

Bounding Gait in a Hybrid Wheeled-Leg Robot

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Abstract— This paper discusses the first implementation of a dynamically stable bounding gait on a hybrid wheeled-leg robot. Design of the robot is reviewed and the controllers which allow this mode of mobility to occur are discussed. Experimental results demonstrating the key dynamic characteristics of the gait, including footfall patterns, are given. The hypothesis that varying leg takeoff angles can lead to regulation of forward speed of the bounding gait is presented and verified. In addition, comparisons are made between the bounding gait which uses active wheel control and bounding which uses passive mechanical blocking of the wheels.

I. INTRODUCTION

Research in artificial legged systems has flourished over the past two-and-a-half decades. It covers a broad range of topics from the design and synthesis of legged robots to modeling, simulation and intelligent control, [1] - [3]. The inspiration for this work is evident—the biological world is filled with examples of legged locomotion. Despite their limitations legged robots and legged mobile platforms offer a number of advantages over their wheeled or tracked counterparts; indeed this motivates their continued study and development. A number of legged systems, humanoid and others, have been developed commercially as well as within academia and industrial research centres.

Our particular interest in these systems focuses on the *dynamically stable*¹ modes of legged locomotion, such as those exhibited in the running gaits of not only humans but also of animals such as horses and cheetahs. The feasibility of dynamically stable motion was originally demonstrated by the ground-breaking results at the CMU and MIT Leg Labs where simple controllers were made to stabilize high speed motion of monopedal, bipedal and quadrupedal robots, [4]. Even simpler controllers for quadrupedal walking and running gaits have recently been implemented on the Scout I, [5], and Scout II robots, [6] & [7]. The six-legged RHex platform, [8], which uses a compliant, rimless wheel leg design similar to the Whegs series of robots, [9], was shown to be nearly as capable as the tracked PackBot platform under difficult outdoor conditions, [10].

Articulated suspension systems such as Shrimp, Roller-Walker, Hylos and Workpartner have all introduced modes of wheeled locomotion which include aspects analogous to

¹In the context of this paper, stability refers to the tendency of the robot towards cyclic motion with bounded state variables.



Fig. 1. The PAW robot bounding outdoors on concrete using *active wheel control*. Photo courtesy of Defence R&D Canada.

statically stable walking machines, [11] - [14]. The Roller-Walker robot has demonstrated that passive wheels attached to the distal ends of actively-controlled legs can allow a vehicle to roll without directly driving the wheels. The Shrimp system negotiates terrain with actuated wheels and a passive adaptation mechanism. In contrast, the Hylos system uses active posture control to adapt to irregular terrain in order to maintain stability and traction. Defence R&D Canada's ANT platform, [15] was designed in the same statically-stable, adaptable vein as the aforementioned vehicles.

II. THE PAW ROBOT: A HYBRID WHEELED-LEG SYSTEM

PAW (Platform for Ambulating Wheels), shown in Fig. 2, is a quadrupedal robot with wheels on the distal ends of its compliant legs. It was simulated, designed and initially constructed in McGill's Ambulatory Robotics Lab, as discussed previously in [16] and [17]. This previous work, development of rolling behaviours, [18], as well as the work presented in this paper have been sponsored by the Autonomous Intelligent Systems Section at Defence R&D Canada – Suffield (DRDC Suffield). The agency envisions autonomous systems contributing to homeland security, search and rescue, and peacekeeping roles abroad. On the ground, Uncrewed Ground Vehicles (UGVs) will be called upon to enter unknown city blocks to keep soldiers out of harm's way. While the wheeled mechanism addresses this necessity, the compliant leg aspect yields obstacle-overcoming dynamic behaviours. It is proposed here that mobility characteristics of UGVs designed in this manner, combined with intelligent mobility algorithms, should outperform larger UGVs without these capabilities. The PAW

robot, which succeeds the ANT platform mentioned earlier, addresses the need for a UGV to transition from operation in relatively simple environments (composed of streets, sidewalks, trees, bushes) into more complex environments (that include trenches, berms, abandoned vehicles, rubble, wire barricades) and finally into highly complex environments (sewers, tunnels and buildings with tight confines and obstacles designed on a human scale).

