# ATHLETE Mobility Performance in Long-Range Traverse

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**The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) is a modular mobility and manipulation platform being developed to support NASA operations in a variety of missions, including exploration of planetary surfaces. The agile system consists of a symmetrical arrangement of six limbs, each with seven articulated degrees of freedom and a powered wheel. This design enables transport of bulky payloads over a wide range of terrains and is envisioned as a tool to mobilize habitats, power-generation equipment, and other supplies for long-range exploration and outpost construction**

**As a milestone for the 2010 fiscal year, ATHLETE demonstrated the long-range traversing capability of the wheel-on-limb concept. ATHLETE was subjected to eight weeks of traverse testing and demonstrations over rolling natural terrain at two distinct field locations: Hahamongna Watershed Park in Pasadena, CA and the Black Point Lava Flow region north of Flagstaff, AZ. During this period, ATHLETE traversed more than 80 km in total distance, increasing the cumulative traverse distance of all ATHLETE prototypes almost tenfold. This paper evaluates the mobility performance of ATHLETE during these long-range traverses and discusses recent upgrades to the onboard driving algorithms to improve traverse speed and efficiency.**

## I. Introduction

The All-Terrain, Hex-Limbed, Extra-Terrestrial Explorer (ATHLETE) is a multi-functional mobility and manipulation concept envisioned to support NASA activities in a variety of space environments. The ATHLETE platform is a flexible robotic system consisting of a hexagonal platform supported by six articulated robotic limbs, each of which can terminate in a wheel for mobility on planetary surfaces or a variety of tools for operations in low-gravity environments.

When configured for surface mobility, with six wheels each on the end of an articulated limb, ATHLETE can negotiate a wide range of planetary surfaces. On benign terrain, the wheels enable driving to efficiently cover long distances. When the surface is too soft, steep, or rough for driving, the limbs are used for walking, permitting extraction from embedding and mobility progress through areas impassable to most wheeled rovers.

To demonstrate the ATHLETE concept, the Jet Propulsion Laboratory (JPL) has designed and constructed several prototype vehicles, referred to as Software Development Models (SDM). The primary platform for traverse demonstrations is the 2nd-generation ATHLETE prototype, built in 2009 and referred to as SDM-T12.[1,2]

SDM-T12 consists of a pair of triangular three-limbed platforms called Tri-ATHLETEs which, when joined by a cargo pallet, form the hexagonal six-limbed system shown in figure 1. Sized to perform demonstrations at approximately $\frac{1}{2}$ lunar scale, it stands to a maximum height of just over 4 m and carries a payload of up to 450 kg on Earth. Each limb has 7 degrees of freedom (DOF), six for precise positioning and one redundant pitch actuator to enable each limb to stow compactly.

Because ATHLETE's wheels are on limbs rather than a passive suspension system, the ATHLETE prototypes have limited ability to comply to changes in terrain while driving. To compensate for the lack of passive compliance, ATHLETE's limbs are used as an active suspension system. An onboard software algorithm controls limb position in response to changes in estimated ground contact forces. This method of

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active compliance to terrain has been demonstrated to be effective in maintaining an even loading distribution amongst the six limbs when traveling over rolling, rutted, or sloped terrain.[3]

In previous demonstrations and test activities, ATHLETE's driving capability was tested over modest distances of a few kilometers and at ground speeds that rarely exceeded 1 kilometer per hour (kph). A 2010 milestone for the ATHLETE project was to demonstrate ATHLETE's capacity as cargo transporter on a long-range, cross-country traverse. In particular, ATHLETE's was required to perform a 20 km traverse through desert terrain in under seven days. The sections that follow detail ATHLETE's long-range driving performance in the completion of this milestone and related test activities.

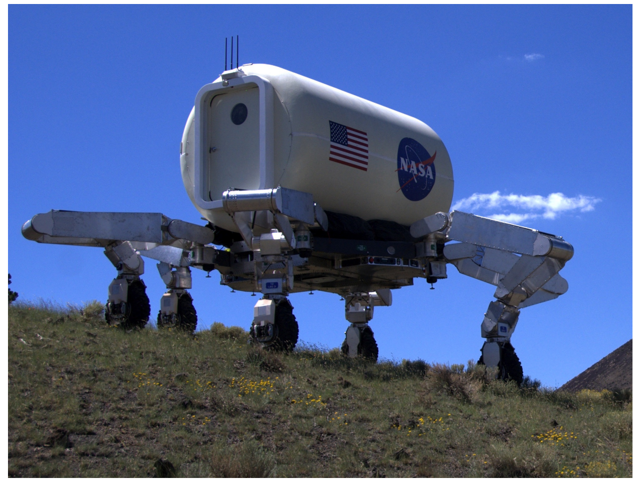



**Figure 1. ATHLETE prototype carrying a $\mu$Hab simulated cargo element during traverse testing at Black Point Lava Flow, AZ, September, 2010.**

