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Dynamic locomotion with four and six-legged robots[1]

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Abstract

Stable and robust autonomous dynamic locomotion is demonstrated experimentally in a four and a six-legged robot. The Scout II quadruped runs on flat ground in a bounding gait, and was motivated by an effort to understand the minimal mechanical design and control complexity for dynamically stable locomotion. The RHex 0 hexapod runs dynamically in a tripod gait over flat and badly broken terrain. Its design and control was motivated by a collaboration of roboticists, biologists, and mathematicians, in an attempt to capture specific biomechanical locomotion principles. Both robots share some basic features: Compliant legs, each with only one actuated degree of freedom, and reliance on (task space) open loop controllers.

1. Introduction

Designers of statically stable autonomous legged robots in the past have paid careful attention to minimize negative work by minimizing vertical body movements during locomotion. This required complex leg designs with at least three degrees of freedom per leg, more if an ankle/foot combination is required. The resulting cost, mechanical complexity, and low reliability make it difficult for these robots to be profitably deployed in real world tasks.

In contrast, dynamic locomotion with compliant legs permits not only higher speeds and the potential for drastically improved mobility compared to statically stable machines, but at the same time permits these improvements with greatly simplified leg mechanics. With compliant legs, instantaneously controlled body motion can no longer be achieved, and energy efficient locomotion must utilize intermittent storage and release of energy in the passive leg compliances. It is remarkable that despite their mechanical simplicity, outstanding dynamic mobility is obtained in both machines described in this paper, based on very simple (task space) open loop controllers.

In the Scout II quadruped we have attempted to demonstrate the limits of mechanical simplicity, while still obtaining a range of useful dynamic mobility. Even with only one actuator per leg, we obtained full mobility in the plane on flat ground, and running speeds of up to 1.2 m/s with a bounding gait [7]. These preliminary results and ongoing research suggest that further speed and mobility improvements, including compliant walking, leaping, and rough terrain handling are within reach.

The extension of the basic engineering design principles of Scout II to the fundamentally different hexapedal running of RHex 0 is based on insights from biomechanics, whose careful consideration exceeds the scope of this paper. In a paper documenting the performance of cockroach locomotion in a setting similar to our recreation in Figure 11, R. J. Full et al., state “Simple feedforward motor output may be effective in negotiation of rough terrain when used in concert with a mechanical system that stabilizes passively. Dynamic stability and a conservative motor program may allow many-legged, sprawled posture animals to miss-step and collide with obstacles, but suffer little loss in performance. Rapid disturbance rejection may be an emergent property of the mechanical system." In particular, Full's video of a Blaberus cockroach racing seemingly effortlessly over a rough surface, shown at an interdisciplinary meeting [6] motivated and initiated the development of RHex.

Though morphologically quite distinct from its biological counterparts, RHex emulates the basic principles of insect locomotion as articulated by Full. The robot’s sprawled posture with properly designed compliant legs affords strong passive stability properties, even on badly broken terrain. These stability properties, combined with a rugged mechanical design forgiving to obstacle collisions permits controllers based on open loop (“clocked”) leg trajectories to negotiate a large variety of terrains.

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Portions of this paper have appeared in the Proc. of the International Conference on Robotics and Automation, 2000 [7,9].

2. Scout II Quadruped

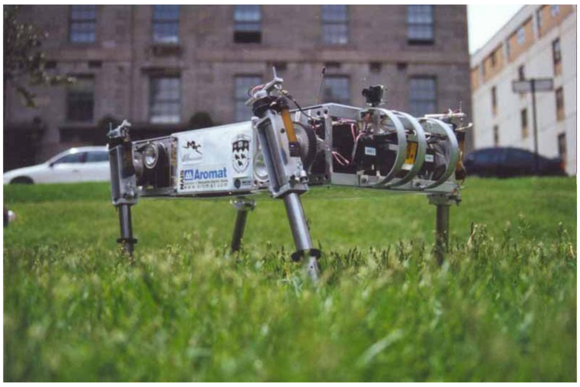

Figure 1: Scout II.

