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WALKING ROBOT WITH A CIRCULATING GAIT

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Abstract: Mobile robots have yet to navigate and explore rough terrains autonomously. The Ambler walking robot has been developed in response to this challenge, specifically autonomous exploration of planetary and lunar surfaces. The Ambler, which maintains its body on a level trajectory while walking, has unique orthogonal legs that are stacked under the body instead of the traditional animal-like arrangement of legs around the body. The resulting stacked configuration leads to a novel circulating gait that promises to improve mobility in terrains of extreme roughness. The Ambler's level body motion, orthogonal legs, and circulating gait greatly simplify physical control, terrain model construction, and motion planning–all of which are traditional impediments to autonomous travel across rough terrain.

1. INTRODUCTION

Rough terrains that occur in mining, construction, and planetary surfaces are vast irregular landscapes of rock, soil, and sand. The surface of Mars (Fig. 1) is a prototypical rough, natural terrain. Such terrain would challenge many animals and defy most mechanical locomotion. Exploration of rough terrain without continuous human monitoring and with only occasional human interaction (termed autonomous exploration) is an unrealized ideal for mobile robots. An autonomous robot fails if it enters a situation from which it cannot reverse–the need for extreme reliability and safety affects the entire system, from mechanical configuration to planning strategy. Unlike their teleoperated counterparts, autonomous explorers are controlled by sensor-driven planning algorithms. If the robot configuration does not permit a feasible strategy for planning and perception, or if the robot is not physically suited to rough terrain operation, competent autonomy is unrealizable.

Fig. 1: Surface of Mars

This paper describes the Ambler[1] a prototype terrestrial walker for rough terrain, and discusses the major advantages of the Ambler's circulating gait configuration in the context of autonomous exploration criteria.

An autonomous rough terrain exploration robot must reliably transport payloads across the terrain. Rough terrain can be characterized by:

- Three-dimensional geometry including boulder-covered steep slopes, steps, and ditches. In addition to being a locomotion challenge, this geometry creates occlusions for terrain sensors. As a result, some areas in the terrain cannot be observed and should be avoided.
- Materials such as sand and dust whose strength and stability for vehicle support cannot be confidently determined by non-contact sensing.

The combination of these factors can cause much of a rough terrain's surface area to be unacceptable for positive, confident vehicle support. Acceptable

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[1] AMBLER is an acronym for Autonomous, MoBiLe, Exploration Robot.

areas for vehicle support may be sparse and noncontiguous.

Straight line traverse of rough terrain is insufficient for exploration: As new information learned during exploration modifies paths and intentions, a robot must respond to ever changing plans. It should be capable of general motion in rough terrain, including turning, reversing, and moving laterally. The planning required to provide the robot with general motion capability should be feasible to implement with available computational equipment. Since exploration robots are far ranging and generate their own power, high payload to weight ratio and extreme efficiency pose additional requirements. An exploring robot's configuration should also strongly consider deployment needs of the payload. For instance, a sampling drill may need to be positioned accurately against the terrain and supported rigidly during operation.

2. WALKING LOCOMOTION

2.1 Advantages of Walking for Rough Terrain

Mobile robot locomotion candidates include mechanisms that roll, walk, or combine rolling and walking (Track laying mechanisms are grouped here with rolling mechanisms because tracks are in continuous terrain contact and are analogous to large wheels.). The fundamental difference between a rolling and walking mechanism is the means by which terrain support is provided. Wheeled machines have rollers in continuous contact with the terrain, while walkers suspend themselves over the terrain on discrete contact points. Because a walker only requires few support areas (footholds) compared to the continuous path required for a wheel, a walker can traverse otherwise impassable terrain. A walking machine isolates its body from the underlying terrain and smoothly propels its body independent of terrain details and foot placement. Large body lifts with respect to gravity (e.g, climbing a step) are difficult moves for a wheeled machine because the motion is accomplished by shearing the terrain–commonly resulting in large energy losses and unstable motion. A walker can smoothly and stably lift and lower its body while maintaining vertical foot forces. Walking machines conserve power in rough terrain in part because the body can be maintained at a fairly constant orientation and elevation with respect to gravity. Additionally, power losses to terrain are through discrete instead of continuous deformations.

