iSprawl: Autonomy, and the Effects of Power Transmission

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Abstract

We describe the design features that underlie the operation of *iSprawl*, a small (0.3 Kg) autonomous, bio-inspired hexapod that runs at 15 body-lengths/second. These features include a light and flexible power transmission system that permits high speed rotary power to be converted to periodic thrusting and distributed to the tips of the legs, and a tuned set of leg compliances for efficient running. Examination of the trajectory of the center of mass and the ground reaction forces for *iSprawl* show that it achieves the same stable, bouncing locomotion seen in insects and in previous (slower) bio-inspired robots.

1 Introduction

In recent years a number of fast, legged robots have been developed that draw their inspiration from running arthropods including *Sprawlita* [5], *Scorpion* [8], *Whegs* [13], and *RHex* [14]. When insects are moving rapidly they typically employ an alternating tripod gait and they rely heavily on passive mechanical properties to achieve dynamic stability. The sprawled posture with large forces in the horizontal plane, and the compliance and damping in the limbs and joints, serve as "preflexes" [9, 11] that promote stable running and rapid recovery from perturbations.

In the case of the *Sprawl* family of robots, the main principles adapted from insects, and the cockroach in particular, are:

- a sprawled posture
- a bouncing, alternating tripod gait based on an open-loop motor pattern
- specialization in which the rear legs primarily accelerate the robot while the front legs decelerate it at the end of each step
- actuators that provide propulsion by thrusting along the axes of the legs

- passive “hip” joints that swing the legs forward between steps
- compliance and damping that absorb perturbations.

The *Sprawl* robots are fabricated using a multi-material rapid prototyping process, Shape Deposition Manufacturing [1, 12], that makes it possible to achieve local variations in structural compliance and damping and to embed components such as sensors and actuators for increased ruggedness. Like their exemplars, the *Sprawl* robots are capable of fast locomotion over belly-height obstacles. Speeds of 7 $bodylengths/s$ (1.0 m/s) have been achieved as well as rapid turns (4.0 rad/s) while running at full speed. The robots can run without any proprioceptive or exteroceptive feedback; however, the addition of ground contact sensors allows the stride period to adapt automatically to changes in terrain or slope [3]. A closer look at the dynamics of the running robots reveals motions and ground reaction forces similar to those found in insects and other small animals. The locomotion pattern has been termed SLIP (spring loaded inverted pendulum) in the literature and is seen in many jogging animals [7].

A limiting factor in the design of the *Sprawl* robots has been their use of pneumatic pistons for propulsion. Although electric motors are ubiquitous in small robots, pistons were chosen for the *Sprawl* robots as powerful, compact linear actuators. The main disadvantage to pneumatic pistons is of course that they virtually preclude autonomous operation. The volume of compressed gas needed for 10 minutes of operation is such that a gas storage tank would be too heavy to carry on board.

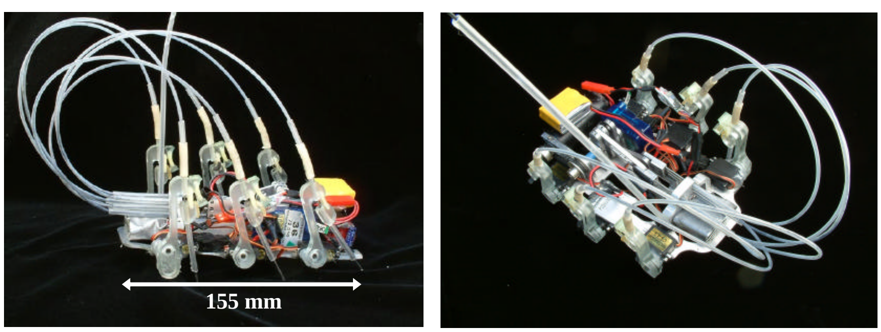

Fig. 1. *iSprawl*: a fully autonomous hexapedal robot driven by an electric motor and flexible push-pull cables.

