Planning Strategies for the Ambler Walking Robot

David Wettergreen, Hans Thomas, and Chuck Thorpe

The Robotics Institute, Carnegie Mellon University

Abstract: Mobile robots that autonomously explore rugged natural terrain must be highly adept at locomotion requiring competent planning strategies in addition to a capable vehicle. We propose and explain a hierarchy of planning strategies for a *walking* robot, the Ambler. The hierarchy decomposes planning into levels of trajectory, gait, and footfall. An abstraction of feasible traversability allows the Ambler's trajectory planner to identify acceptable trajectories by finding paths that guarantee footfalls without specifying exactly which footfalls. Leg and body moves that achieve this trajectory can be generated by the Ambler's gait planner which incorporates pattern constraints and measures of utility to search for the best next move. By combining constraints from the kinematics of the mechanism with constraints from the quality and details of the terrain, the Ambler's footfall planner can select footfalls that insure stability and remain within the tolerances of the gait.

Introduction

Mobile robots that autonomously explore rugged natural terrain must be highly adept at locomotion requiring competent planning strategies in addition to a capable vehicle. We propose and explain a hierarchy of unique planning strategies for a *walking* robot. These strategies decompose rough terrain navigation into levels of resolution that allow novel abstractions and simplifications of the problem. Separate planners in a hierarchy can cooperate effectively if the decomposition is correct. For localized walking, on the scale of fifty meters, planning can be decomposed into levels of trajectories, gaits, and footfalls.

Trajectories link position and orientation objectives in the environment. The trajectories intended here are analogous to the trajectories that connect the knotpoints, or goals, in the configuration space of a standard fixed-base manipulator. An abstraction of "feasible traversability" allows a trajectory planner to identify acceptable trajectories without concern for details at lower levels in the hierarchy by finding paths that guarantee acceptable footfalls without specifying exactly which footfalls.

A *gait* is a sequence of leg and body moves. The usual context of gait studies is the regular, periodic combinations of legs on the ground and leg motions. These different patterns generate trots, canters, gallops and so forth. Walking robots in very rough terrain have a completely different set of constraints. For maximum stability, only one leg is moved at a time. Because of the tight maneuvers and rugged terrain, the sequence of leg movements may not be periodic or fixed but may vary continuously. In this context, gait planning is often a moment-by-moment analysis of which leg should be moved, and approximately where it should be placed. Leg and body moves that achieve a given trajectory can be generated by a gait planner that incorporates pattern constraints to search for the best next move.

Individual *footfalls* are the specific terrain contact points that are derived from the gait pattern. The horse's ability to avoid rocks and fences as it gallops is evidence that the specific foot contact is allowed some variation within the constraints of the gait pattern. By combining constraints from the kinematics of the mechanism with constraints from the quality and details of the terrain, a footfall planner can select footfalls that insure stability and remain within the tolerances of the gait.

The Ambler Walking Robot

Rugged terrain is characterized by featureless landscapes of sand and rock containing obstacles of irregular geometry. Mining, construction and waste disposal sites, and planetary surfaces are examples of rugged terrains. The Martian surface typifies these environments. (Figure 1)

Figure 1 - Surface of Mars from a Viking Lander

Although the problems involved in rugged terrain navigation have been investigated, the vehicles used in these experiments have been primarily wheeled or tracked locomotors. [Rosenblatt88] [Stentz89] Legged vehicles offer advantages in control of stability, isolation from terrain irregularities, power consumption, and rough terrain capability.

The *Ambler*, for autonomous mobile exploratory robot, is a walking robot built at Carnegie Mellon University to traverse rugged terrain with high reliability. (Figure 2) [Bares90] The Ambler is a unique mechanism with six legs each of which consists of two links in the horizontal plane, one rotational and one extensional, and one extensional link in the orthogonal, vertical plane. The rotational links are stacked around two central shafts with three legs on each and are able to rotate continuously. The horizontal links permit planar motion of the

CH2872-0/90/0000-0198 © $1.00 1990 IEEE

leg and the vertical extensional link provides motion of the foot down to ground contact.

