Gait Studies on an Insect-scale Quadruped

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I. Abstract

There are many choices for gaits (e.g. trot, bound, jump, etc.) in legged locomotion. Different gaits can exhibit large differences in common performance metrics such as speed, cost of transport, stability, and maneuverability to name a few. To help understand the effect of gait on performance at small scales, this paper presents a preliminary survey of gaits and the resulting performance of an at-scale, cockroach inspired, quadrupedal microrobot, the Harvard Ambulatory MicroRobot (HAMR). HAMR has eight independently actuated degrees of freedom making it a suitable platform to study these gaits. This survey will help inform gait choice for HAMR in different modes of operation. Furthermore, this work aims to elucidate a broader set of guidelines for understanding the difficult question of gait choice at small scales.

II. Motivation and State of the Art

Studies in biology are commonly used to inform the design of legged robots. Moreover, locomotion studies on legged robots can be used to test biological hypotheses. Fabrication of insect scale robots and locomotion studies, however, have remained a challenge due to manufacturing complexity.

Recent advances in mesoscale manufacturing techniques have enabled the ability to create insect-scale devices that maintain mechanical complexity while still allowing the ability to assemble and actuate highly articulated structures [1]. For example, studies on cockroaches (e.g in [2]) have guided the development of an at-scale cockroach inspired microrobot, the Harvard Ambulatory MicroRobot (HAMR). Inspired by the finding that cockroaches transition from hexapedal running to quadrupedal or bipedal running at high speeds, HAMR has been shown to run at 10.1 body lengths per second (44 cm/s) after moving to a quadrupedal design.

This paper presents a new version of HAMR, named HAMR-V2.0, designed for a more thorough exploration of quadrupedal gaits. A central pattern generator (CPG) with duty cycle control is developed and implemented to conduct gait studies on HAMR-V2.0. The results will generate the first large set of experimental locomotion data for an insect-scale legged robot and will help draw comparisons with biology. Further motivations include understanding the locomotion characteristics of HAMR to inform design improvements and determine if and how hypotheses pertinent to biological locomotion can be tested on HAMR.

A number of insect-scale locomotion studies have been performed in biology (summary in [3]). Detailed studies have been conducted on cockroaches ([2], [4]), wood ants ([5]), and stick insects ([6], [7]). Running cockroaches follow the SLIP (spring-loaded inverted-pendulum) model where vertical and horizontal leg forces vary sinusoidally with the vertical leg forces leading horizontal forces by 90 degrees ([8]). This is subtly different than findings in wood ants, where the maximum vertical force is reached during the first third of the leg contact (instead of at mid stance). With an insect-scale robot, these findings can now be studied in a more controlled fashion.

Legged robots at larger scales have been compared to the SLIP model and more detailed mathematical models in [9] and guide state of the art research (e.g. [10], [11] and [12]). Furthermore, some findings report SLIP-like motions while others explain deviations from this model ([13] and [14]). HAMR is an excellent candidate for gait studies because despite its small scale, the input leg trajectories and phasing can be controlled very accurately.

III. Our Approach

Similar to many of the papers mentioned in section II, this work follows an experimental approach to evaluating the locomotion performance of HAMR.

A. HAMR Design

We first modified HAMR-VP [15] to allow independent control of the phase of each of the four legs. The resulting HAMR-V2.0 is shown in Fig. 1. These design modifications allowed us to explore seven standard quadrupedal gaits: trot, pace, walk, bound, pronk, jump, and canter.

Fig. 1. a) HAMR-VP with swing DOFs coupled. b) HAMR-V2.0 with swing DOFs decoupled

Previously, HAMR has used an alternating tripod or trot gait (hexapedal and quadrupedal versions, respectively). The choice of gait was limited to three standard quadrupedal gaits due to the mechanical coupling between contralateral swing degrees of freedom (DOFs). The three allowable gaits were the walk, trot and pace (only the trot, however, was implemented). The footfall patterns for these gaits are shown in Fig. 2(a). The mechanical coupling that previously limited
gait selection was removed and two additional actuators were added. With these additions, all of the standard quadrupedal gaits can be implemented. The four that experimentally showed the most promise were the pronk, jump, canter, and bound and are shown in Fig. 2(b).

![Footfall patterns for walk, pace, and trot gaits possible in both coupled and decoupled driving schemes](image)

**B. Central Pattern Generator**

We used a CPG to generate the drive signals in real-time for numerous reasons, including a simple representation of the gaits mentioned above, the ability to transition smoothly between these gaits, and the potential for easy integration of periodic feedback. Each leg was driven by two Hopf oscillators, which were fixed at 90 degrees out of phase, for a total of eight oscillators. Hopf oscillators were chosen as they generate pure sinusoids, are two dimensional allowing for precise phase control, and have been extensively studied by Ijspeert et al. (16). The phase between oscillators on the same leg and between legs was controlled by rotating the oscillator trajectory in phase space by the phase angle as done in [17].

