Autonomous Walking Results with the Ambler Hexapod Planetary Rover

Eric Krotkov, Reid Simmons, William Whittaker

Robotics Institute, School of Computer Science
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213

Abstract

In this paper we present experimental results of autonomous walking experiments with the Ambler, a six-legged robot configured for autonomous traversal of Mars-like terrain. We describe the results in terms of terrain traversed, number of steps taken, distance travelled, Vial duration, and walking speed.

1 Introduction

Exploration of planetary surfaces by mobile robots is now within technical reach. On the Moon, robots could be used to explore for lunar resources, to conduct scientific observations, and to carry out a variety of simple construction tasks. On Mars, robots could be employed to survey the planet's composition, monitor its weather, and return samples for analysis on Earth.

To plan such missions, a host of technical questions must be answered. What degree of mobility must be achieved to accomplish different missions? What rates of power consumption are required for different terrains? What levels of precision and accuracy are necessary? What art the proven capabilities of autonomous machines in terms of a long-duration mission?

Planetary rover researchers around the world are attempting to answer these questions. Significant research efforts are underway in Europe [4], Japan [5], North America [2, 9], and Russia [3]. Many of the research programs are in the early stages, and have not yet produced extensive experimental performance results.

In the spirit of providing data to mission planners, in this paper we attempt to provide quantitative answers to the last of the questions posed earlier. The answers art based on our practical experience with the performance of an autonomous, six-legged robot for an exploration mission in Mars-like terrain. In Section 2, we briefly describe the configuration and operation of the Ambler walking robot. In Secion 3, we describe results of autonomous walking experiments conducted in a wide range of settings.

This paper presents new results. It does not provide comprehensive views of the work, because these have already appeared. Reference [8] addresses the technical approach taken

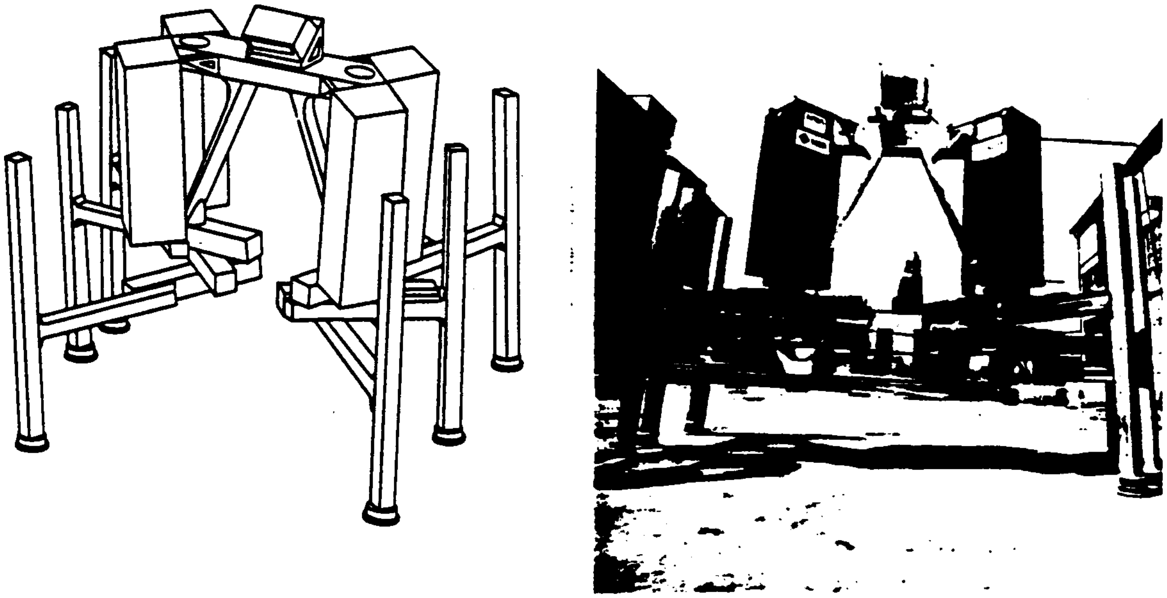

Figure 1: Ambler

in the integrated walking system. Reference [6] provides performance data for power consumption and navigation accuracy.