On-board sensing consists of a scanning laser range-finder and foot-mounted force-torque sensors. The range finder is used to generate depth maps of the terrain. [Kweon89] At close range the depth maps are of high resolution suitable for selecting individual footfalls, while at long range they provide adequate information to determine the traversability of distant terrain. The force-torque sensors provide support information about the terrain and the stability of the current *stance*, the static arrangement of the legs and body. Although the specific position of the legs changes the overall height, width and length of the Ambler, a typical stance is 5 meters tall, 4.5 meters wide and 3.5 meters long.

The orthogonal leg design of the Ambler decouples horizontal and vertical motions for energy and planning efficiency. Each vertical link adjusts to the terrain roughness so that the Ambler remains constantly level providing a stable platform for sensing and sampling operations.

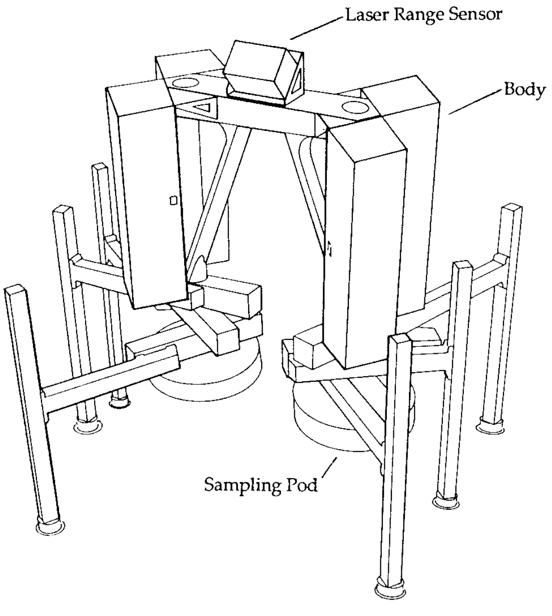

Figure 2 - Ambler Walking Robot

The Ambler walks by lifting a leg vertically, swinging it in the horizontal plane, extending it down to terrain contact, and then gliding the body forward at level elevation by coordinated actuation of the joints in the supporting legs. The Ambler can perform any of the gaits associated with hexapods including the alternating tripod, in which three legs move while three support, and crab walking which is an alternating tripod in the lateral direction. Follow-the-leader, ratchet or wave gaits, where some legs move to new locations while others adjust into available locations — in the manner of centipede — are also possible for the Ambler.

The Ambler's primary mode of walking is a *circulating* gait. This gait, which has no natural counterpart, is performed by lifting a rear trailing leg, passing it through the body cavity, and placing it out in front of a leading leg. When this circulation of the rear legs to the front is repeated six times, all six legs will have made a complete circulation of their stack axis. The circulating gait can reduce the number of footfalls per equivalent body advance to less than that of any naturally occurring gait. By circulating one stack forward and one stack back (retrograde) the Ambler can turn in place. Through proper selection of gait and foot placement, the Ambler can follow an arc of any radius (from zero for a point turn, to infinity for a straight line).

Trajectories

Trajectories define the desired vehicle path through ten to twenty meters of terrain, limited by the sensor field of view. The Ambler needs a trajectory planner that can contend with occluded regions, limited resolution, and the computational explosion of potential paths, and still find acceptable trajectories to follow. It must enable the Ambler to avoid vehicle-sized obstacles and otherwise impassible regions. The challenge of trajectory planning for a walking vehicle is to find an abstraction for traversability that is tractable to calculate but does not simplify the problem to the point that only the most ideal cases can be addressed.

It is possible, but undesirable, to search for a trajectory by enumerating and testing each potential footfall and the actuating motions. This would have the advantage of finding all possible trajectories, but is unrealistic for actual operation. The difficulty is the overwhelming amount of data to consider. Any exhaustive approach is infeasible in all but the simplest cases.

The opposite approach to exhaustive search is to select trajectories through "smooth" or "easy" terrain, as determined by a simple terrain-smoothness operation, and gamble that, as the robot approaches each point along the path, suitable footfalls will be found. Such an abstraction operates quickly but may generate infeasible trajectories, or overlook feasible trajectories, because its abstraction of terrain over-generalizes.

