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AMBLER: PERFORMANCE OF A SIX-LEGGED PLANETARY ROVER†

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Abstract—In this paper we quantify several performance metrics for the Ambler, a six-legged robot configured for autonomous traversal of Mars-like terrain. We present power consumption measures for walking on sandy terrain and for vertical lifts at different velocities. We document the performance of a novel dead-reckoning approach, and analyze its accuracy. We describe the results of autonomous walking experiments in terms of terrain traversed, walking speed and endurance.

1. INTRODUCTION

Exploration of planetary surfaces by mobile robots is now within technical reach. On the Moon, robots could be used to explore 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 are 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[6], Japan[4], North America[2,11] 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 some of the questions posed earlier. The answers are 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 the next three sections, we concentrate on performance metrics in power consumption, positioning accuracy and autonomous walking. For each of these topics, we present our approach, describe the experimental methods, analyze the results and outline future research directions.

2. AMBLER

This section describes the Ambler configuration and operation. Because these topics have been covered in detail elsewhere[1,8], 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" 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) Energy 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 (Fig. l). 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.

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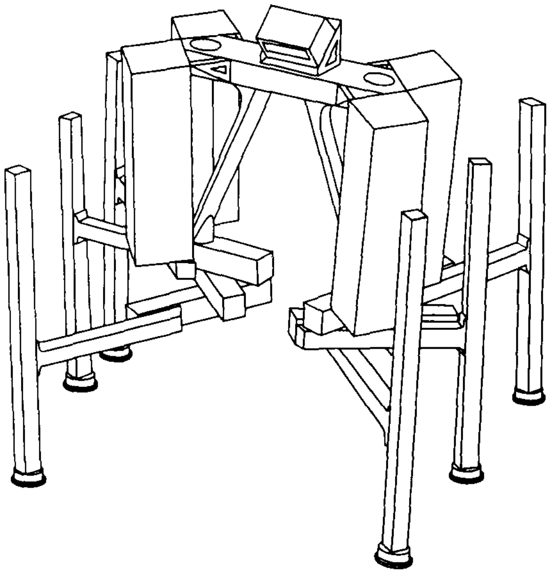


Fig. 1. Ambler.

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 (excluding power generation and storage) is about 2500 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 on the rotational link houses the multiplexing hardware, motor amplifiers and brake relays 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. POWER

For extraterrestrial missions, power is at a premium, and for a planetary rover mission, energy-efficient locomotion is critical. This section describes how the design of the Ambler achieves energy efficiency, and then presents power consumption data for the current implementation of the design. For further details of the power budget, we refer interested readers to Ref. [1].

Like all walkers, the Ambler benefits from discrete foot placements that theoretically transfer less energy to the terrain than does the continuous terrain contact of wheels or tracks. The design of the Ambler aims to further reduce power consumption with orthogonal legs, level body motion and a circulating gait. The orthogonal legs eliminate energy losses due to geometric work, a principle cause of inefficiency for many walkers[10]. The level body attitude makes propulsion more efficient, because the vertical actuators can be locked and support the rover's weight without servoing, while only the horizontal joints are servoed to move the body. The circulating gait reduces energy loss due to soil work by requiring fewer footfalls (two to three times fewer than a follow-the-leader gait).

To measure power consumption, we installed a digital power meter on the line between the 208 V supply and the Ambler. We digitized the analog output of the meter at 10 Hz, and synchronized the readings with the real-time robot controller. We then commanded the Ambler to perform various motions, and recorded the sum of the three phases of effective power (as distinct from reactive and apparent power).

Figure 2 illustrates the power consumed while walking 2 m in four steps on sandy terrain. The raw power data are noisy, probably due to amplifier noise; the data shown have been smoothed by a 50-point running average. The figure reveals that circulating a single leg consumes 150 W above steady state, and that propelling the body horizontally at 7.5 cm/s (roughly one-half the maximum velocity) requires 600 W above steady state. To our knowledge, this level of propulsive power is unprecedented for a 2500 kg vehicle traversing rough terrain.

