UNDERGRADUATE REPORT

Planetary Rover Hybrid Locomotion-System Design

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Having already proven their worth several times in extraterrestrial environments, rovers can be highly versatile and valuable machines. Previous rovers have been designed to transport astronauts and materials, perform strenuous tasks that an astronaut in a pressurized suit may be unable to do, analyze foreign substances, create virtual maps of regions, and serve as a life support platform to increase operational safety and chances of mission success. However, a successful rover design is often difficult to engineer and manufacture. Before a rover can be considered a valuable asset to mission success, it must be capable of operating in a variety of conditions and without requiring a great deal of human supervision. Specifically, it must be able to traverse irregular and treacherous terrain in a timely and efficient manner; it must be able to safely go where an astronaut can travel, and, in some cases, go and return from areas deemed too dangerous for human exploration. To do this, the rover needs an effective, yet simple locomotion system capable of crossing relatively flat terrain quickly and efficiently while also capable of adapting to rough terrain without undue difficulty. Inspired by the Jet Propulsion Laboratory's (JPL) All-Terrain Hex-Legged Extra-Terrestrial Explorer (ATHLETE) and the University of Pennsylvania's (UPenn) RHex, this paper proposes a simple experimental prototype locomotion system design that enables a rover to alternate between "walking" and "rolling" modes to successfully navigate variable and unpredictable terrain.

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I. Introduction

Although rovers have been used in planetary exploration before, limited capabilities due to developing technologies have generally shaped mission objectives. For example, during the Apollo 15, 16, and 17 missions a rover was used as a source of transportation for astronauts and supplies and allowed the mission to expand its exploratory and terrain-mapping capabilities with the added benefit of back-up life support.[1] However, because technologies such as autonomous operation were highly undeveloped, the vehicle functioned similarly to a large go-kart and could do little more. The locomotion system was simple and designed specifically for the lunar environment; it traversed using zinc-coated steel wire-mesh wheels and was driven by an electric motor capable of 10,000 RPM with a reduction ratio of 80:1. Unfortunately, while the system was very adept at handling soft, dusty terrain, it was unable to overcome large rocks or obstacles. Thus, it required constant attention from the operator (leaving him or her unable to perform even the simplest multitasks) and significantly limiting possible areas for exploration[1]. If the rover had been capable of operating on very rough terrain, the goals of the mission could have been grossly modified to include countless other operations.

In an effort to increase rover versatility and mission capabilities, the goal of this project is to design a mechanical locomotion system capable of aiding a Martian or Lunar rover in traveling over relatively flat terrain in a timely manner while also enabling the rover to traverse rocky terrain otherwise deemed uncrossable for standard 4-wheeled rovers. The mechanical system will then be implemented on a basic rover prototype to investigate overall potential for future development. Because prototype development is a main focus of this project, little time will be devoted to material optimization or final design practicality; instead much attention will be given to the system's mechanical ability to progress forward and over obstacles in a safe and timely manner.

Initial ideas for development were taken from JPL's ATHLETE, which can be seen in Fig. 1. The All-Terrain Hex-Legged Extra-Terrestrial Explorer is one of the most advanced robots ever developed for interplanetary exploration. Each of six, 7-DOF legs offers unrivaled mobility and dexterity, while the wheels on each foot provide an efficient method of timely transportation over relatively flat surfaces. ATHLETE is capable of moving at 10 km/hr over Apollo-like terrain, climbing vertical steps of at least 70% of the maximum stowed dimension of the vehicle, and climb slopes of 50 degrees on rock and 25 degrees on soft sand.[2] Unfortunately, along with these high levels of dexterity and versatility come a wide variety of complicated problems with complex motion planning. In fact, no one has yet been allowed in the same room as ATHLETE while the robot is operational because unpredictable motions present safety hazards.[3] Thus, the design presented in this paper seeks to find a compromise between performance and complexity; it attempts to present a locomotion system with significantly fewer degrees of freedom but with comparable abilities. Ultimately, the goal is to engineer a simple system using Vex© robotics parts that allows a rover to alternate between walking and rolling modes.

