Tsuneo Yoshikawa and Fumio Miyazaki (Eds.)

Photo: Yasaka-no-To (Yasaka Tower), Higashiyama-ku, Kyoto

Design: Yasuyoshi Yokokohji and Masamitsu Kurisu

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Autonomous Walking in Natural Terrain: A Retrospective on the Performance of the Ambler

Eric Krotkov Reid Simmons

Robotics Institute
Carnegie Mellon University
Pittsburgh, PA 15213

Abstract— The objective of our research is to enable robotic exploration of remote, natural areas. Toward this end, we have developed an integrated walking system for the Ambler—a six-legged walking robot designed for planetary exploration—and tested it in indoor and outdoor autonomous walking trials. In this paper, we summarize our approach to autonomous walking, compare it to other approaches from the literature, and present results of the walking trials. Then we assess the performance relative to our objectives for self-reliant control, power-efficient locomotion, and traversal of rugged terrain.

1. Introduction

In our extensive reporting on the Ambler walking robot, we have concentrated on technical approaches (mechanisms, perception, planning, real-time control and task-level control) and experimental results. In this paper, we aim instead for an "intellectual audit" that compares the experimental results with the initial objectives, and reckons the difference. We find this topic especially appropriate because the Ambler has recently retired from active duty.

In the next section, we articulate the broad goals, the principal challenges, and the distinguishing features of our approach. In Section 3, we review related research, and identify the respects in which the Ambler walking system is unique. In Section 4, we briefly introduces the integrated walking system and documents the main experimental walking results. We conclude in Section 5 with a summary, a critical evaluation (the audit), and a look to the future.

2. Objective, Challenges, and Approach

2.1. Objective

The chief objective of this work is to enable robotic exploration of remote, natural areas. We consider exploration missions with two defining characteristics:

1. Remote area. By "remote" we mean conditions under which operator intervention is either not feasible (typically because of delay) or not cost-effective (typically because of the high cost of ground support).
2. Natural environment. The forces of nature produce irregular shapes and materials, causing natural terrain to exhibit roughness over a wide range of scales [5]. There are no prepared surfaces in nature.

To motivate the objective and make it more concrete, we consider the planet Mars as an instance of an area that is remote, natural, and unexplored. Others have detailed the expected benefits of observing geophysical, meteorological, and biological conditions on Mars, and have assessed the risks and costs of sending human crews [19]. Robotic exploration of Mars provides an alternative that eliminates risk to human lives and promises to substantially reduce mission cost.

The motivation of Mars exploration exists, but it is not unique. Other natural, remote areas such as the Moon, seabeds, and subsurface mines would suit our purposes equally well. Further, Mars exploration is a motivation, not an objective. As a consequence, the research does not require flight-qualified components for computing, data storage, or communications, nor does it require formulation for extremes of gravity, vacuum, or other conditions.

2.2. Challenges

From the stated characteristics of the mission follow specific challenges to be addressed:

1. Self-reliant control. The remoteness of the area to be explored impacts the feasibility and cost of different control regimes, ranging from pure teleoperation (reliance on operator) to pure rover autonomy (reliance on self). Regimes from the teleoperation end of the spectrum are less feasible, because round-trip signal delays preclude the rover from responding quickly to hazardous conditions (e.g., sinking into quicksand), and less cost-effective, because it requires costly ground support. The challenge is self-reliant control that enables timely rover responses, requires little ground processing, and enables operation for extended periods and distances. The longer the duration and wider the coverage, the greater the likelihood of meaningful return from exploration missions.
2. Limited power. The remoteness of the area requires the rover to supply its own power, which in turn dictates power budgets that are meager by laboratory standards. Limited power places a premium on efficiency of operation and penalizes unproductive behavior such as bumping into obstacles (which transfers energy to the terrain) and wandering repeatedly in the same small subregion (which serves no exploration purpose).
3. Rugged terrain traversal. The surface of Mars viewed by the Viking landers is rugged, uneven, and rocky (Figure 1). This terrain challenges most existing mobile robot mechanisms [2]. Even with a suitable form of locomotion, the terrain poses significant stability control challenges, since the natural, irregular materials may shift, fracture, and deform. The irregular terrain also challenges established machine perception techniques, because it does not satisfy standard constraints on shape (e.g., symmetry) or surface properties (e.g., smoothness), nor does it admit controlled lighting or fixtured objects.

