Towards Dynamic Step Climbing For A Quadruped Robot with Compliant Legs

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1 ABSTRACT

Animals are capable of breathtaking dynamic rough terrain mobility – far superior to that of any existing wheeled, tracked or legged robot. Our research aims to endow our legged robots with increasingly capable dynamic abilities. In this paper, we are presenting a controller that expands the rough terrain abilities of our four-legged robot, Scout II, to dynamic step climbing. Dynamic step climbing permits not only faster operation, but also requires fewer actuated degrees of degrees of freedom than statically stable operation. Indeed, our quadruped model features, like our experimental platform, only one actuator per leg. Ongoing work will expand this behavior to dynamic stair climbing - an essential capability for applications in indoor and urban settings.

2 INTRODUCTION

While several wheeled and tracked vehicles have been built which are capable of step and stair climbing, few legged robots are able to overcome a significant step or negotiate stairs. Even fewer can do this dynamically but operate at the slowest speeds. The first biped to climb stairs was SD-2 [1], which had large enough feet to permit statically stable stair climbing. Matsumo et al [2] introduced a planar biped with active wheels. It was able to walk/roll up and down shallow stairs, following reference trajectories that keep the robot in a quasi-static equilibrium. Several stair-climbing bipeds have been built with sufficiently large feet to permit control based on the zero-momentum point idea (ZMP), the latest example being the Honda P2 and P3 robots [3]. Hirose and Umetani implemented stair climbing on their PV II quadruped [4]. Several versions of TITAN quadrupeds capable of statically stable stair climbing [5,6,7,8]. Among the six legged robot, Waldron's ASV [9,10] was able to overcome substantial obstacles, and would likely have been able to climb stairs, as well.

In contrast to these robots, animals negotiate obstacles dynamically [11]. Raibert's planar biped demonstrated the first fully dynamically stable robotic stair climbing [12,13]. These experiments clearly showed the advantages of dynamic operation – simplicity (only two actuators per leg) and speed. Dynamic quadruped step climbing was first reported in our earlier research [14] where Scout I, a robot with stiff legs, and only one actuator per leg, climbed a step with a height corresponding to 40% of it's leg length. A controller for dynamic stair climbing was shown in simulation. The work presented here develops a step climbing controller for Scout II, and based on our earlier work on compliant quadruped running [15]. Experiments to validate the simulated controller are currently under way.

3 SCOUT II MECHANICAL STRUCTURE AND MODELLING

Scout II is a four-legged robot, shown in Fig. 1. The legs are attached to the body via actuated revolute hip joints. Each leg consists of an upper and a lower leg, acting as a compliant prismatic joint. When the leg is not in contact with ground (flight or swing phase), the spring acts to extend the leg to maximum length. When the leg is in contact with ground (stance phase), ground forces cause the spring to extend, the lower leg slides inside the upper leg, and the overall leg length is reduced (Fig. 2).

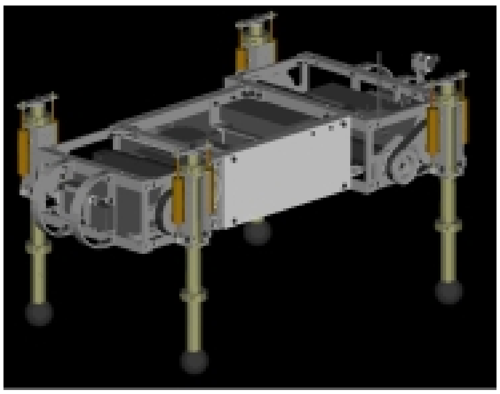


Figure 1. Scout II

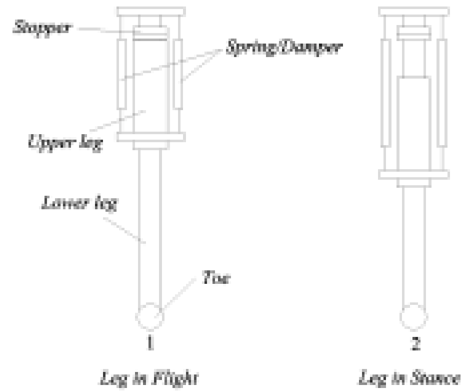


Figure 2. Leg mechanical structure

The motion of Scout II in the sagittal plane can be modeled as five-body mechanism – torso, upper legs, and lower legs. The front and back leg pairs of the real robot are modeled as one virtual leg each. The front and back legs are attached to the torso by the front and back hip actuators and there is a system of spring/damper along each leg that provides a passive change in leg length.