Figure 1. JPL's All-Terrain Hex-Legged Extra-Terrestrial Explorer with "walking" and "rolling" capabilities.[2]

The following sections present the work done on this project to-date. Sec. II tracks the evolution of the hybrid locomotion system; it will present reasons for design changes as well as references to other rovers that currently use a form of wheel articulation. Sec. III will discuss implementation results on a basic chassis design. It will review minor improvements made since the final virtual design. Sec. IV will then discuss the various algorithms that need to be developed to traverse different terrains. Conclusions and ideas for future work are presented in Sec. V.

II. Locomotion System Evolution

A. Wheel Articulation

After initial consideration, some form of wheel articulation was accepted for incorporation into the hybrid locomotion system design. The initial design was adopted from the Astronaut Support Rover that was designed at the University of Maryland. It can be seen in Fig. 2. The wheels are capable of rotating 360 degrees about the hip joint; the rover in Fig. 2 uses this capability to raise and lower the chassis to alter static and quasi-static stability features.[4] For the purposes of this project, the articulation capability is expanded to actually enable a rover to "step" over an obstacle lower then the hip joint or even help raise the rover up onto an obstacle higher than the hip joint. Renderings of an articulating hip joint locomotion system using Vex©

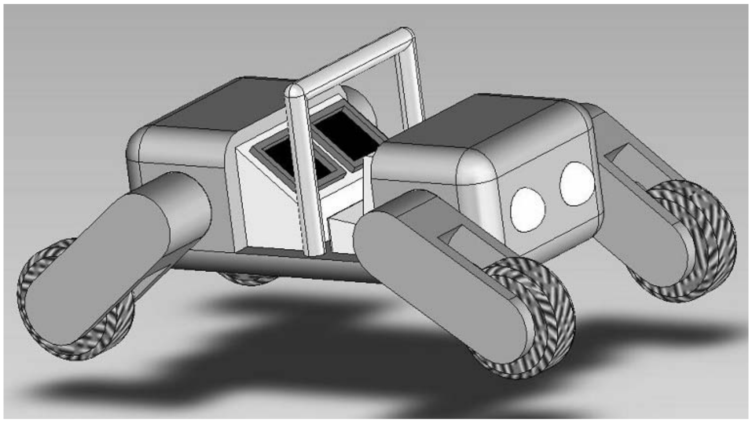


Figure 2. An Astronaut Support Rover Concept from the University of Marlyand's Planetary Surface Robotics Class demonstrating articulated wheel capabilities to improve stability.[4]

robotics parts can be seen in Fig. 3. Unfortunately 4-legged prototype designs using the locomotion system in Fig. 3 proved ineffective for smooth motion. Although the legs were capable of complete 360 degree rotation and could even lift the chassis over some obstacles, significant shifts in cg due to articulation often caused the rover to topple over. After analyzing