## II. System Improvements for Long-Range Traversing

Prior to FY2010, most ATHLETE milestones focused on demonstrating the platform's ability to manipulate cargo and surface materials, including offloading of cargo from landers, precision alignment of cargo for mating, and the use of end effector tools for anchoring, scooping, inspecting, and lifting. To outfit SDM-T12 for long-distance traversing, several upgrades were made to the robot and its supporting operations interface.

### A. ATHLETE Hardware and Software Upgrades

SDM-T12's mechanical system was upgraded for greater strength and robustness to driving loads. The ankle pitch joint and wheel mounting hardware, inherited from the lighter first-generation ATHLETE prototype, were identified as weaknesses during field testing in 2009. Carrying the increased weight of SDM-T12 caused several degrees of backlash in the ankle pitch joints, introducing large errors in the wheel loading estimate, which depends on accurate knowledge of joint positions.[4] For the 2010 demonstration the ankle pitch joints and wheel forks were redesigned for better compatibility with the mass and strong upper limbs of SDM-T12. In addition, motor controller gains were tuned to improve joint position tracking performance in configurations requiring high torque.

A key upgrade to the ATHLETE onboard software in FY2010 was the implementation of inverse kinematics for the 7-DOF limbs. The 7-DOF limbs were new in summer 2009 and the inverse kinematics software handling the new redundant degree of freedom was suboptimal. Coordinated motion was limited to six joints at a time, locking the excluded joint during motion. Several combinations of joints were possible, but understanding and handling the limitations to limb range of motion made operation difficult.

To support long-range driving and improve all robot activities, an inverse kinematics solution was implemented to enable use of all seven joints in coordinated motion. Analysis showed that a simple solution would be very effective. Building upon a reliable 6-DOF inverse kinematics solution from the first generation prototype, the new algorithm used a heuristic to select an angle for the redundant thigh pitch joint, then solved for the other six joints using the legacy algorithm. The heuristic for selection of the thigh pitch angle was a simple linear interpolation and employed the same method used by the active compliance algorithm for calculating many pose corrections.[3] In the case of the thigh pitch position, the interpolation was between a fully folded thigh pitch, $-180°$, for a wheel close to its hip pitch joint, and a fully extended thigh pitch, $0°$, for a limb at full extension. Figure 2 shows an ATHLETE limb for reference, and highlights the thigh pitch joint.

While the onboard algorithm for active terrain compliance performed well in previous testing, two upgrades improved its behavior for long traverses. One change disabled the reinforcement of wheel pitch and roll orientation prior to the start of an active drive. This action required coordinated motion of all joints in all limbs, and unbalanced wheel loading from the preceding motion frequently resulted in stalled joints. Since the active compliance algorithm continuously reinforces wheel orientation while driving, when continuous force balancing reduces the incidence of uneven loading, disabling the pre-drive reinforcement reduced failures without affecting performance.

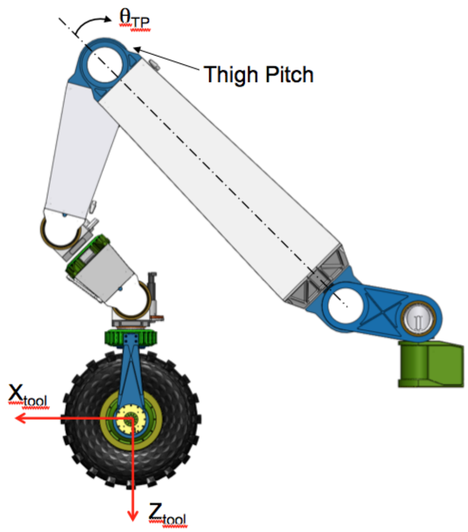



**Figure 2. Diagram of an ATHLETE 7-DOF limb. The tool frame is a right-handed coordinate frame with its origin located at the center of the wheel hub.**

The second change addressed the gradual migration of each wheel away from its nominal drive position due to repeated limb and body repositioning in compliance to terrain. Left unregulated, the wheels continued to migrate until the overall position change resulted in a stall, torque, or reachability error due to adverse kinematic positioning. Negative effects were typically observed after drive distances on the order of 100 m, and manually correcting limb positions at this frequency was frustrating and time consuming. To address the issue, the algorithm was upgraded to autonomously monitor and correct wheel positions in the normal course of the traverse activity.