The Ambler uses a strategy that improves on both of these approaches, by developing a terrain representation that reduces the computational and data representation complexity, without losing the ability to distinguish feasible from infeasible trajectories. The result of this planner is a path with high probability of successful execution without the expense of individual foot placement enumeration.

The most difficult part of trajectory planning for the Ambler is determining where, on the terrain, the vehicle can feasibly stand. Models of the robot's kinematic capabilities, maneuverability, and support constraints provide reasonable measures that can be used to evaluate terrain for traversability. The important considerations for stability are the body height and feasible footfall locations. Minimum body height is limited by the highest point below the vehicle. Given the minimum body height, a set of feasible footfalls are determined by maximum vertical leg extension and feasible horizontal leg placements. The strategy for a given *x* and *y* position is to:

- Calculate the minimum Ambler height so the body or sweeping legs just contacts the highest point of nearby terrain.
- Find all reachable footfalls. Footfalls must be acceptable in vertical extension as well as horizontal reach.
- Examine the set of reachable terrain points to identify a set of five feasible footfalls that provide stable support. If a set exists, then this terrain patch will support the vehicle; if not, it is impassible. (Figure 3)

In moderate terrain, it is possible to look at larger areas of terrain. If the maximum difference in elevation over an area of terrain is less than the leg *stroke*, the range of vertical leg extensions, then all points in that area are feasible footfalls, and the terrain is automatically traversable. This simplification is particularly useful in moderate terrain characterized by small surface slope and sparse obstacles.

In the opposite extreme there are pathological cases in which the Ambler can stand in various locations in the terrain but cannot move from one to the next. This generally occurs when the number of changes in leg placement from one stance to the next is high. Such failure cases indicate two things. First, that the terrain is extremely complex — subsequent failure by lower level planners will indicate that it is impassible. Second, the trajectory planner is not operating at fine enough resolution in position and/or orientation to detect impassible intermediate terrains. Failure indicates that the trajectory planning should be repeated at finer resolution. There is a clear relationship between the complexity of the terrain and the resolution of trajectory planning required.

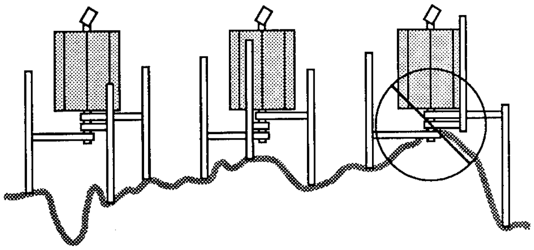

Figure 3 - Low traversable, high traversable and impassible terrains.

Given a traversable passage, a specific path has to be found for the Ambler to follow. The Ambler lacks the non-holonomic constraints found in most conventional wheeled vehicles. It possess the ability to vary its foot placement and perform omnidirectional body motion. Unlike a car, it is not constrained to navigate along arcs greater than some minimum radius — turns of zero radius are possible. Although this is attractive from the standpoint of agility, it complicates the planning process. A sequence of point-turn to face the goal, move in a straight line to the goal position, and point-turn to the goal orientation, can connect any positional objectives by the shortest path but not necessarily by the least number of footfalls. In many cases an arc is a more efficient trajectory between goals. The planning strategy must identify the best path within the traversable area to attain positional goals and we are currently exploring ways of selecting such a path. We will be developing measures of the relative expense in energy, time, and stability of various arcs and transitions, and using them to search for the best path. A method developed on the Carnegie Mellon Navlab, to build a configuration space using similar metrics, holds promise for the Ambler as well. [Stentz89] The actual selection of a trajectory is then a search through feasible positions and orientations in the configurations from the start point to the goal.

Gaits

When the vehicle trajectory has been designated, a gait that executes this trajectory efficiently must be planned. The trajectory may be complicated. It may include turns, reversals, and lateral motions. Much of the research performed to date on gaits concerned itself with either analyzing the patterns underlying the gait or the realization of a particular gait on a physical mechanism. Although this has succeeded in identifying the major elements which characterize a gait (such as the *pitch* which is the spacing between legs along the direction of motion and the *tread* which is the distance from the direction of motion to the foot) as well as several dominant gait patterns (like alternating tripod and follow-the-leader) a method for generating a gait from basic characteristics has not been forthcoming.