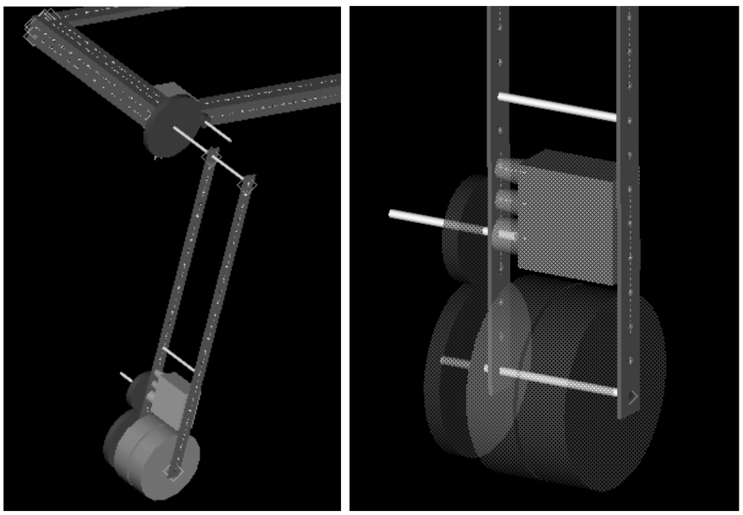
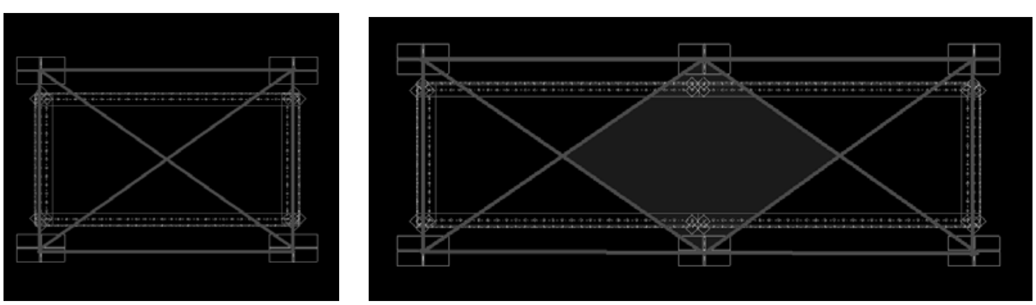


Figure 3. I-DEAS assembly of a possible articulated wheel system using Vex© components.

cg positions during articulation algorithms, it was decided that a hexapod rover was necessary. A basic summary of the cg analysis can be seen in Fig. 4. The green rectangles represent wheels (points of contact; POC's) and the purple represents a chassis. Assuming the quadruped



(a) **(b)**

Figure 4. (a) The quadruped rover with zero blue "safe cg" zone during articulation, and (b) the hexapod rover with a blue diamond region "safe cg" zone assuming an alternating wheel articulation algorithm is used.

configuration never articulates more than one leg at once, and that the hexapod configuration articulates alternating legs at once to create a triangle pattern, the blue region represents a "safe cg" zone. This means that in static conditions, the cg can rest anywhere within the blue region and the rover will be statically stable. Additionally, it must be noted that the current rover design masses in excess of seven lbs. More wheels contacting the ground provide more surface area over which to distribute the weight.[5] Thus, it can be seen that if articulated wheels are to be used, a hexapod configuration is entirely necessary and the quadruped configuration can be eliminated from the final design. Later cg analysis will be conducted to determine quasi-static stability once locomotion moments are known.

B. RHex

However, after initial prototype designs lacked smooth, efficient functionality, the awkward straight-legged articulated wheel locomotion design was abandoned as an effective "walking" mechanism. Instead, attention was turned towards a small, versatile, and robust hexapod named RHex. RHex can be seen in Fig. 5. By implementing a half-circle leg design capable of articulating 360 degrees about the hip, the robot executes a passive leg length change which offers an effective method for legged locomotion. As stated by its developers, RHex is the smallest and simplest legged robot that can effectively climb man-made stairs consistently and without difficulty.[6] Although it is unlikely that a rover will encounter stairs in an extraterrestrial

