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# Gait Generation for Legged Robots

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***Abstract*—Gait generation is the formulation and selection of a sequence of coordinated leg and body motions that propel a legged robot along a desired path. Approaches to gait generation can be classified into control, behavioral, rule-based, and constraint-based paradigms. We survey these models of gait generation and introduce the Ambler, a hexapod robot that can circulate its legs to produce unique gaits. Then we present kinematic, collision, terrain, support, and stability constraints available for gait generation, and discuss our progress using a constraint-based method to generate the Ambler's gait.**

## I. Introduction

In comparison to wheeled mechanisms, legged mechanisms require complex design, move slowly, and are difficult to control. However, for locomotion over rough or discontinuous terrain, legged mechanisms are potentially superior to wheeled mechanisms.[1] Legged mechanisms make discrete terrain contacts and avoid undesirable footholds while wheeled mechanisms have rollers in continuous contact with the ground. The posture of a wheeled mechanism is dependent upon the terrain, but a legged mechanism can isolate its body from the terrain—achieving a more stable *stance*[1] and allowing smooth level motion. Legged locomotion is theoretically more energy efficient because body propulsion does not expend as much energy in soil compaction and body motion can occur in a level plane decoupled from the effects of gravity. Legged mechanisms can actively position their center of gravity to maximize stability. Dead reckoning (estimating position by integrating motion over time) can be more accurate in a legged machine where feet make discrete contacts and do not slip or skid like a wheel.

The complexity in the design of legged mechanisms can be achieved, as is demonstrated by the working systems examined in this paper. We believe that the slow, smooth motion of legged devices is advantageous in rough terrain where caution (and, sometimes, sensing) will limit the speed of wheeled and legged mechanisms alike. The significant drawback to legs has been the difficulty in control. For a slow-moving walker, this challenge is not in moving the individual legs, as this is directly analogous to well-understood manipulator control, but in the coordination of leg and body motions. The legged robot, either with a real-time controller, low-level planner, or as an artifact of its architecture, must generate a sequence of leg and body motions, a *gait,* that will propel it along some path.

Gait *generation* is the formulation and selection of a sequence of coordinated leg and body motions that propel the robot along a desired path. In this paper we survey several approaches taken toward gait generation and present some of the key issues involved. We then introduce the Ambler legged robot and discuss our work on gait generation for the Ambler.

Fig. 1. The Ambler indoors among sand and rocks

## II. Approaches

One classification of the various approaches to generating gaits is into control, behavioral, rule-based, and constraint-based paradigms. This is an approximate decomposition since specific systems use techniques from more than one area, but it is useful in distinguishing the most appropriate system model for a given legged robot.

### *A. Control*

Walking (or running) in some legged mechanisms can be modeled using appropriate feedback as a control system. Control laws generate a gait as an inherent property of the system by defining a stable feedback system that alternately drives the legs and body. Gait generation by control law is used, to date, in most biped mechanisms. It has the advantage of speed. Bipeds and legged mechanisms that run quickly require this speed in order to remain stable.

An important distinction in the taxonomy of legged robots is between statically and dynamically stable mechanisms. A legged robot exhibits *static stability* by keeping, at least, three feet planted on the ground and maintaining the center of gravity within the foot/ground contact points. *Dynamic stability* is achieved by continuously moving either the feet or the body to maintain balance.[2] Dynamic walking mechanisms require

[1] A *stance* is any specific configuration of the joints of a legged robot—a point in configuration space.

fast feedback loops to maintain stability. Gait is generated as a by-product of maintaining stability while progressing forward. Raibert controlled one- and two-legged dynamically stable mechanisms with three servo loops. One loop controlled vertical motion (hopping height), one controlled body attitude, and one controlled balance (foot placement), which dictates the forward speed.[3] More complicated control laws have been applied to a quadruped (four legged mechanism) and have executed the more highly synchronized gaits of a horse.

Sutherland's walking machine used a control law to synchronize a series of hydraulic valves in order to produce a *ratchet*[2] gait. A behavioral interaction of the control processes developed by Donner used inhibition and excitation between adjacent legs to vary the gait. [4]

### B. Behavioral

Gait has been examined in studies of biological systems that sought to identify patterns in both quadrupeds and hexapods. [5][6] The neurological basis of walking and some aspects of walking behaviors have been examined.[7] Biological systems produce gaits in a manner unlike conscious reasoning. The physical symbol systems hypothesis—formal symbol manipulation is necessary and sufficient for general intelligent behavior—does not apply to walking for this reason.[8]

The behavioral approach characteristically rejects symbols and reasoning about gaits, instead embodying the generation of the gait in a control network. To generate robot walking, such a network is patterned after a particular animal neural-system or after an abstraction of a behavioral hierarchy. Beer and Chiel have developed a simplified version of the cockroach nervous system.[9] They focused on walking behavior and built a heterogeneous artificial neural network, in which individual nerve cells can excite or inhibit leg motions or act as pace makers to sequence legs and coordinate body motion. A lesion study demonstrated the robustness of the nervous system, and showed that high-speed gaits, such as the *tripod*[3] gait, are coordinated centrally while low-speed gaits, such as the *wave*[4] gait, are not.[10]