A vehicle's support polygon is defined by the lines connecting the points of ground support when projected on a ground plane (plane orthogonal to the gravity vector). Stability can be described as the distance from the vehicle's center of gravity projected on the ground plane to the polygon edge in the direction of interest. Most rolling vehicles have little control over their stability. Alternately, a walker can move its body (i.e., center of gravity) with respect to its ground support points (feet) to affect its stability.

Walkers are quite amenable to the deployment needs of scientific and sampling payloads. Smooth, stable body motion is ideal for sensor perspectives on the terrain. With its feet in fixed locations, a walker can precisely move its body three-dimensionally to position body-mounted instruments and tools over, on, and into the terrain surface.

Walking was selected as an advantageous means of locomotion for rough terrain exploration. Walkers are able to succeed with few acceptable terrain support areas, body-terrain isolate, and provide unique benefits to scientific and sampling payloads. Furthermore, legged machines can optimize their stability and conserve power during traversal of rough terrains.

2.2 Terrain Adaptive Walkers

Perhaps the simplest walkers that can traverse rough terrain are frame-type walkers. An example is the Komatsu underwater octopod ReCUS, which consists of two rectangular frames, each with four vertically telescoping legs–the machine walks over rough terrain by supporting itself on one four-legged frame while advancing the other frame (4). The ReCUS steers by rotating the lifted frame with respect to the supporting frame. Since groups of legs are advanced and placed together, a frame walker's capability is limited in terrain where many areas are deemed unsuitable for footholds.

Unlike frame walkers, terrain adaptive walkers place feet individually–each foot can be moved in three dimensions to conform to the terrain. The Adaptive Suspension Vehicle (ASV) (11), Aquarobot (5), and Odex I (9) are terrain adaptive walkers. Terrain adaptive walkers are able to select high confidence footholds and optimize stability even in very rough terrains. The difficulty of complete freedom of foot motion is that selection of individual footholds in rough terrain requires intensive modelling and planning. The ASV lessens this burden by relying on its human operator to select footholds and plan body moves through rough terrain.

An alternate method that reduces the complexity of foothold selection is to use precomputed templates that automatically place feet in patterns with little or no consideration for the specifics of the underlying terrain. An alternating tripod gait, used by the Odex I, Aquarobot, and other six-leg walkers is an example. In this gait, legs support and advance in sets of three. However, since patterned groups of acceptable footholds are required, the capability of this gait in rough terrain is limited. Furthermore, during each advance cycle the vehicle's safety is quite vulnerable as failure of any one of the three supporting legs would destabilize the walker.

3. AMBLER

The Ambler (Fig. 2 and Table 1) is a prototype rough terrain robot that is responsive to the basic needs of autonomous exploration of planetary and lunar surfaces. Terrains considered for Ambler mobility included slopes up to 30° with frequent surface features (e.g., ditches, boulders, and steps) of up to one meter in size. Design payloads consisted of scientific and sampling equipment such as tooling for grasping, digging, and deep coring (several meter). The power budget was taken as one kilowatt for travel speed of 1 meter/minute.

