RePaC design and control:
Cheap and fast autonomous runners

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SYNOPSIS

Evolving dynamically stable robots from traditional statically stable walkers has not yet been feasible due to fundamental task differences, kinematic, actuation and energetic constraints. Instead, simple solutions to the dynamic locomotion problem are available, based on "RePaC" Revolute Passive Compliance design and control. We will describe the RePaC design and control principles and show how they result in inexpensive, autonomous, energy efficient running and walking robots.

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. Moreover, it has proven impossible so far, due to limitations of present day actuation technologies, to design legged robots with multi-degree of freedom legs, where actuators are simultaneously strong enough to support a robot's weight and fast enough to permit the speeds necessary for dynamic locomotion.

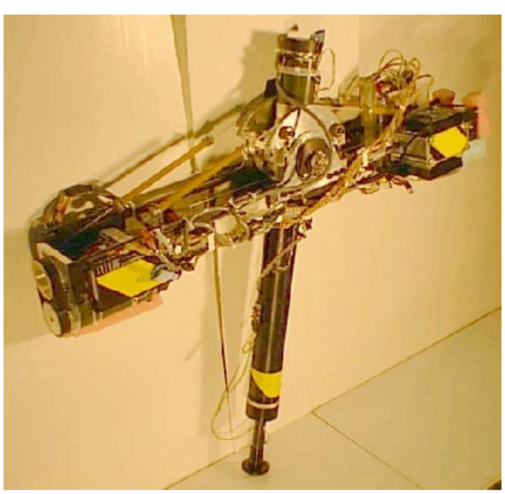
The legged robots we have built to date that are capable of dynamically stable locomotion at speeds over 1 m/s feature leg designs that essentially decouple the gravitational loading from the actuators altogether via a very simple revolute passive compliance (RePaC) design: The main propulsion is provided by a hip actuator, whose axis is perpendicular to the sagittal plane, and the leg behaves like an unactuated (passive) prismatic compliant joint.

Dynamic locomotion possible with such 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 the machines described in this paper, based in part on very simple (task space) open loop controllers.

This presentation will describe the design and control of three different dynamically stable robot systems, which all have broken new ground in terms of speed, mobility, power autonomy or energy efficiency, and which have been developed in the Ambulatory Robotics Lab at McGill, and with collaborators at U. Michigan and U. Berkeley (a more complete acknowledgement can be found in Section 3). All three robots feature simple, low dof RePaC legs, and rely on the robot's passive dynamics arising from careful overall mechanical design, and all three can attain speeds above 1 m/s.

2 ARL MONOPOD II [12,13,14]

This is our first dynamically stable robot, and already featured a simple revolute compliant leg, and since it was inspired by the pioneering work of Raibert and his robot designs, also featured two degree of freedom leg actuation (though proving the feasibility of using off-the-shelf low power electric actuation), one at the hip and one in series with the leg spring. As such it differs from the simpler, single actuation RePaC leg designs of Scout II and RHex. The system (Figure 1) has a total of seven motion degrees of freedom, including the leg length, r, the leg actuator displacement, p_l, the hip actuator displacement, p_h, the leg angle, θ, and the body's three degrees of freedom. Due to kinematic constraints, not all are free simultaneously – during stance there are five and during flight there are six motion degrees of freedom. Nevertheless, the system is highly under-actuated, with its two input torques, one for the hip motor, and one for the leg motor.



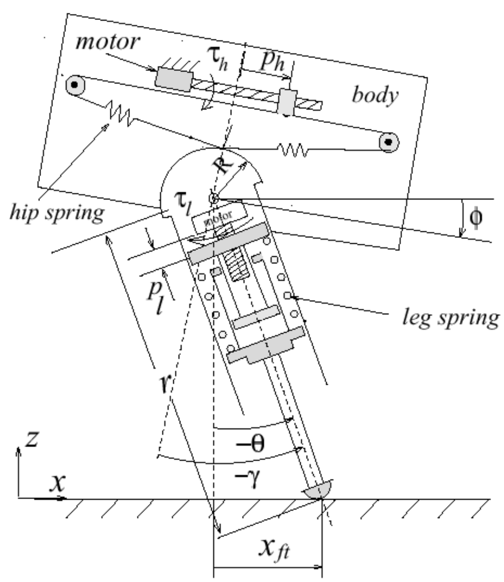


Figure 1. ARL Monopod II

Control was achieved as follows. An adaptive, energy based strategy first stabilized a certain total vertical energy, and thus hopping height. Then, the hip actuator modulated the passive dynamic leg swing oscillation, provided by the counter-oscillation between the body and leg inertias and the hip spring. A desired forward velocity then was translated into the required leg oscillation amplitude (the frequency is fixed by the hip/leg inertias and the hip spring), and synchronized to the vertical dynamics based on the concept of locomotion time, η, which mapped the vertical oscillation phase onto a unit interval, independent of hopping height (Figure 2).