Just as challenges follow from the characteristics of the mission, so do challenges follow from the mechanical configuration of the Ambler as a hexapod. Designed for mobility and efficiency, the Ambler features orthogonal legs, a circulating gait, and

Figure 1. M[illegible] surface

level body motion [2]. Unlike rolling and crawling mechanisms, walkers are able to select favorable footholds, and to avoid transferring energy to terrain by unsupportive contact. In order to capitalize on these strengths, a key challenge is to accurately model the terrain so that footholds and obstacles can be identified. Other challenges include maintaining stability while advancing, planning the sequence of leg and body motions required to advance or to turn, and coordinating degrees of freedom absent in

2.3. Approach

Our research has addressed each of these challenges, enabling high-performance autonomous walking. We identify two key distinguishing features of the approach:

1. Autonomy. Our strategy is to meet the challenge of self-reliant control by seeking to maximize robot autonomy. The approach is to develop a system that both plans (deliberates, reasons) and reacts (responds reflexively to a stimulus), enabling the Ambler to operate for extended periods. In this approach, planning algorithms evaluate conservatively each Ambler motion, checking them several times for feasibility and stability. While executing the plan, if robot sensors indicate signs of trouble, then reactive behaviors stabilize the robot.

2. Explicit models. We model explicitly terrain geometry, mechanism kinematics, vehicle stability margins, and sensor uncertainty. These models play critical roles in meeting the challenges derived from the mission characteristics and the robot form:

- Models of terrain geometry enable planners to select favorable footholds, thus meeting the challenge of rugged terrain traversal and capitalizing on the high-mobility characteristics of walking robots.
- Models of terrain geometry also permit planners to select leg and body motions minimizing terrain contact, thus meeting the challenge of limited power.
- Models of mechanism kinematics allow controllers to accurately execute the plans, thus addressing the challenges of rugged terrain traversal and limited power.
- Models of stability margins allow planners and controllers to ensure the safety of different motions, thus meeting the challenge of extended operation under self-reliant control.

The complexity of the models is high compared to purely reactive approaches. But the complexity produces significant benefits: using models to plan and analyze moves contributes to the rover safety and power efficiency that are overriding concerns for planetary missions.

3. Related Research

Researchers have advanced a spectrum of mobile robot concepts suited for planetary exploration. In this section we review relevant mobile robots that have been built and operated.

Sustained effort at NASA's Jet Propulsion Laboratory has developed a family of rovers including the Surveyor Lunar Rover Vehicle, Robby, Rocky, and Go-For. Using these wheeled mechanisms as testbeds, JPL researchers have developed control architectures — including Computer-Aided Remote Driving [25], behavior control [10, 11], and Semi-Autonomous Navigation (SAN) [26] — for sharing mission control between human operators and robots. Using these control architectures, various vehicles have successfully demonstrated navigation in desert settings. Still, the degree of autonomy is limited even with SAN, which requires more computation and look-ahead planning than the other control architectures.

Researchers at MIT have argued that small rovers on the order of 1 to 2 kg are suitable for planetary exploration [3] and lunar base construction [4]. They have developed the Attila family of small six-legged walkers, and are striving to make the robots totally autonomous units using the subsumption architecture and "behavior languages" [1]. Although the degree of autonomy inherent in the approach is high, the potential for efficiency appears to be low: local behaviors may cause the rover to take suboptimal or even dangerous actions, and may cause the rover to transfer substantial energy to the terrain by repeatedly bumping into obstacles. Further, the capability of performing meaningfully complex missions in realistic settings is yet to be demonstrated.

Other researchers have built and operated prototype planetary rovers, including the Marsokhod [9, 16], and the Walking Beam [7]. To date, these research efforts have concentrated primarily on mechanical design and real-time control, and have not yet addressed or achieved autonomous performance.