PAW uses a lighter and more compact version of Scout II's T-shaped body. Unlike Scout II, [7], the legs are capable of limited recirculation and are equipped with actuated hard rubber wheels instead of fixed toes. In primarily wheeled modes of operation, the four hip motors can reposition the wheels with respect to the body of the robot. In legged modes, the wheels can be controlled, allowing dynamic behaviours such as the bounding gait presented here and others suggested in the simulations in [16].

While PAW is not the first hybrid wheeled-leg system it *is* the first which combines dynamically stable legged modes of locomotion with more traditional wheeled modes. Some of these latter modes, in which the legs are employed to reposition the wheels with respect to the body to achieve more advantageous turning and braking manoeuvres, are introduced in [18]. The results presented here show the dynamically stable legged modes of mobility, similar to those achieved by the Scout II robot, [7], but with the addition of actively driven wheels instead of simple fixed toes.

III. DESIGN OF PAW, A HYBRID WHEELED-LEG SYSTEM

A. Electromechanical Components

As alluded to earlier, much of the PAW design is based on the Scout II quadrupedal robot: the body of PAW consists of a T-shaped aluminum frame, but it is smaller and lighter (see Table I for the basic parameters). The most notable size differences are PAW's shorter legs, while the leg mass is increased due to the wheel motors. Differently from Scout II, PAW houses twice the number of actuators: four motors actuate the hip joints while another four, located at the distal end of each leg, drive the wheels. More specifically, the

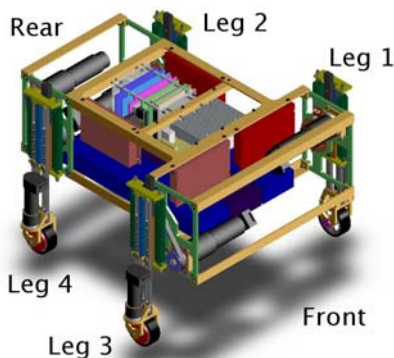


Fig. 2. The PAW Robot CAD Model. Note the leg spring pairs, as well as the wheels and wheel motors on the distal ends of the legs.

hip joints are each actuated by a 90 Watt Maxon 118777 brushed DC motor. The motors contain 73.5:1 gearheads and quadrature encoders with 2000 counts-per-revolution effective resolution. The particular gearhead is identical to that on Scout II and maximizes leg torque. A toothed belt and pair of sprockets provide a further 32:24 reduction ratio. The 0.066 m diameter wheels are each driven by a 20 Watt Maxon 118751 brushed DC motor with a 4.8:1 Maxon 233147 planetary gearbox and a custom 3:1 ratio bevel gear pair connected to a wheel. The wheel motors' quadrature encoders are identical to those of the hip motors. Maximum observed hip torque and speed during bounding are approximately 30 Nm and 600 deg/sec, respectively. Maximum wheel torque and speed observed during rolling at 2 m/s are approximately 1.2 Nm and 3600 deg/sec, respectively. Each leg houses a pair of extension springs for which the combined spring constant is adjustable and to date has varied between 2000 and 3200 N/m (see discussion in Section III-C).

PAW has been designed to be power and computationally autonomous. Accordingly, the body houses a PC/104 computer stack, four AMC 25A8 brushed DC motor amplifiers for driving the hip motors, a custom amplifier board containing Apex SA60 motor amplifiers and three NiMH battery packs. The AMC amplifiers are set to deliver 10 A of continuous, 20 A peak, current to each hip motor, while the Apex amplifiers can deliver 10 A continuous, 15 A peak to each wheel motor.

B. Proprioceptive Sensors

The PAW robot carries very few sensors, and only a subset of these is used for closed-loop control. In addition to the previously mentioned quadrature encoders, the robot uses one linear potentiometer with up to 0.10 m range in each of its four legs to drive the state machine (see Section IV-A.2). Battery voltage and current sensors along with a current sensor on each hip motor amplifier are also available to estimate the robot's power consumption.

