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# Building Walking Gaits for Irregular Terrain from Basis Controllers*

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## Abstract

*This paper presents an on-line technique for constructing walking gaits for legged robots on irregular terrain. The approach involves designating sequences of closed-loop control laws derived from a control basis. A control basis is a set of artificial potential functions that are device and task independent. A variety of walking contexts can be achieved by varying the sequence of controllers drawn from the control basis, avoiding the need to re-plan leg placements or redesign task-specific behaviors. A control basis previously shown to span the task of walking over flat terrain will be shown here to also span the task of locomotion over unknown piece-wise planar terrain by incrementally modifying the control composition policy. The resulting gaits are aperiodic, discontinuous, non-sequential, and incorporate controlled slippage of the feet.*

## 1 Introduction

Most of the early literature on legged locomotion focuses on the design of sequential periodic gaits (*e.g.* the *wave gait*) [15, 13, 16]. These gaits are *sequential* in that they use a fixed stepping pattern specifying the order of foot placement; and they are *periodic* in that the stepping pattern is repeated at regular time intervals. Foot placement is based on geometric models of the robot and the terrain. For smooth terrain, one can often formulate and prove theorems about the kinematics, stability speed, or power consumption of such gaits, allowing for analytical comparisons between gaits.

The convenience of analysis and design, however, comes at the expense of flexibility in the gait itself, and such gaits are only useful on flat terrain, since irregular terrain is usually *not* periodic or sequential. Nevertheless, most research has held fast to the paradigm of geometric gaits, and the focus has become how to adapt these gaits to irregular terrain. For example, parameters of the otherwise fixed gait, such as transfer timing [1] or nominal foot placement [10] can be modified to accommodate irregularities in the terrain. Or, specific sequences of motions can be designed for specific types of obstacles encountered such as ditches, walls, and slopes [15].

The geometric approach to legged locomotion becomes a problem of providing gaits or leg motions for every possible situation and a planner capable of scheduling the different gaits. These approaches work for smooth or sparsely cluttered terrain; unfortunately, they fail to successfully address the uncertainties found in real irregular terrain due to sensor and modeling limitations as well as the computational complexity inherent in geometric planners.

Adding reactive components to a gait controller provides a much needed flexibility to the otherwise rigid geometric approach. For example, active compliance in the feet can be used to suppress disturbances in the terrain so that irregularities become transparent to the fixed gait [3, 17], or more specific behaviors can be augmented to handle deviations from the predicted terrain such as stepping higher when the side of a foot is contacted [8] or making posture adjustments when unexpected sensor data is received [14]. These techniques are, still, limited in the severity of terrain that can be handled, and it becomes difficult to guarantee that deadlock will be avoided since it is hard to predict what terrain elements will trigger the reactive behaviors.

To further address the inherent problem of modeling in geometric gaits, behavior-based controllers, which use minimal central control and modeling, were

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developed [2]. Unfortunately, the controller design in this scheme becomes an *ad hoc* process, and it may be necessary to completely re-design an architecture when a task is scaled up to more difficult goals such as walking over irregular terrain [4].

An alternative approach that generates walking gaits on-line based on sensor data is to use a control basis [7]. The term *control basis* is an abstraction that describes a set of controllers that span a task domain. A *composition policy* activates subsets of these controllers in order to achieve reference states while satisfying operational constraints. Each controller in the basis has stability and convergence properties over a range of possible plants. Convergence events in the controllers cause transitions to new sets of active controllers.

In contrast to geometric and behavior-based gait planning, solutions to tasks are not defined in terms of geometric foot placements or low-level behaviors, but rather as stability, kinematic conditioning, and navigational objectives.

## 2 Flat Terrain

The control basis approach has been previously shown to achieve robust legged locomotion through an unknown obstacle field on flat terrain [9]. This was demonstrated using a basis of three controllers:

$\Phi_0$: **Configuration space motion control.** The harmonic function path controller [6] generates robust, reactive, and collision-free motion through the configuration space of the plant.

$\Phi_1$: **Contact configuration control.** The contact configuration controller [5] moves foot contacts based on the local geometry of the environment in order to minimize residual forces and moments acting on the center-of-mass of the platform.

$\Phi_2$: **Kinematic conditioning.** The kinematic conditioning controller optimizes the posture of the articulated structure for maximum workspace while it is engaged in an interaction with the world.