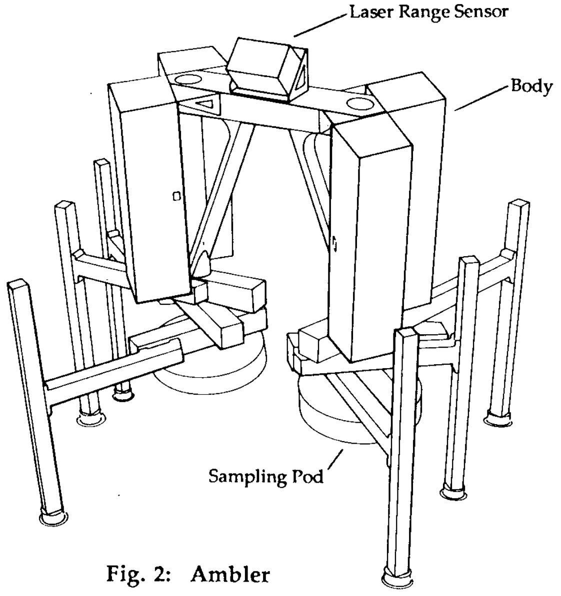

Fig. 2: Ambler

Each Ambler leg consists of a rotational and extensional link that move in the horizontal plane and an orthogonal vertical link. The Ambler's six "orthogonal" legs are stacked on two central body shafts (three legs to a shaft). The two shafts are connected to an arched body structure that includes four enclosures that house power generation, electronics, computing and scientific equipment.

A laser range sensor mounted atop the body builds terrain maps from which footholds are selected. Two sampling "pods" under the leg stacks can accommodate large sampling tools or sensors and can be placed in near proximity to or directly on the terrain. Deep coring equipment could be housed in the central body shafts that extend the full height of the walker. The Ambler's structural elements are primarily aluminum construction.

3.1 Ambler Operation

The Ambler's vertical links individually adjust to terrain roughness and maintain the walker in a continuous level orientation over the terrain (Fig. 3). Equal displacements on all vertical links lift or lower the body to climb or descend slopes, steps, etc. Propulsion of the level body is achieved by coordinated motions of the rotational and extensional links. Passive foot rotation allows the vertical links to pivot about the feet during propulsion.

Table 1: Ambler Specifications

Dimensions	
Typical walking width:	4.5 m
Typical walking length:	3.5 m
Typical foot spacing in direction of motion:	1.5 m
Height:	4.1-6.0 m
Mobility	
Maximum step crossing:	1.9 m
Maximum ditch crossing:	1.5 m
Maximum slope with 1 m wide ditch on slope:	30°
Weight[2]	
Legs and body structure:	2050 kg
Vehicle design weight (with payload):	3180 kg
Power[3]	
Body propulsion at 2 m/min:	650 watts
Leg recovery:	150 watts

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[2] . Because Ambler functionality is essential for experimentation and work in many other program areas, some compromises were made with respect to weight and efficiency to guarantee basic walking performance.

[3] Not included: computing and steady state power (power consumption when walker is not moving).

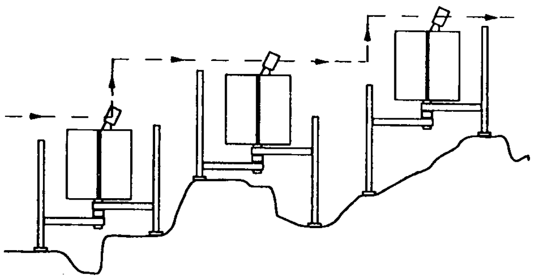

Fig. 3: **Level Body Motion**

As the body progresses, there is a point at which the rearmost leg must be moved ahead. The act of lifting a leg, moving it ahead, and replacing it on the terrain is termed leg "recovery". Ambler leg recovery is quite unique; after a foot is lifted, the extensional link retracts and the rotational link spins to pass the vertical link between the leg stacks and through the body such that the foot can be placed *ahead* of other supporting feet. During propulsion, supporting legs move rearward relative to the body. Therefore, after every six leg recoveries each leg has completed a full revolution about its respective body shaft. This leg motion, termed circulation, is shown in Fig. 4 where a sequence of six leg recoveries and subsequent body propel motions are shown from left to right across the page. As the walker moves forward the bold leg completes a full counter-clockwise revolution about the left side body shaft. During the same period, it can be seen that all other legs have also circulated to their original positions. Circulation is unprecedented in existing walking mechanisms and in the animal kingdom.