Brooks implemented walking in the subsumption architecture with a distributed network of finite state machines augmented by internal clocks.[11] In this instance, the network formed an abstraction of the behaviors necessary for walking. The robot, Genghis, performed a rear-propagated, ratchet gait. Genghis was also able to learn a tripod gait by converging on the pattern. Learning was reinforced by an incentive to keep legs from contacting each other.[12]

*Free* gaits are gaits in which any leg is permitted to move at any time. *Fixed*, or regular, gaits are those in which a specific pattern of leg movement is imposed. These biologically based systems exhibit fixed gaits (although some perform several different fixed gaits) because the pattern is dictated by the encoding of the network. All animals locomote with fixed gaits. A tenet of behavioral systems is that the emulation of animal behavior, hence fixed gaits, is sufficient. Stability and efficiency are not primary issues.

### C. Rule-Based

In the control and behavioral approaches to walking there is no explicit planning. The robot exhibits a patterned behavior of leg placement and body regulation. For rough terrain situations where legged mechanisms are most appropriate, the specific foot placements, body motions, and gait type can be optimized to improve efficiency and reliability. Rule-based gait generation uses a set of rules or heuristics to prescribe (plan) a gait.

McGhee developed a hexapod device and a free gait generating algorithm that found reachable stances by exhaustively searching from the kinematic limits of the current stance. [13] This search was apparently prohibitive since a fixed wave gait was developed for the robot when perception of terrain was incorporated in the system.[14]

Waldron led the design of the Adaptive Suspension Vehicle (ASV) on which a number of gait generation systems were developed.[15] Rule-based generation of gaits produces patterns, usually fixed, for example tripod gaits, that can be commanded to the mechanism. Song developed a provably efficient wave gait.[16] In one system the gait pattern remained the same but specific foot placements were adjusted.[17] In another, hand-crafted gaits were developed to cross ditches and climb over obstacles.[18] A heuristic rule-based mechanism was used to help the operator select the appropriate strategy. An approach that applies gait strategies to specific terrain instances is not amenable to autonomy because of the difficulty determining a spanning set of strategies, selecting the proper strategy in non-typical terrain, and transitioning between various strategies.

Kumar used a number of control schemes to modify various gait parameters, such as the stepping rate and the amount of time a leg supports, to optimize a wave gait for a given path. Transitions between gaits are a problem in this system.[19] Using finite state machines to model individual legs, Kwak coded rules in Prolog to govern a free gait generator for the ASV.[20][21]

By identifying a set of heuristics, Hirose designed a hierarchy of rules that limited possible leg moves and generated a free gait for a quadruped mechanism.[22] The quadruped used a *crab*[5] ratchet or wave gait. An analysis to determine the optimal *crab angle*[6] for any given stance of a quadruped was developed.[23]

### D. Constraint-Based

Constraint-based approaches to gait generation utilize various factors, such as kinematics, terrain, and stability to constrain the range of possible moves and then order the remaining

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[2] A *ratchet* gait is the sequential movement of front, opposite-side middle, then rear (front-propagated); or rear, opposite-side middle, and then front (rear-propagated) legs followed by the same order for the opposite side.

[3] In the *tripod* gait, three legs that enclose the center of gravity support the mechanism while the other legs simultaneously lift and recover. The ratchet is a *crawling* or *creeping* (one leg moves at any time) form of the tripod gait.

[4] The sequential movement of legs front, middle, and then rear (front-propagated); or rear, middle, and then front (rear-propagated) is called a *wave* gait (also called metachronal wave or follow-the-leader).

[5] A gait is called *crab* if body motion is not along the longitudinal (or primary) axis of the robot. Ratchet and wave gaits can be crabbed.

[6] The *crab angle* is the angle of the direction of body motion relative to longitudinal (or primary) axis.

moves so that search or optimization can be used to select the best gait to achieve the goal.

There are two basic problems with searching in constraint space for an optimal gait. First, the space grows exponentially with the number of degrees-of-freedom in the robot and is more difficult to search with increasing numbers of constraints.[24] Pal kept the search space manageable by considering only four leg placements for each body move. [25] This restriction compromises the optimality of the resulting gait. Second, the horizon effect for limited search implies that successfully finding a gait to an intermediate goal is no guarantee of reaching the ultimate goal. For most legged mechanisms, one or two *gait cycles*[7] are sufficient to reconfigure to any arbitrary stance, so the search need only look ahead by that amount to ensure that any terrain challenge can be met.

Pal discretized the local (leg workspace) and global (terrain) reference frames to constrain the possible gaits and then searched the space for possible leg and body move sequences that progressed toward the goal. Free gaits were generated and because the search used the A* algorithm, they are optimal for the search space examined—a very simplified world with restricted leg placement.[26]

Our earlier work applied a costing function to each constraint, then combined costs and selected the gait with the least cost (greatest progress with least danger). This was troubled by the heuristic nature of the costing and combining functions. They had to be carefully tuned to work well and then provided no assurance of generality.[27] We are now trying to analytically select the gait that satisfies all discrete constraints and maximizes continuous constraints.