Scout II, shown in Fig. 1, has a main body and four compliant legs. The body contains all elements for autonomous operation, including computing, I/O, sensing, actuation, and batteries. Each leg is a passive prismatic joint with compliance and rotates in the sagittal plane, actuated at the hip by one motor. Without leg articulation, toe clearance during the swing phase can be achieved with any running gait that includes a flight phase, for example, pronking, trotting and bounding. We have chosen the bounding gait (Fig. 2) since it permits a smooth transition from a bounding walking gait, the subject of current research.

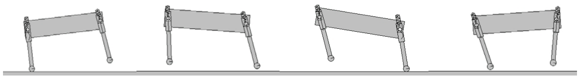

Figure 1: Illustration of a bounding gait.

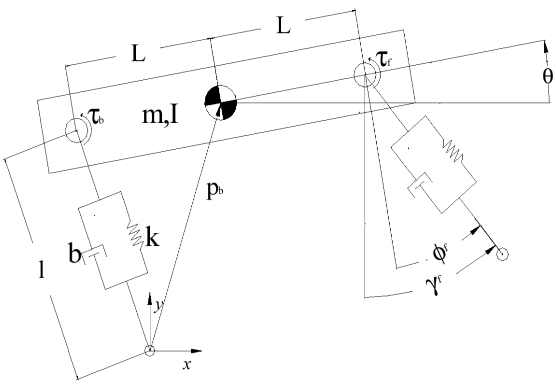

Figure 2: Scout II model

The sagittal plane model, shown in Fig. 3, is a four degree-of-freedom system in each single stance phase, and a five degree-of-freedom system during flight, with only two hip torque control inputs.

Control

The bounding controller accomplishes running at a desired forward speed, $\dot{x}_d$, by placing each leg at the desired angle, ϕ_d,

$$\begin{cases} XCG_d = \dot{x}\, T_S / 2 + k_{\dot{x}} (\dot{x} - \dot{x}_d) + a \\ \gamma_d = \arctan\left(\dfrac{XCG_d}{\sqrt{l^2 - XCG_d^{\,2}}} \right) \\ \phi_d = \gamma_d - \theta \end{cases}, \qquad (1)$$

and applying a leg torque $\tau = k_v(\dot{x} - \dot{x}_d)$ during stance. This controller is motivated by the foot placement algorithm in Raibert's three-part controller [8]. The key differences in our controller are necessitated by the absence of a linear leg thrusting actuator, and thus the lack of a direct means to add energy to the vertical (body pitching) dynamics. First, the offset term, a, in (1), diverts some forward energy to the vertical dynamics in each step. This reduced forward energy (the robot slows down) is then compensated during stance phase via the explicit velocity control.

There is no explicit control of the body pitch oscillation - front and back leg controllers are independent. They only rely on the individual leg states, and make no use of an overall body state. Computer simulations show that this controller, despite its simplicity, succeeds not only in stable velocity control, but also in tracking rapid set point changes in forward velocity, as shown in Fig. 4.

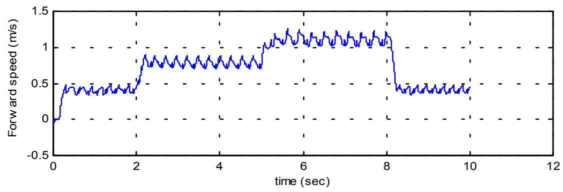

Figure 3: Step changes in forward velocities controlled by the hip actuator torque.

An open loop version of this controller is an attempt to demonstrate the simplest form of compliant quadruped running control without any explicit feedback control of body oscillation and forward speed. It simply commands a constant desired hip torque, τ_d, during stance and a constant desired leg angle, ϕ_d, controlled during flight via a set point PD algorithm. With two values for front and back legs, this controller is determined by only four parameters.

Fig. 5 shows a Working Model 2D® [4] simulation of the open loop controller, with fixed values of touchdown leg angles (18° for the back legs and 22° for the front legs) and stance torques (40 Nm for the back legs and 10 Nm for the front legs). The result is steady running with 1.2 m/s forward speed with body oscillation with an amplitude of 6.5° and a period of 0.29 s.