At times the Ambler does not utilize circulation as described. Tight turns require legs on the inside of the turn to recover from front to back (rear circulation), while the outer legs continue to circulate forward (front circulation). For lateral moves, the Ambler uses a traditional insect style "ratcheting" gait in which legs do not pass through the body during recovery.

Elevation maps are constructed from laser range sensor data. Based on the maps, a gait planner determines body and leg trajectories to move the walker toward a goal while maintaining vehicle safety. A graphic simulator ascertains that the planned trajectories are correct. After verification, trajectories are passed to the robot controller and imposed on the walker. A task-based software architecture connects these various modules and is able to coordinate multiple goals, handle contingencies, and recover from plan failures. Full discussions of the Ambler perception system and gait planning software can be found in (1,2) and (12), respectively. The Ambler's task control architecture is presented in (10).

Models of the Ambler mechanism have been developed to study foot-soil interactions, power consumption, tipover, and foot slippage (8). A comprehensive model incorporates non-conservative foot-soil interactions in a full non-linear dynamic formulation.

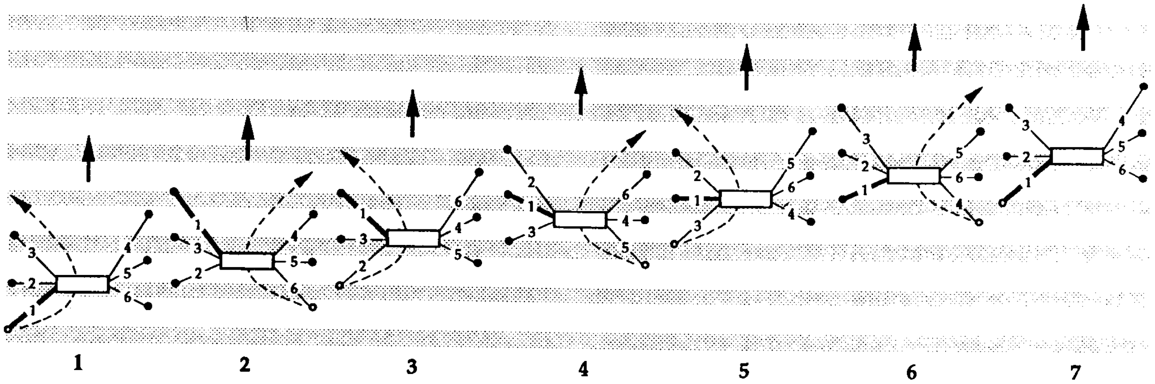

Fig. 4: Circulating Gait. Walker advance is shown in stages from left to right. The dotted curve denotes the path of a recovering leg. Leg #1, the first leg to recover, is shown in bold throughout the sequence to emphasize circulation. After the six steps shown, all legs have completed a full revolution.