In this paper, we present an independent version of the *Sprawl* robots utilizing electric propulsion. The incorporation of a new power transmission system, lithium polymer batteries, and a redesigned set of complaint legs have enabled *iSprawl* to run autonomously at speeds of over 15 $bodylengths/second$

(2.3m/s), or a Froude number of 3.5. Despite significant changes in the actuation and force generation mechanism, we show that by appropriately tuning the passive compliance in the legs the fast, self-stabilizing behavior of the robot is preserved. This invariance to actuation scheme underscores the generality of the locomotion principles encapsulated in the *Sprawl* family of robots.

2 Mechanical Design of *iSprawl*

The most challenging aspects of utilizing electrical actuation for the *Sprawl* robots are converting rotary to linear motion and incorporating sufficient flexibility into the power train to accommodate the repositioning of the compliant legs. Several schemes were investigated before settling on the system presented in this paper. One possibility is to have a motor put energy into an elastic storage device that is released with each step.

A second possibility is to store kinetic energy, in a flywheel or other rotating mass, which can be tapped at various points during the stride period. This is the approach, as shown in figure 2a, that was ultimately adopted for *iSprawl*.

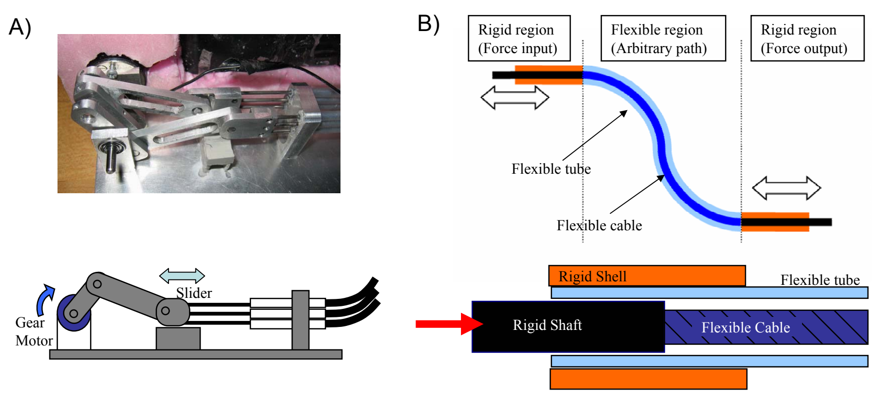

Fig. 2. Power transmission system for *iSprawl*. Figure (a) shows the crank-slider used to store and convert the rotational energy from the motor to linear oscillations. Figure (b) schematically shows the flexible and rigid sections of the push-pull cables.

A particular challenge of the *iSprawl* design is that power must be conveyed to the distal ends of the limbs, which are flexing back and forth with each stride. By utilizing central power source and a lightweight and flexible transmission system, the rotational inertia of the limbs can be minimized, which in turn permits a faster stride frequency. Several transmission mechanisms were explored; ultimately, best results were obtained with the cable system shown in figure 2b. By adding rigid elements to both ends of the shaft and tube, the cables are able to thrust as well as pull.

As in previous *Sprawl* robots, the motions of the legs back and forth with each step are achieved passively by operating the robot as a resonant system. RC servos are mounted at the hips of the middle legs to change the equilibrium leg angles to effect turns, as motivated by the results of [10]. The physical specifications for *iSprawl* are given in table 1.

Table 1. Physical Parameters for *iSprawl*

Body size	155 x 116 x 70 mm (excluding cables)
Body mass	315 g (including batteries and RC circuit)
Maximum speed	2.3 m/s (15 bodylengths/s)
Stride frequency	17 Hz
Power consumption	12 W (0.5 A, 24 V)
Motor	Maxon 2.7 W 2023909; size: 20 x 17.5 x 8 mm
Gear ratio	20:1
Legs	Polyurethane 72DC and 90A from Innovative Polymers
Servo motor	Cirrus cs-5.4g
Typical leg motion	25 mm stroke, 25° swing
Battery	6 pack of lithium polymer (3.7 V, 250 mAh)

