Fast Parametric Transitions for Smooth Quadrupedal Motion*

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Abstract. This paper describes a motion system for a quadruped robot that performs smooth transitions over requested body trajectories. It extends the generality of path based approaches by introducing geometric primitives that guarantee smoothness while decreasing (and in some cases entirely removing) constraints on when and what types of parameter transitions can be made. The overall motion system for the autonomous Sony legged robot that served as our test-bed is also described. This motion system served as a component in our entry in the RoboCup-2000 world robotic soccer championship, in which we placed third, losing only a single game.

1 Introduction

The motion system for a legged robot has to balance requests made by an action selection mechanism with the constraints of the robot's capabilities and requirement for fast, stable motions. The desirable qualities of a system are to provide stable and fast locomotion, which requires smooth body and leg trajectories, and to allow smooth, unrestrictive transitions between different types of locomotion and other motions (such as object manipulation).

The platform we used in our work was the a quadruped robot provided by Sony for competition in the RoboCup robotic soccer competitions [6]. In this domain, each team creates the software for a team of three Sony legged robots that compete with another team of three in a game of soccer. The system as a whole is described in [7], and the legged competition in [9]. Although there is an existing system provided by Sony for locomotion, it does not offer the flexibility and low latency required helpful in playing soccer, which motivated our system.

The field of legged locomotion has a long history, with problem formalizations as early as the late 1960s [8]. Recent work on quadrupeds has focused on pattern generator based methods [5] and parameter learning in fixed gaits [2]. Pattern

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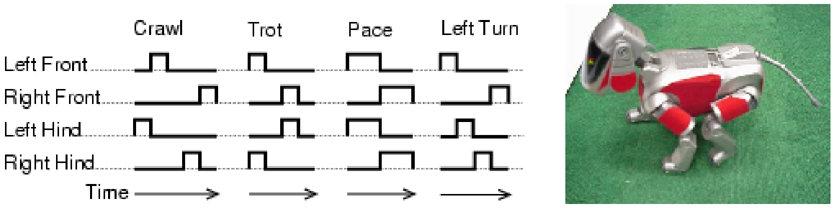

Fig. 1. A timing diagram of various walking gaits. the function is zero when the foot is on the ground and nonzero when it is in the air. To the right is a picture of a robot executing a crawl gait.

generators use internal oscillation methods to drive force based actuators that generate the walking motion through an interaction of motor torques and natural oscillation. While promising, there is still much work to be done in terms of satisfying specific requests on such systems, such as walking or turning on a requested arc. There are also many robots, such as the Sony quadruped, that use more traditional servo actuators which make force-based actuation difficult. State of the art systems for actuated walking include the autonomously learned walks from Sony on their prototype quadruped [2], and later on the release model of the AIBO robot [3]. This system used evolutionary algorithms (EA) to set parameters and test them autonomously for various walking styles. The different gaits focused on are shown in figure 1. The quasi-static crawl moves one foot at a time, maintaining each foot on the ground for at least 75% of the time, this fractional duty cycle is represented as $\beta \geq 0.75$. The supporting basis of feet for a crawl is a triangle. A trotting gait moves diagonally opposite feet at the same time with $\beta \geq 0.50$. Finally the pace gait moves the right and left feet in synchronization and has a $\beta \approx 0.50$ to maintain a side to side oscillation. For our work we focused on the quasi-static crawl for its stability.

While much research has been done in fixed gaits for continuous motion, relatively little work has gone into the area of transitioning among different path targets or from one type of gait to another. One exception is the work of Hugel, which addresses the problem of transitioning among walking and turning gait types as well as arced paths [4]. However a shortcoming of existing transition systems is that the transition points occur at single phase locations in the walk cycle, specifically where leg positions overlap among two gaits or parameter sets. This is quite restrictive on the types of transitions that are then allowed by the system. In the remainder of this paper, we will present a system for transitioning smoothly across more general parameter sets for quasi-static walking and turning gaits. The high level system architecture of our motion system will also be described.

