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SCOUT: A simple quadruped that walks, climbs, and runs.

M. Buehler, R. Battaglia, A. Cocosco, G. Hawker, J. Sarkis, K. Yamazaki.*
Centre for Intelligent Machines, McGill University, Montréal, QC H3A 2A7, Canada

Abstract

A simple mechanical design for quadrupedal locomotion, termed SCOUT, is proposed, featuring only one degree of freedom per leg. This paper demonstrates experimentally that our first prototype SCOUT-1 is capable of walking, turning, and climbing over a step, despite its mechanical simplicity. The underlying principle is dynamic operation, based on controlled momentum transfer. Simulations show successful walking, stair climbing and running.

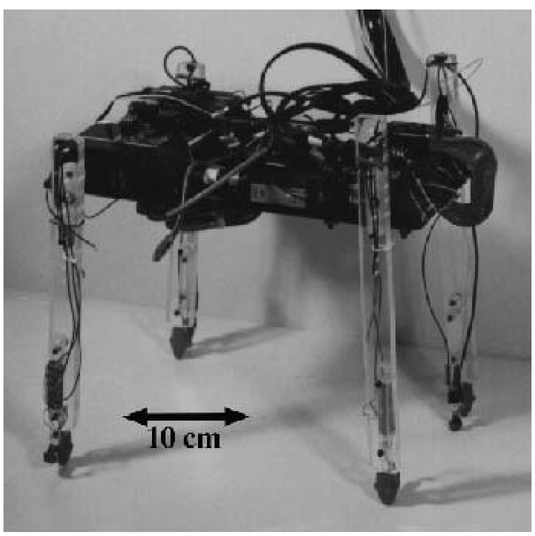

Figure 1: *SCOUT-1*

1 Introduction

Over half of the earth's land mass is inaccessible to wheeled or tracked vehicles. This is one of the primary motivations for the study of alternate forms of locomotion, including the use of legs. However, much of the current need for enhanced machine mobility can be found in relatively structured indoor or urban environments where steps, stairs, narrow hallways, and the like can challenge wheeled or tracked systems. It is here that we may first see legged robots deployed in significant numbers, performing surveillance, inspection, delivery, or entertainment.

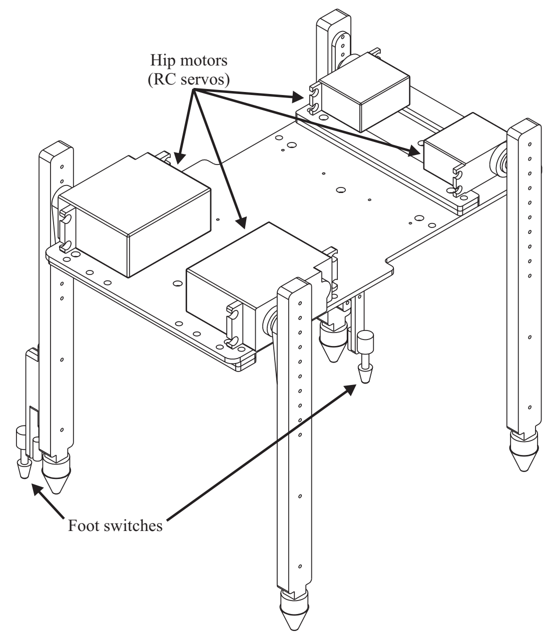

Figure 2: *SCOUT-1 major components.*

In this paper, we propose a new type of four-legged robot with maximum mechanical simplicity - the SCOUT class, as shown via our current robot, SCOUT-1 in Fig. 1. SCOUT quadrupeds feature only one actuated degree of freedom (DOF) per leg. As shown in Fig. 2, each hip is actuated by an RC-Servo motor, which has been modified to provide hip angle feedback. In addition, two legs feature mechanical switches to detect ground contact. Leg lengths and body length (hip to hip) are $20cm$, body width (left toe to right toe) is $14.5cm$ at the front and $19cm$ at the back. The body's mass and moment of inertia are $1.2kg$ and $0.0067kgm^2$, respectively.