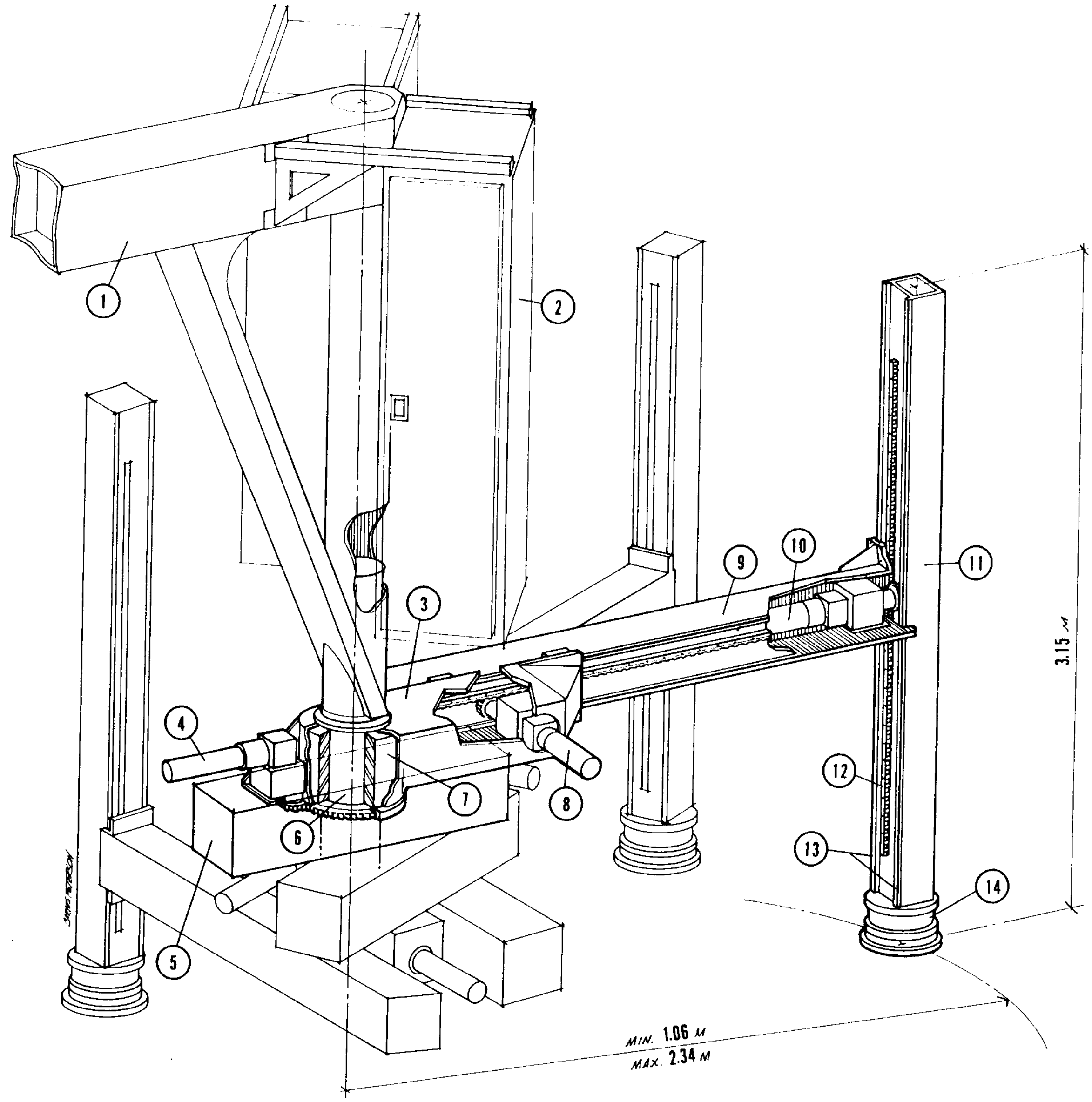

Fig. 5: Ambler Leg and Body Detail

1 – Body structure
2 – Equipment enclosures
3 – Rotational link
4 – Rotational link motor-gearbox
5 – Electronics box
6 – Central shaft
7 – Slipring

8 – Extensional link motor-gearbox
9 – Extensional link
10 – Vertical link motor-gearbox
11 – Vertical link
12 – Rack gear
13 – Linear bearing rails
14 – Force sensor

3.2 Electromechanical Description

Each Ambler leg is identical. Fig. 5 shows three legs, the central shaft about which they rotate, and a section of the body. Components of the uppermost leg have been emphasized. The rotational link gearbox pinion engages a large spur gear affixed to the central shaft. The prismatic links (extensional and vertical) are rack and pinion driven and slide on linear bearings. Each of the three motor-gearbox units include a permanent magnet DC motor, incremental encoder, high efficiency spur gearbox, fail-safe load holding brake, and absolute encoder. A six-axis force/torque sensor mounted to the base of each vertical link provides a full state of force acting on the foot pad.