2 Ambler

This section describes the Ambler configuration and operation. Because these topics have been covered in detail elsewhere [1, 7], we mention only selected key points to acquaint readers with the Ambler.

The Ambler is a prototype robot that responds to the fundamental needs of autonomous exploration. The Ambler was configured *to satisfy* specific constraints imposed by exploration missions to planetary surfaces. (This phase of research has not addressed space qualification issues.)

1. Rough terrain: the Ambler must be able *to* climb 30 deg slopes with frequent surface features (e.g., ditches, boulders, and steps) of up to 1 m in *size.*
2. Scientific payload: the Ambler must accommodate scientific and sampling equipment such as tooling for grasping, digging, and deep coring (several meters).
3. Power efficiency: the power consumed for locomotion should be minimal for velocities of 1 m/min.

The Ambler has six legs, arranged in two stacks on central shafts (Figure 1). The shafts are connected to an arched body that supports four enclosures housing electronics and computing. Each leg consists of a rotational link and an extensional link that move in the horizontal plane, and an orthogonal vertical link. A six-axis force/torque sensor mounted on the base of each vertical link measures the forces acting on the feet.

The height ranges from 4.1 to 6.0 m, and the width varies between 4.5 and 7.1 m. The mass of the mechanism and all equipment (including computing, power generation and storage, and telemetry) is about 2700 kg. On top of the body structure is a scanning laser rangefinder mounted on a panning table, as well as two inclinometers that measure the body's orientation.

A multiple-ring slipring communicates 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 d a y s that operate the leg. A safety circuit monitors all walker motions and immobilizes the robot in response to a variety of sensed unsafe conditions.

The Ambler's vertical links adjust individually to terrain roughness and level the walker. Equal displacements on all vertical links lift or lower the body to climb or descend slopes and steps. 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.

As the body progresses, there is a point at which the rearmost leg must advance. The act of lifting a leg, moving it ahead, and replacing it on the terrain is 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 the other supporting feet. We call this leg motion *circulation*. 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.* Circulation is unprecedented in existing walking mechanisms and in the animal kingdom.

Many variations on circulation are possible. Tight turns require legs on the inside of the turn to recover from front to back, while the outer legs continue to circulate forward. For lateral moves, the Ambler uses a traditional insect-style ratcheting gait in which legs do not pass through the body during recovery.

3 Autonomous Walking

The Ambler walking system [7] consists of a number of distributed modules (processes), each with a specific functionality: perception. planning. real-time control, and task-level control. The perception subsystem uses data from a scanning laser rangefinder to build 3D maps of the terrain. The planning subsystem combines kinematic, terrain, and pragmatic constraints to find leg and body moves that provide good forward progress and stability. The real-time control coordinates the Ambler's joints to perform accurate leg and body moves, maintains the dead-reckoned pose, and monitors the status of the robot. The task-level control facilitates concurrent operation of the subsystems, execution monitoring and error recovery, and management of the Ambler's computational and physical resources.

A typical trial begins by executing perception, planning, and real-time processes on the on-board computers. For convenience, the standard outputs of these processes are displayed on windows on off-board workstations. A human operator enters a path as a sequence of arcs of circles, and issues the command to *start* walking. The Ambler then operates autonomously, planning and executing every footfall, leg move, body move, leveling maneuver, and other action or reaction.

To date, the Ambler has walked autonomously a total of over 4 km, much of it over

Year	Terrain	Body Moves	Planar Travel (m)	Body Rotation (rad)	Leg Travel (m)	Duration (hr)
1990	Indoor obstacle course	27	9	2	—	0.7
1991	Outdoor obstacle course	88	30	11	—	3.5
1992	Indoor obstacle course	397	107	55	901	7.0
1992	Outdoor field	1219	527	20	3330	20.8

Table 1: Statistics from selected walking trials

rugged, difficult terrain. Table 1 reports statistics of several walking trials, which were selected to indicate the progressive escalation of challenges and capability. In the table, the planar travel term represents the planar distance traveled by the Ambler body. The leg travel term represents the sum of the planar distances traveled by the legs, measured from pick-up to set-down. Most of the leg travel occurs during circulation. Walking time includes the time required for movement, sensing, mapping, planning, and all processing; it excludes idle time due, for instance, to debugging.

