3rd Int. Conf. on Climbing and Walking Robots, Madrid, Spain, Oct 2000.

Dynamic Compliant Walking of a Quadruped Robot: Preliminary Experiments

Martin de Lasa and Martin Buehler
Dept. of Electrical Engineering & Dept. of Mechanical Engineering
Center for Intelligent Machines, McGill University
Montreal, Quebec, H3A 2A7, Canada
mdelasa | buehler@cim.mcgill.ca

1 ABSTRACT

To increase reliability and decrease cost of legged robotic systems it is advantageous to limit actuated degrees of freedom and instead exploit passive elements, such as springs, to provide compliance. Although literature exists on the design and dynamical control of running gaits for such robotic systems, no work exists for slower modes of locomotion such as walking. This paper presents a walking controller for an under-actuated robot, Scout II, with only one actuator per leg, based on commanding a fixed front hip angle and a constant back hip horizontal velocity during stance. Using this straightforward control strategy, we show that the robot achieves stable walking using only limited feedback. Preliminary experimental results are presented and discussed.

2 INTRODUCTION

Synthesis of dynamic locomotion controllers for legged robots poses numerous challenges. In particular, these systems exhibit discontinuous dynamics at state transitions, are multi-input multi-output, act in gravity fields, and interact with unstructured, complex environments (9). Controller synthesis can be further complicated since it is advantageous to limit or reduce actuated degrees of freedom in robot design and instead exploit passive elements, such as springs, to provide compliance. Although controller derivation can become more complicated, the savings can be significant. Incorporating hip compliance Ahmadi and Buehler (1) showed a mechanical energy saving of nearly 40 % for a one legged robot. Buehler et al. (2)(3), also showed that with only limited sensing and actuation, stiff legged walking could be achieved. Furthermore, this reduction in mechanical complexity lowers cost and increases reliability, without sacrificing mobility, traits that go a long way in helping to bring legged robots out of the research lab and into the real world.

To date, little work exists on dynamical walking controller design for underactuated quadruped robots with the exceptions of research in two closely related areas: control of dynamic running robots and control of dynamic walking robots with articulated legs. In the area of running robots, Raibert (10) obtained a large array of behaviours for one, two, and four legged robots by using a simple strategy that partitioned control of running into three decoupled parts, synchronized by a leg finite state machine. Papadopoulos and Buehler (8) showed that with a modified version of the three-part algorithm, simple torque control in stance, and a quasi-static slip control algorithm, pronking and bounding at speeds of up to 1.2 m/s could be obtained, despite a robot design that did not include linear leg actuation.

In the area of dynamical study of walking with articulated legs, Dunn and Howe (4)(6) proposed a dynamic bipedal walking controller that constrained touchdown hip velocity.

Forward velocity tracking, and step length control was also achievable with this control approach. This approach was similar to previous work by Daberkow et al. (4). More biologically inspired methods of control generation also exist. Motivated by the findings of Shik et al. (11) who induced a decerebrated cat to walk by applying electrical impulses to the mid-brain, various neural control approaches have appeared in the literature. Using a neural oscillator model developed by Matsuoka (7) and previously used by Taga (13)(13) in bipedal simulation, Kimura (11) realized stable quadrupedal walking and bounding on a robot. Addition of reflexes to the control also allowed walking on irregular terrain and over small obstacles.

3 CONTROLLER DESIGN

Robots with articulated legs use the swing phase of leg motion to retract legs, avoid toe stubbing, and position legs for subsequent periods of stance. Since Scout II does not have knees, it relies on steady pitching of the body to maintain alternating periods of leg stance and swing. Therefore, the walk and trot gaits observed in nature are not currently realizable on Scout II. Instead a modified version of the bound, which we call a bounding walk, was investigated. This gait is different from the running bound observed in nature since the robot is never ballistic during a locomotion stride. Figure 1 shows a schematic of Scout II. Given that Scout II uses front and back pair of legs together, a simple planar model of Scout II in the sagital plane was used to develop our controller. Figure 2 presents this model, showing nomenclature used.