TABLE I
PAW BODY PARAMETERS

| Parameter | Value |
|---|--|
| front body width | 0.366 m |
| rear body width | 0.240 m |
| front wheel-to-wheel width | 0.478 m |
| rear wheel-to-wheel width | 0.352 m |
| body length | 0.494 m |
| hip separation | 0.322 m |
| wheel diameter | 0.066 m |
| leg length | 0.212 m |
| body height | 0.170 m |
| max body clearance | 0.124 m |
| leg mass (each) | 1.2 kg |
| body mass | 15.7 kg |
| m. of inertia (I_{xx}, I_{yy}, I_{zz}) | (0.170, 0.469, 0.372) kg m ² |
| pr. of inertia (I_{xy}, I_{xz}, I_{yz}) | (0.001, -0.001, 0.007) kg m ² |
| leg spring constant | 2000 - 3200 N/m |

C. Spring and Wheel Selection

Selection of the spring constant for each leg is a compromise between many factors. The higher the spring constant the more energy can be stored and released in each stride. A higher spring constant also leads to a higher frequency of motion, although this frequency is limited by the maximum sweep speed of the leg under load.

The experiments conducted using the stiff 3200 N/m springs exhibit a one-beat pronking gait which easily develops large apex heights during the ballistic phase of the gait. While useful for obstacle clearance, large apex heights are detrimental to gait controllers which do not use inertial feedback to compensate for uncontrolled variations in pitch and roll during the ballistic phase.

PAW currently uses two parallel 1000 N/m springs in each leg. This provides the robot with sufficient kinetic energy during takeoff to achieve a ballistic phase which is necessary for toe clearance. It also provides sufficient time for the leg to sweep to the takeoff angle prior to full leg decompression. This is critical for developing controlled dynamically stable gaits such as the two-beat bound discussed in this paper.

While larger wheels would be an asset for obstacle traversal and high-speed rolling, small wheels were chosen to minimize the effects of toe shape on legged gaits. Larger wheels would reduce control bandwidth and would necessitate larger motors to counteract the larger moments due to wheel-ground interaction. Hard, solid rubber wheels, as opposed to pneumatic tires were chosen to minimize chattering due to their higher spring constant.

IV. THE BOUNDING GAIT CONTROLLER

A. Bounding Control

The bound gait is a two-beat gait in which there is a large degree of symmetry in both control and overall motion along the spinal or *sagittal* plane. A schematic of the sagittal plane representation of the robot is found in Fig. 3. System parameters and variables include the mass and pitch moment of inertia (m and I), the leg spring constant (k), the half hip spacing (L), the leg length (l) and the leg angle with respect to the body (φ). The f and r subscripts refer to front and rear ends of the robot, respectively.

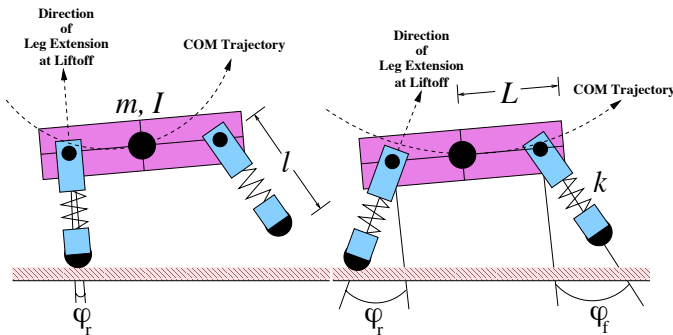


Fig. 3. Increasing the takeoff angle, such as φ_r in the rear legs, can increase forward speed.

1) *Wheel and Hip Motor Control*: The wheel motors are actively driven by a PID position controller (as opposed to a velocity controller for the rolling modes in [18]). The equation for position control of a particular joint:

$$\tau_{desired} = k_p \Delta_{position} + k_i \Sigma \Delta_{position} + k_d \Delta_{velocity} \quad (1)$$

where $\tau_{desired}$ is the desired motor torque, $\Delta_{position}$ is the error between actual and desired motor angle, $\Delta_{velocity}$ is the error between actual and desired motor angular velocities, $\Sigma \Delta_{position}$ is the accumulated error in motor angle, and k_p , k_i and k_d are the proportional, integral and derivative gains, respectively.

