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A Biologically Inspired Robot for Lunar *In-Situ* Resource Utilization

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Abstract—**Successful long-term settlements on the Moon will need a supply of resources such as oxygen and water, yet the process of regularly transporting these resources from Earth would be prohibitively costly and dangerous. One alternative would be an approach using heterogeneous, autonomous robotic teams, which could collect and extract these resources from the surrounding environment (*In-Situ* Resource Utilization). The Whegs™ robotic platform, with its demonstrated capability to negotiate obstacles and traverse irregular terrain, is a good candidate for a lunar rover concept. In this research, Lunar Whegs™ is constructed as a proof-of-concept rover that would be able to navigate the surface of the moon, collect a quantity of regolith, and transport it back to a central processing station. The robot incorporates an actuated scoop, specialized feet for locomotion on loose substrates, Light Detection and Ranging (LIDAR) obstacle sensing and avoidance, and sealing and durability features for operation in an abrasive environment.**

I. INTRODUCTION

One of the most significant needs of any long-term or permanent settlement on the Moon is oxygen, and while limited supplies could be brought from Earth, the cost of routinely providing a lunar base with oxygen would be quite high. As a result, the concept of *in-situ* resource utilization (ISRU) is being pursued as a means of supporting lunar habitation.

The lunar regolith, consisting of all material on the surface of the Moon above the bedrock layer, ranges widely in particle size. It includes the extremely fine and abrasive top layer, only a few centimeters deep, and is capable of providing quantities of oxygen, hydrogen, and possibly water in the form of ice [1]. If this regolith can be collected from the lunar surface and transported to a central processing location at a suitable rate, the oxygen produced could indefinitely sustain the base's oxygen needs for fuel and breathing.

Because the required volume of regolith for the planned lunar settlement is approximately 2 m^3 per day, astronauts collecting the necessary quantity of regolith would have less time for scientific activities and would incur additional risk. Excavation equipment could be used to perform the task, but at that scale it would have to be large enough that launch costs would go up and an on-site repair would be difficult and dangerous.

Robotic teams provide a different approach to the problem of regolith collection. Autonomously operating heterogeneous robotic teams could easily collect regolith from the loose top layer and would free the astronauts to perform more scientific and mission-critical tasks. A single excavation team could comprise one large hauler vehicle (approximately $0.5m^3$ in size) which would be able to perform some regolith collection on its own as well as transporting multiple smaller, more agile robots (approximately $0.1m^3$ in size) to and from excavation sites. Additionally, these teams of multiple smaller robots provide a degree of redundancy not found with a single larger device. Table I shows the comparison between a rover-mounted loader assembly and a robotic excavation team consisting of one hauler robot and two smaller assisting robots.

TABLE I
SINGLE REGOLITH COLLECTION VEHICLE VS. HETEROGENEOUS ROBOTIC EXCAVATION TEAM

	Human Rover with Loader	Robotic Excavation Team
Mass	200-300 kg (loader assembly)	100 kg (per team)
Power Consumption	4000-6000 W	250-400 W
Payload	0.25 m^3	0.25 m^3
Estimated sortie time	30 min	60 min
Time to collect 2 m^3	4 h	8 h

A robotic team suited for collecting regolith could also perform other useful tasks when not occupied with regolith collection. Robots could operate as robotic geologists or communications relays, or could be outfitted with bulldozer-type attachments for the purpose of building berms to shield the settlement from a rocket launch site.

This paper introduces Lunar Whegs™ (Fig. 1), a proof-of-concept rover for a team that would navigate the surface of the moon, collect a quantity of regolith, and transport it back to a larger vehicle or central processing station. The

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robot incorporates an actuated scoop, specialized feet for locomotion on loose substrates, Light Detection and Ranging (LIDAR) obstacle sensing and avoidance, and a sealed chassis with durability features for operation in an abrasive environment.

Fig. 1. Lunar Whegs™ climbing a rocky, sandy incline at the Canadian Space Agency's Mars Yard in Montreal, Canada.

II. BACKGROUND

While all of the rovers that have landed on extraterrestrial bodies have been wheeled [2], [3], legged locomotion has shown to be effective in robots, making them more adept at climbing over obstacles and navigating irregular terrain. Legged robots also maintain an advantage over wheeled robots when operating on loose substrates, because they avoid compaction resistance. Wheeled and tracked vehicles run into this problem, caused by substrate material building up in front of the vehicle's footprint, which resists forward motion. Legged vehicles can avoid this problem because they acquire a discrete foothold before pushing off from that foothold.