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In the past, there has been strong interest in biped locomotion [8, 5, 2, 6, 7, 3], yet only a few dynamically stable quadrupeds have been developed. Raibert's quadruped featured 3 DOF per leg, and additional linear compliance, and was able to trot, pace and bound [7]. Sano and Furusho developed COLT-3, with 3 DOF per leg, which was able to pace. Subsequently, Furusho et al [1] introduced SCAMPER, with 2 DOF per leg. This quadruped was able to run with a transverse gallop gait, which included a flight phase.

Most quadruped robots built to date possess so many actuated degrees of freedom (typically 12, three per leg) that they are too expensive to be used in practice. The proposed four DOF design should be substantially cheaper. Furthermore, reliability is a key factor, since robots are typically employed first in high risk environments. A robot like SCOUT with only four actuated DOFs should be far more reliable as well.

Another benefit of simplicity is the potential for more rigorous analysis than what was possible so far in dynamically stable legged locomotion. The SCOUT dynamics, while still non-trivial, are greatly simplified compared to that of higher degree of freedom robots. This paper does not include such an analysis, but rather attempts to provide sufficient experimental evidence to motivate it for future work.

While cost and reliability are necessary conditions for successful application of legged robots, functionality is of prime importance. Can SCOUT-1 still accomplish sufficient mobility, despite its potentially stifling simplicity? The answer, given in this paper, is a resounding yes, at least for indoor environments: SCOUT-1 can walk, make turns, climb a step, and simulations show it climbing stairs and running.

2 SCOUT-1 Modeling

The SCOUT-1 kinematics are illustrated in Fig. 3. We assume that the mass and inertia of the legs are negligible compared to that of the body. In addition, we model the legs' contact with the ground as free pin joints. For notation, by default (unless indicated as dependent on time) all variables are taken at the time of front or back leg impact (superscript F or B). Since velocities undergo step changes upon impact, they can be taken just before or just after impact (superscript - or +). Using this notation, the main variables to be controlled are the leg angles at impact $\phi_1^B, \phi_2^B, \phi_1^F, \phi_1^F$ and the body angular velocities just after impact, $\dot{\theta}^{B+}, \dot{\theta}^{F+}$.

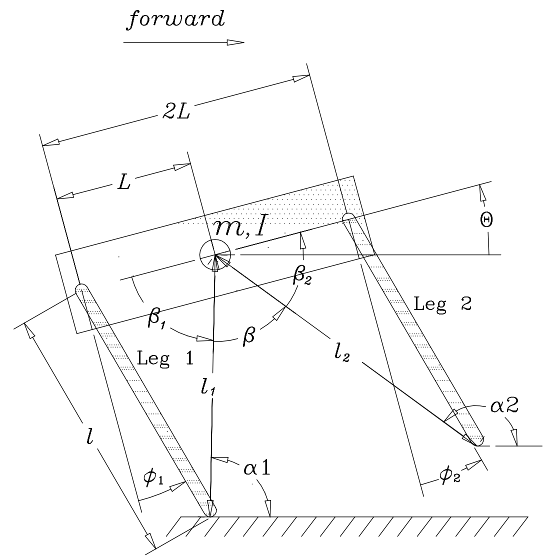

Figure 3: *SCOUT-1 model*

Since we assume instantaneous inelastic impacts (and thus energy losses) when a leg touches the ground, there will be a momentum transfer resulting in step changes in the linear and angular velocities. These changes can be calculated based on the principle of conservation of angular momentum with respect to the impact toe, since that point acts like a pivot, or a pin joint, where no torques are applied. In the sequel all angular momentum calculations will be expressed with respect to the impact toe. To simplify controller development we define two virtual legs with varying lengths l_i, and their angles with the horizontal, α_i.