## III. Ambler

Having examined some approaches to gait generation, we now present our progress on gait generation for the *Ambler*.[8] We present the Ambler, then we discuss the available constraints and how they can be used to generate gaits.[28]

### A. Mechanism

Extreme 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 extreme terrain. The Martian surface, shown in Fig. 2., typifies these environments.

Although the problems involved in extreme terrain navigation have been investigated, the mechanisms used in these experiments have been primarily wheeled or tracked locomotors.[29][30] Legged mechanisms offer advantages in extreme terrain because of control of stability, isolation from terrain irregularities, power consumption, and physical capability.

The *Ambler* is a legged robot built to traverse extreme terrain with high reliability.[31] (See Fig. 3.) 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

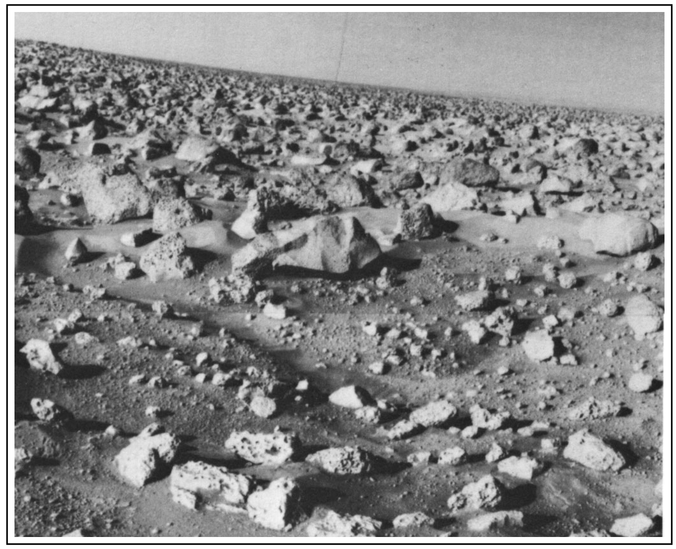

Fig. 2. The surface of Mars from a Viking lander

links permit planar motion of the leg and the vertical extensional link provides motion of the foot into ground contact. 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.

On-board sensing consists of a scanning laser rangefinder and foot-mounted force-torque sensors. The rangefinder is used to generate depth maps of the terrain.[32] At close range the depth maps are of high resolution suitable to selecting individual footfalls, while at long range they provide adequate information to determine the ability to traverse distant terrain. Depth maps are generated on demand for small regions of interest because large global maps are both computationally expensive and unnecessary. The force-torque sensors provide support information about the terrain and the stability of the current stance. Although the specific position of the legs changes the overall height, width and length of the Ambler, a typical stance is 5 meters in height, 4.5 meters in width and 3.5 meters in depth.

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 constant elevation by coordinated actuation of the joints in the supporting legs. The Ambler can perform any of the gaits typically associated with hexapods including the wave, ratchet, and tripod gaits. In addition the Ambler is capable of a unique *circulating* gait. The circulating gait, which has no natural counterpart, is performed by lifting a trailing leg, passing it through the body cavity, and placing it out in front of a leading leg. The final foot positions are the same as a rear-propagated wave gait but only one leg has moved. 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 axes. 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

[7] A gait cycle is a sequence of leg moves during which each leg moves once.
[8] Ambler is an acronym for autonomous mobile exploration robot.

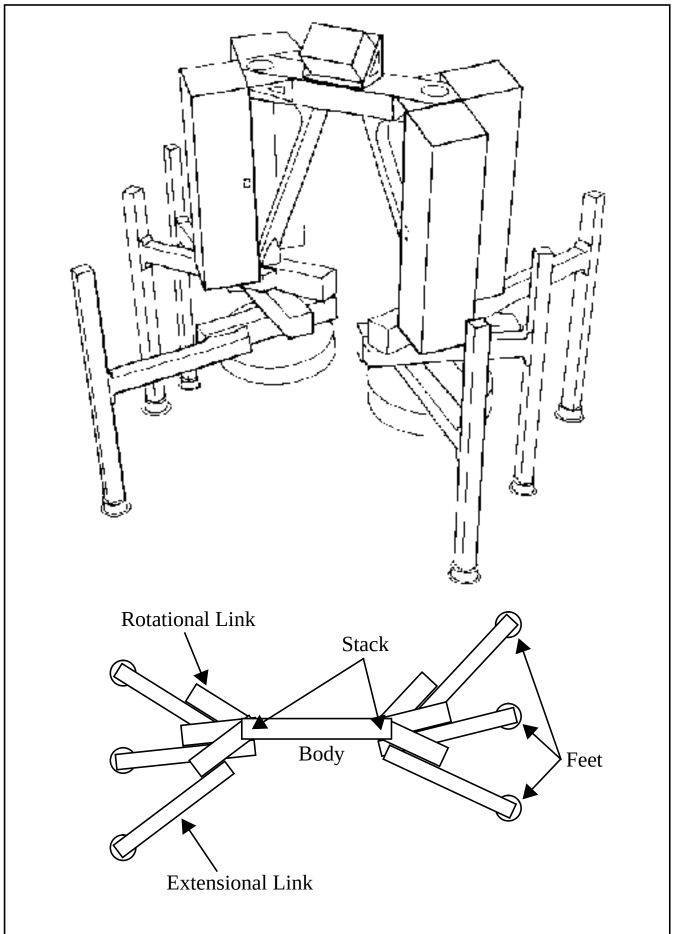

Fig. 3. Perspective and top view line drawings of the Ambler

Ambler can follow an arc of any radius (from zero for a point turn, to infinity for a straight line).