3 Transmission Effects on Locomotion

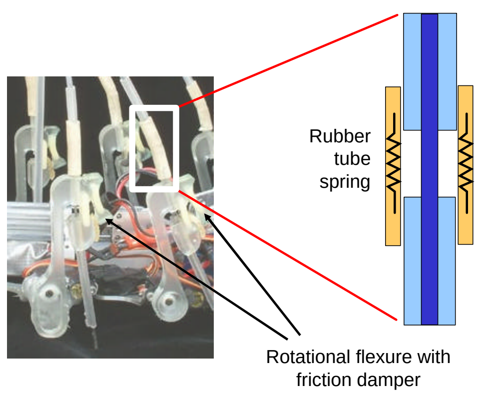

Fig. 3. Schematic of the leg compression spring design utilizing a tension spring on the flexible tubing around the push-pull cable. Also shown are the frictional dampers on the front and middle legs

Early experiments with cable-driven *iSprawl* revealed that vertical foot forces increased too rapidly after inital contact. This caused abrupt changes to the momentum of the robot, increasing wear and reducing efficiency. This is not surprising given that we have replaced a compliant force actuator (pneumatics) with a displacement actuation from the slider-crank mechanism. To achieve a smoother, more SLIP-like motion, it was necessary to add some tuned axial compliance to the push/pull cables, as shown in figure 3.

3.1 Leg Extension Profile and SLIP-like Motion

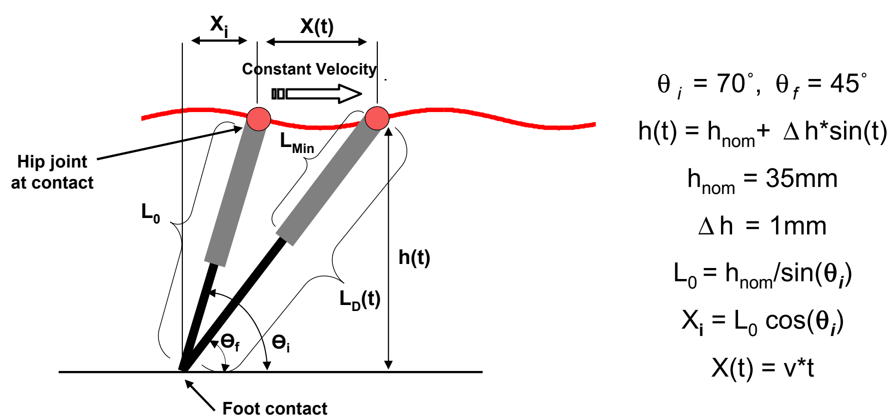

Fig. 4. Schematic of the desired leg extension profile needed to produce a sinusoidal trajectory of the center of mass during stance

We desire SLIP-like running for the robot, in which the center of mass moves along an approximately sinusoidal trajectory, as shown in figure 4. Using the geometric relationships depicted in figure 4, we can calculate the desired axial stiffness of the legs to minimize body accelerations at contact while maintaining a desired level of thrust. The values of the constants in figure 4 were measured experimentally. If the body is assumed to move along a sinusoidal path during contact, the desired leg length $L_D(t)$ is given by:

$$L_D(t) = \sqrt{h(t)^2 + (x_i + x(t))^2} \tag{1}$$

For *iSprawl* the nominal leg extension profile $L_{nom}(t)$ is fixed as:

$$L_{nom}(t) = A_0\ sin(\omega t)\ \ where\ A_0 = 12.5mm \tag{2}$$

The leg compression L_s is given by the difference between these and is:

$$L_s(t) = L_{nom}(t) - (L_D(t) - L_0) \tag{3}$$

We can then tune the stiffness of the spring such that the vertical energy at impact equals the potential energy stored in the spring at maximum compression. Due to the geometry and pitching dynamics of *iSprawl* the gravitational potential energy and rotational kinetic energy are non-negligible, and the total vertical energy at contact (E_{impact}) is 0.026 Nm. If we approximate the desired maximum compression of the spring to equal the maximum of $L_s(t)$, with the potential energy stored in the spring being:

$$PE_{spring} = \frac{1}{2}k\,(\Delta L)^2 \tag{4}$$

where $\Delta L = max(L_s(t)) = 4mm$, then the desired stiffness for a tripod is:

$$k = \frac{E_{impact}}{\frac{1}{2}(\Delta L)^2} = 3.3\ N/mm \tag{5}$$

The front leg has the largest contribution (about 50%) to the vertical stiffness of the tripod. Accordingly, springs with a stiffness of 1.7 N/mm were inserted into each leg.

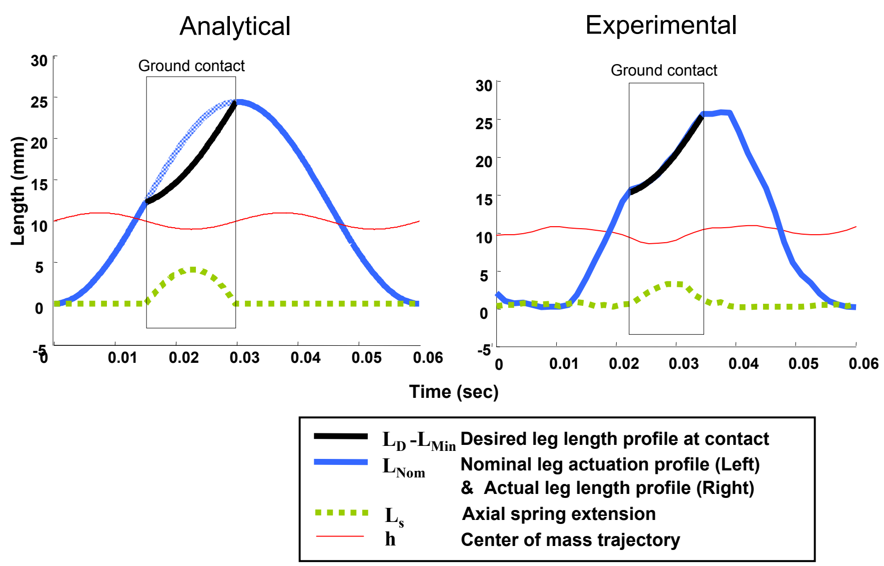

Fig. 5. The theoretical and experimental leg extension profiles for *iSprawl*. Also shown are the path of the COM and the extension of the axial spring for each case.

Figure 5 shows the theoretical and the measured leg trajectories. The trajectories for the measured case were obtained by filming *iSprawl* at 500 frames/second as it ran on a treadmill. The dark lines represent the desired leg extension profile during contact, and the thin lines represent the trajectory of the center of mass. The dotted segment in the analytical plot indicates the center of mass trajectory that would occur without the leg spring, whose compression is indicated by the dashed line at the bottom of the plot. The experimental data show that both the leg extension and center of mass trajectories match the model predictions closely. The experimentally measured axial spring compression is slightly smaller than the predicted value. This is compensated for by the inherent elasticity of the push-pull cable system.

After adding axial compliance to the legs the robot ran 50% faster than before. It also had a considerably smoother period-1 gait and a reduction in mechanical failures.

In addition to tuning the axial compliance of the leg extension system, it is necessary to adjust to rotational compliance and damping of the passive hips. As with the earlier *iSprawl* robots, the legs are multi-material structures of hard and soft urethane. If the urethane flexures are too stiff, the legs do not flex enough and the stride length is reduced; if they are too soft the robot stumbles and loses open-loop stability [4]. Empirically, rotational stiffnesses of approximately 72 Nmm for the front legs, 54 Nmm for the middle, and 36 Nmm for the rear legs was found to give best results. In earlier *Sprawl* robots, the inherent visco-elasticity of the soft urethane provided adequate damping; for *iSprawl* it was necessary to add small friction dampers to the front and middle legs, as seen in figure 3