A multiple-ring slipring commutates power and signals from each leg to the body. Custom digital and analog multiplexors reduce the number of individual rings in the slipring. On each leg, an electronics box mounted to the rotational link houses the multiplexing hardware, motor amplifiers, and brake relays that operate the leg.

The Ambler controller is a combination of single-board computers, motion control boards, and input/output boards on a VME bus. A common real time operating system synchronizes input/output and motion control. Digital boards route a variety of signals including brake control and force sensor control. Analog-to-digital converters read signals from the force sensors, absolute encoders, and inclinometers. A safety circuit monitors all walker motions and immobilizes the robot in response to a variety of sensed unsafe conditions.

A tether connected to the body supplies power as well as linking the robot controller, which currently resides off-board. Eventually, the controller, power generation equipment, and telemetry equipment will be housed in the body, and the tether eliminated.

4. AMBLER CONFIGURATION ADVANTAGES

4.1 Circulating Gait

A traditional rough terrain gait is follow-the-leader: The computer (or human operator) selects front footholds and trailing feet step next to or in the vacated footprints of leading feet (11). There are several reasons why the Ambler's circulating gait should enable it to succeed in terrains that would frustrate or impede walkers with traditional gaits. First, since circulation places recovering feet ahead of supporting feet, the total number of foot placements on the terrain is greatly reduced. A circulating gait requires three to four times fewer foot placements than traditional terrain adaptive gaits (e.g., follow-the-leader). Foothold selection and leg recovery planning difficulty is a function of terrain roughness–as roughness increases, fewer foot placements should be highly advantageous. Furthermore, since foot placements are likely jolt the vehicle's terrain modelling sensors, fewer placements should improve model accuracy.

A second advantage of circulation is that large foot size does not limit rough terrain mobility. For instance, consider a rear-propogating follow-the-leader gait in which trailing feet are placed adjacent to leading feet: Footholds must be large enough to accommodate two feet. Since circulation does not place feet in proximity to each other, footholds need not be oversize. The result is that foothold planning in rough terrain is less constrained and more likely to succeed.

4.2 Decoupled Body Support and Propulsion

Several existing terrain adaptive walkers such as the MELWALK Mark-III (6) and Titan III (3) have leg geometries that decouple body support and propulsion. That is, leg actuation for support is independent from actuation for propulsion and no kinematic coupling exists between the two. Decoupling leads to advantages in efficiency, planning, control, and sensor stabilization. The Ambler's vertical links support and level the body over terrain, and its horizontal links propel the body. As the Ambler moves over terrain the body remains level and is only raised or lowered to pass large terrain features thus minimizing energy expenditure. Once a desired vertical elevation has been selected, body motion planning degenerates to position and heading in the horizontal plane. Propulsion of the level body requires only a determinate subset (three) of the horizontal actuators.

Body support and propulsion decoupling is also advantageous during the development of planning and control software. The Ambler's decoupled configuration permits the vertical links to be locked while propulsion control is developed and alternately, the planar links can be locked while vertical control (e.g., leveling control) is developed. This mode of decoupled development has enabled rapid testing and demonstration of Ambler's basic walking capabilities.

A critical task for an autonomous explorer is mapping its surrounding terrain. The resulting terrain map is the basis for planning and safeguard, so its accuracy directly governs the capability and reliability of the vehicle. Since the perception sensor field of view does not include terrain under or to the immediate sides of the walker and because multiple perspectives of the same scene are required to resolve unknown and occluded areas, registration of multiple images is desirable to build a sufficient map of the local terrain. Maintaining the sensor on a smooth, level trajectory is very advantageous to the speed and accuracy of image registration and correlation.