The gains for this active wheel controller are determined by a compromise between rapid reaction and available electrical current. The torque is proportional to the current, which is itself dependent on the internal resistance of the onboard battery, wiring and other components in the amplifiers. Gains must also be sufficiently small to not drive the wheels to instability during the flight phase when they are effectively unloaded. Since the PID gains cannot be arbitrarily large (which would yield stiff response during stance) the wheel will react compliantly as a relatively soft torsional spring and damper during the stance phase of motion. This is reflected in the wheel response observed in Fig. 8. While gain scheduling could limit the oscillation of the wheel during the flight phase, it adds unnecessary complexity since the effect of the low-mass wheel on the robot's flight phase dynamics is negligible. In addition it would delay reaction of the wheel to ground contact while the leg compressed sufficiently to change the leg state.

As with the wheel motors, control of the hip motors is by a combination of PID position controller and open loop commanded torque. The details about the switching between these modes are found below. The PID control gains for both the hip and wheel motors are listed in Table II.

2) *Bounding State Machine*: As with the Scout II robot's bound, PAW's bound incorporates virtual leg symmetry, [4] effectively leading to a planar representation as shown in Fig. 3. The gait is controlled by two separate state machines, one for the rear "virtual" leg pair and one for the front, [7] (see Fig. 4 for a visual representation of these two state machines.) As

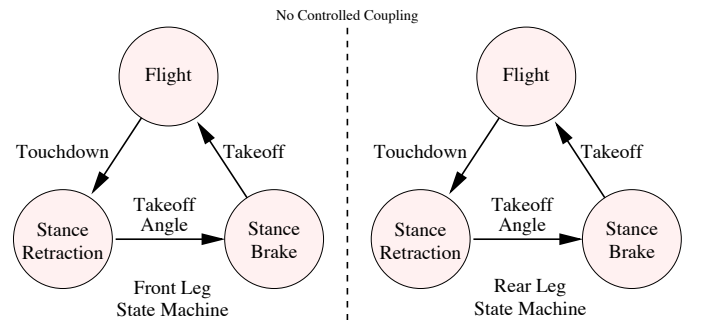


Fig. 4. Separate bounding state machines for front and rear legs.

with Scout II the bounding behaviour begins from a standing position proceeded by a combination of open-loop lean-back and kicking motions.

During the flight phase the leg is actuated to a desired touchdown angle using a position-based PID controller. During the stance retraction phase a constant desired stance torque is commanded in order to drive the motors to saturation. When the takeoff angle is reached during retraction the state switches to stance brake. During the stance brake a position PID controller engages, holding the leg at the takeoff angle. It should be noted that if the takeoff angle is not reached prior to takeoff being detected the stance brake phase is bypassed. The switching between these modes is determined by the high level controller (the bounding state machine). The leg length potentiometers are responsible for determining the detection of the transitions to the flight and stance retraction states, while the hip motor encoders are used for transition to the stance brake state.

TABLE II
HIP AND WHEEL MOTOR CONTROL GAINS

| Type | Proportional k_p | Integral k_i | Derivative k_d |
|---------------------------|-----------------------|-------------------|------------------------|
| Hip | 150 [Nm/rad] | 1.5 [Nm/rad] | 0.3 [Nm/(rad/sec)] |
| Wheel (active lock) | 7 [Nm/rad] | 0.005 [Nm/rad] | 0.04 [Nm/(rad/sec)] |

V. EXPERIMENTAL RESULTS

In this section experimental results are presented and discussed. Two variations of bounding have been achieved on the PAW robot. The first uses unactuated, *mechanically blocked* wheels. The second uses *actively controlled* wheels to approximate fixed toes during the bounding gait. The first set of experiments provides a *baseline* set of results using fixed toes which can be compared with the results generated in the second set of experiments. Also, the hypothesis that takeoff angles, rather than touchdown angles, can be manipulated to control forward speed has been verified.

A. Mechanically Blocked Wheel Bounding

A set of bounding tests was performed using mechanically blocked wheels to help identify whether active control of the wheels had any significant effect on the bounding gait. To block the wheels without permanently changing the wheel drive mechanism an adhesive was poured between the teeth of the bevel gear pair which couple the wheel and wheel motor at the distal end of each leg. In addition, rubber wedges were inserted between the rubber wheel and the wheel motor housing. A photo of this arrangement can be found in Fig. 5.