The angular momentum just before the front leg impact can be expressed as

$$H^{F-} = mr^2\dot{\theta}^{F-} + m|\vec{d} \times \vec{v}^{F-}|$$

where r is the body's radius of gyration, $\vec{d}$ is the position vector from the impact toe to the center of mass of the body, and $\vec{v}$ is the mass center's velocity. It is convenient to decompose $\vec{v}$ into a radial component collinear with virtual leg 1, and a tangential component,

$$v_r^{F-} = \dot{l}_1^F, \quad v_t^{F-} = l_1^F \dot{\alpha}_1^{F-}.$$

The resulting angular momentum is

$$H^{F-} = m(r^2\dot{\theta}^{F-} + l_1^F l_2^F \dot{\alpha}_1^{F-} \cos\beta^F - \dot{l}_1^F l_2^F \sin\beta^F).$$

where $\dot{\alpha}_1^{F-} = \dot{\theta}^{F-} - \dot{l}_1^F C(l_1^F)$ and

$$C(l_1^F) = \frac{1}{l_1^F 4L^2} \frac{3L^2 + (l_1^F)^2}{\sqrt{1 - (\frac{5}{4} - (\frac{l_1^F}{2L})^2)^2}}.$$

With these relationships, the system's angular momentum just before impact can be expressed as

$$\begin{aligned} H^{F-} &= m(r^2 + l_1^F l_2^F \cos\beta)\dot{\theta}^{F-} \\ &- m\dot{l}_1^F (l_1^F l_2^F C(l_1^F)\cos\beta + l_2^F \sin\beta). \end{aligned} \quad (1)$$

To express the angular momentum after impact, H^{F+}, we will assume that the front hip actuator is locked. This means first that $\dot{\alpha}_2^{F+} = \dot{\theta}^{F+}$, and second that there is only a tangential linear velocity component of the center of mass, perpendicular to leg 2, $v_t^{F+} = l_2^F \dot{\alpha}_2^{F+} = l_2^F \dot{\theta}^{F+}$. Therefore the angular momentum after impact can be expressed as

$$H^{F+} = I\dot{\theta}^{F+} + m l_2^F v_t^{F+} = m[r^2 + (l_2^F)^2]\dot{\theta}^{F+}. \quad (2)$$

Due to conservation of angular momentum at the instant of impact, we can now equate (1) and (2). If the angular velocity of the body just before impact $\dot{\theta}^{F-}$ is known, then, given a desired angular body velocity after impact, $\dot{\theta}^{F+}$, the required virtual leg linear velocity at the front leg impact is

$$\dot{l}_1^F = \frac{[r^2 + l_1^F l_2^F \cos\beta^F]\dot{\theta}^{F-} - [r^2 + (l_2^F)^2]\dot{\theta}^{F+}}{l_2^F [C(l_1^F) l_1^F \cos\beta^F + \sin\beta^F]}. \quad (3)$$

The momentum transfer equation for the back leg impact is derived in the same fashion.

3 Walking

Dynamic walking can be specified via a six parameters, one triplet $(\phi_1^B, \phi_2^B, \dot{\theta}^{B+})$ for the back leg impacts, and one for the front leg impacts, $(\phi_1^F, \phi_2^F, \dot{\theta}^{F+})$. However, not all sets of triplets are physically feasible, or result in implementable virtual leg velocities. An analysis of the this problem would require a closed form expression for the solution of the controlled dynamics between impacts, which are those of an underactuated, inverted double pendulum. Given the highly nonlinear nature of these equations, a closed form solution is not available.

Nevertheless, integration of the impact-to-impact dynamics and thus a systematic method to search feasible double-triplets would be highly valuable in practice. This becomes possible if we make two strong assumptions about the hip controllers, illustrated here via the back hip controller for $\phi_1, \dot{\phi}_1$: First, ϕ_1 changes as a step function instantaneously when the body is at maximum height. Second, the required linear impact velocity, $\dot{l}_1^F$ is implemented via a step change in velocity just before impact, with negligeable effect on the impact angle. Both are strong assumptions which can be implemented only approximately in practice. Now however, all four phases of dynamic walking can be written explicitly, where the constants c_j depend only on $\phi_1^B, \phi_2^B, \phi_1^F, \phi_2^F$.

$$\begin{aligned} \text{Back leg stance:} \quad & (\dot{\theta}^{F-})^2 &= c_0(\dot{\theta}^{B+})^2 + c_1 \\ \text{Front leg mom. transfer:} \quad & \dot{\theta}^{F+} &= c_2\dot{\theta}^{F-} + c_3\dot{l}_1^F \\ \text{Front leg stance:} \quad & (\dot{\theta}^{B-})^2 &= c_4(\dot{\theta}^{F+})^2 + c_5 \\ \text{Back leg mom. transfer:} \quad & \dot{\theta}^{B+} &= c_6\dot{\theta}^{B-} + c_7\dot{l}_2^B. \end{aligned}$$