Highly articulated legged robots, however, require large numbers of actuators and substantial computational power in order to coordinate the robot's movement. Reduced-actuation design has proved to be an effective means by which robots can maintain a high level of mobility while achieving favorable power-to-weight ratios and limiting the necessary computational power. PROLERO [4], a prototype Mars rover, rotates its six independently actuated spoke-like legs in a circle while dropping its body onto the substrate in between steps. RHex [5], another robot with six independently actuated spoke-like legs, holds its body off the substrate with the use of six independent motors, controlled to vary actuation speed from the stance to the swing phases. RHex can walk in a number of different insect gaits, including an alternating tripod gait. Also, unlike PROLERO, RHex incorporates flexible legs to allow vertical compliance and enhance stability.

Whegs™ robots were designed based upon cockroach locomotion principles and with the goal of further reducing the number of required actuators while maintaining mobility [6]. The Whegs™ concept uses a single drive motor to power three drive axles. Six three-spoke wheel-legs are mounted on the drive axles, one on each end, and are mounted anti-phase with respect to adjacent and contralateral wheel-legs in order to produce a nominal tripod gait while walking. Whereas RHex uses software to control its gait, Whegs™ gait controller is imbedded in its mechanical design, thus eliminating the necessity for complex computer control. Whegs™ robots achieve passive gait adaptation by means of unidirectional torsional springs mounted in series with each wheel-leg, which allow contralateral spokes to rotate into phase in order to aid climbing obstacles or inclines. Steering is accomplished by means of two small servo motors which drive opposing steering linkages on the front and rear axles. In addition, an actuated body joint inspired by cockroach climbing motions permits the rover to acquire a foothold on top of larger obstacles and subsequently prevents the robot from high-centering and tipping backwards as it climbs the obstacle [6], [7].

The Whegs™ platform is well-suited for adaptation as a planetary rover. For a given size they are remarkably agile (Fig. 2) especially given their few actuators. Robots with articulated legs require actuation at each joint, but the increased number of joints increases the likelihood that the moving parts will be abraded and fail sooner. Because Whegs™ robots use non-actuated wheel-legs, more of the joints and bearings are kept away from the abrasive regolith. Distally mounted actuators, such as those used on both independently actuated legs as well as rocker-bogie mechanisms, will tend to dissipate heat to the environment; a Whegs™ rover with one main actuator mounted within the robot's body could store the heat generated by that actuator and use it to warm the robot's electronics.

Fig. 2. Whegs™ II climbing a rubble pile.

III. DESIGN

A. *Whegs™ Platform*

The principal objective for the new robotic chassis design was to protect the robot against harsh environments. Lunar Whegs™ (Fig. 3) was designed as a fully enclosed robot to withstand abrasive terrestrial conditions simulating a lunar environment.

Because Whegs™ robots use steering and body joint actuators as well as torsional compliance devices, the design of these components needed to be adapted for the new platform iteration in order to prevent any foreign material from entering the robot. Early Whegs™ robots of this scale used open or partially sealed body joint configurations in order to accommodate power transmission to the body joint, while DAGSI Whegs™, a recent, larger robot [8], uses an anodized and lubricated body joint bearing that seals the body joint, allowing electronic cables and a drive shaft to pass through the joint.

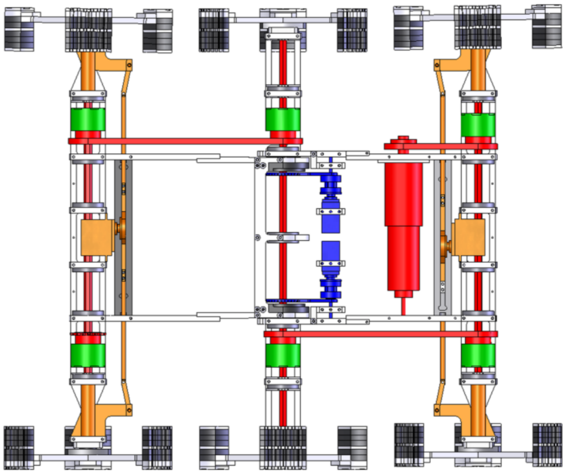

Fig. 3. Chassis configuration of Lunar Whegs™. Internal view of the drivetrain (red), torsional compliance system (green), steering (orange), and body flexion joint (blue).