Three combinations of touchdown and takeoff angles have been tested for the mechanically blocked wheel configuration. The relevant parameters and results from the experiments using these settings are listed in Table III. Ten trials were performed for each parameter setting; the robot took between

9 and 14 stable bounding strides per trial. Note that by varying the touchdown and takeoff angles, it is possible to increase the speed of a stable bounding gait from 0.81 m/s to 0.99 m/s.

As can be seen in Fig. 6 mechanical blocking of the wheel limits measurable² wheel rotations to below two degrees, peak-to-peak.

A typical footfall pattern as well as the leg compression during bounding with mechanically blocked wheels are shown in Fig. 6. The footfall clearly shows a bounding gait while the leg length graph illustrates how larger loads are observed in the rear legs (2 & 4), a result also supported by the wheel rotations in the mechanically blocked wheels of Fig. 6.

B. Active Wheel Control Bounding

A number of bounding experiments has also been performed using actively controlled wheels. Figures 6 - 9 compare results using the same touchdown and takeoff angles in both cases.

Wheel rotation is obviously greater in the actively controlled wheels than in the case of blocked wheels, as can be seen in Figs. 6 and 8. It notable that it is difficult – without detailed analysis of the robot telemetry – to observe significant differences between bounding with mechanically blocked wheels and bounding with actively controlled wheels. That said, for the same touchdown angles, bounding with actively controlled wheels is about 15% slower. In addition, for the same speed, bounding with actively controlled wheels is less efficient. For instance, at 0.98 m/s with mechanically blocked wheels, the specific resistance, [19], is 2.0, while bounding with actively controlled wheels at 1.0 m/s, it is 2.4.

C. Controlling Forward Speed with Takeoff Angles

While the bounding gait on Scout II used variable touchdown angles with fixed takeoff angles to regulate forward speed, the notion that variable takeoff angles (and fixed touchdown angles) could be used to control forward speed was tested on the PAW robot. As shown in Fig. 3, by increasing the takeoff angle the direction of thrust can be varied to produce more forward motion than vertical motion. This hypothesis was tested for both bounding modes and the speed was shown to increase with takeoff angle, as shown in Table III (Exps. 2 & 3) and Table IV.

²Measured wheel rotation does not include components due to backlash in the motor gearhead and bevel gear pair coupling the wheel to the motor.



Fig. 5. The mechanically blocked wheel.

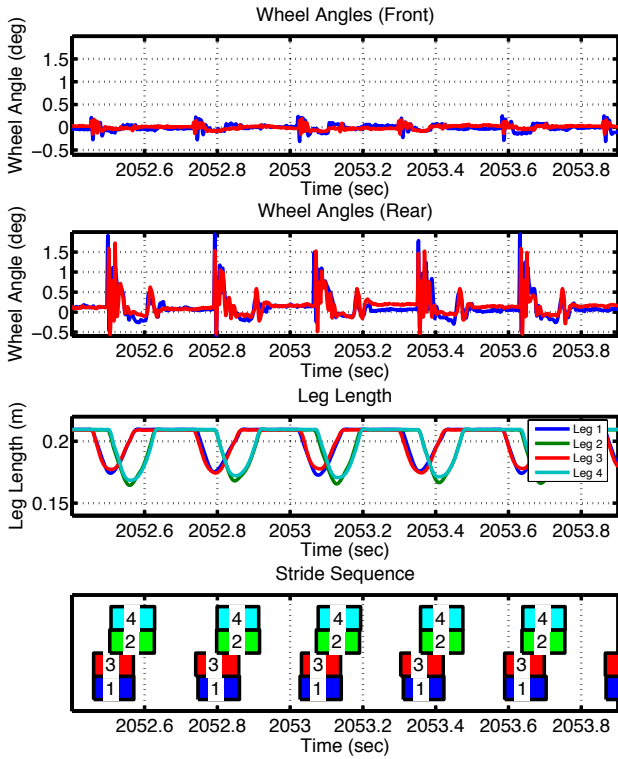


Fig. 6. Wheel rotation & leg length while bounding with *mechanically blocked* wheels. Hip angle settings correspond to Exp. 2 of Table III.