Walking can be generated by combining several independently-operating behaviors as demonstrated on a recent walking insect robot. [Brooks90] The walking insect featured a rear-propogated wave gait implemented as a finite state machine, with legs adapting to minimize the body tilt. This algorithm is similar to that employed by the Adaptive Suspension Vehicle (ASV) and the MELWALK III vehicle. [Song88] [Kaneko89] The walking insect was also able to learn to walk by converging on regular pattern of motion. This was particularly interesting because it demonstrated the fundamental nature of the alternating tripod gait and the notion that gait is essentially a pattern generation problem.

The ASV demonstrated the feasibility of rugged terrain locomotion with a legged vehicle, using a human "planner". [Lee88] Various gaits were developed for traversing moderately difficult terrain. In order to overcome large obstacles, however, pre-programmed walking modes for specific classes of obstacles (ditches, walls, hills) had to be initiated by the operator. More desirable is a mode-less form of walking in which the direction of travel generates the gait, rather than by selection from a discrete set of options. The ideal mode-less walking is a smooth glide over terrain with no rough transitions.

The significant gait characteristics necessary to achieve arbitrary motion are the length and direction of the stride, the width of its stance, and the sequence of leg recoveries. A global search for appropriate values quickly leads to a combinatorially explosive situation, even for short vehicle motion. Such global optimization is unnecessary — gait is a local phenomenon. The choice of a footfall or body move at one point in time rarely has any relevance to footfalls or body moves far in the future. It must be opportunistic to take advantage of the vehicle's current configuration, desired path, and terrain. The primary constraints governing gaits are also local in nature, such as maintaining stability and maintaining advance. In order to plan a gait that satisfies these constraints, some degree of forward search is necessary. Otherwise, there is the obvious danger that obstacles would not be detected until they impeded vehicle advance. A more subtle danger is that a stance, at the limit of its support or kinematic constraints, may not be able to move 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 minimum bounding polygon, on the ground plane, that includes all leg-ground contact points. As long as the vehicle's center of force (approximately the center of gravity for a slow-moving vehicle) is held above the support polygon, the vehicle is statically stable. If five legs are on the ground while the sixth is recovering, the support polygon is generally a pentagon. If one of the five supporting legs fails, either due to mechanical failure or soil collapse, the support polygon would be reduced to a quadrilateral. 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 even if any one of the supporting legs fails. When five legs are in contact with the ground, as during a leg recovery, the CSP is usually a pentagon. (Figure 4).

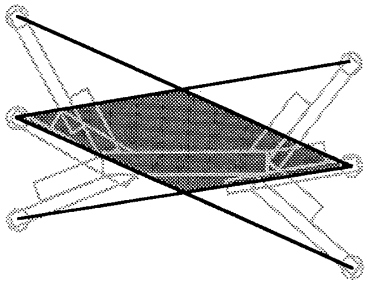

Figure 4 - Five Leg Conservative Support Polygon

When six legs are in contact with the ground, as during a body move, the CSP is generally a quadrilateral that subsumes all the five leg conservative support polygons. (Figure 5)

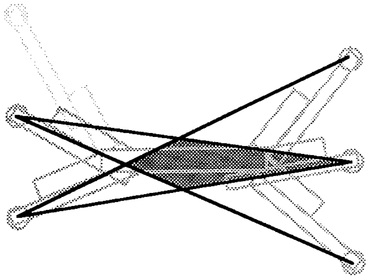

Figure 5 - Six Leg Conservative Support Polygon

The CSP abstraction is useful in the planning process because it provides limitations on the movement of the body and this in turn limits the footfalls that must be considered. (Figure 6) A feasible sequence of stable moves must chain together moves so that the body can glide from one CSP to the next.