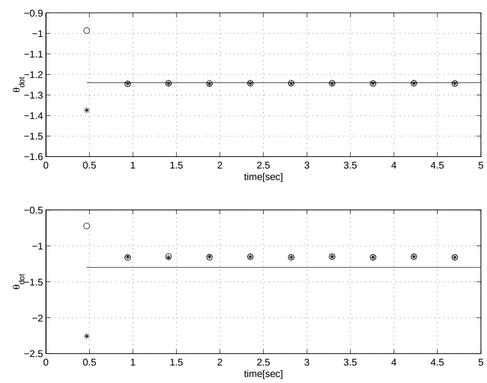

Figure 4: *SCOUT-1 dynamic walk: Simulation*

For simplicity, we used the above equations to select walking triplets which require no actuation at impact, that is $\dot{l}_1^F = \dot{l}_2^B = 0$. We chose $(0.14rad, -0.035rad, 0.952rad/s)$ for the back leg impact and $(-0.14rad, -0.035rad, -1.24rad/s)$ for the front leg impact. A successful controller must still be able to compensate disturbances. If there is a sufficient range of permissible $\dot{l}_1^F, \dot{l}_2^B$ around the nominal value, (3) and its counterpart for the back leg impact can be utilized to eliminate errors online and to achieve the desired body rotational velocities $\dot{\theta}^{F+}$ are shown in the top graph of Fig. 4. However, we are interested in control strategies which are robust and can be implemented with minimal sensing, as follows: The stance leg remains fixed until the body reaches its apex. At that time, a polynomial for $\phi_1(t)$ (or $\phi_2(t)$ for back leg impacts) is planned using (3) which achieves the desired $\dot{\theta}^{F+}(\dot{\theta}^{B+})$ based on the *predicted* $\dot{\theta}^{F-}(\dot{\theta}^{B-})$ *of the unactuated inverted pendulum dynamics.* This is a major simplification, but results in a stable system with good performance as shown in bottom graph of Fig. 4.

We implemented this strategy using the same walking triplets on SCOUT-1. The time of maximum body height was estimated as one half the previous stance time. The resulting performance is demonstrated in Fig. 5. It is interesting to note that no actively stabilizing feedback was implemented, yet the walking was stable, even in the face of severe perturbations after $32s$, as shown via the peak in cycle time. The disturbance was caused by changing the speed of the treadmill, on which SCOUT-1 was walking.

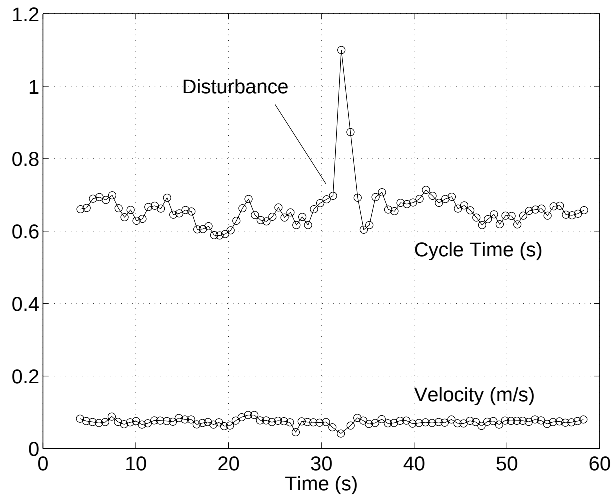

Figure 5: *SCOUT-1 dynamic walk: Experiment*

4 Turning

Turning was implemented by adding offsets to the nominal desired hip angles at impact for the left legs, $\phi_1^F + \phi_1^{turn}$ and the right legs $\phi_1^F - \phi_i^{turn}$. For small turning angles per step, the interaction between the walking and the turning dynamics is small and can be neglected. Fig. 6 shows experimental data of SCOUT-1 making a 90 deg turn in four steps.