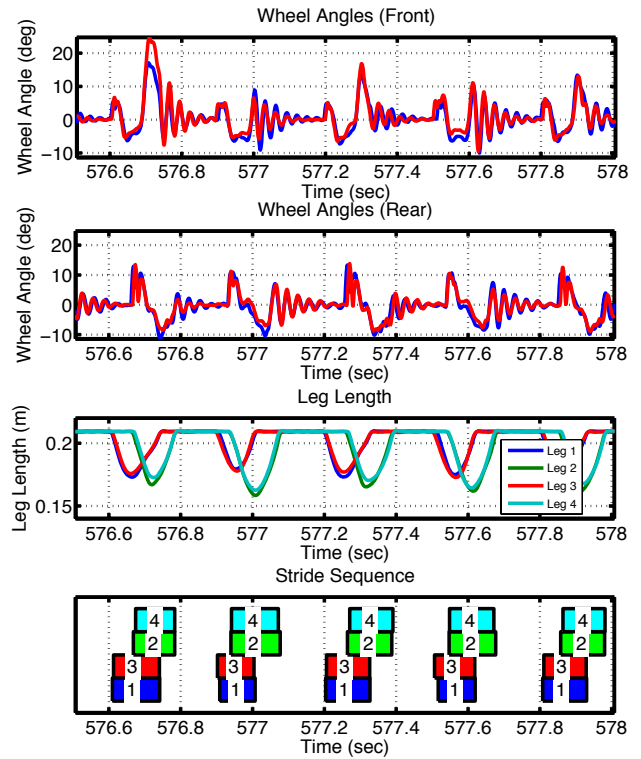


Fig. 8. Wheel rotation & leg length while bounding with *actively controlled* wheels. Hip angle settings correspond to Exp. 1 of Table IV.

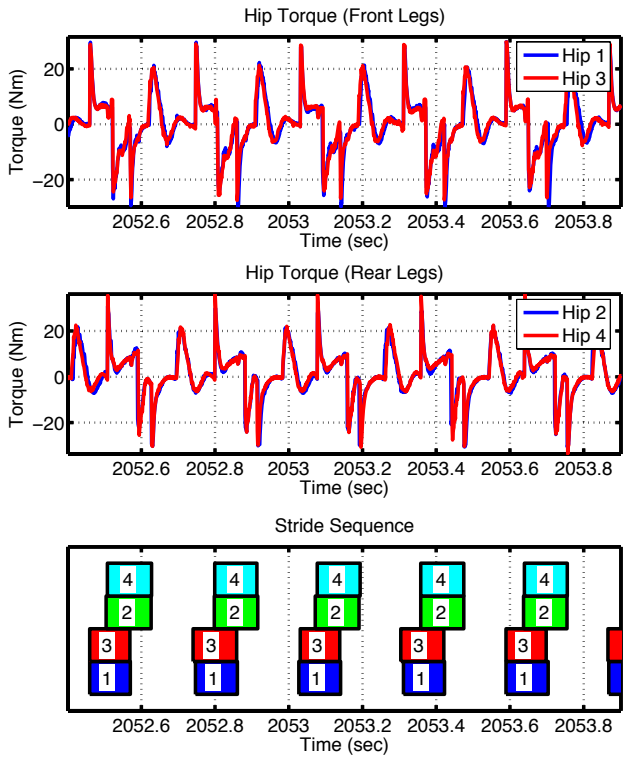


Fig. 7. Hip torque plots of the robot while bounding with *mechanically blocked* wheels. Hip angle settings correspond to Exp. 2 of Table III.