*B. Constraints*

The Ambler walks with static stability, using a free circulating gait. The Ambler must be efficient and reliable. Because it explores extreme terrain, it must constantly step deftly among obstacles. Considerations of slow-moving static stability, efficiency and reliability, and a free ever-changing gait led us to the constraint-based approach to gait generation. Our solution has been to satisfy: kinematic, collision, terrain, support constraints and maximize stability and advance (productivity).

Kinematic Constraints—Of course, feet must be placed within kinematic limits of the leg. These minimum and maximum leg extensions also limit body motion. To maintain productive advance the abstraction of reachable area for the leg stack simplifies the selection of the most productive rotation and translation. Each stack is maintained in its reachable area. The regions, shaped like the webbed foot of a four-toed duck, are kinematically feasible for the given leg placements. (See the area formed by overlapping circles shown in Fig. 4.) Any translation and rotation that maintains each stack in its respective stack reachable area is feasible.

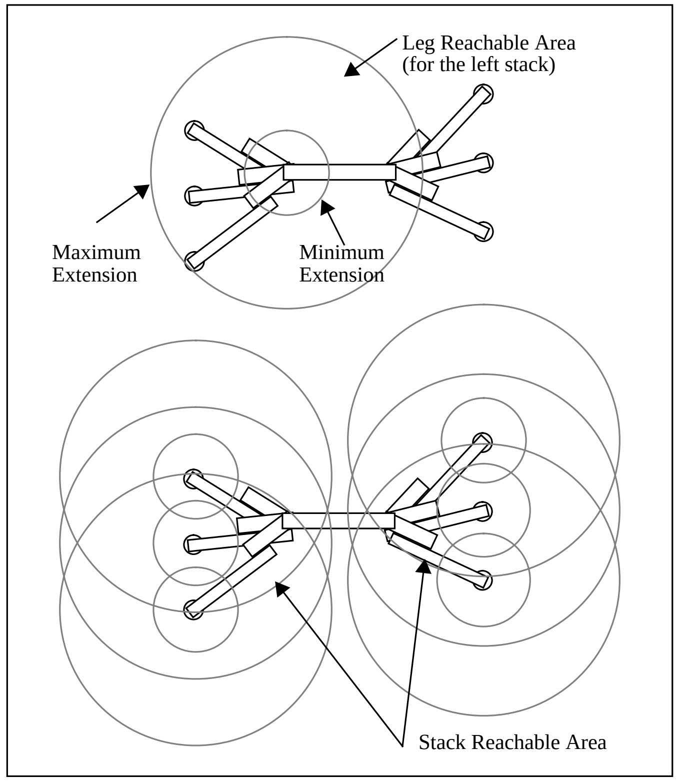

Fig. 4. Leg reachable area and kinematic constraints on the body motion (stack reachable area) as a composite of the individual leg reachable areas

Collision constraints—By accurately modeling the mechanism to determine the position at which a collision between two legs (or between a leg and the body) occurs, those free gaits that would result in an inter-leg collision are eliminated from consideration. The collision constraint is particularly important when the robot is in an irregular stance. (See Fig. 5.) It generally governs body motion for small radius turns. To squeeze out the maximum performance, we carefully calibrated the collision limits throughout the workspace of each joint.

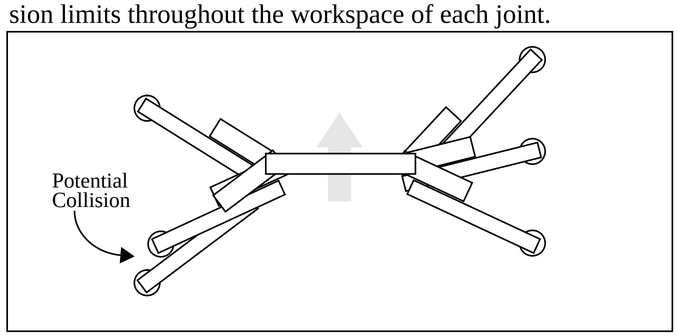

Fig. 5. Collision constraint during straight line body motion

Terrain Constraints—Footholds must be within the maximum and minimum vertical travel of the leg, adjusted by the elevation of the body. By examining an elevation map of the terrain, the areas that allow foot placement and clear leg recovery are identified. Body motion is selected to avoid terrain collision.

Support Constraints—The *support polygon* for a stance is the minimum bounding polygon, on the ground plane, that includes all leg-ground contact points. If the robot's center-of-force (approximately the center-of-gravity for a slow walker) is held above the support polygon, it is statically stable. If five legs are on the ground while the sixth is recovering, the support polygon is the convex hull of those five legs. If one of the five supporting legs fails, either due to mechanical failure or soil collapse, the system is statically stable if the center-of-force is within the convex hull of the remaining four legs. Considering the failure of each of the legs in turn generates a number of 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 single supporting leg fails. [33] When five legs are in ground contact, as during a leg recovery, the CSP appears as the shaded region of Fig. 6.