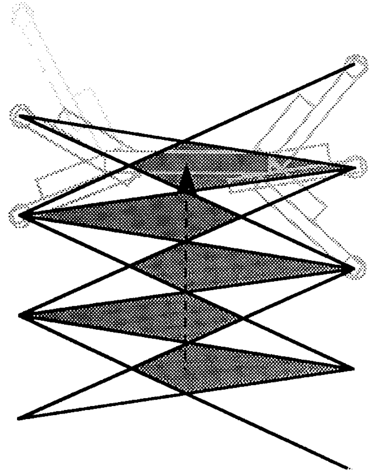

Figure 6 - Walking with continuous CSP security

To maintain productive advance the abstraction of reachable space for the leg stack simplifies the selection of the most productive rotation and translation. Each stack must be maintained in its reachable volume. (Figure 7) The crescent shaped regions are kinematically feasible based on the leg placements. Any translation and rotation that maintains each stack in its respective crescent is allowable. A search through this space quickly identifies the possible motion along any arc in space. The intersection of the CSP and stack reachability constraints limit the next body move.

Given the stack reachable space and CSP constraint abstractions there are two different and complementary ways of computing standard gaits: either as pattern of uniform stances which are modified based on the desired vehicle motion, or as a combination of evaluated features which cooperate to determine a preferred foot placement so that body motion may continue.

A uniform patterned circulating gait is set by fixing the pitch and tread at constant values. 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 the between the legs (short pitch and wide tread) the greatest rotation is possible.

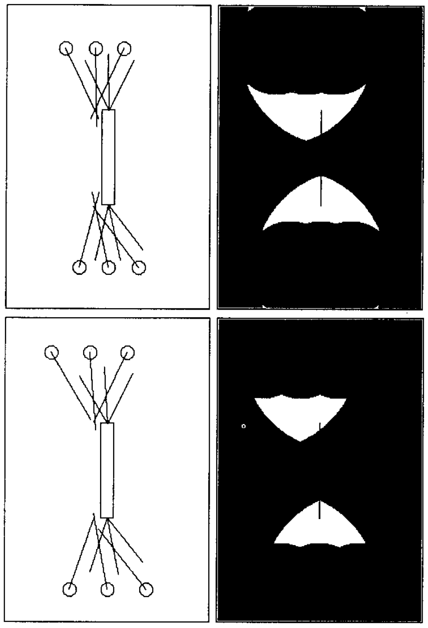

Figure 7 - Stack Reachable Space: Short Pitch/ Wide Tread and Long Pitch/Narrow Tread

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 of the stack to the inside of the turn are out of reach when the alternate backward pitch and tread are reachable so the action is to retrograde on the inside. Turns that are nearly centered on one set of feet would bind on each other and require occasional shuffle steps.

This strategy of adjusting the pitch and tread values based on the intended motion and using the stack-reachable space and CSP to constrain each move has demonstrated the generalized arc walking that was desired for the Ambler.

The advantage of the uniform gait approach 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 algorithm specifies the ideal locations of footfalls on moderate terrain. If there are obstacles, or if the legs start in an irregular configuration, other constraints are considered as well. The ideal footfalls, plus the other constraints are algebraically combined as utility functions by considering each factor that impedes body advance.

There are four ways in which the legs can constrain body motion: (1) conflicts among the legs, (2) conflicts between a leg and the body, (3) leg kinematic limits, or (4) when the body exceeds its conservative support polygon. When one of these constraints is reached, the planner evaluates metrics to determine where to recover the appropriate leg. Metrics for the *local* advance (the advance over the next body move), the *global* advance (the advance possible until the recovered leg must be recovered again), and the area of the support polygon are normalized and multiplied to determine each potential leg move's relative merit. (Figure 8) These constraints, when combined, determine a footfall that maintains vehicle stability and advance.

These utility metrics are all very local in nature; thus, the gait produced at this stage is locally optimal, but may be globally sub-optimal. Determining the proper foot to recover is simple in the cases of kinematic limits since the offending leg can be identified directly.