Each instance of a controller takes the form $\Phi_i{}^{\sigma}_{\tau}$, where $\Phi_i$ is an element of the control basis, and superscript $\sigma$ and subscript $\tau$ denote the sets of input and output resources respectively which are bound to this instance of controller $i$. These resources are combinations of legs $0, 1, 2$, and $3$, and of the position and orientation of the center-of-mass of the robot $(x, y, \varphi)$. The task of walking is implemented in the form of a finite state control policy as shown in Figure 1. The representative positions of the feet are shown next to each state to clarify the resulting gait. The current polygon of support is indicated by solid lines, and the next support polygon planned by the contact controller is shown by dashed lines.

The control policy at each point in time is shown inside each state. Multiple controllers can run simultaneously, managed by the "subject to" operator ("$\triangleleft$") in which the subordinate controller operates in the *null space* of the dominant controller, meaning it may only introduce actions that do not disturb the equilibrium of the dominant controller. For example, $\Phi_i \triangleleft \Phi_j$ means controller $i$ is running in the null space of, or subject to, controller $j$.

If the equilibrium condition of a particular controller meets the control objective (*e.g.* a stability controller achieves a stable stance), then it asserts a condition predicate. Transitions in this predicate space are controller activations triggered by convergence events. In Figure 1, progression through predicate space is shown as sequential state transitions.

The robot maintains stability while cycling through a sequence of three and four-legged stances, moving the individual legs in the sequence $3, 2, 0, 1$. At the same time, the posture controller attempts to optimize the kinematic configuration of the legs subject to the stability constraints imposed by the contact controller. As an example, $\left(\Phi_2{}^{3}_{\underline{3}} \triangleleft \Phi_1{}^{0,1,3}_{\underline{3}}\right)$ activates the contact controller, $\Phi_1$, in order to establish a stable three-legged stance on legs $0, 1,$ and $3$ by moving leg 3. Limited by the "subject to" constraint, the posture controller, $\Phi_2$, optimizes the posture of leg 3 within the range of stable stances.

## 3 Irregular Terrain

The control basis approach, was designed to be flexible across task domains. The goals of maintaining stability, kinematic conditioning, and navigational objectives do not change when walking on irregular, instead of flat, terrain.

The control composition shown in Figure 1 was built by identifying convergence events that would result in stable locomotion on flat terrain. The required state transitions are not *guaranteed* to occur, but *do* in the case of flat terrain. When the robot, using this composition policy, is placed on *irregular* terrain, it usually fails to execute the required trajectory through