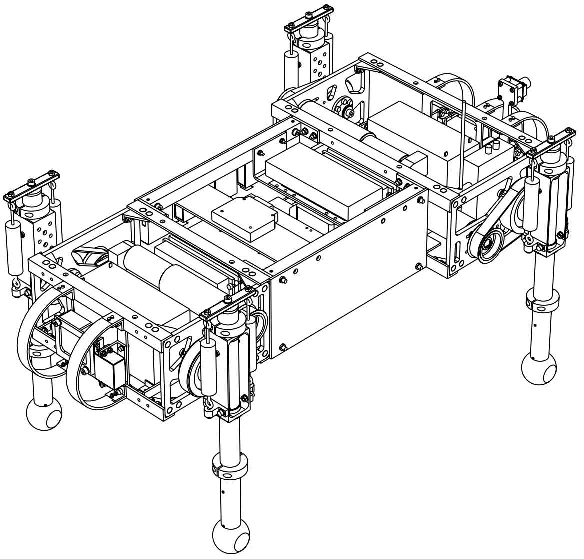

Figure 1 – Scout II with linear compliant legs as rendered by pro/engineer.

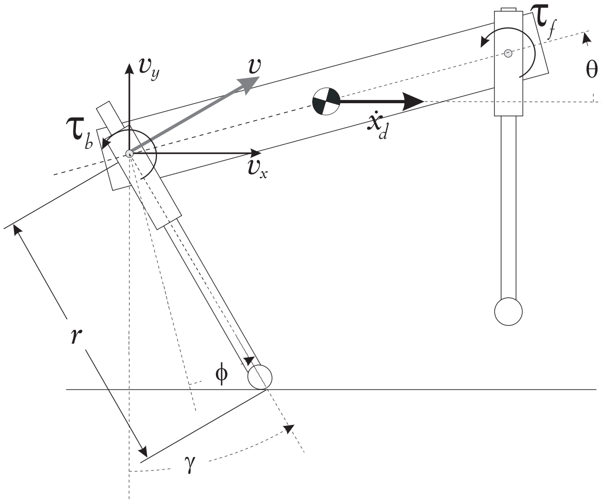

Figure 2 – Hip Velocity Controller Schematic. r is the leg length at a particular instant in time during leg sweep.

Another key requirement for a successful walking controller is to minimize or eliminate the presence of slippage between the toe and the ground. This is of particular concern in walking, which does not benefit from the same magnitude of normal contact forces, as those observed in running. Even the indoor environments of research labs can pose significant challenges to a walking robot if slip cannot be detected and avoided. In steady state stable walking if the robot hips travel at the same speed as the center of mass of the body, the toe will not experience slip, with this approach being principally constrained by the ground coulomb friction factor.

With this in mind, a simple control strategy is proposed. A two-state state machine to synchronize leg behavior is used that switches between *stance* and *flight* for each leg pair. Since preliminary experiments showed that the front legs did not contribute significantly to propelling the body forward and that the front leg braking torque is essential in obtaining back leg liftoff, they are actively servoed to a fixed desired front leg touchdown angle $\gamma_{d\_td\_f}$ throughout both leg states. In flight the back legs are servoed to a desired touchdown angle $\gamma_{d\_td\_b}$ using a high gain PD controller. In stance the back legs are commanded to track a user specified forward horizontal hip velocity $\dot{x}_d$, via $\dot{\gamma}_{d\_b} = \frac{\dot{x}_d}{r_b(t)\cos\gamma_b(t)}$. Experiments were conducted using the following parameters : $\dot{x}_d = 0.3\ m/s$, $\gamma_{d\_td\_f} = -5^o$, $\gamma_{d\_td\_b} = 10^o$.

