Ambler: A Six-Legged Planetary Rover*

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Abstract—**The goal of the CMU Planetary Rover project is to prototype an autonomous mobile robot for planetary exploration. We have constructed a six-legged walking robot, called the Ambler, that features orthogonal legs, an overlapping gait, and a scanning laser rangefinder to model terrain. To enable the Ambler to walk over rugged terrain, we have combined perception, planning, and real-time control into a comprehensive robotic system.**

1 Introduction

The goal of the Carnegie Mellon University Planetary Rover project is to prototype an autonomous mobile robot for planetary exploration. We have constructed a six-legged walking robot, called the Ambler, that features orthogonal legs, an overlapping gait, and a laser rangefinder to preview terrain. To enable the Ambler to walk over rugged terrain, we have combined perception, planning, and real-time control into a comprehensive robotic system.

A previous article [3] presented a scenario for a robotic mission to Mars or the Moon, outlined our technical approach toward enabling such a mission, and contrasted it to other research efforts in autonomous walking, which include [1, 4, 5, 6, 8]. This article concentrates on specific technical achievements of the research program rather than on its broad objectives, focusing on the Ambler mechanism in the next section, the components of the integrated walking system in Section 3, and results from walking experiments in Section 4. We conclude by discussing future research directions.

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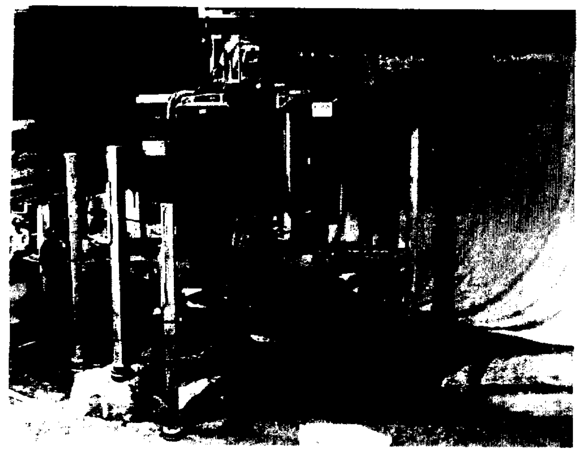

Figure 1: Ambler on indoor test course

2 Ambler

The Ambler (Figure 1) 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.

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. Low power: the power budget must not exceed 1 kW for velocities of 1 m/min.

The advantages of the Ambler configuration are presented elsewhere [2, 3].

Each Ambler leg consists of a rotational link and an extensional link that move in the horizontal plane, and an

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orthogonal vertical link. The Ambler's six legs are stacked on two central body shafts, three legs to a shaft. Each shaft is connected to an arched body structure that includes four enclosures housing power generation, electronics, computing, and scientific equipment. The structural elements are primarily of aluminum construction. 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.

Each Ambler leg is identical. 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 includes 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 on the base of each vertical link measures the forces acting on the feet.

A tether—46m of protective fabric sheathing that contains 130 shielded twisted pairs, 30 coaxial cables, and power cables—carries power and control signals to the Ambler. Eventually, the controller, power generation equipment, and telemetry devices will be housed in the body, eliminating the need for the tether.

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 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.

Two sampling pods under the leg stacks can accommodate large sampling tools or sensors. The Ambler can place them in close 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 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 Integrated Walking System

What are the processes that coordinate and control the Ambler mechanism, allowing it to walk over rough terrain? We begin with task control, and then turn to real-time control, perception, and planning; more complete descriptions of these processes can be found in [7].

3.1 Task Control

The Task Control Architecture (TCA) was designed to integrate sub-systems developed by different researchers into a complete robotic system. TCA provides mechanisms to support message passing between distributed processes, hierarchical planning, plan execution, monitoring the environment, and exception handling. A system built using TCA consists of a number of task-specific processes, called *modules*, and a general *central control* process that directs the flow of communication between modules. The integrated walking system consists of six modules plus the central control (Figure 2).

A prominent aspect of TCA is centralized control. Although researchers have recently advocated decentralized control for mobile robots, we believe that centralized control has many advantages for supporting the above capabilities. First, it can more easily control multiple tasks by synchronizing them, allocating resources, and determining which tasks have priority. Second, centralized control makes the system more understandable and easier to modify. Since there is a single point through which all communication flows, one can easily monitor and analyze the communication. Finally, centralized control has not proved to be a system bottleneck in our applications; TCA can process a message in approximately 80 msec, faster than either the perception or control systems operate.