Mobile roboticists have developed a number of integrated systems that exhibit (or potentially exhibit) relatively high degrees of autonomy. Examples of indoor robots with autonomous capabilities include Hilare [6], Carmel, Xavier, and many others. Examples of outdoor robots with autonomous capabilities include the Autonomous Land Vehicle [24], the Navlab [23], and VaMoRs [8]. These robots typically operate in environments relatively rich in structure (e.g., well-defined hallway corridors, or roadways with lane markings) compared to the surface of the Moon or Mars.

Researchers have developed a variety of walking mechanisms with the high mobility required by planetary rovers. These walkers include the Adaptive Suspension Vehicle [22], Titan I through Titan VI [12, 13], hopping machines [14, 17], the Odex [18], the Recus [15], and the Aquabot [15]. Many of these efforts emphasize electromechanical design and performance. Thus, these robots tend to be either teleoperated or operate under supervisory control, so the degree of autonomy achieved is low.

In summary, related research (i) produces mechanisms with high mobility but without high autonomy, (ii) researches autonomous units but without mission capabilities, and (iii) develops autonomous systems with mission capabilities but only in structured environments. To our knowledge, there are no robot systems other than the Ambler with high mobility, high autonomy, and mission capabilities for unstructured, remote, natural environments.

4. Autonomous Walking

To date, the Ambler has walked autonomously a total of over 4 km, much of it over rugged, difficult terrain. Table 1 reports statistics of several walking trials, which were selected to indicate the progressive escalation of challenges and capability.

The Ambler integrated walking system [21] consists of a number of distributed

Date	Terrain	Body Moves	Planar Travel (m)	Body Rotation (rad)	Leg Travel (m)
1990	Indoor obstacle course	27	11	2	—
1991	Outdoor obstacle course	100	25	2	—
1992	Indoor obstacle course	397	107	55	901
1992	Outdoor field	151	46	—	—
1992	Outdoor field	1219	527	20	2220

Table 1. Statistics from selected walking trials

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. A null entry indicates insufficient data to calculate statistics. Most of the leg travel occurs during circulation.

Figure 2. Ambler traversing indoor obstacle course

Ambler on sandy terrain with meter-tall boulders.

modules (processes), each with a specific functionality: the Task Controller coordinates the distributed robot system; the Real-Time Controller implements motion control; the perception modules acquire and store images, and construct terrain elevation maps; the planning modules plan footfalls, leg trajectories, and gaits; and the graphical user interface enables simple interaction.

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.

4.1. 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). 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 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 about 107 meters following a figure-eight pattern, each circuit of which covers about 35 m and 550 deg of turn. Figure 3 illustrates the elevation map constructed and used by the