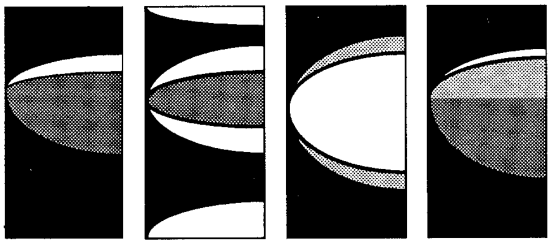

Figure 8 - Leg Placement (in configuration space): Global Advance, Local Advance, Area and Combined Cost Maps

When legs interfere, the leg with the larger unobstructed shoulder swing is chosen from the legs involved. Because the Ambler uses a circular gait, recovering this leg generally produces a larger body advance.

Through stages of refinement the Ambler's gait planner generates a uniform gait through easily travesable terrain but still selects acceptable leg and body moves in difficult terrain or transitions.

Footfalls

The gait selected by the gait planner prescribes the preferred leg placement area and provides reasonable assurance that a good footfall will exist. Within this area, approximately a square meter, it is necessary to examine the terrain and vehicle configuration to select the exact point of terrain contact. By combining features such as terrain roughness, required reach of the leg, and the complexity of the step in a geometrical representation the footfall planner selects the best footfall location.

There are a number of potential evaluation criteria for selecting acceptable footfalls. Considerations for a single footfall can be classified as pertaining to either the robot configuration or the terrain characteristics. For example, a walking robot just as a standard robotic manipulator, has workspaces that it can reach. Given the gait, a fixed reachable space is defined. This reachable space constrains the set of possible footfalls. Terrain features such as the slope and traction of the terrain can also be evaluated to provide constraint to the planning problem.

Constraints can be classified into discrete and continuous. (Table 1) Discrete constraints are those that *must* be met by a potential footfall. For example, a footfall must be within reach of the robot at the time the leg is recovered. Continuous constraints are those that have a scaled effect and therefore can be minimized to identify least constrained, or most desirable, footfalls.

	Robot Configuration	Terrain Features
Discrete	Maximum Reach Minimum Reach	Maximum Elevation Minimum Elevation
Continuous	Body Advance Visibility	Roughness

Table 1 - Implemented Footfall Constraints

The strategy for footfall planning is that discrete constraints threshold the evaluation space and then continuous constraints are combined in a adjustable weighting function. This weighting function combines measures of reachability, visibility, and potential body advance robot configuration constraints with elevation and roughness terrain feature constraints to produce a relative scaling, or cost map, of the appropriateness of each footfall. (Figure 9)

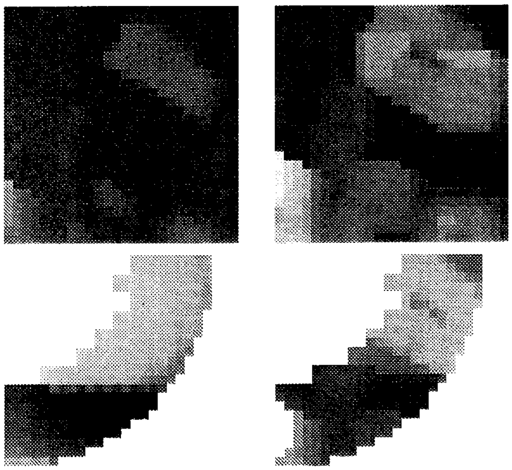

Figure 9 (clockwise from upper left) - Terrain elevation, terrain flatness, and body advance evaluations and the combined cost map.

The resultant cost map of the terrain locations scales the relative appropriateness of each footfall. The best location to place the foot can then be selected from the map.

Results

The implementation of planners has proceeded from the bottom of the hierarchy upwards. We have tested various forms of these planners in three environments, a single-leg test environment, a series of simulators and on the Ambler itself.

A test environment for a single Ambler leg was built with an overhead carriage hung from ceiling mounted rails. The footfall planner has proven highly capable in commanding the leg to step through terrain strewn with rocks and meter-scale obstacles. The carriage can be pulled along once the leg is planted and a test terrain ten meters long has been traversed. Experiments in the test terrain guided the development of the footfall cost maps and proved that the footfall planner can advance through difficult rough terrain.

A simulator of the six-legged Ambler, implemented on a graphics supercomputer, has provided preliminary results of the effectiveness of the gait planning strategies. The uniform gait approach has been successfully demonstrated as have cases of the utility based gait planning. Neither planner has been integrated with the footfall planner and tested in rough terrain. Work is ongoing to integrate the planning strategies into a single planner that generates smooth gaits with smooth transitions.