3.1 Indoor

For indoor trials, the Ambler operated on obstacle courses fashioned from 40 tons of sand, 20 tons of boulders, a 30° wooden ramp, and various other objects (Figure 2). In this figure, the Ambler is on sandy terrain with meter-tall boulders (under the legs and body), ditches (the center leg on the far stack is standing in one), and a ramp (lower right). The courses typically include rolling, sandy terrain with several boulders 1 m tall, ten or so boulders 0.5 m tall, a ditch, and a ramp. The largest of the boulders, affectionately called "the Prudential," is 1.5 m tall, 4 m long, and 2 m wide. With such materials, the obstacle courses pose significant barriers to locomotion. We know of no other robot that could surmount all of the obstacles in the course.

Traversing a variety of these obstacle courses, the Ambler has demonstrated long-term autonomous walking. In one trial, the Ambler took 397 steps and traveled 107 meters following a figure-eight pattern, each circuit of which covers 35 m and 550 deg of turn (Figure 3). In this figure, the thin line indicates the course followed by the center of the Ambler's body for one complete circuit. Boulders are drawn grey, the triangle indicates a randomly selected body pose, and the units are meters. Completing more than two circuits during the trial, the Ambler turned nearly 9 complete revolutions, thus devoting a significant fraction of the trial to turning rather than to advancing. The two circuits were different in the sense that the robot did not take the same step twice. To accomplish this, the walking system passed 3.7×10^4 messages and 4 Gb of data between processes.

In one indoor trial covering 11.1 m, the average leg stride was 3.2 m. These long strides decrease the number of steps required, thus saving energy and saving computation by the perception and planning modules.