4 EXPERIMENTAL RESULTS

To validate the proposed walking algorithm, a set of experiments was conducted on Scout II. Figure 3 shows snapshots from a typical locomotion stride from one of these experiments. The presented frames show key phases of motion during walking, including back and front support, as well as intermediate periods of double support. As can be observed from figure 3, good toe clearance is achieved for both the front and back legs (front 0.02 m, back 0.06 m). Four seconds of experimental results for this same run are shown in figures 4-6. For clarity, individual leg state are super imposed on top of each plot, with the high portion and low periods of the curve being periods of leg stance and of flight respectively for the corresponding leg.

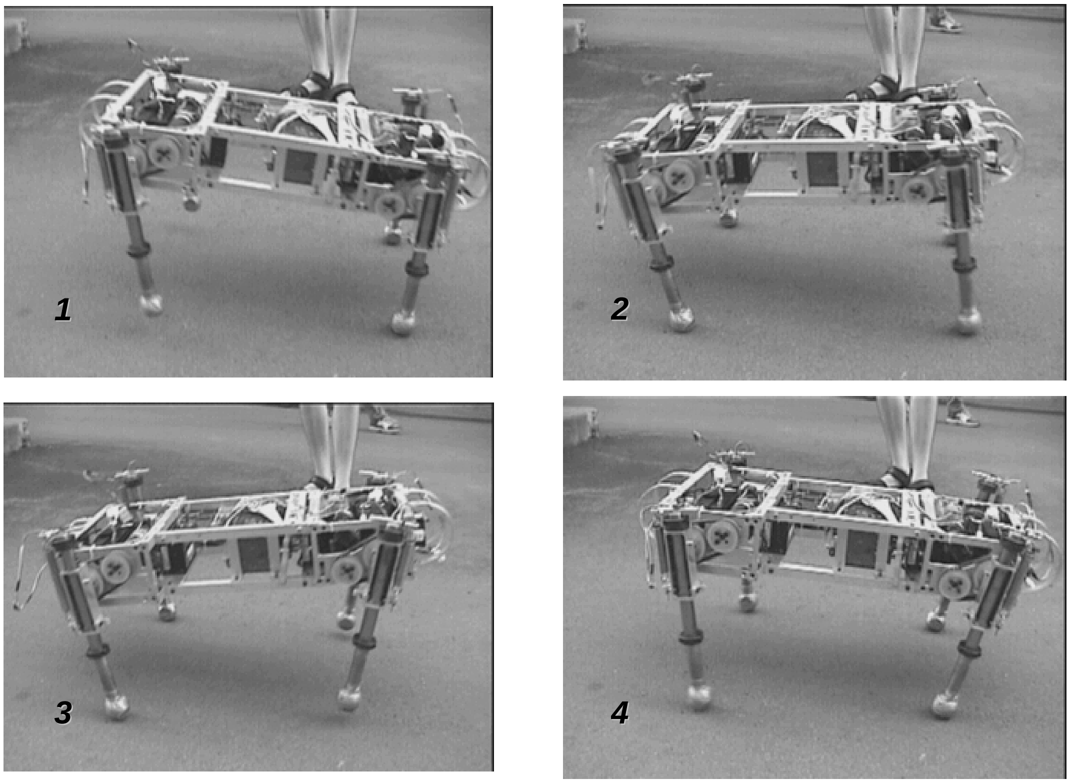

Figure 3 – Scout II in Bounding Walk Gait

As can be observed from figure 6, the body pitches in a repeatable manner with a peak to peak amplitude of approximately 14°. In addition the legs track the commanded trajectories nicely for both front and back sets of legs. As mentioned, throughout the gait, the front legs are fixed at –5°. The back legs on the other hand sweep from 10° until they go into flight. Once in flight back legs return to the desired touchdown angle.