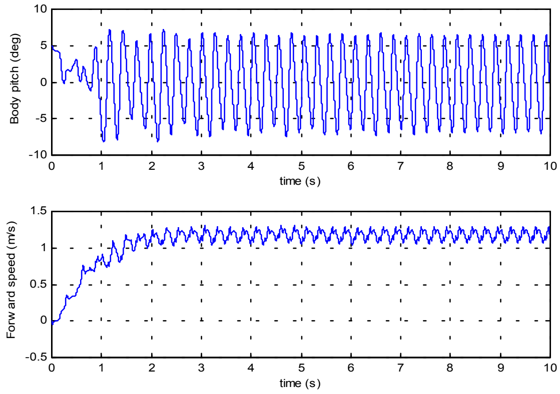

Figure 4: Body pitch and forward velocity during running with the open loop controller.

Thus, surprisingly, compliant quadruped running is possible without explicit feedback control of forward speed or stance time. The disadvantage of this controller is that each particular speed requires the selection of the appropriate touchdown leg angles and stance torques. However, this could be implemented in a straightforward fashion as a lookup table, and could serve as a potentially robot-saving backup controller in case of sensor failure.

Experiments

As suggested by the simulations, it is possible to achieve a steady bounding gait by choosing a suitable set of constant motor torques during stance and leg touchdown angles during flight. Even though there is no active control of the body roll dynamics in the experimental four-legged robot, the damping in the leg springs was sufficient for passive roll stability.

We have implemented the open loop controller on Scout II. A back torque of 35 Nm per leg and a front torque of 10 Nm per leg was used. A touchdown angle of 22° with respect to the vertical for the front legs and 18° for the back legs was commanded for the flight phases.

A slip prevention torque limit (described in [7] and omitted here for brevity) was implemented in simulation and experiments. The only difference in the experimental slip prevention function is that it dealt with each of the two front and back legs independently.

Both simulation and experimental runs started at zero speed and accelerated until steady state speeds were achieved. While the first two to three seconds transition phase is different in simulation and experiment, the remaining operating time is comparable. Both speeds reach a steady value of about 1.2 m/s. The large experimental speed fluctuations in Fig. 6 are primarily an artifact of our speed calculation, based on the hip angular velocities, which suffers due to the combined backlash of the gear and the belt transmission of several degrees.

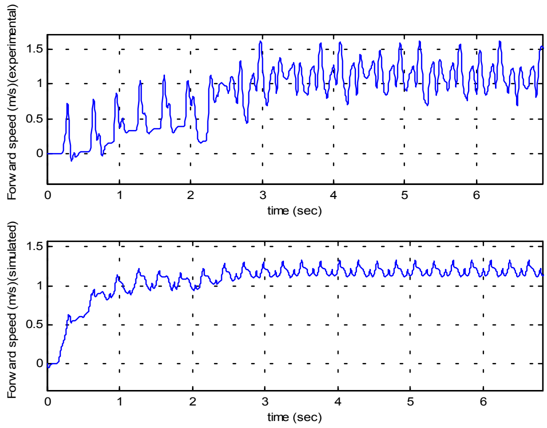

Figure 5: Forward velocity. Top: Experiment. Bottom: Simulation.

Turning while running is accomplished via a simple modification to the open loop bounding controller. The idea is to apply differential torques to the left and right sides of the legs during the stance phases. Implementation of the turning algorithm resulted in rapid turns as illustrated in Fig. 7.

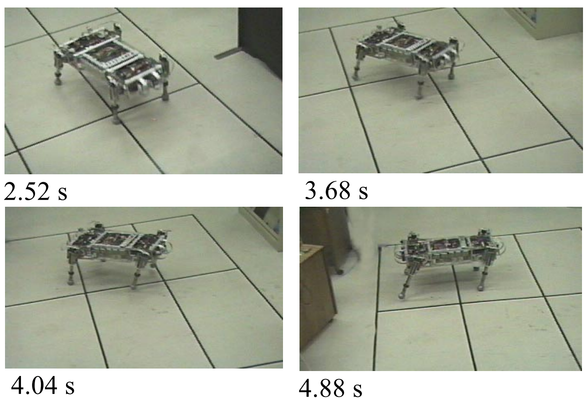

Figure 6: Turning experiment.