### B. Upgrades to the Operator Interface

One of the greatest limitations to long-range driving with the ATHLETE prototypes was the operational infrastructure, which prevented vehicle motion without direct communication with the operators at base camp. This characteristic was a design feature intended to prevent an SDM from driving while not under the direct control of an operator. Permitting SDM-T12 to traverse out of the direct communication link required changes to this operations concept to preserve the safety feature without requiring the direct link to camp.

As a solution to this challenge, the interface team introduced the Portable Operations (PortOps) console. This new interface permitted a local operator to control ATHLETE via a handheld computer and joystick combination. The loss-of-control safety feature was transferred to require communication with PortOps rather than the base camp consoles, allowing a local operator to safely continue traverse in the face of a broken communication link to the remote operators.

## III. Traverse Environments

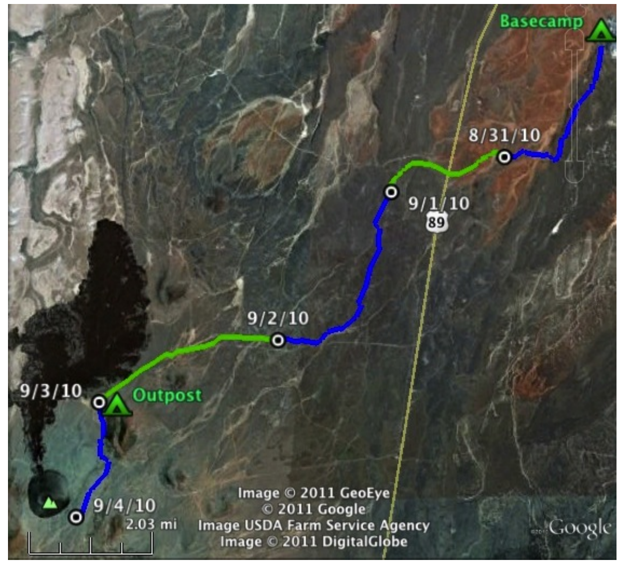
The ATHLETE traverse milestone in FY2010 was a traverse of 20 km across desert terrain and lava flows from the D-RATS Base Camp site to the simulated lunar Outpost site. ATHLETE's traverse route is shown in figure 3(b). The D-RATS timeline dictated a round trip from Base Camp to Outpost and back within 14 days, with a desired performance metric of 5 km per day.

A major challenge in preparing ATHLETE to complete this traverse milestone was finding a place to test and debug SDM-T12's traversing capability before the field demonstration. The Jet Propulsion Laboratory, located on a hillside in a densely populated suburban area, has several test areas for robotic mobility, both indoors and outdoors, but none of sufficient size to accommodate traverses of more than 50 m for a robot of SDM-T12's size.

After unsuccessfully searching the laboratory grounds for a suitable testing venue, the ATHLETE team approached the City of Pasadena to request use of Hahamongna Watershed Park for this purpose. Because Hahamongna Watershed Park is a busy community park and home to several protected plant species, the ATHLETE team received permission to test the robot on specified graded dirt service roads within the park, where the robot's size could be accommodated with minimum impact to endangered plants. The approved route, shown in figure 3(a), covered approximately 2 km of service road. A trip out to each point of the permitted route and back resulted in a round-trip traverse distance of approximately 4.8 km.

In the Park, ATHLETE traversed primarily well-graded dirt roads. While some road sections were flat and straight, others curved around collection pools with shallowly rolling peaks and valleys. The roads were generally free of ruts and obstacles, easier for the robot to comply to than the bumpy scrub plains and


(a) Map of ATHLETE test route in Hahamongna Watershed Park, Pasadena, CA.




(b) Map of outbound traverse by ATHLETE SDM-T12, Black Point Lava Flow, AZ, 2010. The path shown was reconstructed from robot GPS data.

**Figure 3. Maps of ATHLETE traverse routes**

rocky lava flows of Black Point. This enabled traverse at fairly high speeds in the straightaway sections. Navigation on the curved sections of road, however was challenging for the operators, particularly where the road scarcely accommodated SDM-T12's width.

The only major variations in terrain along the route were the sloped access roads that approached the watershed crossing and the crossing itself. The slopes were helpful in preparing both robot and operators for ascents and descents of lava flows expected in Black Point. The watershed, filled with silt from torrential flooding the preceding spring, was soft enough to embed our two-wheel-drive chase vehicles.

In contrast to the Park, terrain at Black Point Lava Flow was significantly rougher, forcing a slower ground speed to negotiate terrain features like rocks, vegetation, and runoff channels. When ascending and descending lava flows, while the slopes were similar to the Park's watershed access, some were covered with dense deposits of 10-30 cm rocks that made them more difficult to navigate.