Building on the design of the DAGSI Whegs™ body joint, Lunar Whegs™ miniaturizes the sealed body joint and accommodates a powerful servo-driven design that is smaller and lighter (Fig. 4). Twin custom fabricated aluminum bearings were anodized and greased to provide a seal that protect the chains and sprockets necessary to transmit the power to the body joint and prevent abrasion.

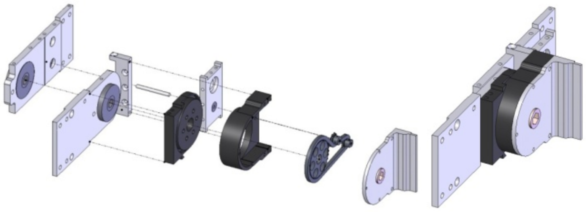

Fig. 4. Body flexion joint design, shown in exploded view (left) and assembled (right).

In addition to a sealed body joint, the steering system and torsional compliance devices were also sealed against the exterior environment. A rack-and-pinion steering mechanism was chosen because it allows for a sliding contact bearing at the point where the steering arm exits the body. The implementation of fully sealed torsional compliance devices (Fig. 5) allowed them to be mounted outside of the robot body, conserving interior space.

B. Mission-Specific Features

With the goal of designing an agile Whegs™-type rover as part of a heterogeneous robotic team, locomotion on a variety of substrates was a primary design criterion. Previous Whegs™ foot designs were intended for travel over solid terrain and for climbing over discrete obstacles, but were sub-optimal for movement on loose materials (Fig. 6). Whegs™ II, like legged robots in general, tended to dig or sink into loose sand and was not able to keep the robot body above the surface of the substrate. Lunar Whegs™ would have to be able to travel over these kinds of loose substrates as well as solid rocks.

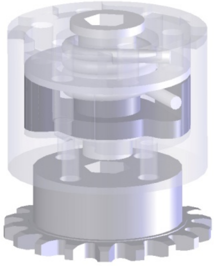

Fig. 5. Sealed torsional compliance device.

Because gravity on Moon is one sixth that of gravity on Earth, Lunar Whegs™, like all Moon rovers, will have one sixth the traction force on the moon relative to Earth, which slows its accelerations. However, the advantages are that it will also be much less likely to sink into a soft substrate and it will require one sixth the motor torque to climb rocky obstacles because it will weigh six times less.

Fig. 6. Whegs™ II's feet sink into loose sand.

In order to combine obstacle climbing with the ability to travel on loose substrates, and in keeping with our strategy of solving locomotion problems with mechanical solutions, wheel-legs were designed with feet that have a concave contact area. This design distributes the weight of the robot over a larger surface area, reducing the likelihood of sinking into the sand. It also tends to compress the underlying material under the foothold in order to aid both support and traction. The feet on the robot's wheel-legs have open compartments to contain and compress the underlying material, while vertical partitions provide added traction (Fig. 7).

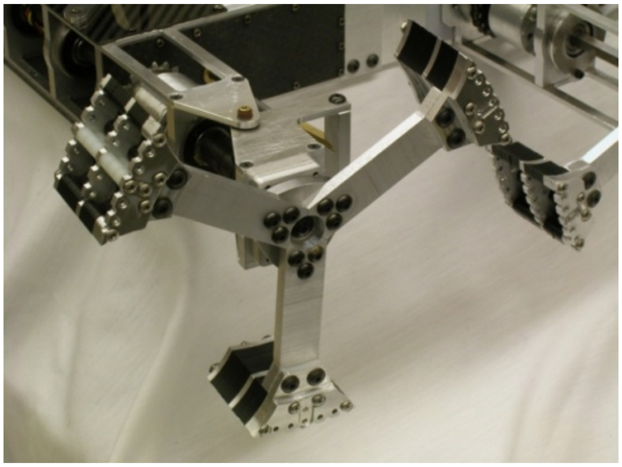

Fig. 7. Wheel-leg design, showing concave foot for increased support and traction on loose substrates.

Additionally, previous Whegs™ robots have successfully used ultrasonic sensing to detect and avoid obstacles [9]. The lack of a lunar atmosphere, however, necessitates the use of a different sensing mechanism for autonomous navigation. Lunar Whegs™ employs a miniature LIDAR sensing unit to scan for objects in its path (Fig. 8). The sensor is capable of detecting objects up to 4m away and is programmed to scan an angular range of 90 degrees in front of the robot (±45 deg from the robot's heading) at a rate of 10 Hz. The autonomy algorithm controls the robot's speed and heading, slowing the robot as it approaches obstacles and steering towards the heading with the clearest path. The simple algorithm is also capable of detecting and avoiding headings of converging distances that indicate an inside corner or closed path.