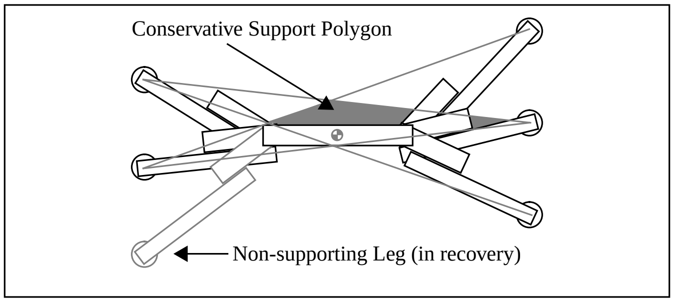


Fig. 6. Conservative support polygon with five supporting legs

When six legs are in ground contact, the CSP becomes the polygon that subsumes all the five leg CSPs as in Fig. 7.

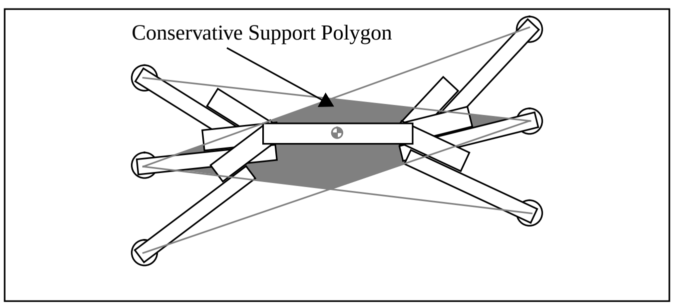


Fig. 7. Conservative support polygon with six supporting legs

The CSP abstraction is useful in the planning process because it provides limitations on the movement of the body, which must stay behind the leading boundary of the CSP. This in turn limits the footfalls that must be considered, because a feasible gait must sequence moves so that the body can glide from one CSP to the next.

Stability Metric—The stability of a stance can be evaluated by computing its energy stability which is a measure of the work required to tip the center-of-mass over an edge of the support boundary. [34] The energy, *e*, required to overturn when standing on a level plane is computed by (1).[9]

$$e = mgh = mg(\|\vec{r}\| - z) \quad (1)$$

The center-of-mass must undergo a change in height, *h*, for the mechanism to overturn, as shown in Fig. 8.

Presumably, the greater the energy required to tip over from a given stance, the more stable the stance. Fig. 12. shows the

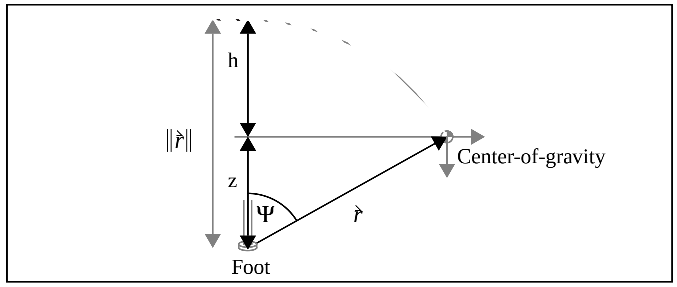


Fig. 8. Illustration of height change to tip over two feet in the plane (2D)

energy to tip over a sample flat-terrain stance and plots the minimum energy for all possible tipping directions, as a function of the position of the center-of-mass. The peak of the energy

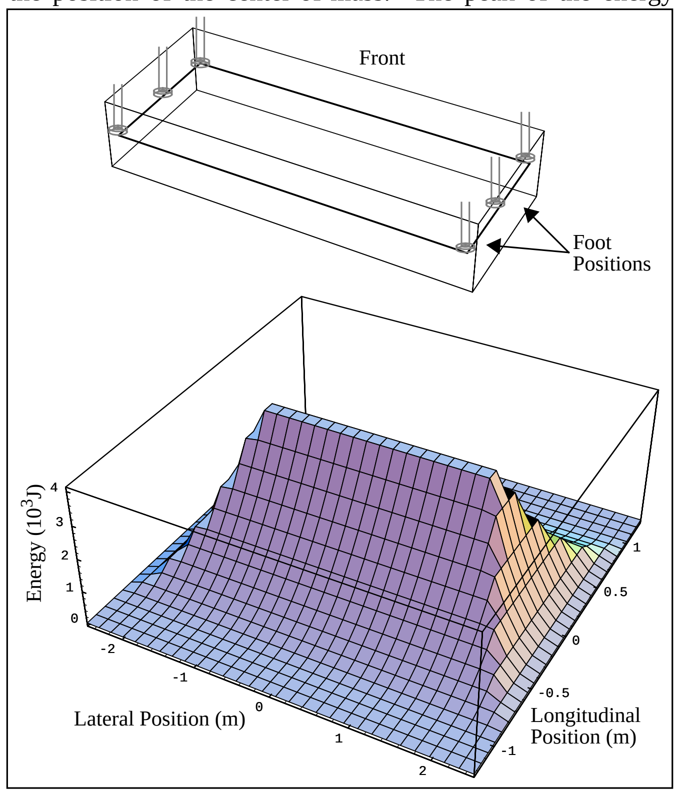


Fig. 9. Flat terrain stance (top) and a plot of the energy stability (bottom)

function occurs along the ridge where the mechanism is most stable because its center-of-mass is farthest from all the sides of its support boundary.