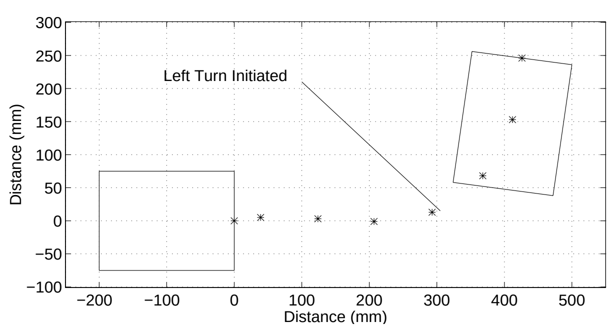

Figure 6: *SCOUT-1 turning: Experiment*

5 Step Climbing

SCOUT-1 is able, despite its simple mechanics, to climb on a step whose height is up to 45% of its leg length. To accomplish this, open loop hip trajectories were synthesized, which achieved the required momentum transfer at the impacts to clear the step and locomote forward. The resulting step climbing is shown via a photographic playback in Fig. 7. The sequence consists of four general actions. In the first action (0.0 - 3.0 s) SCOUT-1 leans backwards and launches itself so that its forward feet land on the step. In the second action (3.0 - 3.5 s), SCOUT-1 rocks on its forward legs, allowing the back legs to be brought closer to the base of the step. With the third action (3.5 - 4.0 s), SCOUT-1 once again launches itself, allowing its forward feet to move farther on to the step. Finally, the fourth action (4.0 - 6.0 s) enables SCOUT-1 to place its back feet on the step, completing the sequence.

6 Stair Climbing

Stair climbing simulations were run with Working Model [4], using SCOUT-2, a larger (body: length $55cm$, mass $23kg$, inertia $1.2kgm^2$; legs: length $25cm$, mass $1kg$, inertia $0.05kgm^2$), and more powerful ($38Nm$ per leg) version of SCOUT-1, which we are currently developing as an industrial prototype.

The control was implemented like in the previous step climbing task, via hip torque or angle trajectories which ensure sufficient momentum transfer to clear the stairs, and which return SCOUT-2 into the initial configuration, but advanced by one step. The control was divided into 6 phases, shown in Fig. 8. In phase 1, the body rocks back in order to place its center of mass over the rear legs. In phase 2 a torque is applied at the rear legs which forces the front legs to rise up thus clearing the step. The controllers for phase 3 are such that the front legs contact the ground at the far corner of the step. In phase 4, zero torque is applied at the front legs and a large torque is applied at the rear legs, giving the body enough vertical velocity for the rear legs to clear the step. Phase 5 has the rear legs swinging clockwise while the front legs adjust their angle such that the rear feet will contact the step at mid depth. For the 7th and final phase, a torque is applied at the front legs in order to pull the body up so that the center of mass lies between the front and rear feet. At this stage, SCOUT is once again in the 1st phase and is therefore ready to continue onto its next step.

7 Running

Since walking speeds are limited, we investigated if a SCOUT type robot could run as well. For this purpose, we enhanced the SCOUT-1 model in Fig. 3 with linear leg springs ($1,500N/m$)and dampers ($1Ns/m$), and increased the inertia to $0.5kgm^2$. In contrast to the previous controllers, running control does not rely explicitly on controlled momentum transfer, but on a modification of Raibert's three-part controller [7]. The particular gait that was implemented in simulation [4] is the pronk, where all four legs touch down and lift off (ideally) at the same time, and the body attitude remains horizontal.

Raibert's quadruped employs linear leg actuators to control the hopping height, and the hip actuators to control forward speed during flight (via adjusting the impact angle), and the body attitude during stance. Since SCOUT-1 is eliminating the linear leg actuators, the hip actuator must now control all three quantities. This is accomplished by alternating between controlling forward speed, height, and body attitude as follows.