## IV. Traverse Performance

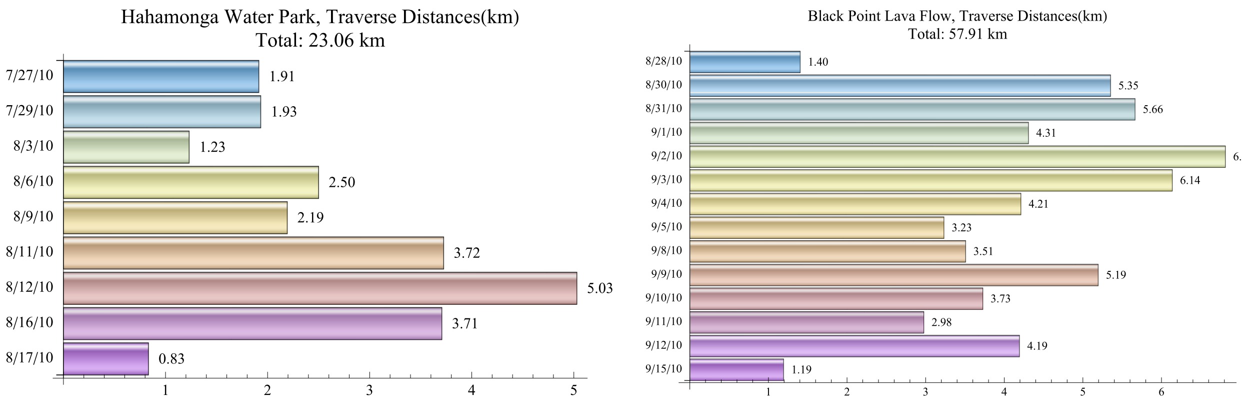
### A. Traverse Distance

ATHLETE met and exceeded all distance milestones and traversed a total of 82.5 km, 23.1 km in Hahamongna Watershed Park and 59.8 km at Black Point Lava Flow. Distances traveled during each day of testing or demonstration are shown in figure 4. To improve clarity in the charts, data for days with traverses of less than 1 km have not been included in the Black Point Lava Flow figures. Not shown are 0.6 km on September 6, 0.39 km on September 13, and 0.91 km on September 16, a total of 1.9 km.

In the milestone demonstration at Black Point Lava Flow, ATHLETE reached the Outpost location in four days of traverse, averaging over 5 km per day. Figure 3(b) shows ATHLETE's traverse path from Base Camp to Outpost as reconstructed from onboard GPS data. On the fifth day, ATHLETE traversed 4.21 km beyond the milestone to rendezvous with the Space Exploration Vehicles[5] from Johnson Space Center at their overnight location.

### B. Traverse Speed

Figure 5 shows the average traverse speeds for each day of testing at both Hahamongna Watershed Park and Black Point Lava Flow. The average speeds were calculated by comparing the total distance traveled to the time spent traversing. Stationary intervals of more than 10 minutes were excluded from the calculation

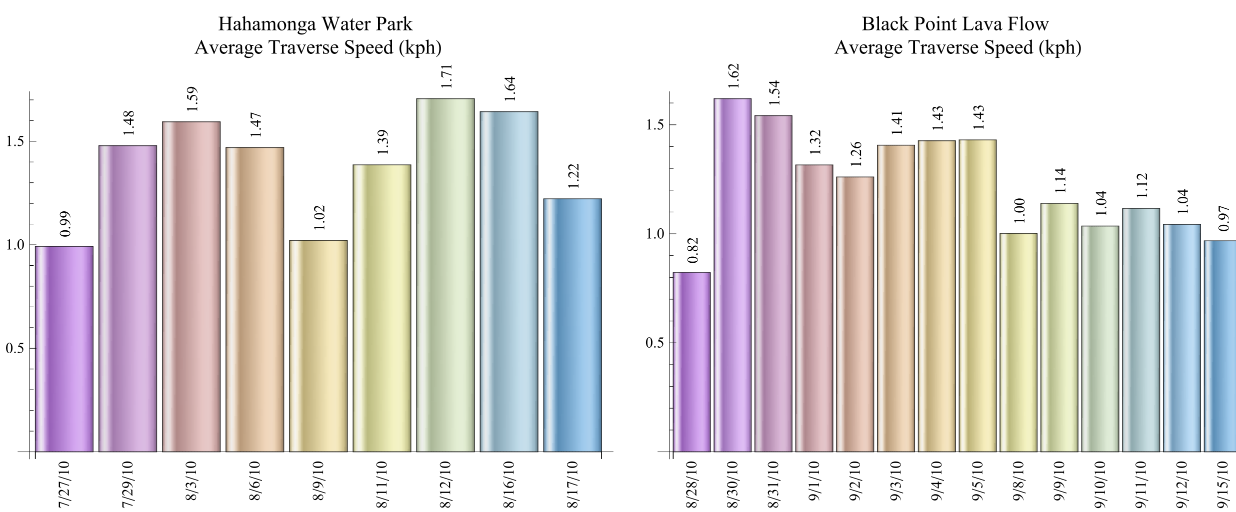



(a) (b)