Figure 3. Scout II mechanical system

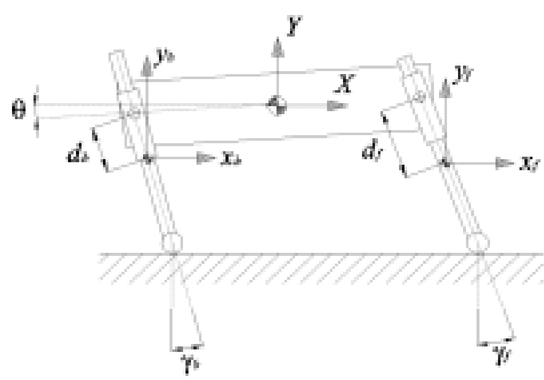


Figure 4. Modeling parameters

During motion, there are four states for the robot, which are dependent upon the state of the front and back legs: stance or flight. The equations of motion in each state are

$$M(x)\ddot{x} = V(x,\dot{x}) + Q(x)U + R(x)W \quad \text{with the state vector} \quad x = [x_b, y_b, \gamma_b, \gamma_f, \theta, d_f, d_b],$$

where M, Q, and R are matrices with entries as functions of state vector variables. V is the matrix with entries as functions of state vector variables and their first-time derivatives. U is the control input vector, containing the front and back hip actuator torques. W is a vector including the body and legs masses.

The robot motion is simulated in each state using the developed dynamical equations. Transition between states involves leg touchdown or liftoff, which are modeled as instantaneous impact. Linear and angular momentum equations are used to calculate the momentum change of the torso, the front legs, and the back legs. The robot is assumed to maintain the same configuration throughout the transition. The equations

$$\sum P = m\Delta\dot{x} \ , \ \sum T = m\Delta\dot{\theta} \ ; \ \ P = \int_{\Delta t} F dt \ , \ M = \int_{\Delta t} T dt$$

are used to model the transitions where P and M are impulse force and torque, respectively. x and $\dot{\theta}$ are linear and angular displacements.

4 SCOUT II STEP CLIMBING ALGORITHM

The Scout II dynamical system is under-actuated and uncontrollable in the classical sense. However, by exploiting lower level state-based controllers, stable cyclic walking and running behaviors are achievable. The two control inputs are the front and back hip actuator torques. With these actuators, leg angles can be controlled, but not independently of the torso angle (pitch). Conversely, the body pitch can be controlled but the leg angles are also affected. Since the torso has a much higher inertia than the legs, leg angles can be controlled more rapidly than the torso pitch. Thus we control the leg angles instead of controlling the body pitch directly. Two algorithms have been designed and simulated successfully for Scout II step climbing - starting from the rest position and during running.

The step-climbing algorithm consists of a bounding controller and a toe stepping controller. The bounding controller causes the robot to run in bound gait. In stance, a constant torque is applied to the leg, and in flight, leg angle is controlled to the desired touchdown angle by a PD controller. During stance, the leg angle is controlled to the maximum sweeping angle limit if it exceeds this limit. The setting parameters for this controller are stance torque τ_s, touchdown leg angle γ_d, and maximum sweeping angle in stance $\gamma_{lower\,\lim it}$.

Successful step climbing requires toe height control during flight, to a desired value h_d. This is accomplished by adjusting the leg angle, using the hip actuator (up to an upper bound, the maximum leg angle $\gamma_{upper\,\lim it}$) via

$$\tau = k_p \cdot (h - h_d) + k_v \cdot \dot{h},$$

where k_p and k_v are gains, h is the toe height and τ is the commanded torque to the actuator.

A simulation study has been carried out to develop the step-climbing algorithm using the developed model of the robot. The procedure is to apply the bounding and toe stepping structure in sequence to make the robot climb a step. Two step-climbing behaviors of the robot are developed that show the robot is able to climb the step both from rest and during running. Not surprisingly, the achievable step size is higher if the robot is running prior to step climbing, and this is explained by the larger energy in the system during running.

Step climbing when starting from rest is accomplished via the control sequence:
1. Lean back
2. Front toe stepping (Fig. 5)
3. Bounding toward the step (Fig. 6)
4. Back toe stepping (Fig. 5)

To lean back, constant torque is applied on the front and back legs. This increases the back leg angles and increases the maximum allowable torque applied on the back legs without causing toe slipping.