Interestingly, the front legs can be observed as applying mostly positive torque during stance, acting to brake the body and shifting support back onto the back legs. Conversely, the back legs lift the front toes off the ground and propel the body forward, accounting for the large negative torques commanded during stance. The dotted lines on the torque plots of figure 5 represent the desired torques commanded to the motors. As can be observed commanded and actual torque values differ near peak values due to the motor torque/speed characteristics, which limits the applied torque in the no-load case. These effects are brought on by the presence of toe/ground slip.

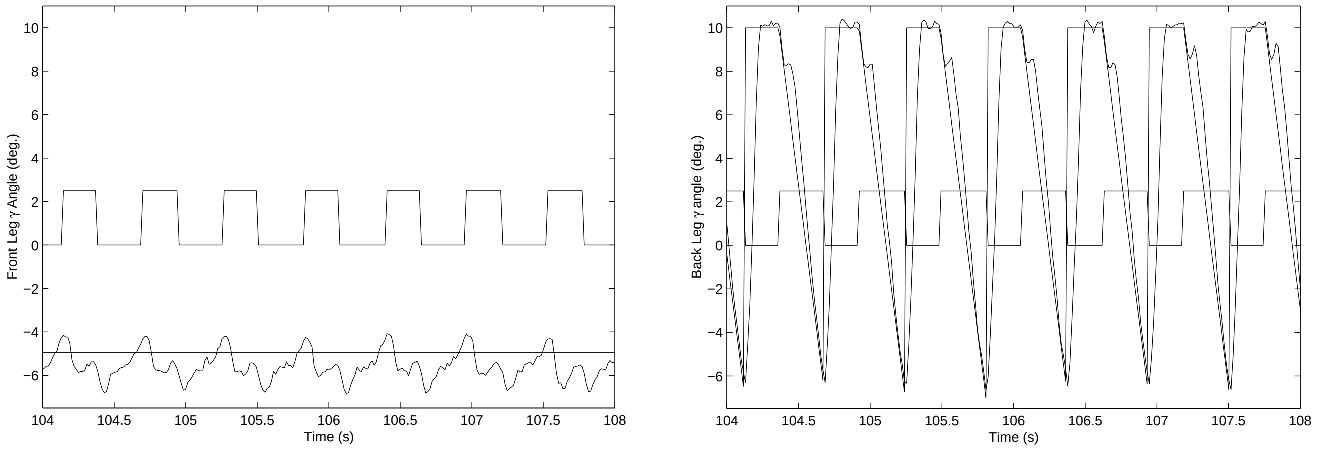

Figure 4 – Commanded (Dashed) and Actual (Solid)
Front and Back Leg Trajectories : Experiment