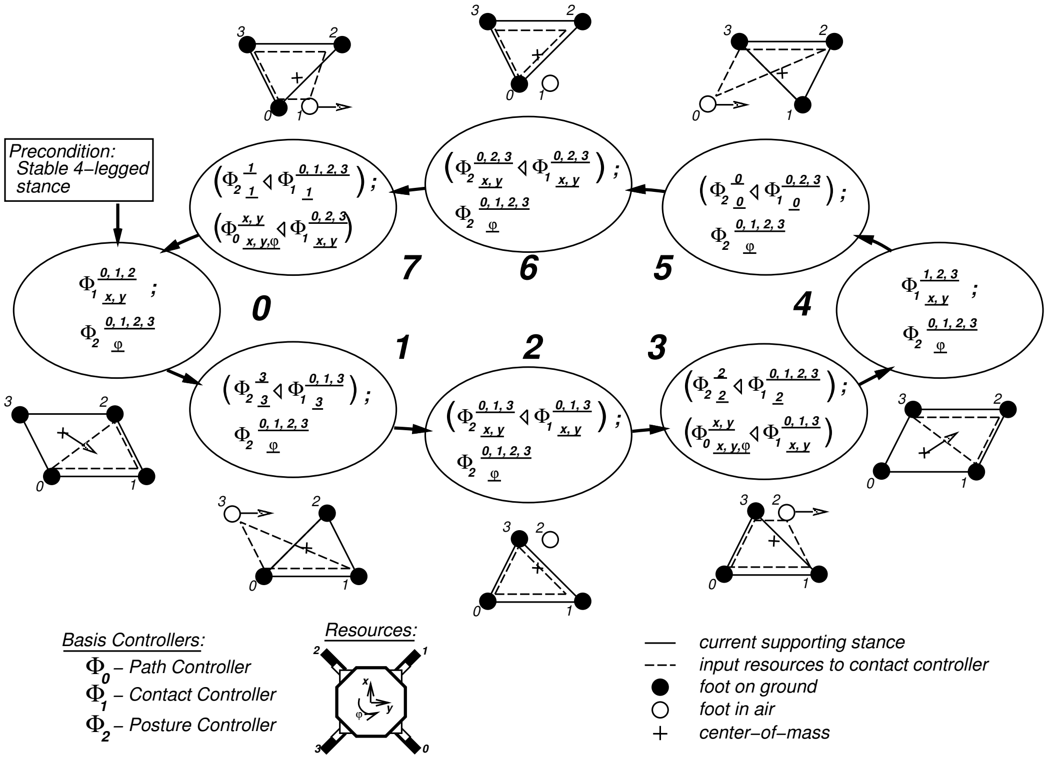


Figure 1: Control Composition for Flat Terrain.

predicate space due to one or more controllers failing to achieve its reference state.

These failures result in non-determinism in the behavior graph and can be addressed by modifying controller instantiations and/or including error recovery behaviors should these predicate states occur. These changes are made in the composition policy, not the control basis, and are drawn from the set of possible permutations of the elemental controllers and system resources.

Walking over irregular terrain was accomplished using the *same* control basis as for flat terrain. Incremental modifications made to the control composition based on deficiencies observed in behavior are presented in the following sections.

### 3.1 Mapping Terrain

The contact controller requires an approximation of the local planar facet under each foot [5]. For flat terrain, this was trivial. For irregular terrain, a linear regression technique based on contact position data was used to postulate facets [12]. Multiple probes are made each time a foot is placed. Each probe point consists of lowering the foot until a contact force threshold is reached and then recording the foot position. Given a set of contact points, a weighted least-square approximation to the facet is made. New points are checked to see if they statistically predict the facet being formed. If the variance of a point does not contain the facet, then additional points are taken, and a new facet is mapped.

### 3.2 Avoiding Toe-Holds

The experimental work reported here was conducted on piece-wise planar terrain that consisted of discrete vertical steps, as shown in Figures 2 and 5. Occasionally, marginally stable "toe-holds" occurred. To avoid this situation, edges were treated as configuration space obstacles, and the path controller was employed to guide the foot away from the edge based on a harmonic potential gradient. This influence on foot placement was "subject to" the desired stable stance. For example, in state (1) of Figure 1, the control composition was changed to:

$$\left(\Phi_2\frac{3}{\underline{3}} \lhd \Phi_0\frac{3}{\underline{3}} \lhd \Phi_1\frac{0,1,3}{\underline{3}}\right) ; \left(\Phi_2\frac{0,1,2,3}{\underline{\phi}}\right)$$

Notice that the instantiation of the posture controller $\Phi_2\frac{3}{\underline{3}}$ is still included, but now it runs "subject to" the contact controller ($\Phi_1$) *and* the path controller ($\Phi_0$). This is a different use of the path controller than in states (3) and (7), where it is directing the body of the robot along a harmonic gradient that avoids large obstacles. In this case, it is being used to direct only the placement of a single foot.

### 3.3 Vertical Posture Control

As feet are placed higher or lower with respect to the body due to terrain inclination or declination, workspace is used up, as shown in Figure 2.

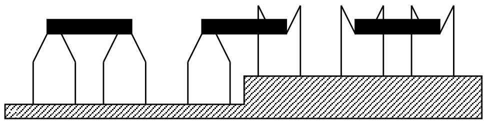

Figure 2: Effect of Neglecting Body Posture in $\hat{z}$ .

Vertical workspace can be recovered by activating the posture controller with the z position of the center-of-mass of the body as the output resource: $\Phi_2\frac{0,1,2,3}{\underline{z}}$. This instantiation adjusts the body vertically in order to maximize workspace in the legs. Notice that, like the activation of the posture controller with center-of-mass *rotation* as the output, $\Phi_2\frac{0,1,2,3}{\underline{\varphi}}$, the output of this new activation is orthogonal to that of the other controller activations and, therefore, can operate without the "subject to" constraint. This allows the robot to adjust its height at the same time as all the other controllers are running.

To solve this same problem in a behavior-based walker, a new behavior had to be designed from scratch [4]. When using a control basis, the capability of the system is already built into the basis controllers, so the designer only has to identify new combinations of controllers and input/output resources that address the problem.