Step climbing during running is accomplished via:

1. Maximize the hopping height during bounding as the robot approaches the step (Fig. 6)
2. Front toe stepping (Fig. 5)
3. Bounding toward the step (Fig. 6)
4. Back toe stepping (Fig. 5)

The first step maximizes the front toe clearance prior to step climbing. It is shown in simulation that hopping height during running is controllable by adjusting the front leg touchdown angle.

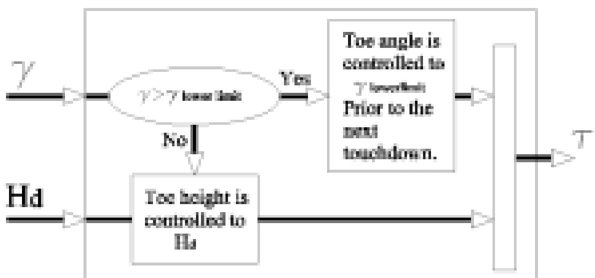


Figure 5. Toe Stepping Controller

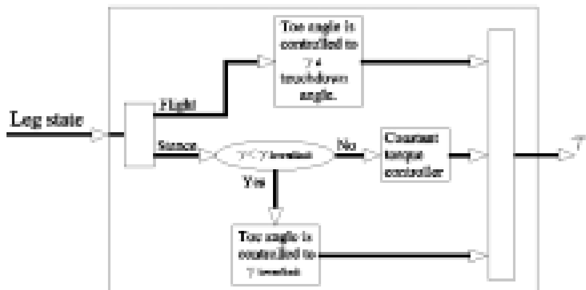
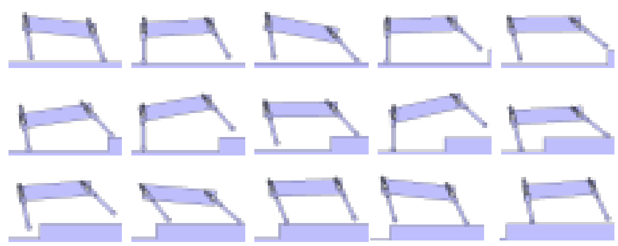


Figure 6. Bounding Controller



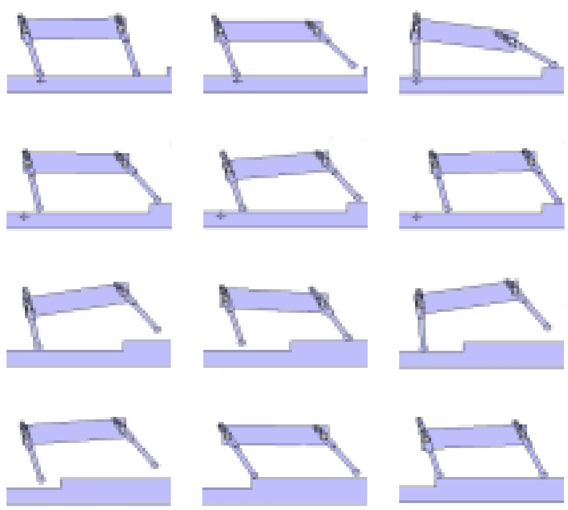
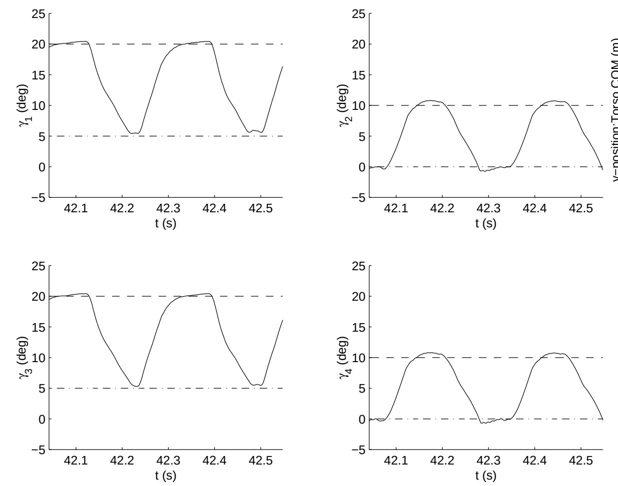


Figure 7: Step Climbing Simulation;
Top: Robot starts from rest;
Left: During running

4 BOUNDING CONTROLLER

The total energy available in a running robot can greatly improve the ability to climb steps and overcome obstacles in general. To this end, we have developed a simple, yet effective bounding controller, based on earlier work [15] on Scout II. During flight, the front and back legs are commanded to $\gamma_{fd} = 20^{\circ}$ and $\gamma_{bd} = 10^{\circ}$, respectively. During stance, we simply command maximum torque. The actually applied torque is determined in practice by the motor's torque-speed limits, and (less frequently) by our quasi-static slip prevention torque limit. This maximum torque is commanded until the leg angles exceed a specified limit

$\gamma_{f-lower\,\lim it} = 5^\circ$, $\gamma_{b-lower\,\lim it} = 0^\circ$ for the front and back legs, respectively. At this time, the legs are simply commanded to maintain those limit angles until liftoff (end of stance). This algorithm results in stable and robust bounding performance in experiments. Data plots from a representative run are shown in Fig. 8-10.