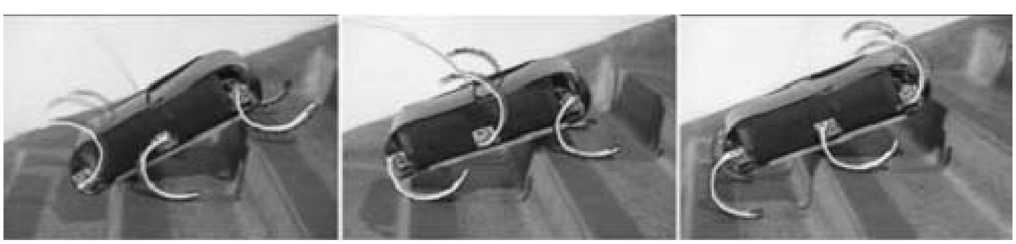
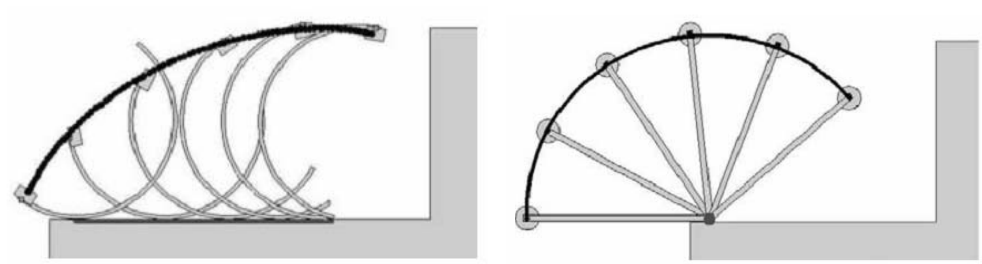


Figure 5. RHex climbing stairs using half-circle wheels with full articulation capabilities.[6]

environment, this attribute is especially appealing because it represents the ability to overcome obstacles of significant height relative to the rover. RHex is also thought to hold the current speed record for power autonomous legged locomotion. RHex has proven itself capable of



(a) **(b)**

Figure 6. (a) Visual representation of the half-circle legs' passive length change, and (b) motion path of the straight leg. The half-circle leg is more efficient.[6]

crossing grassy, rocky, sandy, even aquatic terrain.[7] Clearly, RHex's locomotion system is able to handle many different kinds of terrain; this is an extremely useful attribute for an interplanetary rover. Additionally, although rolling locomotion is accepted as a more efficient way of traveling than walking locomotion, the half circle legs offer a compromise between the two while retaining the ability to travel quickly over flat ground using a triangle configuration algorithm and the ability to traverse highly fractured terrain. A visual comparison of the motion of half-circle legs and straight legs can be seen in Fig. 6. These desirable attributes are largely accredited to the passive leg length change, and its ability to smoothly "step" a hexapod configuration forward because discontinuity in hip motion is significantly reduced. However, because rolling is still more efficient on flat ground than the locomotion system used by RHex, this project implements a hybrid motion system. The first prototype design capable of alternating between half-circle legs and wheeled locomotion is shown in Fig. 7. When on very

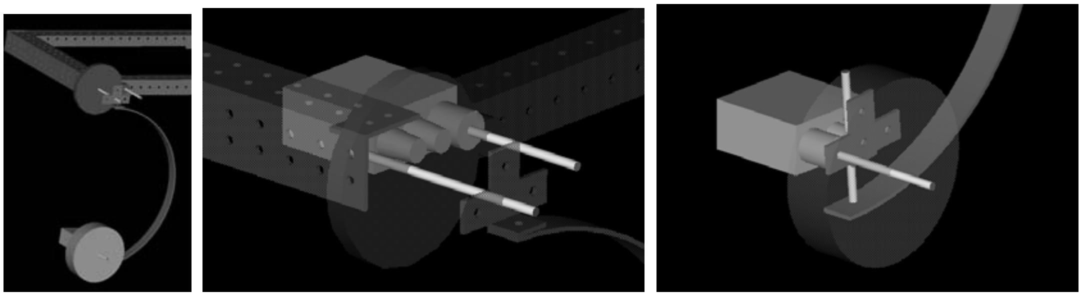


Figure 7. The second locomotion system prototype. The hybrid system incorporates half-circle legged locomotion and rolling locomotion.

smooth ground, the rover will use the energy-efficient rolling locomotion system installed at the tips of each curved leg. When rough terrain is encountered, the rover will simply lock the wheels and traverse using the half-circle legs in a manner similar to RHex.