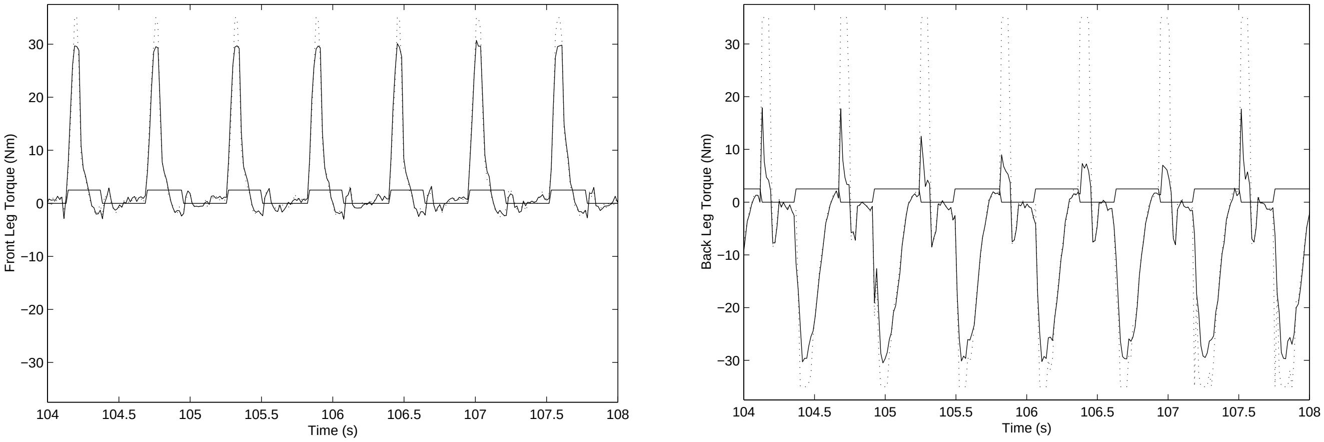

Figure 5 – Commanded (Dashed) and Actual (Solid)
Front and Back Leg Torques : Experiment

5 DISCUSSION

It is interesting to observe that the simple control strategy proposed in this paper yields stable walking. This result is consistent with earlier experiments by Buehler et al. (2), who used a similar approach for stiff legged walking. However, instead of relying on momentum transfer to maintain steady pitching, compliant walking relies principally on stable periodic excitation of the equivalent linear spring/damper system formed by Scout's legs.

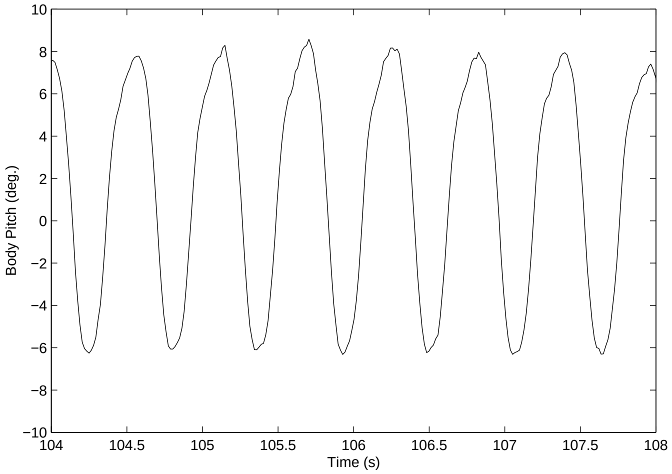

Figure 6 – Body Pitch During Walk : Experiment

In general, the open loop walking algorithm with the documented parameters did not prove to be very robust. For example, variations in terrain slope or uneven ground had a large effect on controller performance. To study controller robustness and the role of front and back legs, we investigated controller parameter sensitivity. First, the front leg touchdown angle $\gamma_{d\_td\ f}$ was varied and the effect on pitching stability was observed. Although stable walking resulted for variations of up $\pm 10^{o}$, increases in back leg clearance became significant for decreasing front touchdown angles. Increasing front touchdown angles, had the reverse effect, but perhaps more importantly made the front legs more prone slip.

Next, the effect of changing desired forward back hip velocity, beginning at some intermediate sweep threshold angle $\gamma_{d\_th\_b}$ was examined. By decreasing the commanded target hip velocity to 20% of the original value, at increasingly small threshold angles, front stance time decreased and front toe clearance during pitching increased significantly.

In summary, experiments showed that in Scout II quadrupedal walking, front and back legs seemed to play markedly different roles. The front legs act as brakes, slowing the forward motion of the body and helping the back legs to lift off the ground. In contrast, the back legs provide bulk forward propulsion for locomotion. This is consistent with the observation that most four-legged animals have larger muscles in their hind legs.

The performed parameter analysis suggests a means of providing feedback to stabilize walking and perhaps stationary rocking. Given the marginal stability of the currently proposed controller this feedback mechanism should help to significantly improve controller robustness.

6 CONCLUSION

This paper presented a simple control strategy for stable compliant walking for an underactuated robot, Scout II. Although the open loop controller has only marginal stability, parameter variation has provided some hints into how feedback may be incorporated to stabilize walking over a larger set of desired input velocities, as well as providing improved controller robustness. We are in the process of investigating various feedback strategies and gait transitions between walking and bounding which have already been experimentally implemented on our platform.