The figure shows that the steady-state power consumption of the motors, amplifiers and associated electronics (but without computing) is about 1400 W. Including the laser scanner, the figure would be about 210 W larger. Using more efficient components, particularly multiplexor power supplies and servo amplifiers, could substantially reduce this steady-state power draw. (In constructing the Ambler, we selected

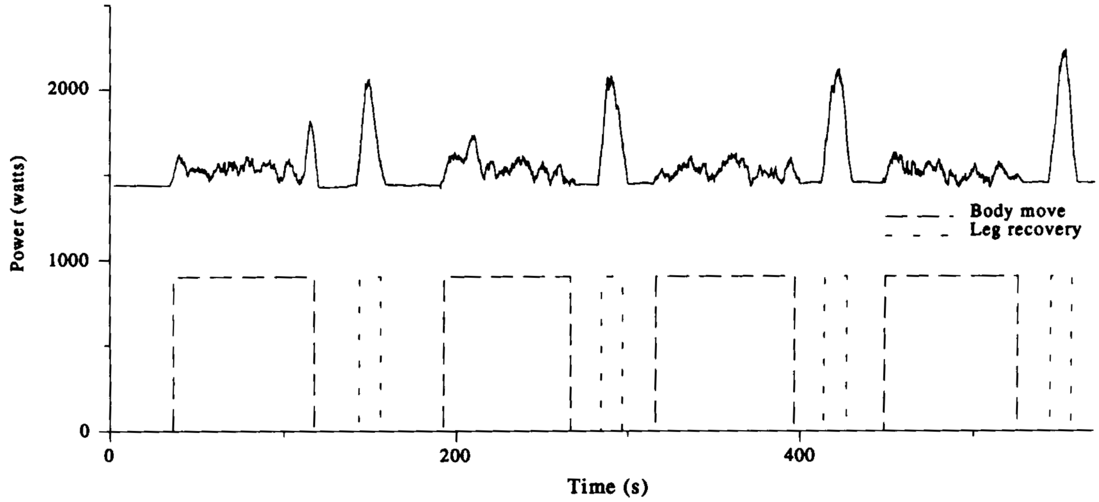
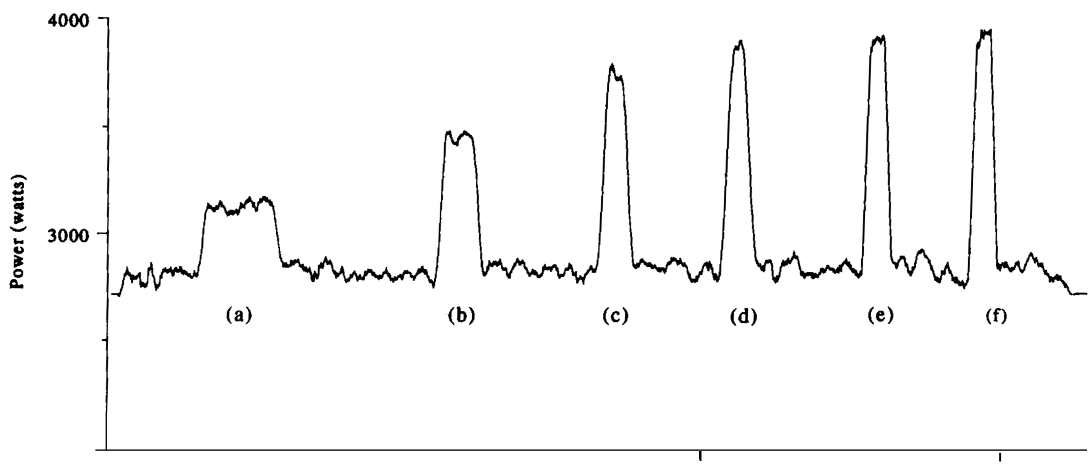


Fig. 2. Power consumption during walking cycle. Power consumed while walking 2 m in four steps on sandy terrain. The longer dashed lines represent leg moves and the shorter dashed lines represent body moves. The distance that the body moves is 50 cm. The peak body velocity is 7.5 cm/s (4.5 m/min).

devices based primarily on cost and availability, rather than efficiency.)