C. Final Design

However, testing of the design presented in Fig. 7 showed that the weight of the motor on the end of the half-circle leg produced a great deal of counter-productive torque that resulted in excess strain on the motor at the hip joint. Additionally, the rover could only overcome very small obstacles of less than one inch when using the rolling locomotion system because the half-circle legs scraped the ground and impeded forward motion. Finally, the legged locomotion did not function smoothly because the wheels protruded beyond the tip of the leg; this protrusion caused hip motion discontinuity.

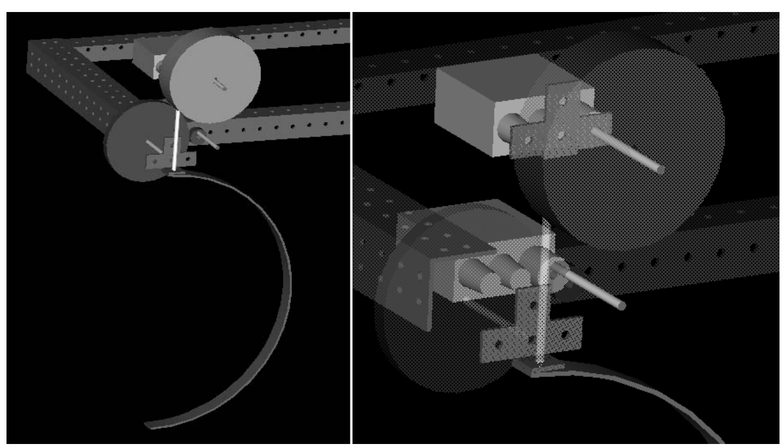
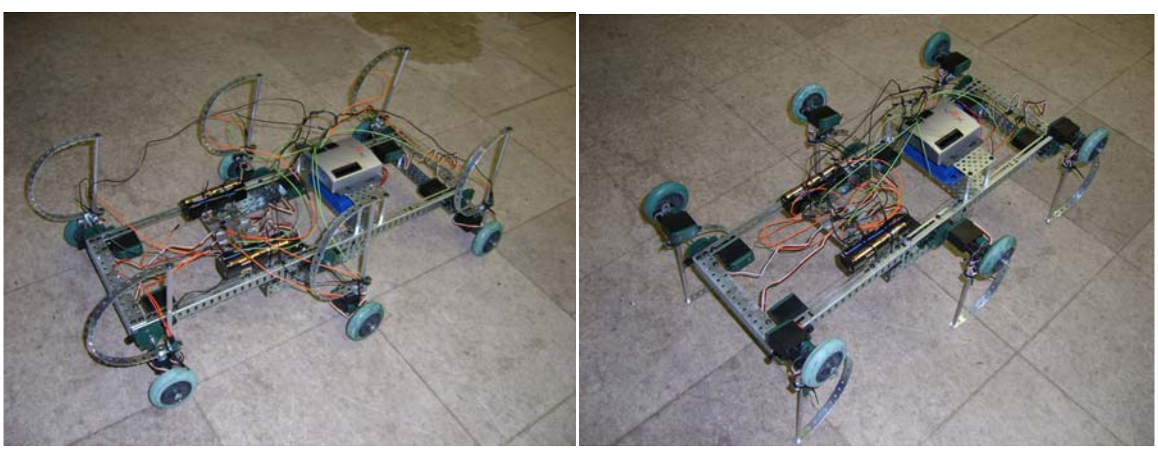


Figure 8. The final hybrid locomotion system design. The rolling and legged systems exist across from each other on a shared hip axis.

Thus, a final locomotion system design was assembled where the rolling system lies juxtaposed to the half-circle leg on a shared hip axis. This is shown in Fig. 8. Such a configuration offers several advantages. Firstly, by separating the two locomotion systems, they encounter minimal interference; the half-circle legs no longer cause the rolling system excess friction with the ground, and the wheels no longer cause hip motion discontinuity. Secondly, the two systems help create balance about the hip axis and reduce torque on the hip motor. Thirdly, this design significantly lowers the cg when using the rolling locomotion system. Although the cg is raised from the Fig. 7 prototype when using half-circle legged locomotion, it was decided that the other benefits outweigh this fact. Thus, in function, a rover will be able to alternate at will between the two locomotion systems by simply rotating all six hip joints 180 degrees simultaneously.