ACKNOWLEDGEMENTS

The authors would like to thank IRIS, a Federal Network of Centres of Excellence, and the Natural Science and Engineering Research Council of Canada for their support of this work. Don Campbell also helped greatly in experiments and with Scout II's ongoing development.

REFERENCES

(1) M. Ahmadi and M. Buehler, "*The ARL Monopod II Running Robot: Control and Energetics*", IEEE Int. Conf. Robotics and Automation, p. 1689-1694, Detroit, Michigan, May 1999, http://www.cim.mcgill.ca/~arlweb

(2) M. Buehler, A. Cocosco, K. Yamazaki, and R. Battaglia, "*Stable Open Loop Walking in Quadruped Robots with Stick Legs*", IEEE Int. Conf. Robotics and Automation, p. 2348-2353, Detroit, Michigan, May 1999, http://www.cim.mcgill.ca/~arlweb

(3) M. Buehler, R. Battaglia, A. Cocosco, G. Hawker, J. Sarkis, and K. Yamazaki, "*SCOUT: A Simple Quadruped that Walks, Climbs, and Runs*", IEEE Int. Conf. Robotics and Automation, p. 1701-1712, Leuven, Belgium, May 1998, http://www.cim.mcgill.ca/~arlweb

(4) A. Daberkow, J. Gao, and W. Schielden, "Walking without impacts", CISM-IFToMM Symp. on the Theory and Practice of Robots and Manipulators, p. 2489-2494, 1994.

(5) E. Dunn and R. D. Howe, "*Towards Smooth Bipedal Walking*", IEEE Int. Conf. Robotics and Automation, p. 2489-2494, 1994.

(6) E. Dunn and R. D. Howe, *"Foot Placement and Velocity Control in Smooth Bipedal Walking*", IEEE Int. Conf. Robotics and Automation, p. 2489-2494, 1996.

(7) K. Matsuoka, "*Sustained Oscillations Generated by Mutually Inhibiting Neurons with Adaptation*", Journal of Biological Cybernetics, 52: 367-376, 1985.

(8) D. Papadopoulos and M. Buehler, "*Stable Running in a Quadruped Robot with Compliant Legs"*, IEEE Int. Conf. Robotics and Automation, San Francisco, CA, April 2000, http://www.cim.mcgill.ca/~arlweb/

(9) G. Pratt, J. Pratt, and P. Dilworth, "*Virtual model control of a biped walking robot*", IEEE Int. Conf. Robotics and Automation, p. 193-198, Albuquerque, NM, 1997, http://www.ai.mit.edu/projects/leglab/

(10) M. H. Raibert, "*Legged Robots that Balance*", MIT Press, Cambridge, MA, 1986.

(11) H. Kimura and Y. Fukuoka, "*Adaptive Dynamic Walking of the Quadruped on Irregular Terrain – autonomous adaptation using neural system model*", IEEE Int. Conf. Robotics and Automation, San Francisco, CA, p.436-443, April 2000, http://www.kimura.is.uec.ac.jp/

(12) M. L. Shik, F. V. Severin, and G. N. Orlovsky, "*Control Of Walking And Running By Means Of Electrical Stimulation To The Mid-Brain*", Biophysics, 11:756-765, 1966.

(13) G. Taga, Y. Yamaguchi, and H. Shimizu, *"Self-Organized Control Of Bipedal Locomotion By Neural Oscillators In Unpredictable Environment*", Journal of Biological Cybernetics, p. 147-159, 1991.

(14) G. Taga, "*A Model Of The Neuro-Musculo-Skeletal System For Human Locomotion II - Real-Time Adaptability Under Various Constraints*", Journal of Biological Cybernetics, 73: 113-121, 1995.