**Figure 4. Distance traversed by ATHLETE in each day of testing or demonstration.**

of traversing time to avoid including long downtimes for operator breaks, refueling, or equipment repairs in the speed calculation.

The average speed of traverse varied with the terrain and the planned activities on any given day, but typically ranged between 1 kph and 1.5 kph. At Black Point Lava Flow, daily traverse speeds of around 1.5 kph for the first week dropped to 1 kph during the second week. This was the result of a decision by the operations team, upon discovery of a mechanical weakness in the knee pitch joints, to reduce stresses on the system by driving more slowly.




(a) (b)

**Figure 5. Average traverse rates for each day of testing. Pauses in motion of over 10 minutes are excluded from the rate calculation.**

While overall traverse speeds rarely exceeded 1.5 kph, ATHLETE's rate of travel while driving was significantly faster. As figure 6 shows, the vast majority of distance traversed at both sites was covered at speeds of 1.5 kph or higher. This remarkable disparity highlights a lack of efficiency in driving operations.

Efficient driving operations were hampered by frequent pauses from a variety of sources. At the root of the problem was a characteristic of the drive software that limited commanded motions to no more than 50 m in length. In the absence of errors, ATHLETE paused at least 20 times per kilometer as a result of this distance limit. In addition, the software often brings the robot to a complete stop to execute a change in heading or steering angle.

This limitation was compounded by a variety of errors that frequently stopped ATHLETE short before 50 meters could successfully complete. Spurious communication losses between the PortOps controller and the robot were frequent and triggered the loss-of-control safety feature. PortOps also employed a deadman's switch to stop the robot if the joystick controller was dropped. It was common for an operator to lose contact with the deadman's switch accidentally while shifting his or her grip on the joystick.

Hardware idiosyncrasies were another source of stopped drives. Actuator stalls and motor controller errors were significantly reduced as a result of the testing in Hahamongna Watershed Park, but a few lingering issues continued to crop up during the demonstrations at Black Point Lava Flow.

Finally, PortOps is very sensitive to small variations in operator inputs, making it difficult to command motion in the desired direction on the first attempt, particularly for slight heading adjustments. As a result, it was typical to abort several command attempts before achieving the desired result, further extending the pause before traversing resumed.