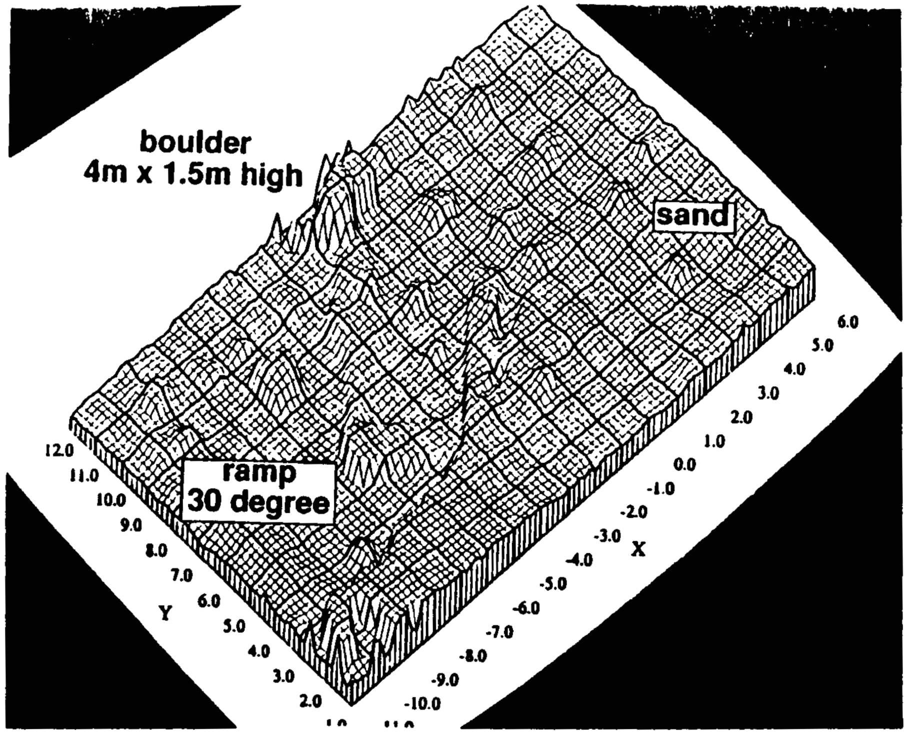

Figure 3. Elevation m of indoor obstacle course

Ambler. 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.

4.2. Outdoor

For one set of outdoor trials, 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 meters horizontally and 25 meters 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 meters, 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 indoor figure-eight pattern because it involves less turning and less acute turning. In the process, the robot ascended a 30 percent grade, and traversed side slopes on 15 percent grades.

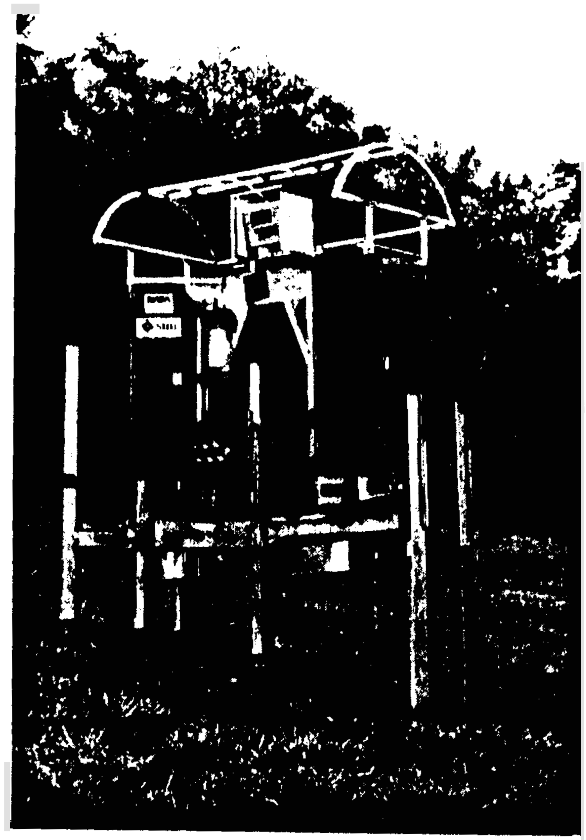

Figure 4. Ambler walking 527 meters in field

5. Discussion

The results of the indoor and outdoor walking trials show that the approach meets the challenges identified earlier:

1. Self-reliant control. The approach meets this challenge, since the integrated walking system exhibits a high level of autonomy in planning and executing motions (e.g., traversing a specified path), reacting to unsafe conditions (e.g., leveling), learning good footfalls on the basis of experience, and operating for extended periods.

2. Limited power. The approach meets this challenge by reducing unwanted terrain contact to a negligible (but non-zero) level. Thus, the system transfers far less energy to the terrain than would a purely reactive or purely randomized robot.

3. Rugged terrain traversal. The approach enables locomotion over challenging obstacle courses, soft ground, and significant slopes and side-slopes.

Based on this analysis, we find the Ambler system to be well-suited for the class of exploration missions originally intended. Thus, as "intellectual auditors" we are satisfied that the account balances. However, we *were* surprised by the level of effort required to meet all of the challenges. We knew that we could use a simple system to accomplish simple tasks, but we did not appreciate in advance how much more complex the system would be to accomplish the moderately difficult tasks attempted.

We continue to pursue this line of research (see [20] for details). In our ongoing work, we are developing a legged robot system that will perform multi-day, multi-kilometer missions, with the robot acting as a capable, remote science assistant. We seek to achieve levels of autonomy comparable to the Ambler, but with a system characterized by simplicity and extreme reliability.

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