The figure illustrates one reason that predicting the power required to traverse natural terrain is difficult: the spike at the end of the first leg recovery. The reason for this spike is that the Ambler is driving the foot into the ground, because force sensor transients prevented the real-time controller from terminating the move quickly enough. To predict this behavior analytically requires advance knowledge of the foot–terrain interaction, which is virtually impossible to acquire. Statistical prediction of power consumption is a realistic alternative, which requires, in turn, more experimental data.

Figure 3 illustrates the power consumed while raising and lowering the body at different rates. Again, the data have been smoothed by a running average over 50 points. The figure shows that lifting the body at 7 cm/s (maximum velocity) consumes approx. 1800 W above steady state. Lifting the body, power consumption increases approximately linearly with velocity. Lowering the body, power consumption is constant and equal to the steady-state level, because lost potential energy is dissipated as heat by the amplifiers. As shown in Fig. 3(d)–(f), the power profile does not depend significantly on acceleration. From the experimental data, we computed the efficiency of the mechanism as the ratio of mechanical



Fig, 3. Power consumption during vertical body motion. Power consumed while raising and lowering the body 1 m at different velocities and accelerations: (a) 2 cm/s^2, (b) 4 cm/s, 1 cm/s^2, (c) 6 cm/s^2, (d) 7 cm/s, 1 cm/s^2, (e) 7 cm/s, 10 cm/s^2 and (f) 7 cm/s, 100 cm/s^2.

output power to measured input electrical power. While lifting the body at 7.5 cm/s, the efficiency is 70% [1].

In summary, when the Ambler can glide on a level trajectory over the terrain, its propulsion power requirements are low in comparison with other walkers. For example, the Adaptive Suspension Vehicle requires about *22* kW to stand in place, and a total of about *26* kW to walk at 1 m/s [9]. In addition, when the Ambler travels laterally, or when it lifts to climb a slope in a stair-step fashion, its power efficiency is high.

Future power studies will collect statistics that include the power consumed by sensing and computing devices that are now on-board. Future development efforts will modify the planning and control algorithms to generate and execute more efficient motions based on a better understanding of the power consumed by each of the axes of motion.

4. POSITIONING

Dead reckoning is a widely used method that identifies the pose (position and orientation) of a vehicle by integrating its position history. We have developed a weighted least-squares approach to dead reckoning for legged mechanisms, and measured its performance on the Ambler, whose prismatic joints can be controlled within millimeters of the commanded motion, and whose rotary joint backlash is less than a hundredth of a radian. This section states the problem, describes the solution approach, and presents experimental results.

To formulate the problem, we define a stationary world reference frame $\mathscr{W}$, and a body frame $\mathscr{B}$ attached to the Ambler body, which moves with respect to $\mathscr{W}$. Let $\mathbf{x}_{w,i}$ denote the position of foot *i* in $\mathscr{W}$; we store these positions for each body pose of interest. Let $\mathbf{x}_{B,i}$ denote the position of foot *i* in $\mathscr{B}$; these positions can be computed using the mechanism kinematics.

We assume that the Ambler can be treated as a rigid body, or equivalently, that the feet do not move unless commanded. Then the dead-reckoning problem amounts to finding the rigid body transformation (the rotation matrix R and the translation vector **t**) such that

$$\mathbf{x}_{w,j} = \mathbf{R}\mathbf{x}_{B,j} + \mathbf{t}. \tag{1}$$

We seek a solution that minimizes the squared error

$$\sum_{i=1}^{6} w_j \mathbf{e}_j^T \mathbf{e}_j, \tag{2}$$

where $\mathbf{e}_j = \mathbf{x}_{w,j} - \mathbf{R}\mathbf{x}_{B,j} - \mathbf{t}$, and the w_j are weights on the observed positions.