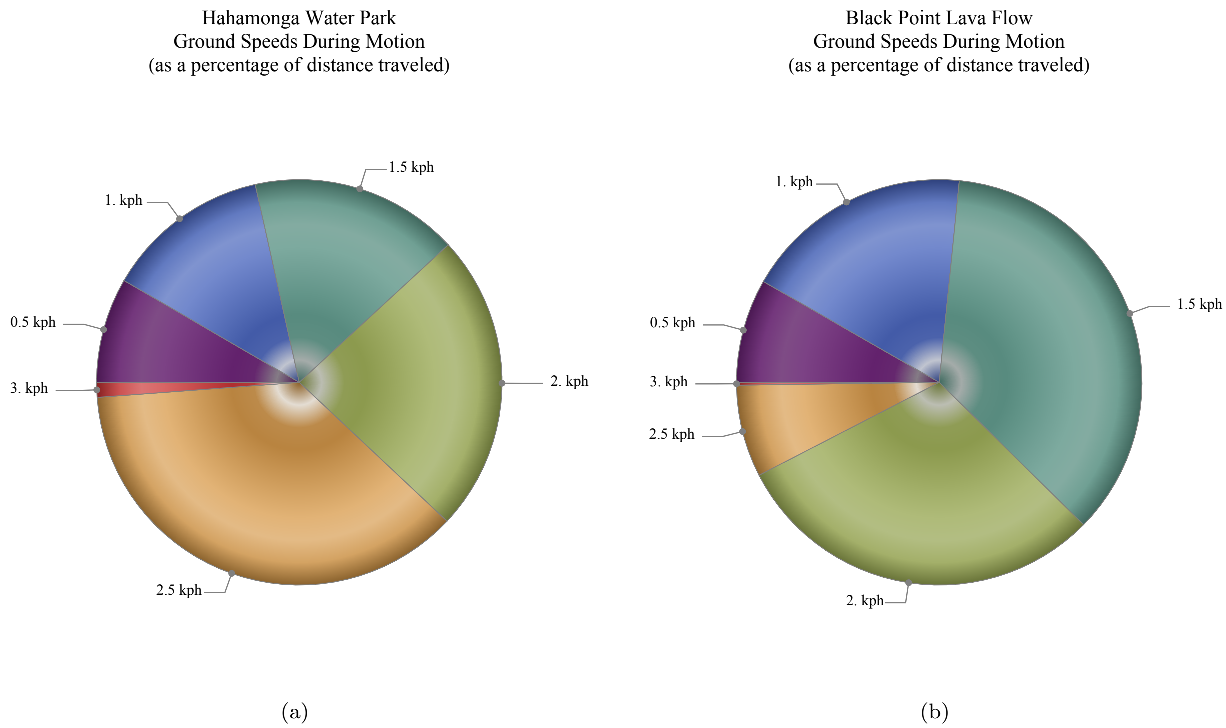



**Figure 6. ATHLETE ground speed during traverse. The section size represents the percentage of total distance traveled at each ground speed.**

All this stopping adds up to a lot of idle time, as illustrated in figure 7, which directly compares the time in motion to the time spent paused during each day's traverse. Pauses of more than 10 minutes are excluded, so the idle time shown excludes stops for breaks or repairs and represents time lost when ATHLETE was intended to be making progress.

The data in figure 7 shows improvement in traversing efficiency over time. As operators gained experience with the system and the drive interface and as system issues were identified and fixed, efficiency improved. However, even during the most efficient driving at Black Point Lava Flow, over 30% of traverse time was spent idling, and in general the idle time is over 40%.

## C. Active Suspension Performance

The main objective of the ATHLETE's active compliance algorithm is to distribute the robot's weight evenly over all six wheels. Figure 8 shows the mean normal force, along the $Z_{tool}$ direction as illustrated in figure 2, seen by each wheel during each day's traverse, with $\frac{1}{4}\sigma$ variation in loading represented by the radius of each dot. The clustering of each day's six dots indicates an even weight distribution across all wheels. Some variation in loads is expected, due to errors in the force estimation on the order of $10^2$ Newtons and corresponding hysteresis in the active compliance algorithm.

It can be observed from figure 8 that the normal forces observed at Hahamongna Watershed Park were lower than those seen during testing at Black Point Lava Flow. ATHLETE was actually heavier at Black

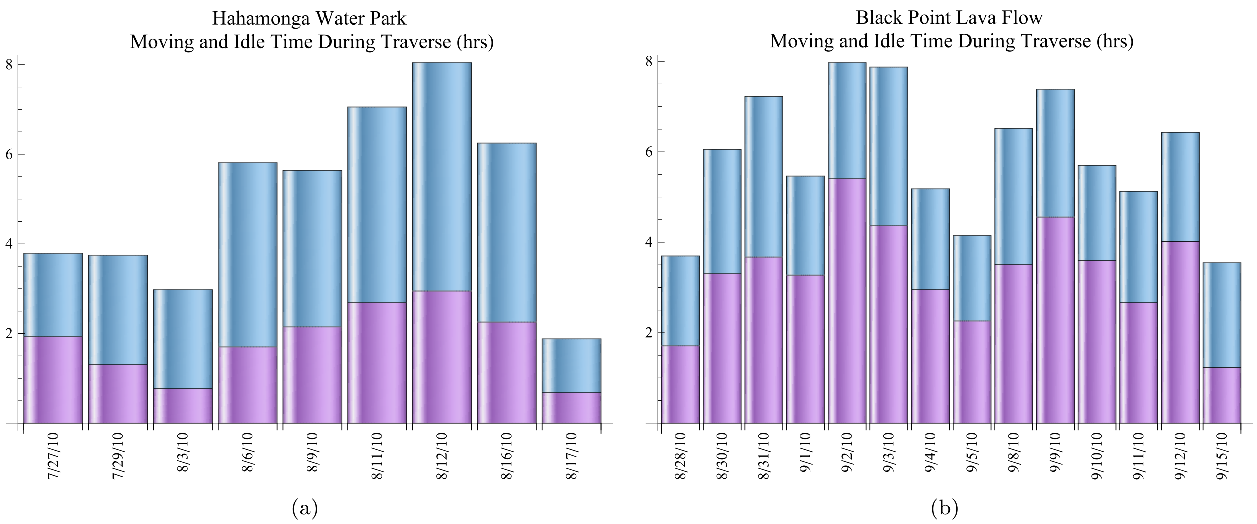



**Figure 7. Comparison of vehicle-in-motion time during traverse to idle time. The lower portion of each bar represents time ATHLETE was moving. The upper portion of each bar represents time spent in pauses of less than 10 minutes while traversing.**

Point, carrying foul weather gear and a collection of tools for field repairs. The magnitude of the observed forces are unimportant in the scope of active compliance as long as the forces are distributed evenly. Even on September 3, when the mean forces are unusually low due to poor zeroing of the force estimator during a large portion of the day's traverse, the clustering of mean normal force on each wheel is consistent with expectations.

