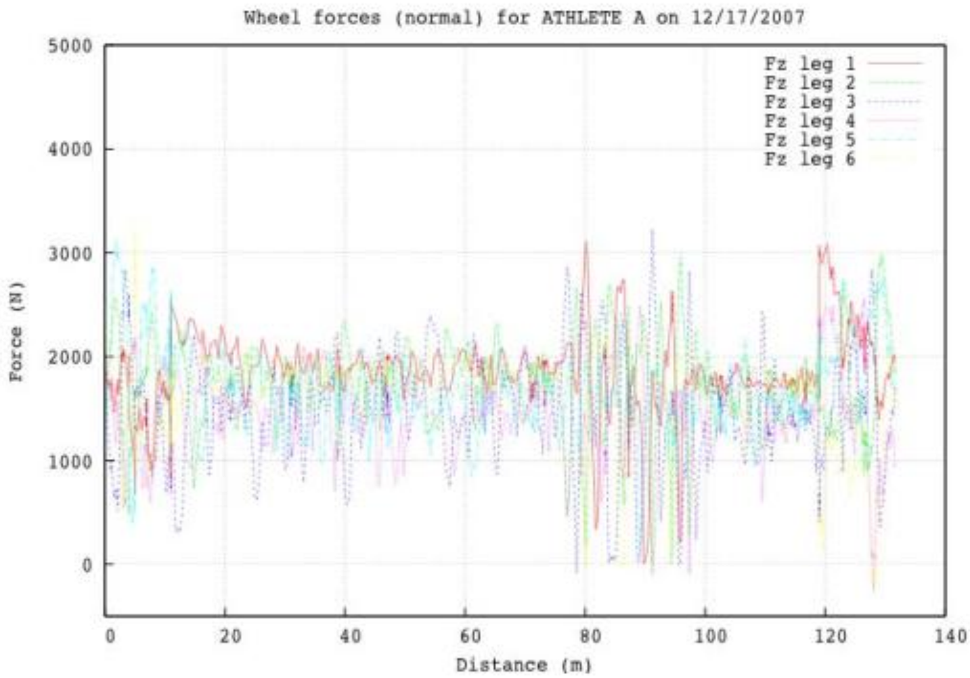

Fig. 8. Force Distribution while driving with Active Compliance

M. Heverly, J. Matthews, M. Frost, and C. Mcquin (2010) Here Tri-ATHLETE vehicle is the second generation of a wheel-on-limb vehicle being developed to support the return of humans to the lunar surface is discussed. This paper describes the design, assembly, and test of the Tri-ATHLETE robotic system with a specific emphasis on the limb joint actuators a novel and low cost approach to approximating flight-like cabling is also presented.

The second generation ATHLETE system stands 4.1m at full height and is approximately half scale of the conceived flight vehicle. This will allow for payload retrieval from the top of a 6.4m tall Altair Lunar Lander as outlined in the Constellation Lunar architecture. This also allows for a 3.5m diameter x 8m long cylindrical habitat that is potentially suitable as long duration living quarters for multiple crew members on the lunar surface. While the ATHLETE vehicle concept is highly scalable, the current ½ scale was chosen due to practical limitations of transporting reasonable payloads in Earth gravity. Each Tri-ATHELTE has a mass of 720 kg and the two Tri-ATHLETEs combine to have a payload capacity of 500 kg. For the lunar environment, the payload / vehicle mass fraction would increase drastically allowing the mass of the entire ATHLETE mobility system to be between 15 – 20% of the payload mass that it transports.

For the second generation of the robot, the cable harness is completely internal to the limb structure. This is implemented using essentially a round wire harness imbedded in a flat silicone extrusion. This technique, developed by Cicoil™, allows for the use of any combination of round wires, packaged in a flexible, flat ribbon arrangement. The harness is routed down along the limb and an internal cable spool is used to create a clock spring configuration with the cable that allows for the +/- 180 degree range of motion at each joint.