The general form of the equation of *e* is computed by (2) in which $cg_x$ stands for the *x* position of the center-of-gravity, $f^n$ stands for foot *n* and $i_x$ is the *x* position of the intersection of *r* and the line of the support boundary.

$$e = mg((\|\vec{r}\| \cos\Phi) - z) \quad (2)$$

where

$$\|\vec{r}\| = \sqrt{(cg_x - i_x)^2 + (cg_y - i_y)^2 + (cg_z - i_z)^2}$$

$$\cos\Phi = \sqrt{\frac{(f_x^n - f_x^{n+1})^2 + (f_y^n - f_y^{n+1})^2}{(f_x^n - f_x^{n+1})^2 + (f_y^n - f_y^{n+1})^2 + (f_z^n - f_z^{n+1})^2}}$$

[9] In [34], $h = \|\vec{r}\|(1 - \cos\Psi)$, but for us, where *z* is known, the formulation, $h = \|\vec{r}\| - z$ is less complex to compute.

In order to overturn the vehicle, a force must rotate the center-of-mass of the machine in an arc (pivoting about a line between two adjacent feet—a support boundary). In three dimensions, the change in height, *h*, to tip over a support boundary at arbitrary orientation appears as in Fig. 10.

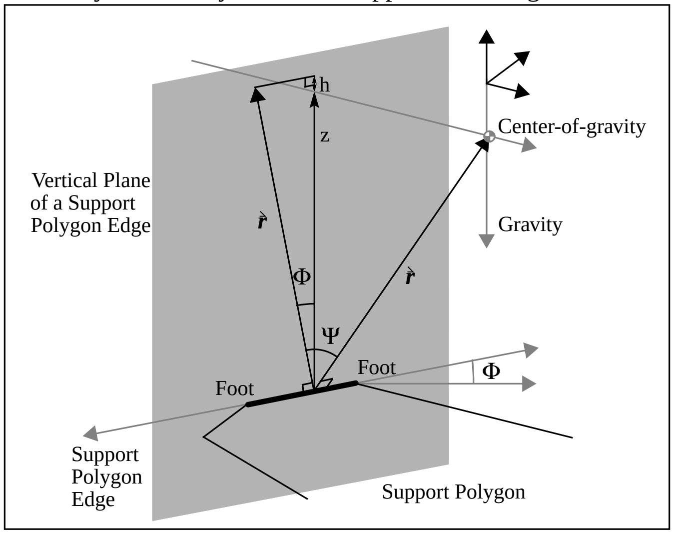


Fig. 10. Illustration of height change required to tip over two feet in arbitrary positions (3D)

On sloped terrain the stability constraint appears as in Fig. 11. where the peak is shifted into the slope. This clearly illustrates the value of biasing the center-of-mass toward the slope to increase stability. Energy stability in one example of actual rough terrain appears as in Fig. 12. For a given direction of

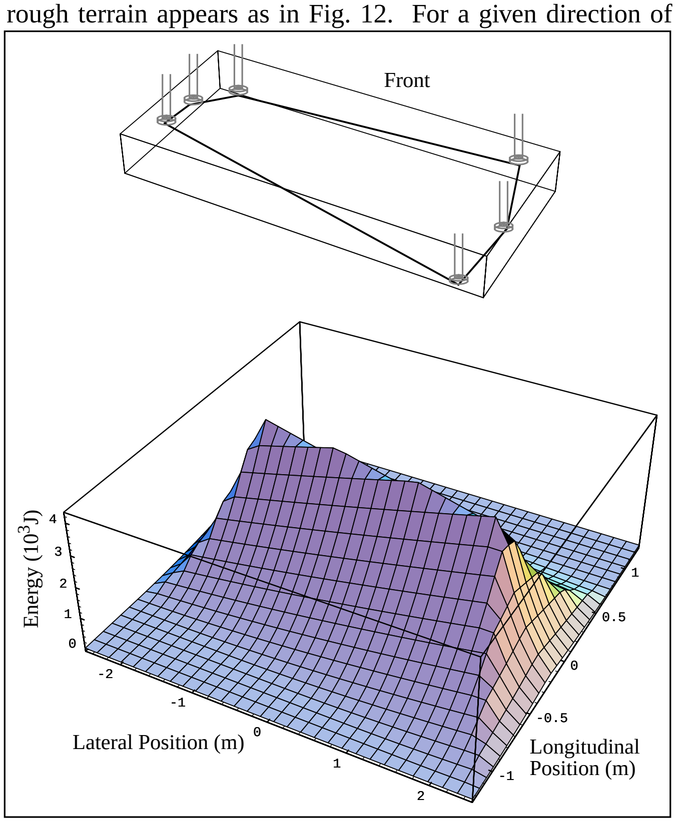


Fig. 12. Stance in actual rough terrain during a point turn (top) and plot of the energy stability (bottom)