During even flight phases, the neutral impact leg angle (w.r.t. vertical) γ_d^* [7] which results in no net velocity change is commanded. Hopping height is controlled by adding an offset leg angle $\gamma_{off} = a_0 + a_1\dot{x}$, ($a_0 = 19.5\,\mathrm{deg}$, $a_1 = -7.5\,\mathrm{deg}\,s/m$) which converts some of the forward kinetic energy into vertical energy (4). During even stance phases, velocity control is implemented via (5). Due to the conversion of horizontal energy to vertical energy, an almost constant velocity tracking error remained. This was virtually eliminated by adding a constant offset $\dot{x}_{off} = 0.2m/s$. During odd flight phases, Raibert's forward velocity control algorithm is employed unchanged (6), where γ_d is determined from the foot placement algorithm [7]. Similarly, during odd stance phases, body attitude is controlled, as prescribed by Raibert, via a simple PD law (7).

$$\begin{aligned} \text{Even flight:} \quad \tau &= \kappa_p(\gamma - \gamma_d^* + \gamma_{off}) + \kappa_v\dot{\gamma} && (4)\\ \text{Even stance:} \quad \tau &= \kappa_p(\dot{x} - \dot{x}_d + \dot{x}_{off}) && (5)\\ \text{Odd flight:} \quad \tau &= \kappa_p(\gamma - \gamma_d) + \kappa_v\dot{\gamma} && (6)\\ \text{Odd stance:} \quad \tau &= \kappa_p(\theta - \theta_d) + \kappa_v\dot{\theta}. && (7) \end{aligned}$$

To test these controllers, a planar simulation was performed on Working Model [4]. The control algorithms above were applied independently in both front and back legs, without synchronization. In order to render the results more realistic the hip motor torques were limited to $\pm 10Nm$. Step changes in the desired running speed were introduced, and plots of resulting forward speed, hopping height and body attitude are shown in Fig. 9.

Conclusion

This paper introduced a stunningly simple mechanical design for a quadruped robot. Despite its simplicity, and based on dynamically stable operation, this design was shown to be capable of a rich set of behaviors, including walking, turning, step and stair climbing, as well as running (with added leg compliance). It is our hope that the simplicity, potential low cost, and mechanical robustness of the SCOUT class will open new opportunities for legged robots in practical applications.

References

[1] J. Furusho, A. Sano, M. Sakaguchi, and E. Koizumi. Realization of bounce gait in a quadruped robot with articular-joint-type legs. In *Proc. IEEE Int. Conf. Robotics and Automation*, pages 697–702, May 1995.

[2] F. Gubina, H. Hemami, and R. McGhee. On the dynamic stability of biped locomotion. *IEEE Trans. Biom. Eng.*, BME-21(2):102–108, Mar 1974.

[3] S. Kajita and K. Tani. Experimental study of biped dynamic walking in the linear inverted pendulum mode. In *Proc. IEEE Int. Conf. Robotics and Automation*, pages 2885–2891, May 1995.

[4] Knowledge Revolution. *Working Model 2D*. San Mateo, CA, 1996, (www.krev.com).

[5] T. McGeer. Passive dynamic walking. *Int. J. Robotics Research*, 9(2):62–82, 1990.

[6] H. Miura and I. Shimoyama. Dynamic walk of a biped. *Int. J. Robotics Research*, 3(2):60–74, 1984.

[7] M. H. Raibert. *Legged Robots That Balance*. MIT Press, Cambridge, MA, 1986.

[8] M. Vukobratović, B. Borovac, D. Surla, and D. Stokić. *Biped Locomotion*. Springer-Verlag, NY, 1990.