The current required for all joint motors can be as large as 100A, the power bus is implemented using 15 twisted and shielded 22-gauge wire pairs, connected to the main power system in parallel. These power lines are configured such that 5 pairs provide power the upper most actuators in the kinematic chain (Hip Yaw, Hip Pitch, & Thigh Pitch). The next five pairs of the 60V bus power the actuators in the lower portion of the limb (Knee Pitch, Knee Roll, Ankle Pitch, & Ankle Roll). The last five pairs power the wheel motor, which can consume 30A continuous and 60A peak current. In this way, the power axes can be stripped away from the main harness as the cable progresses down the limb, incrementally shrinking the width of the cable. A cross section of the cable harness is shown in Fig. 9.

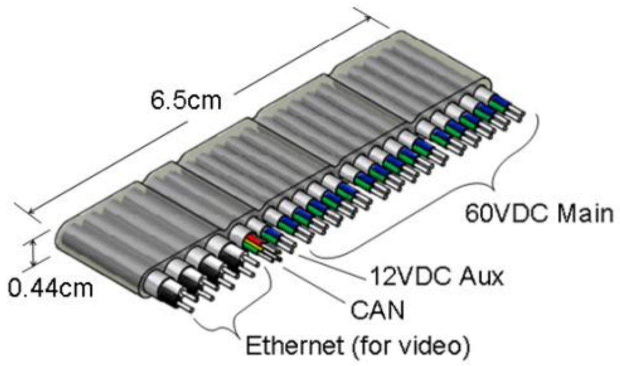

Fig. 9. Leg Harness Cross Section

The test demonstrated an initial set of capabilities for the vehicle, including demonstrating the offloading of cargo from a 3.2m tall mock lander, walking over obstacles over 1m tall, excavating soil using a backhoe tool attachment, and accumulating more than 6km of total traverse distance. This field test also highlighted the shortcomings and exposed some of the complexities of the system. All of these shortcomings, however, can be overcome and the Tri-ATHLETE system has proven to provide a unique capability of cargo handling and transportation, as well as tool use and payload manipulation that fits well within the current lunar architecture.

A. S. Howe and B. Wilcox (2016) In this paper author discuss that Using the All-Terrain Hex-Limbed Extra Terrestrial Explorer (ATHLETE) limbed robotic mobility system, the outpost site can be prepared in advance through leveling, paving, and in-situ structures. As a planetary surface outpost will likely consist of elements delivered on multiple manifests, that will need to be assembled from a scattering of landings. ATHLETE will be able to carry pressurized and non-pressurized payloads overland from the lander descent stage to the outpost location, and perform precision docking and assembly of components.

Here they have shown the assembly of outpost which consist of many process such as first of all comes the site preparation, here the key design feature of ATHLETE is that each of limb can serve as the general purpose robotic manipulators and those manipulators have tools such as Scoops, augers, grippers and other. Now after the assembly of outpost the next part is Lander Offload and Mobility here using ATHLETE Lunar surface systems are offloaded and then it is carried to desired location. And at last the outpost is build. A scenario for automated outpost build-up using the conventional approach would process as follow:

1. Mobility, construction equipment and power system are delivered.
2. Outpost site is smoothed and prepared, power system placed.
3. First habitat module is delivered, and carried to its location at the prepared site.
4. Subsequent landers deliver additional modules, which are sequentially docked to the first module to expand the pressurized volume.

ATHLETE is not just a heavy cargo carrier, but has multiple uses, including excavation, site preparation, lander off-load, cargo handling, tool manipulation, outpost constructor, paver, driller, and many other uses. These various uses have been demonstrated in the field using prototype hardware. As human mars mission are planned and executed, many of the challenges of the planetary outpost construction can be enabled by these demonstrated capabilities.

III. SUMMARY

This paper provides details about complex design concepts like Joint Design, Wheel Design, Structural Design, and Driving Electronics are discussed in papers related to these subjects. And later the applications of the ATHLETE are discussed in various lunar missions, how it can be used. It gives a wholesome approach towards rover design and will definitely be helpful to anyone working towards a complete literature review for any rover performing walking and rolling motions.

IV. ACKNOWLEDGMENT

I would like to thank Indian Space Research Organization for providing me this opportunity to study and understand the complexities and challenges of designing a rover for manned planetary exploration.

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