### 3.4 Dragging Trailing Feet

In states (0) and (4) of Figure 1 it was observed that the trailing leg would often run up against its joint limits as the controller tried to shift the robot into a new three-legged stance. If the other legs are allowed to continue their trajectories while the trailing leg stops at the end of its workspace, there is an internal build-up of forces in the robot, leading to slippage of the foot and a loss of position reference. Such slippage, however, can be exploited if it is explicitly incorporated into the controller. For example, in state (4) of Figure 1, the contact controller, $\Phi_1$, is moving the center-of-mass into a stable three-legged stance on legs 1, 2 and 3—moving away from leg 0. Often leg 0 runs into its joint limits, preventing the center-of-mass from reaching the supporting triangle, as shown in Figure 3a. If leg 0 is allowed to be *dragged*, as in Figure 3b, then the stable tripod can be reached.

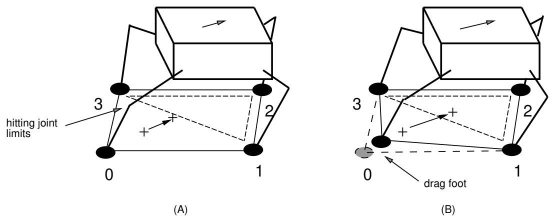


Figure 3: (A) Joint Limits Preventing Stable Stance. (B) Dragging Leg 0 Allows Stable Stance.

This dragging behavior can be governed by the composition hierarchy:

$$\left(\Phi_1\frac{1,2,3}{\underline{x,y}} \lhd \Phi_1\frac{0,1,2,3}{\underline{x,y}}\right)$$

The leftmost instance of $\Phi_1$ drives the robot into the three legged stance, possibly dragging leg 0, while the rightmost instance makes sure the robot is stable during the move. Note that state (0) can benefit in the same way, this time with leg 3 being dragged. Adding the above changes dramatically improved performance on irregular terrain due to the effective increase in workspace.

### 3.5 Error Recovery

An alternative to trying to avoid control transitions that fail to assert functional predicates, as the above techniques have done, is to add alternate paths in the predicate space. For example, in state (4) the robot is being supported by all four legs and is trying to establish a three legged stance on legs 1, 2, and 3. The inability to reach this next three legged stance—despite dragging the trailing leg— would cause the predicate condition $\neg p_1$ (failed convergence of controller $\Phi_1$) in state (4). This condition can cause a transition to an *alternate* state, (4.1), as shown in Figure 4. State (4.1) establishes a stable stance on legs $0, 2$, and 3 by moving the center of mass *backwards*, and then state (4.2) places leg 1 in order to achieve the stable $1, 2, 3$ stance that state (4) was not able to reach. Then, the gait proceeds as before by transitioning to state (5). The same type of alternate state transition can be added coming from state (0). These alternate state transitions can result in non-sequential—and hence more flexible—stepping patterns since legs are placed based on stability and kinematic constraints rather than based on a fixed stepping sequence.

The final control composition used for walking on irregular terrain, including terrain probing, edge avoidance, z-posture control, foot dragging, and alternate state transitions, is shown in Figure 4.

## 4 Experimental Hardware

The experimental platform used to test the techniques reported in this paper is a four-legged 12 degree-of-freedom walking robot named *Thing* [11, 12]. It stands $0.25m$ tall and weighs approximately $1.5kg$. In this work, it is linked via a serial tether to a separate workstation.

The sensory suite on Thing consists of infrared sensors for sensing large obstacles in the terrain that must be walked around and force sensing on the legs that allow the robot to map local terrain and choose foot holds.

## 5 Walking Experiment on Irregular Terrain

Figure 5 shows a demonstration of the gait in Figure 4. Steps (verticals painted white) are $1cm$ high, and there are a total of five of them. The tops of the steps are flat horizontal planes, however, the step edges are at arbitrary angles. The robot has no *a priori* knowledge of the terrain.

At different times during this walking segment, the legs spanned three steps—more than 50% of the robot's maximum step height. The entire experiment took approximately 13 minutes with the walking gait generated on-line by a Sun SPARC 10 workstation tethered to the robot.