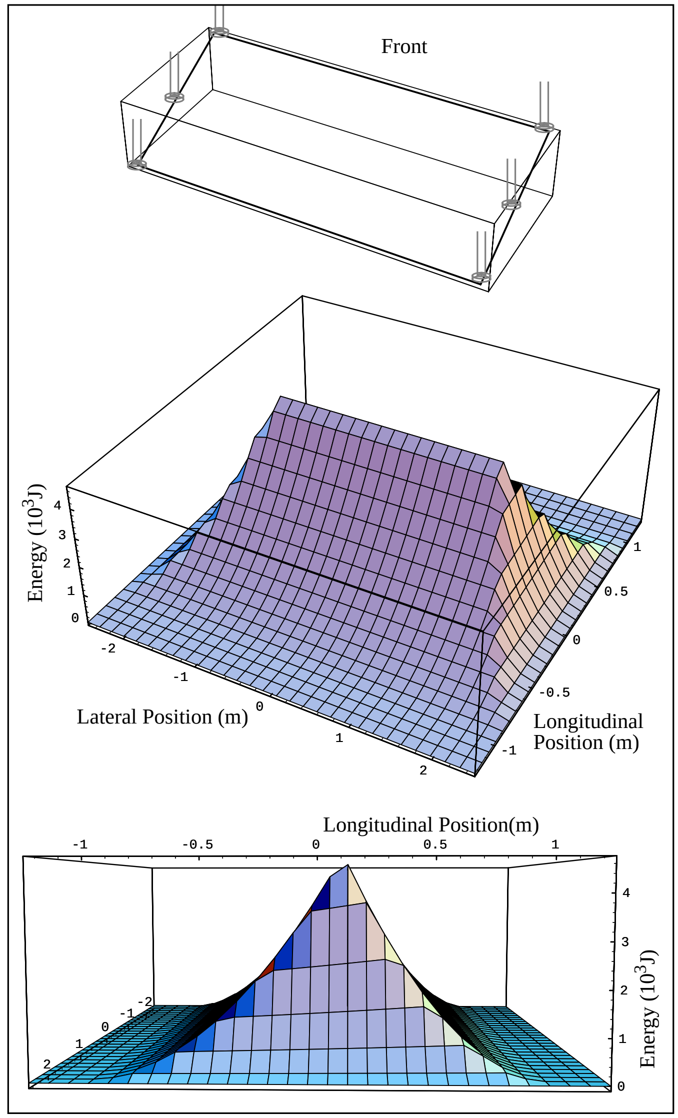


Fig. 11. Stance on a slope (top), plot of the energy stability on a slope (middle), and side view of the energy stability plot (bottom)

travel, a slice through the energy stability surface produces a continuous stability constraint that is used to optimize the Ambler's stability. This stability metric also provides a quantitative measure that can be used to compare the relative stability of possible stances.

### *C. Gait Generation*

A robot, operating in extreme terrain, should walk:

- using the minimum number of steps
- to produce the maximum rate of progress
- with adequate caution.

This frames gait generation as a bounded optimization problem. For autonomous walking in rough terrain, it is not sufficient to adapt a fixed gait: the robot must operate to the limits of its ability to maximize its performance and achieve reliability and efficiency. We reduce the problem by generating the free gait one stance at a time—the best body move followed by the best leg move(s).

The gait generator for the Ambler requires information about the initial configuration of the mechanism, the surrounding terrain (elevation) and the desired trajectory, specified in the form of arcs of various length and radii.

To formulate a body move that does not violate *transient* or *terminal*[10] constraints from kinematic limits, terrain features, collision conditions, or body support boundaries, we use a number of techniques.

The initial set of possible body moves is intersected with the terrain depth map to eliminate from consideration all moves that contact the terrain. To identify the kinematic limits and collision conditions, which can both be transient in nature, the trajectory between stances is divided into equal increments, each of which is checked for feasibility (linear search). This guarantees that the move is possible to the resolution of the trajectory increments. This can be computationally expensive. Linear search is necessary to detect transient constraints. A recursive decomposition of the trajectory (binary search) from the initial to final position applies an acceptability test to determine the position, if any, at which body kinematic limits are exceeded. Body kinematic limits cannot be solved in closed-form because when moving along an arc, the stacks move along cycloids, precluding simple intersection solutions to the constraints. The conservative support boundary is computed in closed-form so that no search is necessary to determine the maximum supported body move.

Once the range of acceptable body moves has been determined the single move that optimizes performance must be selected. Progress (change in configuration) and stability are two measures that can be maximized. All moves that meet or exceed a specified stability level, which can vary based upon the environment and configuration, are compared and the maximum is selected. The set of feasible (constraint satisfying) stances that progress along the desired path is small at this point so it is not unreasonable to check them all to find the maximum.

There is an interdependence between leg and body moves in that the motion of a leg is constrained by the position of the body, and body motion is constrained by the leg positions.