With TCA, planning and executing a task occurs by modules sending a series of messages to one another. During integrated walking, after all modules have connected to central and registered their messages and message handlers, a message is sent to the gait planner instructing it to begin planning. To plan and execute a single, complete step involves sending about 25 messages.

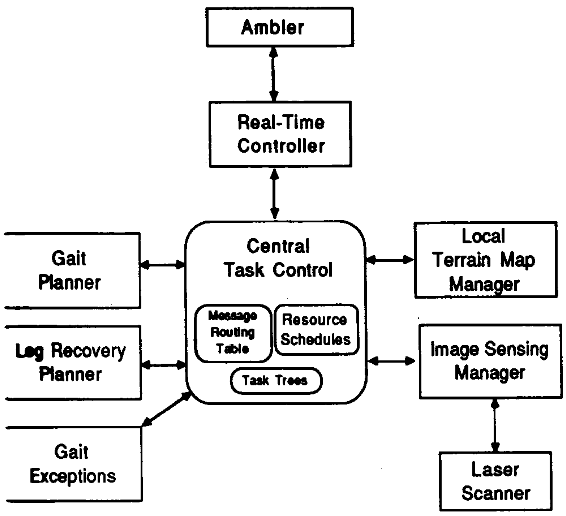

Figure 2: Integrated system modules

There are three types of messages, with each message class having a different semantics and different effects. *Query* messages obtain information about the external or internal environment. *Goal* messages provide a mechanism for hierarchical planning. When a module issues a goal message, TCA creates a node and adds it as a child of the node associated with the handler that issued the message. These nodes form a hierarchical ***task tree*** that TCA uses to schedule planning and execution of tasks. *Command* messages are requests for some action to be performed. Like goal messages, TCA adds them to the task tree; typically, they form the leaf nodes of the tree.

In addition to specifying parent/children relationships in the task tree, TCA provides mechanisms for temporally constraining the relationships between nodes in the tree. Essentially, the task trees plus the temporal constraints form TCA's representation of plans. For example, one can specify that command A must be executed before command B is started, or that goal C cannot be planned until command B has finished. TCA maintains separate constraints for the planning and achievement of tasks—thus, one could specify that the robot should go to a sample site and then acquire a sample, but that it should plan how (and if) it can acquire the sample before planning how to navigate to the site.

Unlike query messages, goal and command messages are non-blocking, i.e., a goal or command message has not necessarily been handled by the time control returns to the module issuing the message. This asynchronous control makes the overall system more reactive since the central process controls when to schedule tasks and when to preempt them. The non-blocking nature of goal and command messages also makes it easy to do planning in advance of execution. The planning modules merely send messages that create task trees, and TCA ensures that the tasks will be executed at the appropriate times.

3.2 Real-Time Control

The real-time controller serves as an interface between the physical robot mechanism and its users, which may be a human operator or other computers. The controller is implemented as a multi-processor VME-based system, using the VxWorks (TM) operating system on 68020- and 68030-based processors. Communication with other modules is accomplished through the TCA over an Ethernet link. Creonics programmable motion control cards supply stable and precise position and velocity servo control over all 18 actuators. Digital status and control signals such as brake control lines or force sensor threshold interrupts are accessed via digital input/output circuits, while force sensor and inclinometer data are acquired via analog-to-digital converter boards.

In normal operation, the controller initializes all hardware components, creates a TCA connection, and waits for commands or queries from other TCA modules. At the same time, an operator console enables access to diagnostic routines and simple control modes similar to a joystick. Commands accepted via the TCA are primarily "move the leg" and "move the body." Queries cause the controller to provide current leg positions with respect to the body, and the body position in global coordinates based on dead-reckoning estimation techniques.

The leg move command format includes a list of points in joint coordinates (called waypoints) which represent the path to be followed by the foot of a given leg. By convention, the motion of all three leg joints is roughly characterized by constant-velocity travel between waypoints and constant-acceleration travel at the waypoints. Typically, waypoints are spaced between 0.5 and 2 m apart. Execution of such leg move commands is achieved by computing the appropriate joint position trajectories with a time resolution of approximately 10 msec and simultaneously updating the reference positions of the individual leg joints at the corresponding rate of 100 Hz. Since most leg moves begin with lifting the foot off the ground and terminate by placing the foot back on the terrain, a control mode called ***transition mode*** can be specified as part of the leg move command. It activates use of the force sensor feedback to detect initial lift-off and subsequent ground contact. In transition mode, no horizontal motion is performed until lift-off has been detected, and the trajectory is terminated as soon as the foot has been placed firmly on the ground. In addition, the force sensor detects terrain collisions during a leg move and causes the controller to immediately stop the motion.