Figure 2: Ambler traversing indoor obstacle course

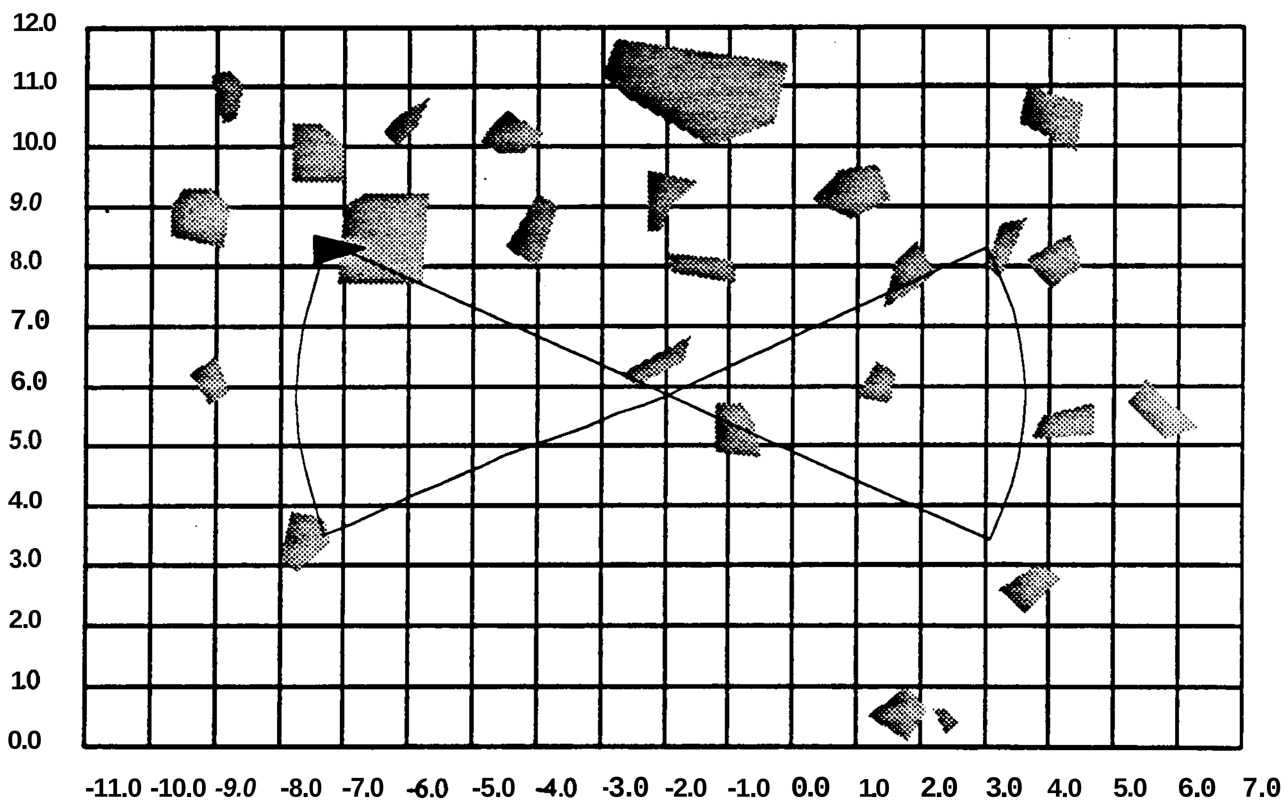

Figure 3: Top view of figure-eight circuit

32 Outdoor

For one set of outdoor uials, the Ambler operated on rolling, *grassy* terrain (Figure 4). The site is a field cleared in a hilly, wooded area at an industrial park. Although it does not contain obstacles like those encountered in the indoor trials, the site poses its own challenges: steeper slopes and side-slopes, and soft ground.

In the longest of these trials, the Ambler took 1219 *steps,* traveling 527 m horizontally and 25 m vertically. It followed a meandering course that included first climbing a hill and descending from it, then roughly following an iso-elevation contour for 250 m, executing a point turn of roughly π radians, and following an iso-elevation contour back to the starting region. This course is significantly simpler to follow than the figure-eight pattern (Figure 3). because it involves less turning and less acute turning. In the process, the robot ascended a 30 percent grade, and traversed side-slop on 15 percent *grades.*

For another set of outdoor uials, the Ambler operated in a parking lot strewn with wooden obstacles such as boxes, pyramids, and ramps. In one of these trials, the Ambler took 88 steps along a gently curving arc, traveling 30 m over a variety of obstacles. In another of these trials, the Ambler walked in the parking lot at night, without lights. The laser rangefinder does not require ambient illumination, unlike *ordinary* cameras. In fact, we observed the range images to be noisier during the day, because the signal-to-noise ratio is higher without ambient illumination.

3.3 Remarks

Average walking speed over these trials, including all computation, is 35 cm/min (typical body moves travel about *50 cm).* Moving the mechanism is the main limitation to the speed. During operation, the real-time controller is active about 80% of the time, while the planners and perception subsystems are each active about *50%* of the time, and the centralized task-level controller is active only about 3% of the time (the total is greater than 100% because operations *occur* concurrently).

4 Discussion

In the spirit of providing data to mission planners, we have attempted to summarize the proven capabilities and practical performance of the Ambler autonomous walking machine. We recognize the incompleteness of the results, and the need for further experimentation and analysis.

No framework has been widely accepted for rigorously comparing rover designs and capabilities, nor for formally evaluating designs with respect *to* mission requirements. Trade studies employing methods such as Kepner-Tregoe analysis have been commonly utilized, but they have also been criticized for possible subjectivity in determining weights, and for not studying all related variables.

We will not propose a common framework here. Instead, based on our experience with the Ambler we conclude this paper by suggesting that such a comparative framework should include meuics in at least three areas.