3. RHex 0 Hexapod

Figure 7: RHex 0.

RHex 0, shown in Fig. 8, has a main body and six compliant legs. As in Scout II, the body contains all elements for autonomous operation, including computing, I/O, sensing, actuation, and batteries. Unlike most hexapodal robots built to date, RHex 0 has compliant legs, and was built to be a runner. Each leg rotates in the sagittal plane, actuated at the hip by one motor. Since a bounding type walking gait is not feasible with six legs, RHex walks with a compliant tripod gait, and eliminates any toe clearance problems by rotating the legs in a full circle.

Control

Since the present prototype robot has no external sensors by which its body coordinates may be estimated, we have used joint space closed loop (“proprioceptive”) but task space open loop control strategies. These are tailored to demonstrate the intrinsic stability properties of the compliant hexapod morphology and emphasize its ability to operate without a sensor-rich environment. Specifically, we present a four-parameter family of controllers that yields stable running and turning of the hexapod on flat terrain, without explicit enforcement of quasi-static stability. All controllers generate periodic desired trajectories for each hip joint, which are then enforced by six local PD controllers, one for each hip actuator. As such, they represent examples near one extreme of possible control strategies, which range from purely open-loop controllers to control laws that are solely functions of the leg and rigid body state. It is evident that neither one of these extremes is the best approach and a combination of these should be adopted. An alternating tripod pattern governs both the running and turning controllers, where the legs forming the left and right tripods are synchronized with each other and are 180° out of phase with the opposite tripod, as shown in Fig. 9.

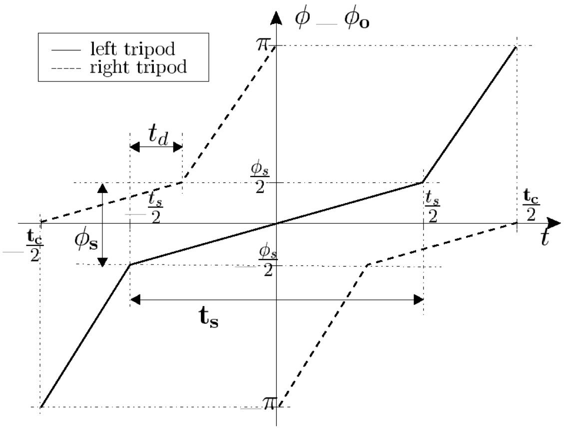

Figure 9: Motion profiles for left and right tripods.

The running controller's target trajectories for each tripod are periodic functions of time, parametrized by four variables: t_c, t_s, ϕ_s and ϕ_o. The period of both profiles is t_c. In conjunction with t_s, it determines the duty factor of each tripod. In a single cycle, both tripods go through their slow and fast phases, covering ϕ_s and 2π - ϕ_s of the complete rotation, respectively. The duration of double support t_d, when all six legs are in contact with the ground, is determined by the duty factors of both tripods. Finally, the ϕ_o parameter offsets the motion profile with respect to the vertical. Note that both profiles are monotonically increasing in time; but they can be negated to obtain backward running. Simulations (Fig. 10) demonstrate that control of average forward running velocity is possible with these controller outputs.

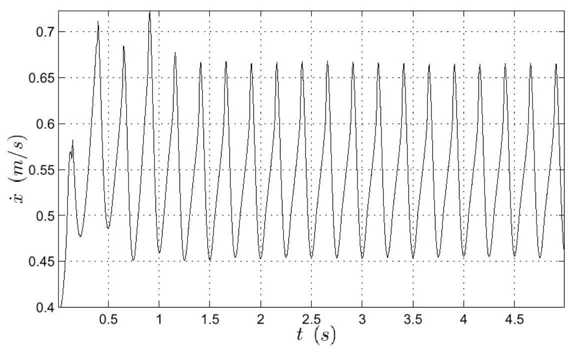

Figure 10: Simulation of forward body velocity.