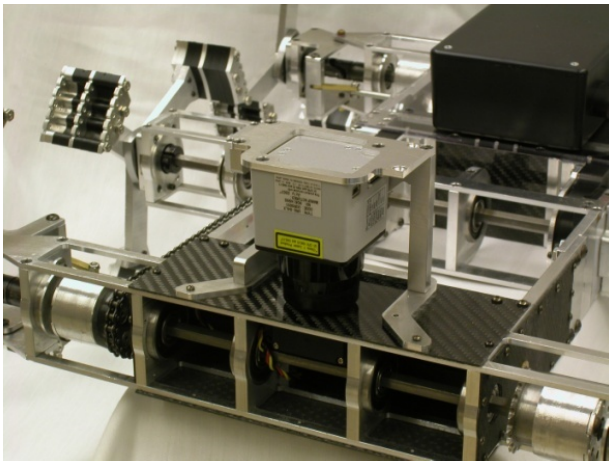

Fig. 8. Mini-LIDAR unit mounted on the front of Lunar Whegs™.

One of the key advantages of using a simple steering algorithm is that the robot can be controlled autonomously using a small PIC-based microcontroller instead of a full computer, allowing more space on the robot to be allocated for payload capacity, sensors, or higher-level computing.

In order to demonstrate the ability of the robot to collect and transport a quantity of material, as is required for ISRU purposes, an actuated scoop was constructed and mounted within the robot. The servo-driven scoop is controlled by means of a four-bar mechanism, and the servos are connected to the linkage through a set of torsion springs and dampers to prevent damage to the mechanism if it strikes a rock while collecting material. The linkage range allows the scoop to actuate down for collection and up for hauling, and acting together with the body joint it achieves a dumping position (Fig. 9).

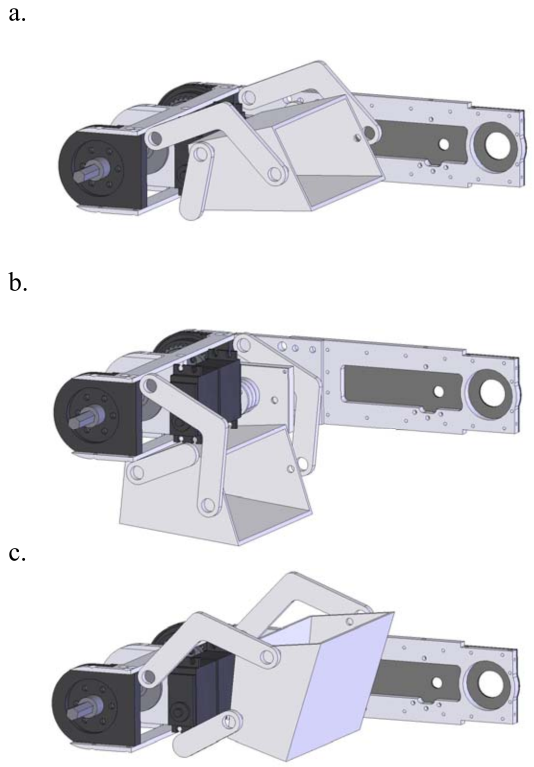

Fig. 9. Design drawings of the actuate scoop shown in the a) initial storage position, b) regolith collection position, and c) regolith hauling position.

IV. RESULTS

A. Robot Specifications

Table II below shows the measured specifications and performance characteristics of Lunar Whegs™.

The optimum turning radius of the robot was measured using rubber-treaded feet on a tile floor. Notable is the fact that the turning radius decreases at full speed; this was observed to be a result of the torsional compliance devices. Because the robot does not use a differential, the robot is unable to adjust actively the speeds of the wheel-legs on the inside of the turn relative to those on the outside of the turn, causing some slipping. At low speeds, the wheel-legs tended to slip on the floor, but at high speeds the torsional compliance devices on the inside of the turn wound through the stance phase, in effect functioning as a passive differential. This phenomenon reduced the amount of slipping through the turn and decreased the robot's turning radius.