3.2 Ground Reaction Forces

A final subject of comparison among *iSprawl*, the earlier *Sprawl* robots, and insects is the pattern of ground reaction forces (GRF). The pattern seen in insects is that the rear legs provide most of the forward propulsion at the start of each step while the front legs provide a braking force at the end of each step. The middle legs provide a mixture of propulsion and braking [6]. In addition, the front legs, being most nearly upright, have the largest vertical and smallest horizontal forces. In the upper half of Figure 6 we see the averaged GRFs for *Sprawlita*, one of the first *Sprawl* robots with pneumatic pistons (from [2]). The pattern is similar to that seen in insects except that the rear legs drag somewhat (with a negative horizontal force) at the end of each stride. The pattern for *iSprawl* is again similar, with a couple of noticeable differences: the front legs provide less braking force and the rear legs have less drag. The reduction in parastic foot drag is partly responsible for the greater speed of *iSprawl*.

4 Discussion of Results and Conclusions

The development of a light and flexible power distribution system has allowed the creation of an autonomous, biomimetic sprawled hexapod. A comparison

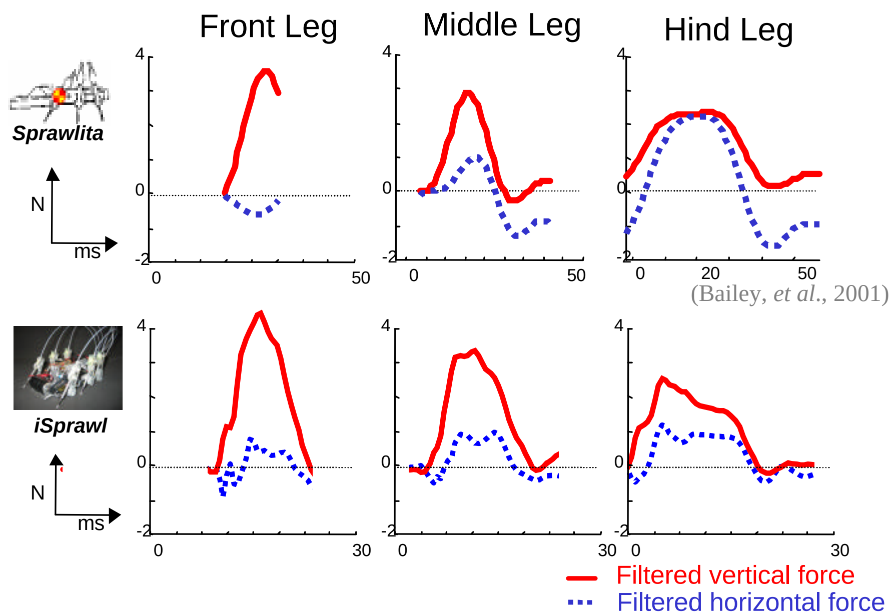

Fig. 6. The vertical and horizontal individual leg ground reaction forces for *Sprawlita* (from [2]) and for *iSprawl*.

of the locomotion dynamics of the electrically powered *iSprawl* and the pneumatically driven *Sprawl* robots shows that despite the difference in actuation schemes, both robots demonstrate comparably fast and stable running with an open-loop actuation pattern. This suggests that the key design principles embodied in the *Sprawl* robots (namely: sprawled posture, thrusting legs, and passive hip joints with rotational compliance and damping) may have practical utility beyond this family of robots. A comparison of the leg extension profiles and ground reaction forces between the electric and pneumatic variants of the *Sprawls* shows that despite small differences, the essential motions and forces for fast and stable locomotion have been preserved. We have also found that by adjusting the passive dynamics of the robot to better match the theoretical predictions of the SLIP model, the robot is able to run more than twice as fast as its tethered cousins. A more detailed tuning of the leg impedance may yet result in faster and more stable running.

Acknowledgements

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