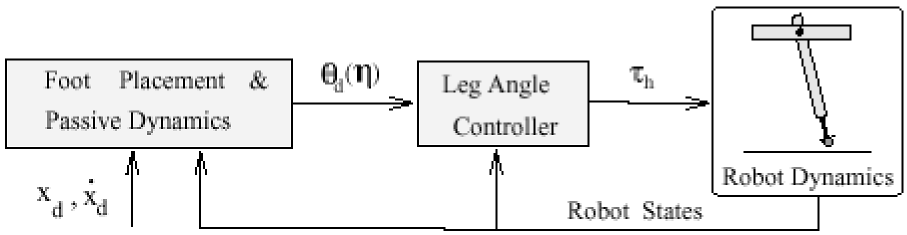


Figure 2. Forward speed control diagram

3 SCOUT II [1,2,5,6,7,9,10,15]

Scout II has been designed from the ground up for autonomous operation: The two hip assemblies contain the actuators and batteries, and the body houses all computing, interfacing and power distribution. The mechanical design of Scout II (Fig. 3) is an exercise in simplicity. Besides its modular design, the most striking feature is the fact that it uses a single actuator per leg – the hip joint provides leg rotation in the sagittal plane. Each leg assembly consists of a lower and an upper leg, connected via a spring to form a compliant prismatic joint. Thus each leg forms a simple RePaC design - with two degrees of freedom, one actuated hip and one unactuated linear spring, resulting in a total of only four actuators for the whole quadruped robot.

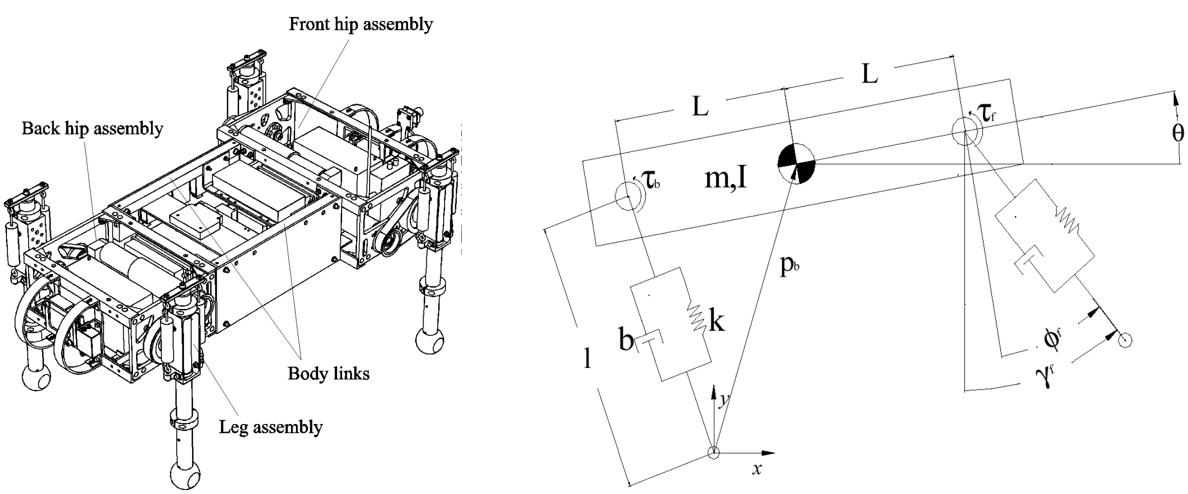


Figure 3. Scout II

Scout II is an under-actuated, highly nonlinear, intermittent dynamical system. Despite this complexity, we found that simple control laws can stabilize periodic motions, resulting in robust and fast running. Surprisingly, the controllers do not require task level feedback like forward velocity, or body angle. What is more, there seem to exist many such simple stabilizing controllers – in [15] three variations are introduced. It is remarkable that the significant controller differences have relatively minor effects on bounding performance! For this reason and for brevity we shall describe one of these controllers here.

The controller is based on two individual, independent leg controllers, without a notion of overall body state. The front and back legs each detect two leg states - stance (touching ground) and flight (otherwise), which are separated by touchdown and lift-off events. There is no actively controlled coupling between the fore and hind legs – the resulting bounding motion is purely the result of the controller interaction through the multi-body dynamic system. During flight, the controller servos the flight leg to a desired touchdown hip angle, ϕ_{td} = 20 deg, then sweeps the leg during stance until a sweep limit, ϕ_{sl} = 0 deg, is reached. In stance phase, a constant torque of 35 Nm is commanded at the hip until the sweep limit is reached. Then a PD controller controls the hip angle at the sweep limit angle.