III. Rover Design

After the locomotion system's final design was approved for further testing, a simple chassis was constructed and fitted with the hybrid design. A Vex© Microcontroller was used to implement basic control algorithms written in EasyC, and several onboard power supplies were used to run the continuous motor modules. The entire rover is displayed in Fig. 9. After further



(a) **(b)**

Figure 9. (a) The rover in "rolling" mode using wheels, and (b) "walking" mode using half-circle legs.

experimentation, several features were changed from the I-DEAS assembly. Primary alterations include decreasing the length of the rod between the hip and the rolling locomotion system from three inches to two, decreasing the gear ratio at the hip from 1:5 to 1:3, adding hip joint and gear protectors on the underbelly of the rover, adding reinforcements to the half-circle legs, and extending the hip axel of the two middle joints to prevent interference between the six half-circle legs during articulation.

A. Basic Rover Characteristics

The rover is primarily constructed of Vex© zinc-plated steel parts. The gears and wheel hubs are plastic, while the wheel tread is comprised of removable rubber.[8] The blue battery pack visible in Fig. 9 under the microcontroller is designed by vex, while the two black onboard power supplies are 12-volt battery packs modified to output 9 volts each. The wiring system is homemade and follows a general color scheme in standard configurations: white/green is the PWM signal; red/orange is power; black is ground; green is extension. Each battery pack powers two motors and outputs approximately 160 mA at up to 9 volts. Each motor independently inhabits a separate PWM control port while in autonomous mode; while in RC mode, two or three motors will inhabit the same PWM control port for synchronization purposes. More statistics are available in Fig. 10.

Rover Length	25 in
Rover Height	10 in
Rover Width	14.5 in
Motor Stall Torque	6.5 in-lbs
Motor speed	100 RPM at 7.5 volts
Hip Gear Ratio	1:3
Max Speed Rolling	.4 ft/sec
Max Speed Walking	Unknown
Rover Mass	7.70 lbs

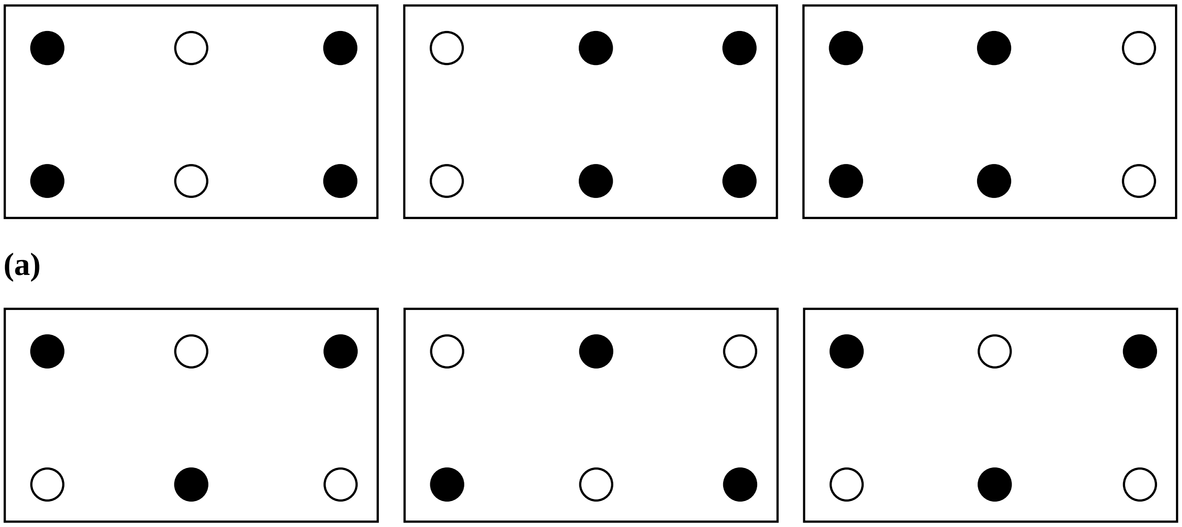
Figure 10. Basic rover characteristics.