A new contribution in this CPG is the development of variable duty cycle signal generation. Variable duty cycle signals are achieved by first constructing a variable duty cycle sinusoid by stitching together two sinusoids at different frequencies; for example, a 75% duty cycle 3 Hz sinusoid was constructed by stitching together a 2Hz sinusoid for the “high” portion of the signal and a 6 Hz sinusoid for the “low” portion of the signal. This hybrid signal was decomposed into a Fourier basis formed by the harmonics of the base 3Hz signal (we use the first five). The five harmonics were generated using five oscillators each running at a different harmonic of the base frequency (for a total of 40 oscillators on the robot). The signals were combined using the Fourier coefficients determined in the decomposition to generate a smooth variable duty cycle sinusoid.

**C. Experimental Setup**

The experimental setup includes a high speed camera mounted orthogonal with the sagittal plane of the robot. Custom vision tracking scripts provide forward and vertical displacements, pitch angle, and leg trajectories. Center of mass (COM) traces provide time course data for kinetic and potential energy data which can be analyzed for SLIP-like motion. Additionally the pitch angle can elucidate differences between the contributions of the front and rear legs. An outline of the inputs and outputs of the experiments is summarized here:

- **Inputs**
  -  Gait phase (e.g. front left *wrt* front right).
  - Frequency (5-50Hz), voltage (100-200V), duty cycle (30-70%), surface (cardstock on acrylic, cardstock on cork).

- **Inputs held constant**
  - Waveform (sinusoidal), turning phase (e.g. lift *wrt* swing – 90° apart), leg neutral position (half bias).

- **Measured outputs**
  - Raw data (currently implemented)
    - COM position (x,y), body pitch angle, front leg position (x,y), rear leg position (x,y).
  - Raw data (future work)
    - Whole body forces (Fx, Fy, Fz), individual leg forces (Fx, Fy, Fz).

- **Calculated outputs**
  - Speed, kinetic energy, potential energy, leg slip-page (front/rear), leg duty factor (front/rear), input power, output energy and power.

**D. Results**

An example trial for the trot at 10Hz is shown in Fig. 3 with all of the metrics of interest recorded.

![Normalized Trajectories per Cycle for Trot at 10Hz, 200 Volts and 50% Duty Cycle](image)

Fig. 3. (a) Raw data for 10Hz trot, 50% duty cycle.
A summary of preliminary results for four of the gaits is shown in Fig. 4. The output is speed in body lengths normalized by drive frequency and the marker size is proportional to the input duty cycle (higher duty cycle indicating less time spent on the ground). The trot from 5 – 17 Hz is the fastest gait (normalized by frequency), and the jump is the fastest gait at medium-high drive frequencies (20 – 37 Hz). These preliminary results elucidate how the speed of the robot changes as a function of gait (leg phase) and frequency.

Additional data needs to be gathered for all remaining gaits. This includes a detailed gait comparison which comprises of analyzing time-course force patterns in conjunction with COM trajectories. Furthermore, a more rigorous statistical analysis will be conducted to determine which inputs or coupling of inputs most affect performance (e.g., speed, cost of transport, stability).

IV. DISCUSSION OUTLINE

One benefit of locomotion at smaller scales is that the body is easier to support since the mass of the body decreases faster than the strength of the supporting structure. This allows for more design freedom for other functional reasons barring any practical manufacturing limitations. For example, adding a tail or having longer legs might be able to substantially improve performance without the need for a bulkier structure.

The importance of these open-ended design steps is counter-intuitively highlighted by the fact that the mass of the device is dominated by the actuators. In biology, 45% is typical [18] and for comparison, 60% of HAMR’s mass is from the actuators). In order to take advantage of the power density of the actuators, the mechanical work needs to be efficiently transferred to the environment. A simple example is that leg length, and therefore stride length, can be changed substantially without greatly affecting the overall mass of the robot – so what is the optimal leg length given an actuator choice? Furthermore, since flexure-based transmissions are unable to alter actuation frequency (unlike conventional gears), energy properties and bandwidth properties must be considered individually.

We hope the results of these locomotion experiments will help inform the design and control of legged robots at the insect scale. Furthermore, the results of this work should be of interest to biologists who have hypotheses about insect-scale locomotion that can be tested in a controlled manner on an at-scale platform.

REFERENCES