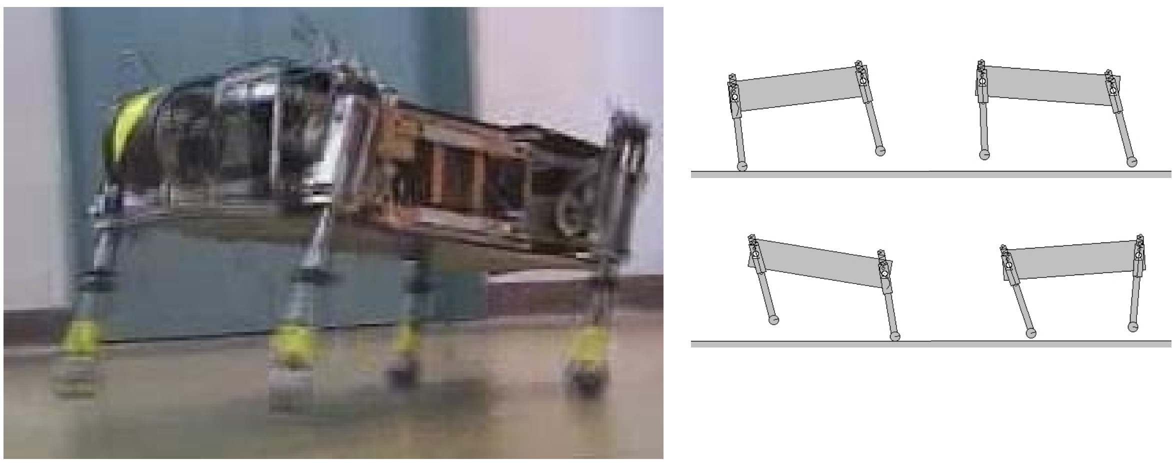


Figure 4. Scout II bounding. Without leg articulation, the body pitching motion during bounding provides the ground clearance necessary for leg protraction.

4 RHEX [3,4,11]

The extension of the basic engineering design principles of Scout II to the fundamentally different hexapedal running of RHex is based on insights from biomechanics, whose careful consideration exceeds the scope of this paper. In a paper documenting the performance of cockroach locomotion, 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, 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.

RHex, shown in Fig. 5, 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 six-legged robots built to date, RHex has compliant legs, and was built to be a runner. Each leg rotates in the sagittal plane, actuated at the hip by one motor, and implements a RePaC design. Unlike the Scout II legs, here the compliance is provided by the compliant four-bar structure in the upper leg as seen in Fig. 5. The leg geometry has been designed such that the leg deflection results in a toe trajectory through the hip joint, emulating a simple linear spring. The advantage of this design over a prismatic joint is greatly reduced complexity and improved ruggedness. The idea for this design comes from Mr. Ben Brown at Carnegie Mellon University.

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. 5.

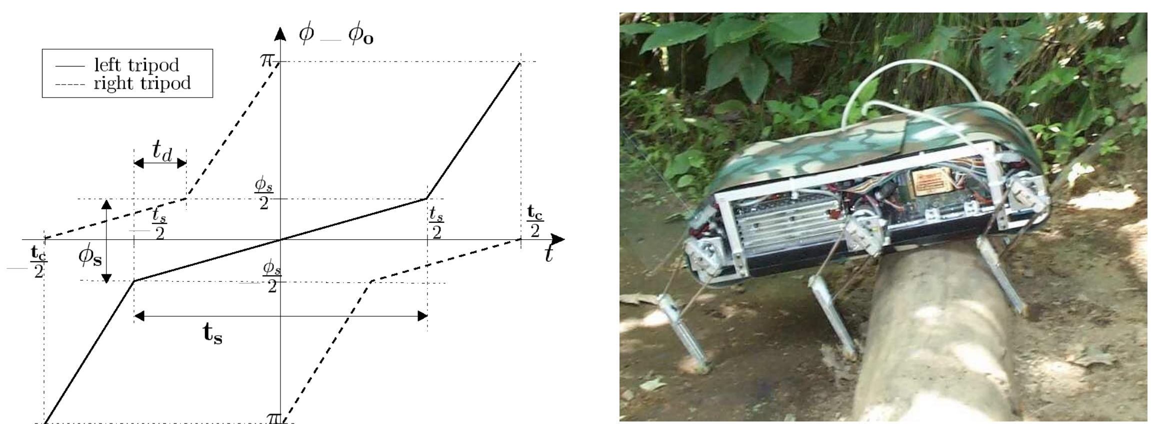


Figure 5: Motion profiles for left and right tripods. RHex outdoors.

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 $2\pi - \phi_s$ 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.

5 Acknowledgements

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