A preliminary gait planner has been used to generate flat floor walking with the Ambler. The implementation of planning software on the Ambler itself is ongoing. Qualitative results will be forthcoming.

Conclusion

We have identified a method of trajectory planning that, through a feasible traversability measure, identifies passable terrain. Further development of this planning strategy will allow identification the most desirable specific path.

The Ambler's gait planning approach develops uniform gaits for general arcs though moderate terrain regions and refines to acceptable leg and body moves in very complex terrain and maneuvering situations. With this strategy a robust and fast gait planning system has enabled the Ambler to walk in simulation and take its first steps in the real world.

Finally, we have demonstrated a footfall planner that can combine both robot configuration and terrain constraints to select terrain contacts. This planner has been proven in rough terrain and will fall into the hierarchy with the Ambler's gait planner as the vehicle begins to walk through rough terrain.

Acknowledgements

We would like to thank all the members of the Planetary Rover project at Carnegie Mellon. Most of them have passed along an idea or note on a scrap of paper at one time or another. In particular, Swami Mahalingham began the work in gait planning, Ben Martin and Joe Hirsch worked on early simulations, and Eric Krotkov and Reid Simmons are leading the effort to integrate the Ambler software system.

We gratefully acknowledge the support for this work provided by NASA under contract NAG-1175.

Bibliography

[Bares89] Bares,J., et al., "Ambler: An Autonomous Rover for Planetary Exploration", in IEEE Computer, Vol. 22, No. 6. 1989.

[Bares90] Bares,J., Whittaker,W., "Walking Robot with a Circulating Gait," IEEE Int'l Workshop on Intelligent Robots an Systems (IROS)'90, July 1990.

[Brooks90] Presentation to the Carnegie Mellon School of Computer Science Distinguished Lecture Series, March 1990.

[Donner84] Donner,M., "Control of Walking: Local Control and Real Time Systems", Carnegie Mellon Department of Computer Science Technical Report CMU-CS-84-121, May 1984

[Kaneko88] Kaneko,M., Abe,M., Tanie,K., "Study on Walking Machines With Decoupled Freedoms," in the Journal of Robotics and Mechatronics, April 1988.

[Kwak88] Kwak,S., McGhee,R.B., "Rule-Based Motion Coordination for the Adaptive Suspension Vehicle," in Technical Report NPS52-88-011, Naval Postgraduate School, May 1988.

[Kweon90] Kweon,I.S., Kanade,T., "High Resolution Terrain Maps from Multiple Sensor Data," IEEE Int'l Workshop on Intelligent Robots an Systems (IROS)'90, July 1990.

[Lee88] Lee, W.J. and Orin, D.E. "The Kinematics of Motion Planning Over Uneven Terrain", IEEE Journal of Robotics and Automation, April 1988, pp. 204-212.

[Mahalingam89] Mahalingam, S., Whittaker,W., "Terrain Adaptive Gaits For Walkers with Completely Overlapping Work Spaces", in the Proceedings of Robots 13, Gaithersburg, MD, pp.1-14, May 1989.

[Rosenblatt88] Kiersey, D.M., Rosenblatt,J.K., Payton, D.W., "Autonomous Navigation in Cross-Country Terrain," Proceedings of the 1988 Image Understanding Workshop, pp. 411-419.

[Simmons89] Simmons,R., Mitchell,T., "A Task Control Architecture for Mobile Robots," in the Proceedings of AAAI Spring Symposium, Stanford, CA, March 1989.

[Song88] Song,S., Waldron, K., "Machines that Walk: The Adaptive Suspension Vehicle," MIT Press, Cambridge, MA, 1988.

[Stentz89] Stentz, A., "Multiresolution Constraint Modeling for Mobile Robot Planning", Proceedings of SPIE Symposium on Advances in Intelligent Robotics Systems, November, 1989.

[Thomas90] Thomas,H., Wettergreen,D., Thorpe,C., "Simulation of the Ambler Environment", Modeling and Simulation Conference, Pittsburgh, PA, May 1990.