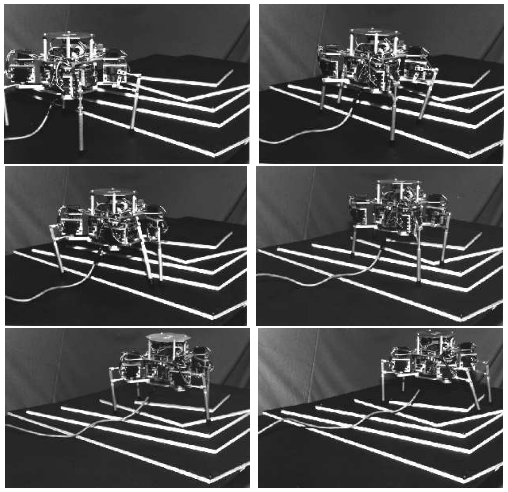

Figure 5: A Demonstration of Walking over Irregular Terrain. Steps (white) are $1cm$ high.

## 6 Conclusions and Future Work

This paper demonstrates the incremental improvement of a control composition policy for the task of traversing irregular terrain. The resulting aperiodic non-sequential gaits were successful on piece-wise planar terrain. The particular solution found is not necessarily the only one, nor is it necessarily the optimal one. A search over all permutations of controllers and resources could lead to a completely different control composition structure. The type of "manual" search conducted here was limited. A better approach may be to incorporate machine learning. Such a scheme could lead to significant improvements in performance.

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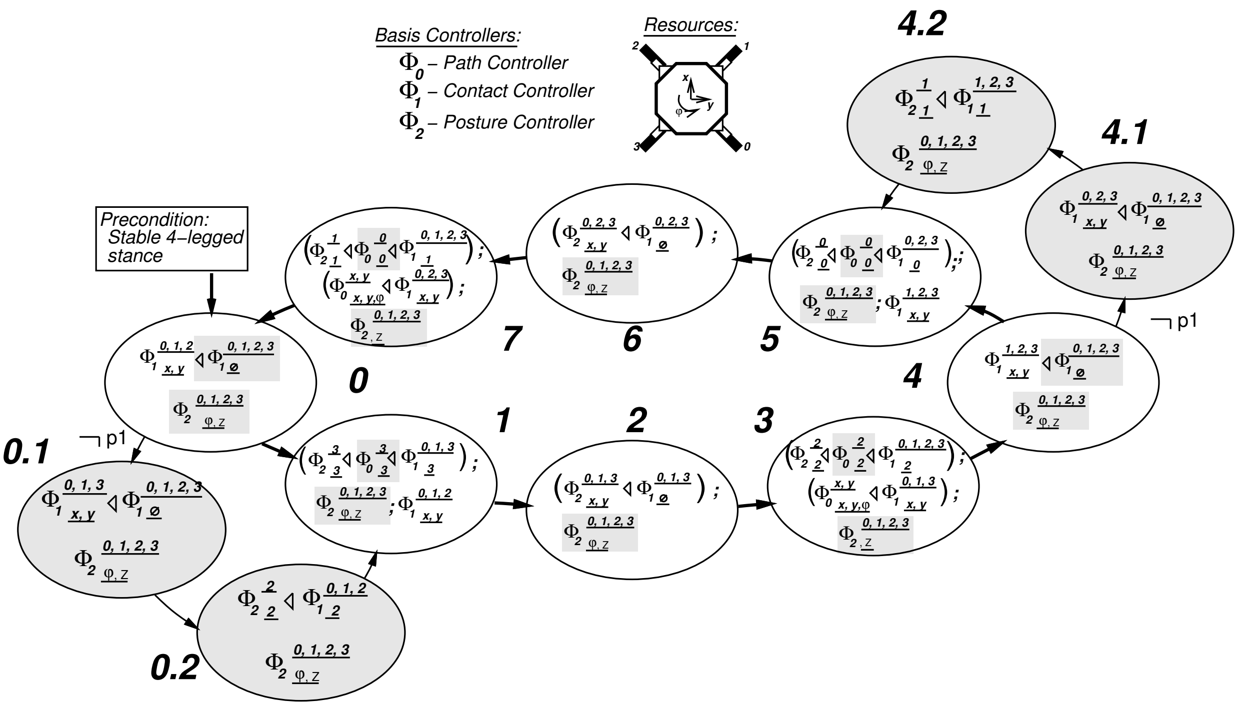


Figure 4: Control Composition for Irregular Terrain. Controller instantiations that are new or modified from Figure 1 are highlighted.


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