We implemented a solution to this minimization problem in three steps [7]:

(1) Identify feet that have slipped, and prevent them from being used in further computation by setting w to zero.
(2) Solve for the rigid body transformation that best transforms foot positions in $\mathscr{B}$ to $\mathscr{W}$, using a technique based on singular value decomposition developed by Matthies [5].
(3) Update foot positions, if necessary, based on the new body pose and the current leg joint angles. Ideally, no update should be required, but in practice, the least-squares solution may cause discrepancies between the current and stored foot positions.

To test the implementation, we conducted trials in which we commanded the Ambler to advance a specified distance. After execution of the command, we computed the dead-reckoned pose and measured the ***ground truth*** pose by aiming a surveying device at three retroreflectors mounted at fixed and known positions on the Ambler, and solving a set of simultaneous equations for the pose. For each move we recorded the dead-reckoned pose and ground truth pose.

Figure **4** illustrates the results of one trial with 12 body advances covering ***6*** m along a straight line. The figure plots the planar error $\sqrt{\delta_x^2 + \delta_y^2}$, where the δ terms represent the component-wise differences between dead reckoned and ground truth poses. These data suggest that the dead-reckoning error ***u*** is ***2%*** of the distance ***d*** traveled. Given the high precision of the prismatic and rotary joints, and the high encoder resolution, this accuracy is lower than expected.

Further analysis of the data shows that systematic error dominates random **error:** dead-reckoning "thinks" that the body travels a smaller distance than does the surveying device. We believe the source of the systematic error to be an incomplete kinematic model of the Ambler mechanism, one that does not adequately address factors such as small differences between leg dimensions or structural deflection. To reduce the systematic error, we adjust the dead-reckoned planar pose by adding ($u \cos\theta$, $u \sin\theta$), where θ is the heading.

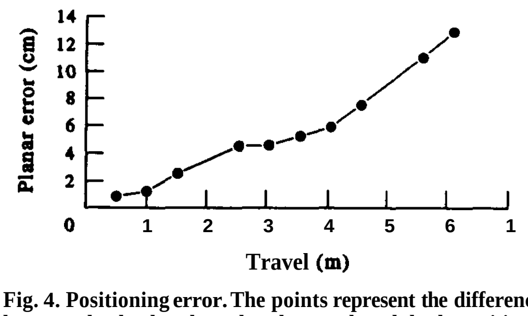


Fig. 4. Positioning error. The points represent the difference between the dead-reckoned and ground truth body positions in the plane of travel. With each advance, the error increases by 2% of the distance traveled.

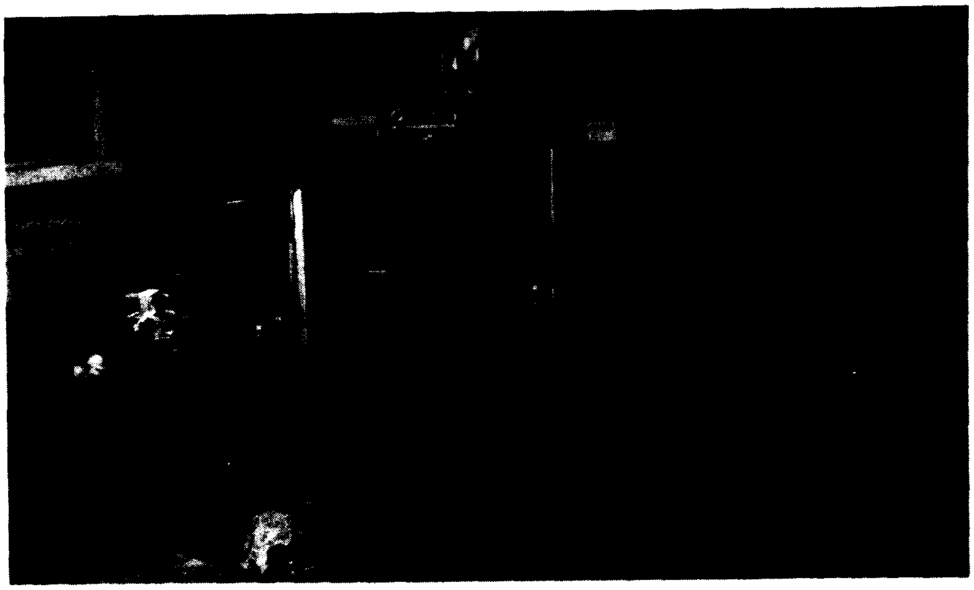


Fig. 5. Ambler on indoor testbed. Ambler on sandy terrain with meter-tall boulders (under legs and body), ditches (the center leg on the far stack is standing in one) and ramps (lower right).