1. Mobility performance. These metrics should include dimensionless quantities such as specific resistance. They should also incorporate meuics related to absolute per-

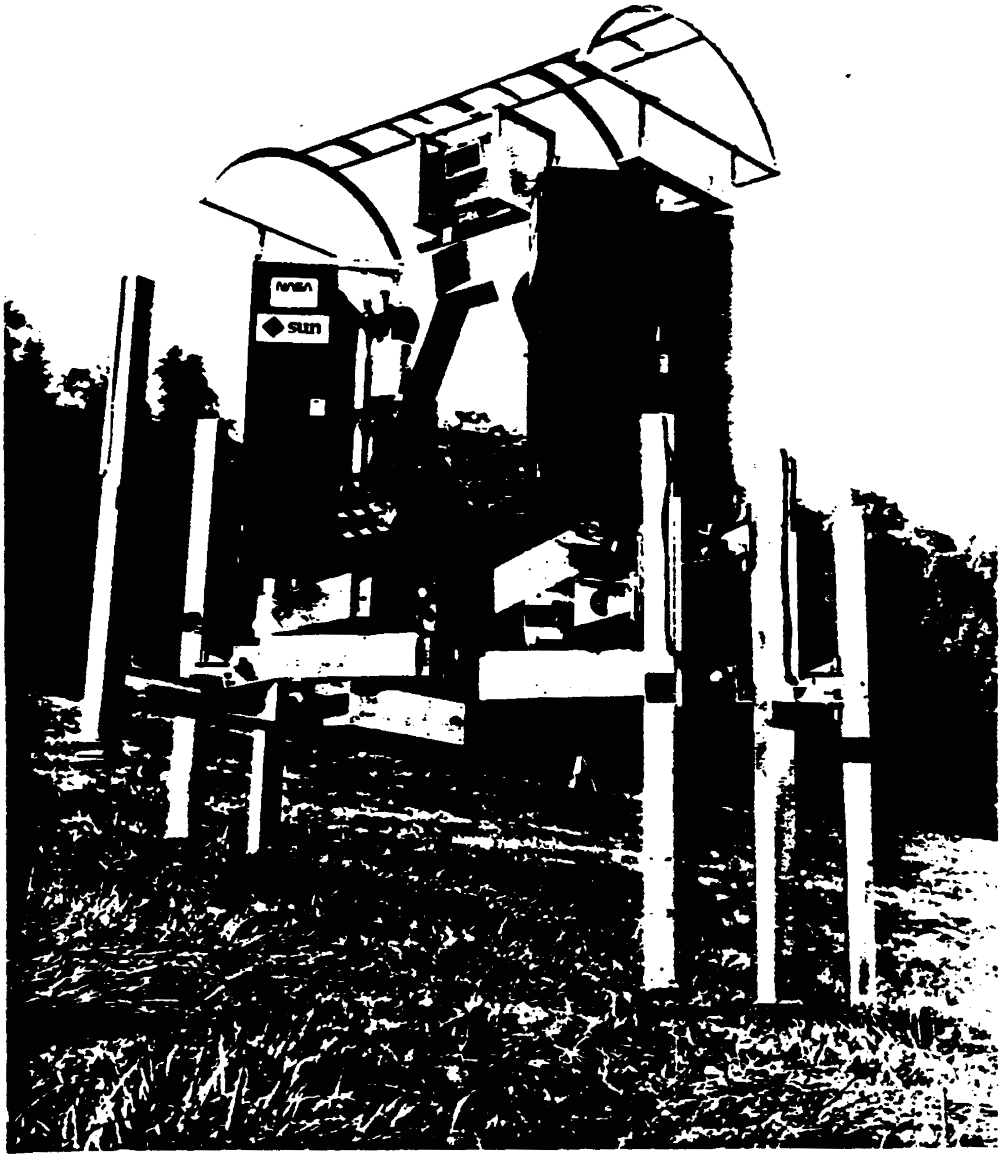

Figure 4: Ambler walking 527 m in field

formance requirements, for example, on bump crossing, maneuverability, and tipover margins. A "Consumer Reports" style evaluation may be appropriate.

2. Power efficiency. These metrics should be evaluated on a variety of slopes, and should include not only the power required for locomotion, but also for computing, sensing, and path planning.

3. Amenability to autonomous control. A high-performance vehicle is a *necessary* but not a sufficient condition for a successful planetary rover, especially one that must operate without supervision for long periods. Rovers should be evaluated on their amenability to robust perception, planning, and real-time control. For example, the Ambler is amenable to robust perception in the degree that level body motion simplifies the problem of merging images and maps from different positions.

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