TABLE II
SPECIFICATIONS AND PERFORMANCE CHARACTERISTICS OF LUNAR WHEGS™

	Overall	Chassis
Length	62 cm	48 cm
Width	50 cm	32 cm
Height	19 cm	7 cm
Mass of chassis		9.8 kg
Mass with batteries		11.0 kg
Maximum speed	1.91 body lengths per second	
Drive motor output torque	64.6 N m	
Turning radius (minimum speed)	1.26 body lengths	
Turning radius (maximum speed)	0.95 body lengths	
Body joint range	±45°	
Body joint payload (dead lift)	1.4 kg	
Body joint payload (holding capacity)	3.7 kg	

B. *Simulated Mars Environment Testing*

Lunar Whegs™ was tested at the Canadian Space Agency's simulated Mars Yard at the 2008 Planetary and Terrestrial Mining Sciences Symposium (PTMSS), where it was able to travel over flat, sandy terrain (Fig. 1). It demonstrated its capability to climb up and down inclines as steep as 30 degrees, and it climbed over rocks as tall as 15 cm (>1.5 times its leg length). The Mars Yard's mixed surface of sand and rocks provided an opportunity to test the robot's locomotion on complex and loose substrate. Because the robot's body joint allowed the robot to flex the robot's front and rear segments, it was able to maintain contact with the surface and shift its weight from a wheel-leg or axle that was slipping onto another axle with a steadier foothold.

Lunar Whegs™ was also tested in the lava tubes near Grants, NM, as part of the 2009 Lavatubes Workshop and at the Mars Dome, University of Toronto Institute for Aerospace Studies (UTIAS) as part of the PTMSS 2009. After a year of testing, the sealing devices of Lunar Whegs™ have been shown to prevent any foreign material from entering the robot and interfering with its function.

C. *Sand Testing*

In addition to the Mars Yard, Lunar Whegs™ was tested in a sandbox in order to quantify precisely its maneuverability and its capability to collect material with the actuated scoop. Fig. 10 shows the robot operating in the test sandbox.

Table III shows the performance characteristics of Lunar Whegs™ operating in sand. The material in the sandbox was fine grit play sand, loosely piled 4 inches (10cm) deep without being packed down, in order to simulate the worst possible substrate conditions. An L-shaped turn in the sandbox allowed for measurement of the robot's turning radius.

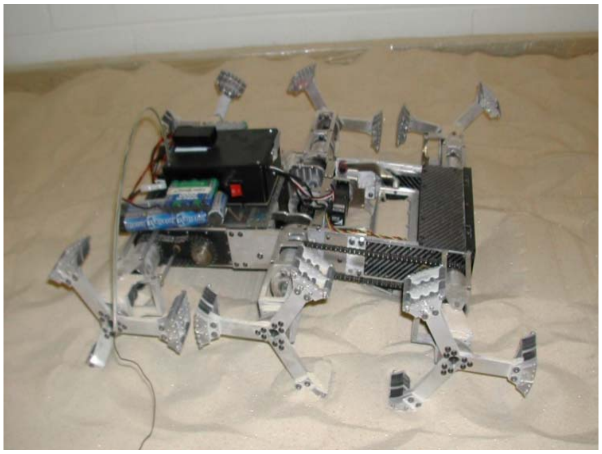

Fig. 10. Lunar Whegs™ operating in the test sandbox, with the scoop mounted on the front of the robot (right side) and filled with sand.

While the top speed of the robot decreases from its speed on a flat, solid surface, it is still able to travel at 0.8 body lengths per second (0.41 m/s). In addition, the function of the torsional compliance devices as a passive differential is more pronounced in sand than on flat ground, illustrated by the fact that the turning radius in sand of 0.85 body lengths is less than the turning radius at full speed on a flat surface. However, because the torsional compliance devices are unidirectional, there is no such effect when the robot travels backwards, and the turning radius in this case was greater than 2.2 body lengths, the maximum measurable turning radius in the test sandbox.

TABLE III
PERFORMANCE OF LUNAR WHEGS™ IN LOOSE FINE-GRIT SAND

Speed	0.8 body lengths per second (0.40 m/s)
Turning Radius (forward)	0.85 body lengths (0.41 m)
Turning Radius (backward)	>2.2 body lengths (>1.04 m)
Pulling Load	60 N
Scoop Volume	442 cm^3

Testing the scoop in the sandbox, the robot was capable of filling more than 95% of the scoop volume, resulting in a payload of 0.56 kg of sand (430 cm^3). With the use of the body joint, the scoop could be emptied completely. The robot was able to travel in the sandbox with a full scoop of sand without any spilling out. Because the loose play sand tends to absorb the impact of the wheel-legs, allowing the robot to move more smoothly across it than on a hard surface, it was decided that the spill testing should be repeated on a hard, tiled floor. However, even with the robot traveling on the tile floor and carrying a full scoop of sand, no material spilled out of the scoop.