The dead-reckoning tests have been informative, yet important questions remain unanswered. In future work, we will determine the accuracy of dead-reckoning while the Ambler rotates, and confirm the results for translation over the course of a longer traverse (perhaps 100 steps rather than 10). We will incorporate results of these future tests in a navigation module that compensates for the systematic errors, and fuses the dead-reckoned pose with poses reckoned by other techniques such as triangulation from visual landmarks.

5. AUTONOMOUS WALKING

The Ambler walking system[8] consists of a number of distributed modules (processes), each with a specific functionality: perception, planning, real-time control and task-level control. The perception

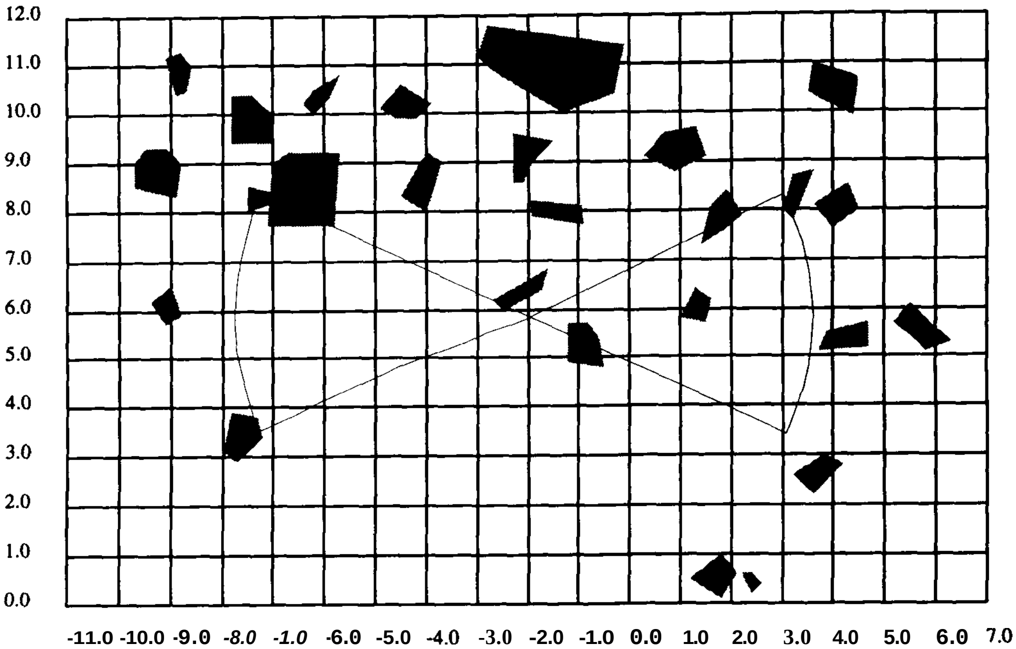


Fig. 6. Figure-eight walking pattern. Top view of obstacle course with figure-eight walking pattern superimposed. The Ambler is drawn as a triangle. Units are meters.

subsystem uses data from a scanning laser rangefinder to build 3-D 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 co-ordinates 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.

The Ambler has operated within a large indoor area that can be sculpted to provide a variety of terrains (Fig. 5). To date, the Ambler has walked autonomously a total of over 2 km, traversing rolling, sandy terrain with meter-tall boulders, ditches and 30" ramps.

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. During another indoor trial, the Ambler autonomously crossed over a 1.5 m tall, 4 m long boulder. To achieve this, the software system automatically raised the height of the Ambler to near full extension.