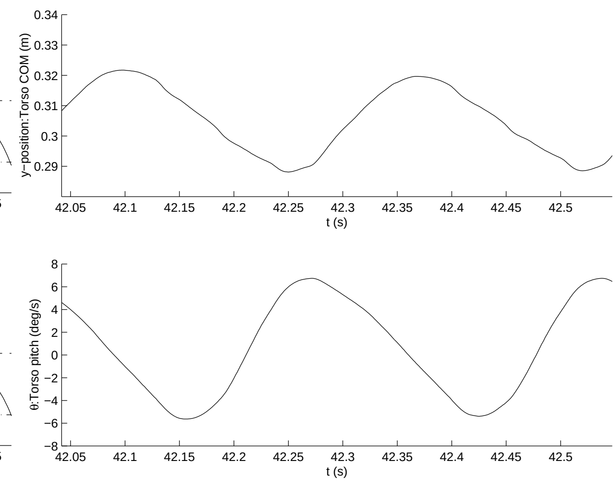


Figure 8. Front leg angles (right), Back leg angles (left); '- -' Touchdown angle, '- . ' Sweep limit.

Figure 9. Torso Vertical (top) and pitching (bottom) oscillations.

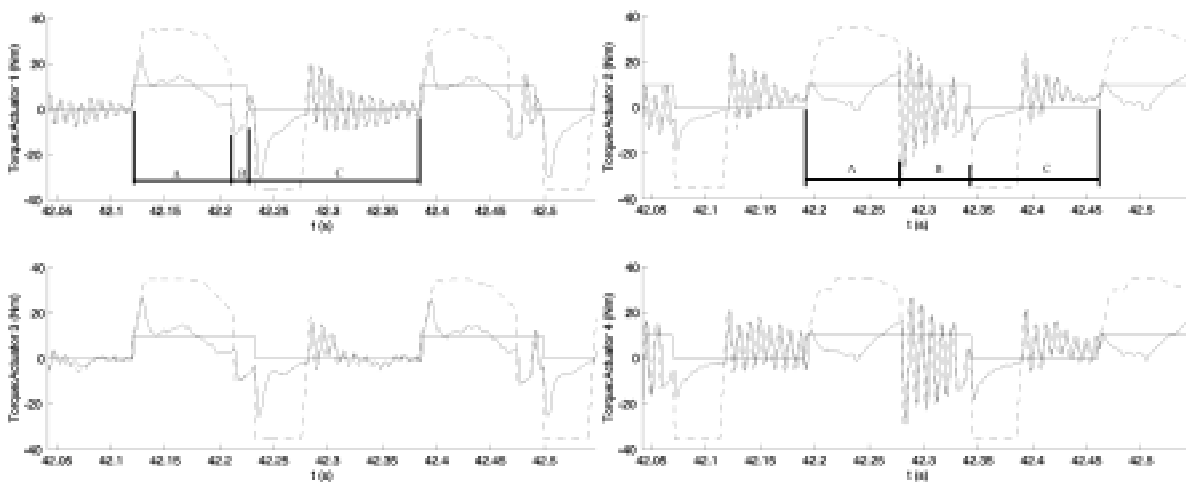


Figure 10. Actuator torques; Front actuators (left), Back actuators (right) ; '-' Commanded torques, '.' Applied torques; A: max. torque controller during stance phase, B: Sweep limit controller during stance phase, C: Flight; The solid square wave denotes the leg state: high (stance), low (flight).

5 CONCLUSION

Two variations of a dynamic step-climbing algorithm for the Scout II quadruped are presented in this paper. The first algorithm steps from standstill, and the second one during a bounding run. Both variations have been successful, in simulation, to negotiate steps with maximum size of 10 cm in height. We have also described a bounding controller that precedes the second step-climbing algorithm. This bounding controller has been experimentally validated. Step climbing experiments are currently under development.

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