4.3 Minimal Lower Leg Motion During Propulsion

As the Ambler's body is propelled, the vertical links rotate on the feet without sweeping any volume–especially important in rough terrain where the lower leg could collide with obstacles and possibly become entrapped. This feature of the orthogonal leg should lessen the search for footholds in rough terrain as feet can be placed very near to terrain obstacles (e.g., steps or ledges). Alternately, the shank (lowest link) of a pantograph style leg pivots on the foot and sweeps a volume during propulsion. Allowance for this additional volume must be made during foothold selection, and limits terrain footholds to those with sufficient surrounding clear space.

4.4 Stability and Redundancy

Reliable locomotion is essential for an autonomous mobile robot which will operate on a distant planet. To this end, the Ambler has excellent stability features. First, by maintaining the body in a level configuration, foot forces can be proportioned as desired (within bounds). For instance, a disproportionate amount of the vehicle weight could be placed on the leading legs when hill climbing so that a terrain failure would result in a stumble into the hill instead of a rearward tumble.

Second, the stacked orthogonal leg configuration permits five-legged crawl gaits (i.e., only one leg in recovery at any time) that keep the walker stable even after the failure of any one supporting leg (7). Finally, since legs can operate in each other's zones, the robot can continue statically stable operation after the failure of any two legs. Impaired modes (i.e., four or five operational legs) would probably not use a circulating gait.

5. EXPERIMENTATION

The Ambler (Fig. 6) is currently undergoing walking experimentation on flat, compliant terrain. Development work continues in the areas of perception, gait planning, foothold selection, and mechanism controller. Circulating gait algorithms are being developed that allow general trajectories with curves of any radius. As perception and planning ability matures, terrain roughness will be increased.

After rough terrain capability has been demonstrated indoors, power, computing, and telemetry will be moved on-board the Ambler so that autonomous walking can be demonstrated in rough outdoor terrains. Missions of extreme capability and endurance are envisioned to quantify the walker's ability. Sensors and tools for sampling will be mounted on the Ambler, so that ultimate terrestrial missions can combine long-range walking and sampling tasks.

Mechanism modelling of the Ambler continues to provide simulated time histories and insight about walker performance in situations that are either too difficult or time consuming to test directly on the prototype walker. Modelling and simulation results (e.g., approaches to power efficient walking) are continuously integrated into the Ambler control system.

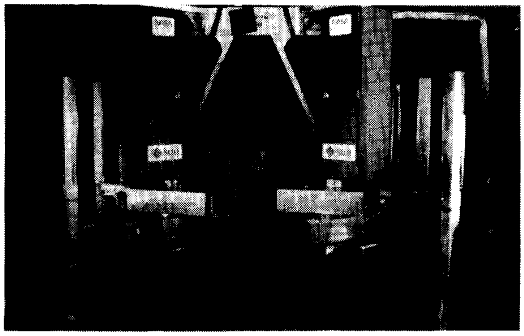

Fig. 6: Ambler on Flat Terrain

6. CONCLUSIONS

Exploration of rough terrain without continual oversight and input from a human operator has yet to be demonstrated by a mobile robot. The Ambler walker configuration holds the promise of performing successful rough terrain exploration because of its unique amenabilities to sensing, planning, and control–the major elements of autonomy:

- Its circulating gait dramatically reduces the number of foot contacts on terrain thus reducing planning constraints and improving mobility.
- Its decoupled leg geometry and level body motion provide simplifications throughout the system architecture from body motion planning to smooth transport of terrain sensors.
- Its orthogonal leg is ideal for rough terrain as the vertical links sweep no volume during propulsion and can be placed close to obstacles.

The Ambler will be an important benchmark for walker mobility, reliability, and efficiency in rough terrain. Objectives include; autonomous traversal and sampling of terrain more extreme than other walkers have attempted, travel rates and payload that are significant relative to available power, and a mandate for operational modes that never compromise safety.

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