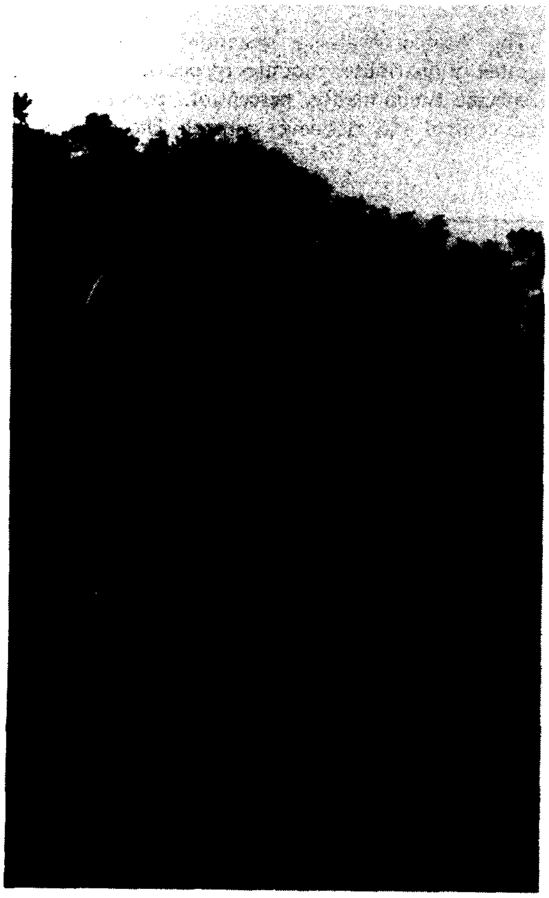


Fig. 7. Ambler **walking outdoors.**

In other indoor trials, the Ambler has demonstrated long-term autonomous walking, following a figure-eight pattern over an obstacle course (Fig. 6). Each figure-eight circuit covers about 35 m and 550" of turn. In one trial, the Ambler traversed 107 m while rotating 55 rad (approx. 9 revolutions), moving the body 397 times and moving the legs 901 m. To accomplish this, the walking system passed about 3.7×10^4 messages and about 4 Gb data between processes.

In one outdoor trial (Fig. 7), the Ambler took 1219 steps over rolling, grassy terrain, traveling 527 m horizontally and 25 m vertically. It followed a 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.

The Ambler has also walked outdoors at night, without lights. The laser rangefinder does not require ambient illumination, unlike ordinary cameras. In fact, we observed the range images to be much noisier during the day, because the signal-to-noise ratio is higher without ambient illumination.

Average walking speed, including all computation, is 35 cm/min (each body move is 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).

We have quantified the computation required to execute some of the perception algorithms on a Sun 3: 2.5 million instructions to acquire a range and reflectance image pair and 20.6 million instructions to construct elevation and footfall maps for 400 points.

6. SUMMARY AND FUTURE WORK

In the spirit of providing data to mission planners, we have attempted to provide quantitative answers to questions about power consumption, positioning accuracy and autonomous walking. The answers are based on our practical experience with the performance of the Ambler, an autonomous, six-legged robot conceived for an exploration mission in Mars-like terrain. We recognize the incompleteness of the results, and the need for further experimentation and analysis.

Toward this end, we have identified two new directions for future work with the Ambler. One is to walk outdoors, traversing more extreme terrain with a more self-reliant rover (with power on-board and extended error recovery procedures) for longer periods. The other is to conduct exploration missions, autonomously searching for a given object of interest in a large, obstacle-strewn area and simultaneously preparing a detailed global map of the terrain encountered, keeping uncertainty in the map to a minimum.

7. DISCUSSION

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 metrics in at least three areas

(1) ***Mobility performance.*** These metrics should include dimensionless quantities such as specific resistance. They should also incorporate metrics related to absolute performance requirements, for example, on bump crossing, maneuverability and tipover margins. A "Consumer Reports" style evaluation may be appropriate.

(2) ***Energy efficiency.*** These metrics should be evaluated on a variety of slopes, and should include not only the energy 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 to the extent that level body motion simplifies the problem of merging images and maps from different positions.

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