We have developed two different controllers for two qualitatively different turning modes: turning in place and turning during running. The controller for turning in place employs the same leg profiles as for running except that contralateral sets of legs rotate in opposite directions. This results in the hexapod turning in place. Note that the tripods are still synchronized internally, maintaining three supporting legs on the ground. Similar to the control of forward speed, the rate of turning depends on the choice of the particular motion parameters, mainly t_c and ϕ_s. In contrast, we achieve turning during forward locomotion by introducing differential perturbations to the forward running controller parameters for contralateral legs. In this scheme, t_c is still constrained to be identical for all legs, which admits differentials in the remaining profile parameters, ϕ_o and t_s, while ϕ_s remains unchanged. Two new gain parameters, Δt_s and $\Delta\phi_o$ are introduced. Consequently, turning in +x (right) direction is achieved by using $u_l = [t_c;\ t_s+\Delta t_s;\ \phi_s;\ \phi_o+\Delta\phi_o]$ and $u_r = [t_c;\ t_s-\Delta t_s;\ \phi_s;\ \phi_o-\Delta\phi_o]$ for the legs on the left and right sides, respectively.

Experiments

We have implemented the open loop controller on the RHex prototype. Extensive testing demonstrated that RHex was able to negotiate a variety of challenging obstacle courses, with obstacles well exceeding the robot's ground clearance, all with fixed (unchanged) open loop control trajectories, and with only minor velocity variations between 0.45 m/s and 0.55 m/s. Detailed statistical performance documentation over all the terrains will be the subject of a forthcoming publication. On flat ground (carpet), the forward speed (averaged over ten runs) is, as predicted by the simulation, slightly above 0.5 m/s, or about one body length/s. On this surface, the average total electrical power consumption is 80 W.

As simulation study had predicted as well, steering is possible, even though the leg actuation is limited to motion in the sagittal plane only, via differential motion between left and right legs. We selected control parameters that resulted in turns in place and robot speeds up to about 0.4 m/s. The maximum forward velocity is reduced during turning, because the differential leg motion precipitates the onset of the speed limiting vertical body oscillations. The maximum yaw angular velocities increase almost linearly with forward velocity up to 0.19 rad/s at 0.39 m/s. Interestingly, the resulting turn radius is almost constant with approximately 2 m. Turning in place provides the highest yaw angular velocity of 0.7 rad/s.

One particular rough terrain experiment was an attempt to evaluate RHex's performance in a similar environment to that negotiated by a Blaberus cockroach in [2]. Our efforts at re-creating such a surface at RHex's scale are shown in Figure 11. To our surprise, RHex was able to traverse this surface with random height variations of up to 20.32 cm (116% leg length) with relative ease at an average velocity of 0.42 m/s (averaged over ten successful runs).

Figure 11: Locomotion on rough terrain.

Accumulating evidence in the biomechanics literature suggests that agile locomotion is organized in nature by recourse to a controlled bouncing gait wherein the "payload", the mass center, behaves mechanically as though it were riding on a pogo stick [1]. While Raibert's running machines were literally embodied pogo sticks, more utilitarian robotic devices such as RHex must actively anchor such templates within their alien morphology if the animals' capabilities are ever to be successfully engineered [3]. A previous publication showed how to anchor a pogo stick template in the more related morphology of a four degree of freedom monopod [10]. The extension of this technique to the far more distant hexapod morphology surely begins with the adoption of an alternating tripod gait, but its exact details remain an open question, and the minimalist RHex design (only six actuators for a six degree of freedom payload!) will likely entail additional compromises in its implementation. Moreover, the only well understood pogo stick is the Spring Loaded Inverted Pendulum [12], a two-degree of freedom sagittal plane template that ignores body attitude and all lateral degrees of freedom. Recent evidence of a horizontal pogo stick in sprawled posture animal running [5] and subsequent analysis of a proposed lateral leg spring template to represent it [11] advance the prospects for developing a spatial pogo stick template in the near future. Much more effort remains before a functionally biomimetic six degree of freedom "payload" controller is available, but we believe that the present understanding of the sagittal plane can already be used to significantly increase RHex's running speed, and, as well, to endow our present prototype with an aerial phase.

Acknowledgments

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