Body moves are specified in a similar format, but only one destination waypoint is given. A body move waypoint, however, combines position and orientation, so that translation and rotation of the body can occur simultaneously. A linear interpolation technique computes a trajectory which translates the body in a straight line to the destination position while rotating about the center of the body to reach the specified final orientation during the same period. A trapezoidal velocity profile, beginning and ending at zero velocity, is imposed to effect smooth motion of the body. This body trajectory is translated into corresponding joint trajectories for all legs and executed in the same way as the leg move trajectory.

3.3 Perception

The perception system consists of two major modules: the Imaging Sensor Manager (ISM), which senses the environment with a scanning laser rangefinder; and the Local Terrain Map Manager (LTM Manager), which constructs elevation maps from the rangefinder data.

The ISM controls the imaging sensors, including initialization, status determination, data acquisition, calibration, aiming, and other operations. The ISM has been implemented and tested for the Erim and Perceptron scanning laser rangefinders. These sensors may be real (i.e., they acquire data in real-time from the physical sensor) or virtual (i.e., they acquire data from storage, not directly from the sensor). We have found virtual devices and virtual images to be useful for developing and testing code without hardware.

The LTM Manager constructs and maintains a Local Terrain Map (LTM) for locomotion guidance, short-range navigation, and sampling operations. An LTM describes the environment in the immediate vicinity of the Ambler, and may extend up to tens of meters on a side. An LTM is not, strictly speaking, a single map; in practice, it is a registered collection of maps, whose descriptions of the environment include geometric characteristics and material properties of the terrain. We have organized the software into three major submodules: one that builds the LTM, one that merges LTMs, and one that focuses attention on parts of the LTM that are closer to the vehicle. Figure 3 illustrates an obstacle course and a map of the course constructed by the perception system from five Erim images.

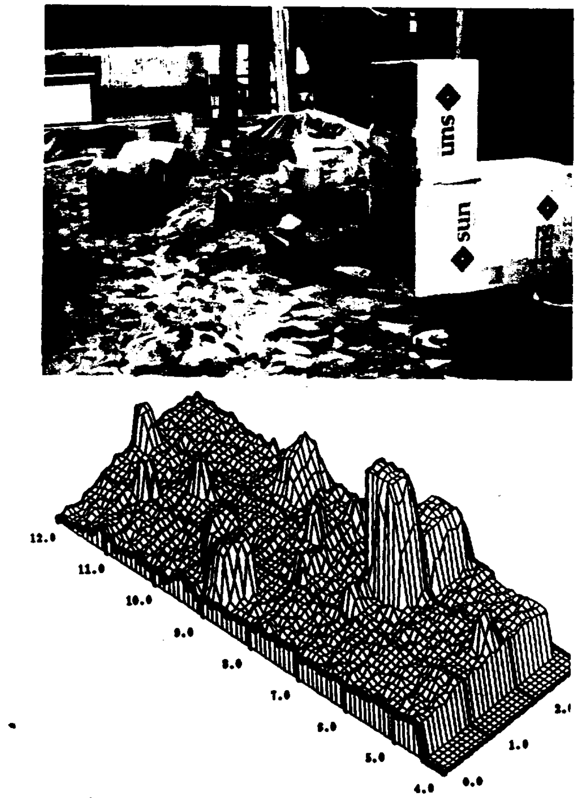

Figure 3: Obstacle course and map

The obstacle course (top, not used for Ambler walking) is 10 long and consists of a box, some pylons, two larger obstacl and a dozen or so smaller obstacles. The perception syst built this elevation map from five Erim range images acquir at different positions. The map resolution is 10 cm, $0 \leq X \leq$ m, and $4 \leq Y \leq 12$ m.

3.4 Planning

To walk through rugged terrain, plans are necessary to specify at least the trajectory to walk along, the body motions that track that trajectory, the foot placements that enable the body motions, the preferred foot placement given the robot and environmental constraints, a the leg recoveries required for the foot placement. W have proposed and begun to implement a hierarchy planning strategies for the Ambler. These strategies c compose rough terrain navigation into levels of resoluti that allow useful abstractions and simplifications. For l calized walking, on the scale of fifty meters, planning decomposed into levels of trajectories, gaits, and footfal Separate planners in a hierarchy can cooperate effective within the TCA.