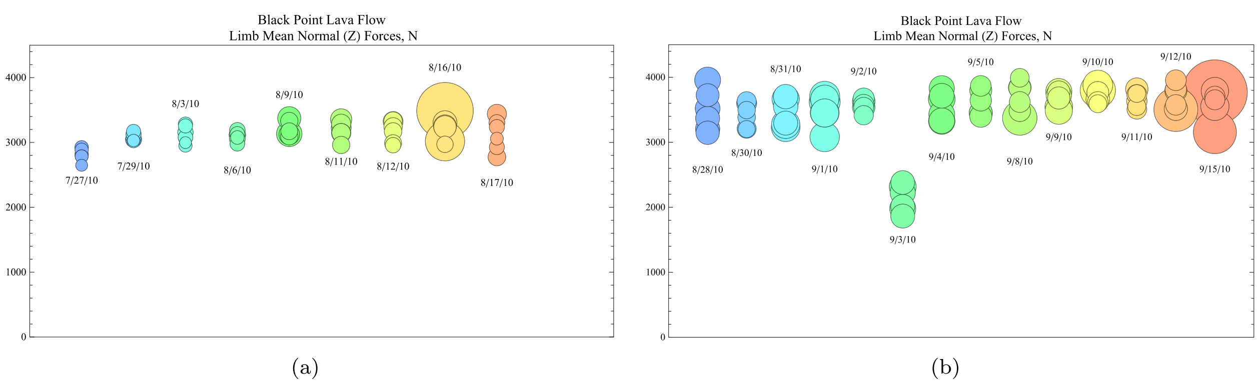



**Figure 8. Mean normal forces on wheels during traverse. Bubble radius represents $\frac{1}{4}\sigma$ variation.**

Figure 9 Shows the mean horizontal loading on all wheels for each day of traverse. Transverse loading, perpendicular to the direction of motion, is shown in (a) and (b), while loading of wheels in the drive direction is shown in (c) and (d). The green and blue bars represent the mean loading averaged over all six wheels for each day's traverse, and the error bars illustrate the $1\sigma$ variation in loading observed from the data. Ideally, forces in both of these directions are controlled to zero by the active compliance algorithm.

In the case of transverse loading, the data shows that ATHLETE was able to keep loads in this direction near zero very successfully in the graded, regular terrain of Hahamongna Watershed Park, but had more difficulty in the varied, rocky terrain of Black Point Lava Flow. It appears that this portion of the active compliance algorithm is sensitive to the interaction between tires and terrain. On September 11, the mechanical team removed SDM-T12's standard tires to test a set of prototype lunar tweels. It is probable that this change, and the associated change in wheel to ground interaction, contributed to the large $\sigma$ in transverse loading on that day.

In the drive direction, along the $X_{tool}$ direction as illustrated in figure 2, average wheel loading deviated more from zero than can be accounted for by force estimate uncertainty during both Hahamongna Watershed

Park and Black Point Lava Flow tests. Observations by ATHLETE operators concurred that drive direction loading on wheels was not handled effectively by the onboard algorithm. In fact, the algorithm reacts to drive direction loads only indirectly, lifting wheels only in response to the normal component of the load. This is viewed as a critical oversight by the team and is a high priority for upgrade.

In both horizontal loading directions, the data shows larger standard deviations in the Black Point Lava Flow traverses in the later days of the test. On September 8th, the controlling parameters of active compliance were adjusted in an attempt to reach a new balance between efficient drive speeds and vehicle safety. It is interesting to note that the $1\sigma$ values roughly doubled for all traverses after this date. This implies that horizontal loading components should be considered when tuning the active compliance algorithm. Focusing solely on the performance at balancing normal forces may not be appropriate or safe.