To select a best leg move, the constraints imposed on body motion are attributed to each leg. Leg moves that relieve constraints, allowing greater body motion or increasing the stability of the stance, are more desirable. The gait generator identifies possible leg moves that allow body progress in the desired direction. Each move must satisfy leg kinematic constraints and remain out of the path of the body so as to not introduce new limits on the body motion (until later in the gait cycle, since it is rarely advantageous to move the same leg twice in sequence). The leg placement that best relieves constraints on the body, meets all leg-specific constraints and allows maximum progress of the body along the path is selected.

Our gait generator can produce locally optimal moves at the expense of global performance. We are working to address this but find that it is largely mitigated by the ability of the Ambler to surmount even the most challenging terrain.

[10]*Transient* constraints exist at positions intermediate between the initial and final positions (non-inclusive). A *terminal* constraint persists to the final position.

## IV. Discussion

The Ambler's gait generation system has performed reasonably well, enabling the Ambler to demonstrate reliable autonomous walking in rough terrain. To date, the Ambler has taken thousands of steps, climbed over hundreds of boulders, and explored continuously for multi-day missions.[11] With the constraint-based gait generator, we were able to walk laterally in a crab ratchet gait with only minor modifications to the software. When the need arose, we also were able to modify constraints to achieve a crippled gait in which only five legs operated after a hardware failure. The constraint-based approached has the flexibility to adjust to varied situations. We are working on ways to automatically cope with changing parameters by basing the constraints on these values.

We have recently begun studying the configuration space representation as a way of formalizing gait generation as a motion planning problem. Gait generation in high-dimension configuration space is poorly defined because the goal (body position and orientation) is specific in at most six dimensions (three is typical). Planning motion toward this subspace is difficult because leg moves do not result in a change in any metric measuring distance to the goal region of configuration space. For the Ambler moving in the plane, the configuration space is 15-dimensional—there are 12 driven degrees-of-freedom and the 3 degrees-of-freedom for the body (the full configuration space is 24-dimensional). Moving the body involves the highly constrained motion in 12 dimensions as the body tracks a trajectory in the other 3 dimensions. Kinematic limits, leg-leg collisions, and out-of-CSP configurations are inadmissable regions. Configuration space obstacles are avoided by moving along the two dimensions of the joints of the constraining leg (moving it out of the way). We are looking at tractable ways of generating efficient gaits using the configuration space representation.

A number of problems still exist with our constraint-based gait planner. When travelling for a number of steps through benign terrain the planner settles on a productive circulating gait. However, in tight situations and during transitions between path segments, the gait planner sometimes fails to find a gait. Some of these problems may be caused by inadequate reasoning about constraints but it also may point out a fundamental short-sightedness in the system. The current interaction of constraints may be too focused on local optimality at the expense of global performance. To improve global performance we can create additional leg placement selection strategies. We have formulated a constraint that utilizes the conservative support polygon and the minimum (tightest) foot placements to project where later legs have to step so that they do not impede the progress of the body. This *future flexibility* constraint reduces the feasible foot placement locations and ensures that none of those that meet the constraint will get in the way later.

The Ambler currently moves in a plane or changes height—more complex body motions will be a challenge. Changing

[11]In its longest single exploration, the Ambler recently traversed 107 meters of linear distance with 3150 degrees of rotation (numerous revolutions) in a cramped rough terrain testbed of sand and boulders. It made nearly 400 body and leg moves during 7.4 hours of runtime (over several days).

elevation is easy since horizontal and vertical motion are decoupled, but changing elevation to reach higher/lower foot placements increases the complexity of selecting a foot position. Also, simultaneous leg and body moves, which require operation in the both time and spatial regimes, will increase complexity. The configuration space representation may be helpful in sorting out these added complications but certainly more constraints must be identified since brute force search in configuration space is intractable.

## V. Summary

Legged robots are uniquely advantageous to autonomously traverse extreme terrain because of their ability to isolate their body from terrain irregularities, avoid undesirable footholds, regulate their stability, and achieve energy efficiency. The difficulty has been to generate gaits that demonstrate these characteristics. Methods of generating gait can be classified into control, behavioral, rule-based, and constraint-based paradigms.

The control approach is characterized by dynamically stable robots using feedback control laws to produce patterned gaits that can reactively adapt to maintain balance. Networks of simple elements (either neural models or primitive behaviors) that interact without symbols to coordinate a gait typify the behavioral approach to gait generation. In rule-based gait generation, either a specific gait pattern is selected and then individual moves are modified by the application of rules or a free gait is generated by applying heuristics to a particular situation to determine actions that will produce progress toward the goal. Constraint-based approaches to gait generation utilize various factors to constrain the range of possible moves and then order the remaining moves so that search or optimization can be used to select the best gait.

The Ambler legged robot is designed for exploration of extremely rough terrain. It possesses a unique circulating gait that improves energy efficiency and enables tight turning maneuvers. By applying kinematic, collision, terrain, support, and stability constraints, a free circulating gait can be generated for the Ambler that propels it along the desired path. The gait planner has succeeded in demonstrating long-duration autonomous walking in rough terrain.

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