2 Approach

The overall approach taken in implementing the walk is to approach the problem from the point of view of the body rather than the legs. Each leg is represented by a state machine; it is either down or in the air. When it is down, it moves relative to the body to satisfy the kinematic constraint of body motion without slippage on the ground plane. When the leg is in the air, it moves to a calculated positional target. The remaining variables left to be defined are the path of the body, the timing of the leg state transitions, and the air path and target of the legs when in the air. Using this approach smooth parametric transitions can be made in path arcs and walk parameters without very restrictive limitations on those transitions. The leg kinematics was implemented in closed form despite offsets at each joint from the rotation axes, but the derivation is omitted for brevity.

2.1 Spline path stitching

We chose to represent the body path of the robot using a piecewise polynomial, specifically a Hermite cubic spline [1]. A Hermite spline is specified by two points (p_0, p_1), and two derivative vectors, $(\delta p_0, \delta p_1)$.

$$\begin{aligned} H(t) &= [x(t)\ y(t)\ z(t)] \\ &= \begin{bmatrix} t^3 \\ t^2 \\ t \\ 1 \end{bmatrix}^T \begin{bmatrix} 2 & -2 & 1 & 1 \\ -3 & 3 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} p_0 \\ p_1 \\ \delta p_0 \\ \delta p_1 \end{bmatrix} \end{aligned}$$

The body path is modeled as a three component spline $B(t) = [x(t)\ y(t)\ \theta(t)]$, which covers the target configuration space. Using a spline as the body path allows us to specify initial and final positions and velocities for a walk cycle, and since the polynomial is easily differentiable, it also allows us to evaluate the velocity at any point as well as the current body position. Thus it allows new motion requests to be "stitched" to the current path rather than executing the entire request for a full cycle. A new target is added in by evaluating the current position and velocity, and using this as the initial state $(p_0, \delta p_0)$ for the new path plotted toward the request of $(p_1, \delta p_1)$. This guarantees that the body motion is C^1 continuous (continuous velocities). It also allows arbitrarily frequent path transitions, which increases the responsiveness and decreases the latency of reacting to the environment.

2.2 Air path and target selection

The air path is one of the most unconstrained parts of a gait, in that the path needs only to allow the foot to clear the ground while moving forward for it to work in our system. The air path and foot placement target are very important however for keeping the robot stable and maintaining the foot position within its reachability space during the entire walk cycle. The air target was chosen so that after the foot is set down it will pass near the neutral position at a specific time in the walk cycle. This can be achieved by evaluating the expected future position of the robot using the current body trajectory $B(t)$. Two points in the future are important for calculating a placement that will pass by the neutral point; The first (t_1) is the body location when the foot is to be set down, and the second (t_2) is the location in the walk cycle when the foot is intended to pass through neutral (usually about halfway through its ground cycle). Since the foot is to be at neutral at t_2, the location relative to the body at that point is known. Using this, the location of that placement can be found relative to the body position at t_1. Thus the robot will reach for the point to put its foot down that will result in that leg position passing through neutral at t_2.

The air target, along with the projected velocity of the ground plane, and the current state of the foot (position, velocity) specify the components of a single spline fully. However, we found that a two segment Hermite spline worked better for the air trajectory, where the middle position is the average (x, y) location of the initial and target positions of the air path, but with z elevated by a constant for foot and toe clearance. The velocity at the center point is given as the average foot velocity required along the entire air path to reach the target point. Finally, the path is continuous in (x, y), but not in z to allow for quick breaking and restoration of contact with the ground. The pickup and set down z velocities are constant parameters for our walk and were chosen empirically. It should be noted that the projection to make the foot pass through neutral is only approximate, since it requires future evaluation of the body path. Due to stitching, this path may be changed by future commands from the behavior system and thus cannot be predicted. Also, once a foot is set down no immediate corrections can be made. Since the path is smooth however, this approach generally works well for keeping the feet passing near the neutral point even during large transitions.

2.3 Other parameters

In addition to smooth path control, we use pure replacement and linear interpolation on several other walk parameters. Two variables that we varied throughout the walk were the β parameter (fraction of the gait that a leg is on the ground), and the total cycle time of the walk. Depending on the speed requested and the amount of curvature in the path, values for the cycle time varied from 1200 ms at the fastest walk up to 1500 ms at the slowest walk. β varied from 0.75 (one leg was always in the air) to 1 (all feet on the ground while stopped).