B. Stability

Basic static stability calculations were performed for the current rover design. All calculations assume slippage is negligible and coefficient of friction is high enough to be disregarded. Thus, all constraints were geometrical and results were derived from cg positions relative to POC's. When in rolling mode, the rover is shown to be stable on up to 79 degree slopes when parked parallel, and 71 degrees when parked perpendicular. When parked in walking mode, which is highly unlikely due to the fact that there is a far greater chance of inherent instability than when in rolling mode, the rover is calculated to be stable on up to 61 degree slopes when parallel and 42 degrees when perpendicular. However, it must be realized that these numbers do not reflect situational factors such as friction. More reliable data should be obtained from experimentation.

IV. Control Algorithms

While rolling locomotion is a familiar topic, basic control algorithms for a wheeled motion system can be as simple as ensuring that the wheels are turning in the correct direction and at the desired RPM. While certain situations may call for more complicated variations, they were ignored due to the premature nature of this project. Also, mainly due to availability of parts and alloted time for design, steering while using the wheeled locomotion system is entirely differential. However, control of the legged locomotion system is much more complicated. In fact, under current circumstances the system is generally considered to difficult to control directly, and must opperate under the jurisdiction of pre-programmed control algorithms. Two possible algorithms already in use by RHex are displayed in Figure 11. The first demonstrates legged articulation in pairs. This is the algorithm used by RHex to climb stairs, and is effective for lifting a rover up onto plateaus. Stairs are ideal because they do not vary in size or shape;



(b)

Figure 11. (a) A possible climbing algorithm, and (b) a possible walking algorithm. Dots indicate legs; white dots represent legs in flight and black dots represent legs in stance. The algorithms progress from left to right.[6]

instead they are flat and the synchronized dual motion of the legs effectively keeps the rover balanced. The second algorithm allows the rover to advance over relatively flat terrain using an alternating triangle stepping method. As shown in Fig. 4, the cg stays within the blue diamond during the entire algorithm, and ensures static stability. In theory, if the terrain is known, a rover can be pre-programmed to traverse it without using any external sensing motion planning. However, this is not a luxury planetary rovers often encounter, especially if the mission is for exploratory purposes. Thus, if this motion system were to be implemented on an exploration rover, an advanced sensing and motion planning system would need to be developed. Half-circle legs are not widely used, so their previous applications and algorithms have been basic. However, their potential to actuate independently as directed by an external sensing motion planning system are largely untapped and must be researched further. Unfortunately, time constraints currently inhibit the adoption of a control algorithm for the legged locomotion system. Motor synchronization is essential for successful algorithmic planning, and the current Vex© motors do not operate at a high enough fidelity to ensure predictable motion. Thus, the current rover design is limited to wheeled locomotion until a solution is developed to the synchronization problem.

V. Conclusion

Although the hybrid locomotion system is not currently functional, it shows potential for significant improvement. The general geometrical design of each leg and wheel assembly shows promise and functions well independently. Ignoring synchronization, the rover is capable of alternating between the two locomotion systems without significant difficulty. Results from general research and RHex indicate that wheeled locomotion and half-circle legged motion are both effective means of transportation; the hybrid locomotion system design is an excellent research tool to determine which is more efficient and effective in various situations.

Future work could initially include determining a method for strengthening the hip joints and for counting rotations of each leg to increase synchronic fidelity. Once this is accomplished, an analysis of power consumption should be performed under various situations to determine when each locomotion system should be used. Then, a unifying software control package should be integrated into the system and include external sensing motion planning algorithms.

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