Trajectories link position and orientation objectives the environment. An abstraction of "feasible traversab ity" allows the trajectory planner to identify acceptab trajectories without concern for details at lower leve the planner finds paths that guarantee acceptable footfa without proceeding to the selection of a specific footfal

A *gait* is a patterned sequence of leg and body moves. The usual context of gait studies is the regular, periodic combinations of supporting and recovering legs. Walking robots in very rough terrain must adapt to the terrain and spontaneously modify their gait. Gait planning becomes a moment-by-moment analysis of leg and body move options [9].

The gait characteristics necessary to achieve arbitrary motion are length of stride (pitch), width of stance (tread), and sequence of leg recoveries. A global search for appropriate values is combinatorially explosive, even for short vehicle motion. Constraints are required to reduce the search space. Also, the choice of a leg or body move has relevance to the robot's next few moves but not necessarily to moves in the distant future. Gait planning can be opportunistic, taking advantage of the Ambler's current stance and surrounding terrain, and not searching far in advance.

The constraints governing gaits, however formulated, are related to maintaining *stability* or maintaining *advance*. In order to plan a gait that satisfies these constraints, local search is necessary to preclude obvious dangers (obstacles must be detected before they impede advance) and subtle ones (a stance at the limit of support or kinematic constraints must transition into the next stance without violating a constraint).

Several abstractions are useful in planning within these constraints. The support polygon for a stance is the convex hull of all ground support points. When the center of force is held above the support polygon, the system is statically stable. If five of the Ambler's legs are supporting while the sixth is recovering and one of the supporting legs fails (due to mechanical failure or soil collapse), then the support polygon is the quadrilateral of the four remaining support points. Considering the failure of each of the legs in turn generates a number of support polygons equal to the number of supporting legs. The intersection of these polygons is the Conservative Support Polygon (CSP)—the area that gives guaranteed static support if one of the supporting legs fails.

The CSP abstraction is useful in the planning process because it provides limitations on the movement of the body, which in turn limits the footfalls that must be considered. In a sequence of stable moves, each CSP overlaps the next so that the body remains continuously within conservative support.

A uniform gait can be set by fixing the pitch and tread at constant values. The advantage of the uniform gait is that planning is greatly simplified—the number of options to consider at each leg move is reduced—and progress along the trajectory is near optimal. The difficulty is choosing values that optimize progress along a given trajectory. For example, by moving the legs in (close to the body laterally) and reaching far forward (narrow tread and long pitch), the body can propel the largest distance forward and backward. However, by stretching out to the sides with narrow spacing between the legs (short pitch and wide tread), the greatest rotation is possible.

Choosing constant pitch and tread lends itself to travel along an arc because as the body changes orientation along the arc, the preferred footfalls distribute uniformly. Fixing the pitch and tread for walking along an arc means that the feet on the outside of the arc must be recovered more often than those on the inside. For arcs of small radius, the forward pitch and tread to the inside of the turn are out of reach when the alternate backward pitch and tread are reachable, so the action is retrograde on the inside.

This approach specifies the ideal locations of footfalls on moderate terrain. If there are obstacles in the terrain, the specific contact points, derived by combining constraints from the kinematics of the mechanism with constraints from the quality and details of the terrain, must be considered. We have developed a footfall planner that selects footfalls that insure stability and remain within the tolerances of the gait.

Through stages of refinement, the Ambler's gait planner generates a uniform gait through easily traversable terrain but still selects acceptable leg and body moves in difficult terrain or transitions. Much of this has been demonstrated in simulation and is being tested on the Ambler.

4 Walking Experiments

After the Ambler's initial power-up in December 1989, a series of walking experiments were conducted on a variety of indoor test courses (e.g., Figure 1). In total, the Ambler has walked autonomously more than 1 km. In most (but not all) cases, an overhead crane passively supported the walker so that it would support the Ambler in the event of a failure, but would not provide support otherwise.

For the first family of experiments, the integrated system consisted of three modules: the central task controller, the real-time controller, and the gait planner. One set of trials from this family involved walking straight ahead, both on a flat, concrete floor and on rolling, sandy terrain. In a typical trial, the Ambler walked forward five or ten steps, advancing the body about 60 cm/step, and then retraced those steps walking backward. Approximately 100 of these traverses were conducted. In another set of trials from this family, on relatively flat, sandy terrain, the Ambler executed a number of point turns (radius 0 m) and followed arcs with radii ranging 5 m (approximately -60 deg) to 1000 m (approximately 0 deg).