Another parameter that proved useful was spread based on angular velocity. We noted that while walking on a tight arc or turning, moving the feet outward from a normal stance allowed more room for motion (leg motion wasn't as constrained by the body), as well as allowing a wider more stable support basis of the feet on the ground. The parameter was varied continuously with angular velocity, although feet would not reflect the change until they were picked up and put down again due to the kinematic constraints for a leg while it was down. The maximum spread was 20%, occurring during fast turning. Very few locomotion systems are capable of varying these parameters during a walk cycle while maintaining kinematic and smoothness constraints, while the spline based motion system presented here supports this quite easily.

2.4 Motion state system

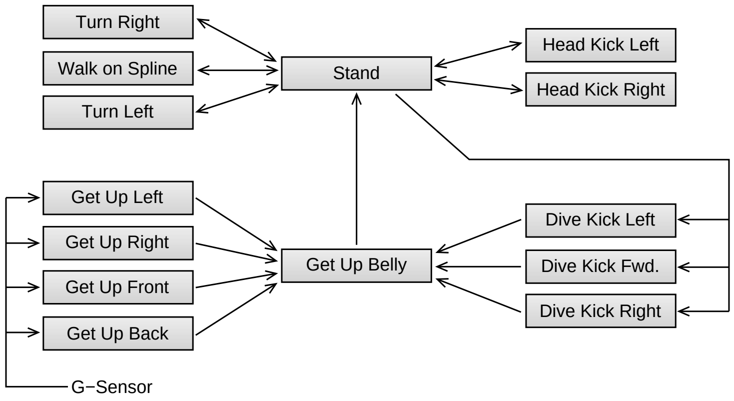

Fig. 2. State diagram of available robot motions.

To put the whole system together, we created a finite state machine model of the family of motions the robot was capable of (see Figure 2). In addition to walking on a path and turning, the robot contained many procedurally defined motions that involved kinematic as well as raw joint angle generating functions. The target state for the motion engine was provided by the action selection system on the robot, and all transitions were constrained by the possible motion on the graph to get to the target states. The one exception was falling, in which case the message from the G-Sensor indicating which side the robot had fallen onto was used to immediately transition to one of the get-up states. The two types of kicks we used to manipulate the ball are head kicks, where the robot dips down and forward and swings its head sideways in the direction it would like to send the ball, and the dive kicks in which the entire robot was controlled to perform a dynamic fall onto the front legs while hitting the ball with its head. Despite the relatively slow motion of the robot, the kick proved highly effective since it used the acceleration of falling as a manipulation tool.

3 Conclusions and Future Work

We presented a complete motion system for an autonomous robot, with special focus on several novel features of the locomotion system. The system was based almost exclusively on kinematics and splines, which allow smooth path generation, and along with a kinematic state machine for the legs enable parametric transitions between motions that do not to pass through the same state. This allows much more general control of the robot, removing restrictive special transition points, all without sacrificing smoothness.

We have a current implementation that can transition four or more times per walk cycle instead of once or twice, and the general approach allows for even more frequent transitions and higher order smoothness. Our current system was tested at the RoboCup-2000 competition in Melbourne, Australia, where we placed 3^{rd}. We demonstrated the fastest quasi-static crawl gait to date on the Sony robots (725 cm/min), out-pacing even the evolved forward only crawl trot (600 cm/min) [3]. However, two of the twelve teams demonstrated non-dynamic trotting gaits that were even faster (UNSW had 1200 cm/min, UPenn had 900 cm/min). A non-dynamic trotting gait lifts two legs at a time but often slides or touches on another part of the robot (front elbows or hind leg toes) so there are three effective contact points [2]. Since our transition system is not specific to a particular gait, it can be applied to guarantee smoothness constraints that neither of the other two systems currently posses. This allows scaling to larger robots where smoothness is necessary to prevent damage to the robot, and it allows transitions between a broad spectrum of walk parameters and gaits for adaptable locomotion.

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