D. *Autonomy Testing*

The autonomous navigation capability of Lunar Whegs™ was tested walking down a corridor and around a corner. The test environment was a 1.83m wide tiled corridor, which contained numerous randomly placed obstacles that required the robot to make course corrections in order to avoid collisions. The robot successfully navigated the corridor, while avoiding the obstacles, and executed three out of three right-hand turns and three out of three left-hand turns without colliding with a wall or any of the obstacles. Fig. 11 shows Lunar Whegs™ autonomously navigating a corner and executing a right turn without any collisions.

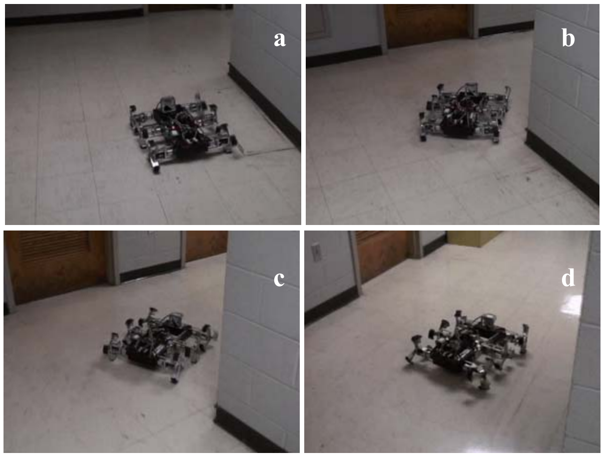

Fig. 11. Sequence of images showing Lunar Whegs™ autonomously executing a right turn by detecting and avoiding a corner.

E. *Obstacle Climbing*

Using the new wheel-leg design optimized for locomotion on sand, Lunar Whegs™ was able to climb a 15 cm obstacle using its body flexion joint, which is equivalent to 1.58 times the wheel-leg length. Typically, a wheeled vehicle can only surmount an obstacle that is 0.5 times its wheel radius, whereas a Whegs™ vehicle can surmount an obstacle 1.4 times its leg length without the aid of a body flexion joint. Fig. 12 shows the robot successfully climbing over the 15 cm obstacle using its body joint.

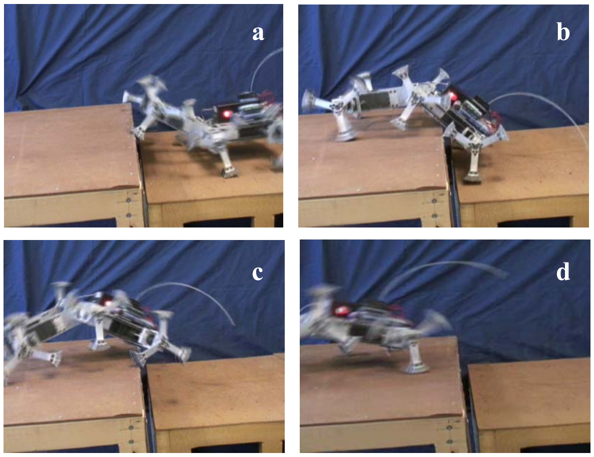

Fig. 12. Sequence of images demonstrating the ability of Lunar Whegs™ to climb a 15 cm obstacle.

While other Whegs™ robots have been able to climb obstacles of similar height relative to their wheel-leg length, these results are notable because the feet on Lunar Whegs™ are made of aluminum and plastic and have a very low coefficient of friction on a smooth surface such as the one used for this testing.

V. CONCLUSIONS

Lunar Whegs™ begins to prove the concept of a team rover that could navigate the surface of the moon, collect a quantity of regolith, and transport it back to a larger vehicle, which could then carry it to a central station for processing into oxygen. It is based upon the Whegs™ concept, but introduces several unique features necessary for its mission. Its chassis components, including its custom body joint bearings, are sealed to protect delicate equipment from loose abrasive material. In keeping with the Whegs™ philosophy of solving locomotion problems with mechanical solutions and reduced actuation, its specialized feet have concave contact areas so they do not sink into loose substrates and also provide improved traction. Furthermore, its collection scoop is actuated by a four-bar mechanism that moves it downward for scooping substrate, up for transport and combines with body joint motions for dumping. A degree of autonomy is achieved with the use of a simple microcontroller and a Mini-LIDAR unit that permits Lunar Whegs™ to move around obstacles too tall for it to climb. As we have previously shown, the Whegs™ design is scalable, so this concept vehicle could be increased in size to meet the needs of a Lunar mining /geologist mission.

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