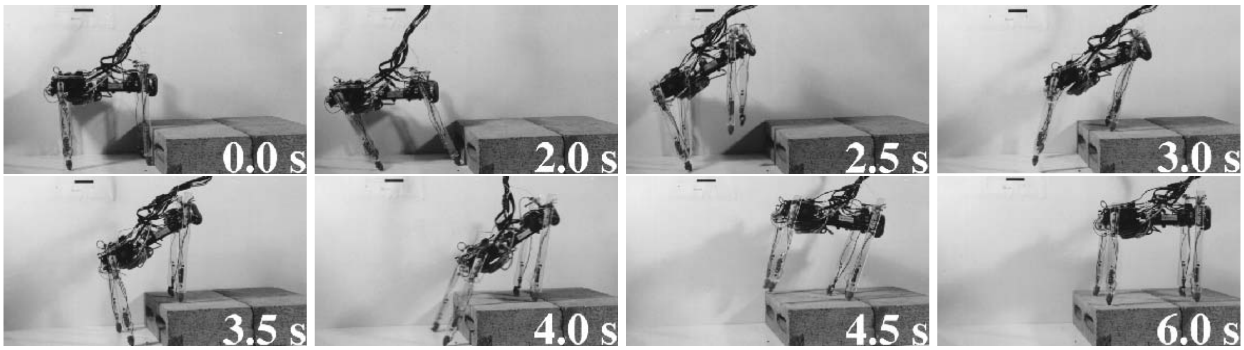

Figure 7: *Photographic playback of SCOUT-1 climbing a 9 cm step.*

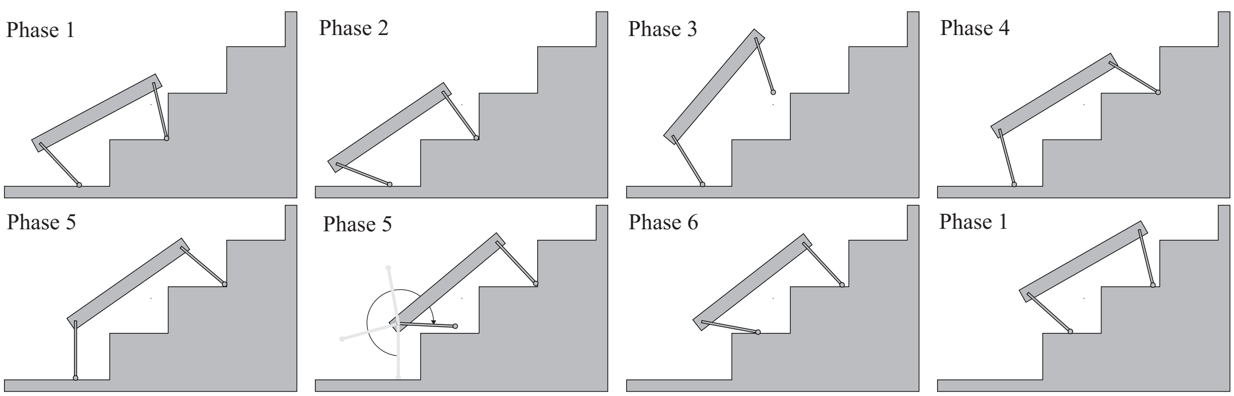

Figure 8: *Simulation playback of SCOUT-2 climbing stairs.*

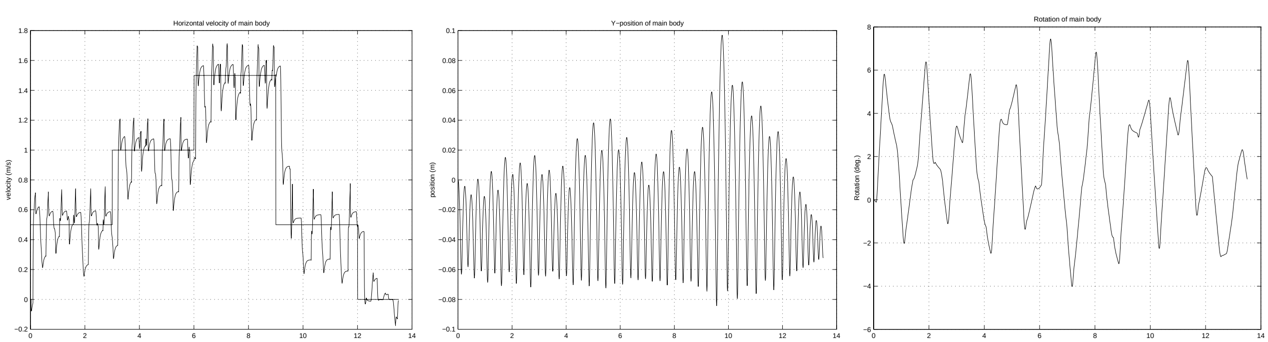

Figure 9: *SCOUT-1 pronking simulation: Forward speed (left), hopping height (middle), and body attitude (right).*