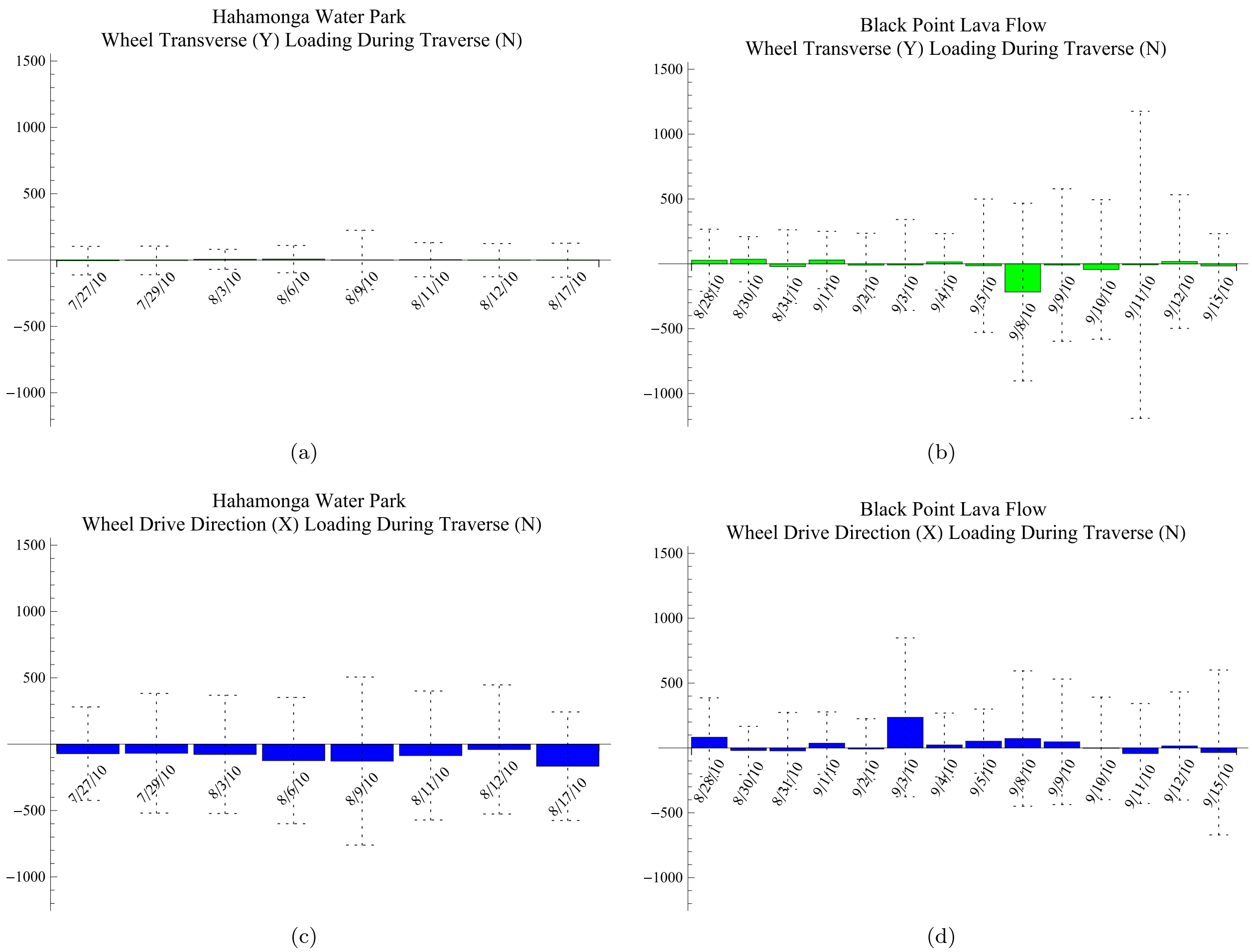



**Figure 9. Mean horizontal forces on wheels during traverse. Error bars show $1\sigma$ variation.**

# V. Conclusions

ATHLETE's long traverse demonstrations in August and September of 2010 were a great success. The prototype mobility system met and exceeded its milestones, traversing over 80 km at rates well over 1 kph. ATHLETE traversed dirt roads, sandy creek beds, desert washes, the rolling rocky terrain of lava flows, and the sandy scrub-covered terrain of the Arizona desert. The onboard active compliance algorithm performed reliably, keeping wheel forces balanced over the desert terrain and while ascending and descending lava flow slopes.

The performance of these long-range traverses provided data and experience that will lead to further improvements in ATHLETE's traverse capability. Better handling of drive direction forces by the onboard active compliance algorithm will enable better terrain interaction and improve vehicle safety in bumpy or rutted terrain. Improvements to the traverse command set and operator interfaces for driving will increase traverse efficiency and enable faster overall traverse speeds.

## Acknowledgments

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