For the second family of experiments, the integrated system consisted of the aforementioned modules plus the perception modules. Here, the gait planner used terrain maps computed by the perception system to plan trajectories. With this input, the Ambler successfully demonstrated walking on the flat, concrete floor, walking on rolling, sandy terrain, and walking up a ramp.

For the final experiment, the integrated system includes all of the modules. The obstacle course consisted of 20 tons of meter-scale boulders, a ramp 2 m long inclined at 30 deg, and 40 tons of sand. Almost any rolling vehicle except a large battlefield tank would encounter substantial difficulty traversing this course. The task was specified to the Ambler as follows:

1. Follow the arc of a circle 6 m in diameter. (This required taking a dozen steps through boulders, and on and over the ramp.)

2. Rotate in place by -60 deg. (This required taking an alternating sequence of prograde leg recoveries on one stack, and retrograde recoveries on the other, avoiding boulders and the ramp on each move).

3. Follow the arc of a circle 1000 m in diameter. (This required walking approximately straight ahead over rolling, bouldered terrain.)

The Ambler successfully negotiated this course tens of times, both with and without the overhead crane. No two traverses were exactly the same, although they all satisfied the commands. Typically, the Ambler took about 40 steps through this course, with an average walking speed of 35 cm/min. The controller module moved the mechanism for three quarters of the time, and the planning and perception modules were each active about half the time.

5 Discussion

This paper has presented the recent technical progress of the Carnegie Mellon University Planetary Rover research program. In this article, we concentrated on the Ambler mechanism and the components of the integrated walking system, and documented the walking experiments.

Currently, we are conducting extensive tests—walking over more and more challenging terrains—to demonstrate the capabilities of the Ambler and the integrated walking system. Future walking experiments will further challenge the Ambler's mobility and autonomy. As the integrated system matures into a reliable appliance, we will eliminate reliance on the overhead crane, allowing the Ambler to confront rougher (greater elevation variation) indoor courses, and permitting the Ambler to move outdoors. The tether will then be reduced, permitting the Ambler to traverse longer-range courses. The objective for December 1991 is for the Ambler to follow an arbitrary user-specified path for four hours.

At the same time, increasing emphasis will be placed on manipulation issues, in the context of performing prospecting missions. Toward this end, sample acquisition tooling and sensors will be mounted on the Ambler, to address the issues involved with coupling mobility and manipulation. Another objective for December 1991 is to demonstrate an indoor sampling mission.

In the course of these experiments, the Ambler will confront many of the problems imposed by harsh terrain and the need for extreme self-reliance. Some of these problems have not even been formulated yet. Research into legged locomotion, real-time control, perception of rugged terrain, and integrated task control must continue to expose and formalize the problems of robotic exploration, and to develop the innovative approaches required to send intelligent machines to Mars and beyond.

References

[1] C. Angle and R. Brooks. Small Planetary Rovers. In *Proc. IEEE Intl. Workshop on Intelligent Robots and Systems*, pages 383–388, Tsuchiura, Japan, July 1990.

[2] J. Bares. *Orthogonal Walkers for Autonomous Exploration of Severe Terrain.* PhD thesis, Department of Civil Engineering, Carnegie Mellon University, To appear, May 1991.

[3] J. Bares, M. Hebert, T. Kanade, E. Krotkov, T. Mitchell, R. Simmons, and W. Whittaker. Ambler: An Autonomous Rover for Planetary Exploration. *IEEE Computer*, 22(6):18–26, June 1989.

[4] D. Gorinevsky and A. Shneider. Force Control in Locomotion of Legged Vehicles over Rigid and Soft Surfaces. *Intl. Journal of Robotics Research*, 9(2):4–23, April 1990.

[5] S. Hirose. A Study of Design and Control of a Quadruped Walking Vehicle. *Intl. Journal of Robotics Research*, 3(2):113–133, Summer 1984.

[6] M. Raibert. *Legged Robots That Balance.* MIT Press, Cambridge, Massachusetts, 1986.

[7] R. Simmons and E. Krotkov. An Integrated Walking System for the Ambler Planetary Rover. In *Proc. IEEE Intl. Conf. Robotics and Automation*, Sacramento, California, April 1991.

[8] S. Song and K. Waldron. *Machines that Walk: The Adaptive Suspension Vehicle.* MIT Press, Cambridge, Massachusetts, 1989.

[9] D. Wettergreen, H. Thomas, and C. Thorpe. Planning Strategies for the Ambler Walking Robot. In *Proc. IEEE Intl. Conf. Systems Engineering*, August 1990.