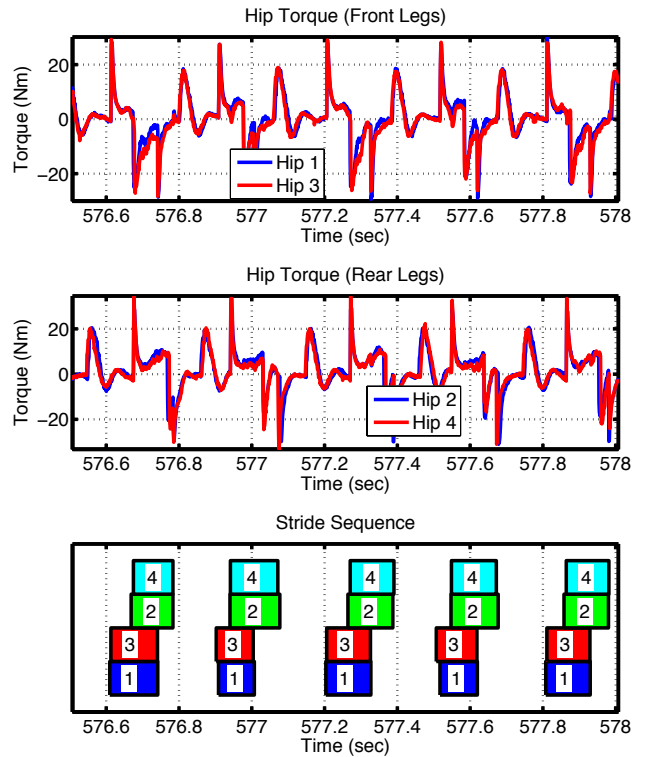


Fig. 9. Hip torque plots of the robot while bounding with *actively controlled* wheels. Hip angle settings correspond to Exp. 1 of Table IV.

TABLE III

EXP. RESULTS: BOUNDING WITH MECHANICALLY BLOCKED WHEELS

| Exp # | Front Leg T. Down, T. Off Angles [deg] | Rear Leg T. Down, T. Off Angles [deg] | COM Speed [m/s] | Max Compr. (Front, Rear) [m] | Stride Freq. [Hz] | Phase Diff. [%] | Duty Cycle (Front, Rear) [%] |
|-------|--|---------------------------------------|-----------------|------------------------------|-------------------|-----------------|------------------------------|
| 1 | -24, 0 | -22, 12 | 0.809 | 0.039, 0.044 | 3.14 | 18 | 36, 41 |
| 2 | -20, 4 | -22, 12 | 0.869 | 0.036, 0.040 | 3.31 | 19 | 36, 39 |
| 3 | -20, 6 | -22, 14 | 0.989 | 0.034, 0.039 | 3.49 | 19 | 40, 42 |

TABLE IV

EXP. RESULTS: BOUNDING WITH ACTIVELY CONTROLLED WHEELS

| Exp # | Front Leg T. Down, T. Off Angles [deg] | Rear Leg T. Down, T. Off Angles [deg] | COM Speed [m/s] | Max Compr. (Front, Rear) [m] | Stride Freq. [Hz] | Phase Diff. [%] | Duty Cycle (Front, Rear) [%] |
|-------|--|---------------------------------------|-----------------|------------------------------|-------------------|-----------------|------------------------------|
| 1 | -20, 4 | -22, 12 | 0.754 | 0.033, 0.043 | 3.353 | 23.7 | 40.6, 41.8 |
| 2 | -20, 6 | -22, 14 | 0.828 | 0.034, 0.044 | 3.348 | 20.1 | 40.4, 41.6 |
| 3 | -20, 6 | -22, 16 | 0.833 | 0.035, 0.045 | 3.375 | 17.0 | 40.4, 41.5 |
| 4 | -20, 8 | -22, 16 | 0.906 | 0.033, 0.043 | 3.517 | 17.0 | 40.7, 42.4 |
| 5 | -20, 10 | -22, 18 | 1.002 | 0.033, 0.042 | 3.568 | 18.3 | 40.9, 43.3 |

VI. CONCLUSIONS & FUTURE WORK

This paper presented details regarding the first implementation of a dynamically stable legged gait on a hybrid wheeled-leg robot. The design of the robot was discussed as was the control of the hip and wheel motors during the bounding gait. Bounding using actively controlled wheels on a real robot platform has been presented here for the first time. While the bounding gait is qualitatively similar in both the actively controlled and mechanically blocked cases, the use of actively controlled wheels not only slows the robot down but it renders it less efficient. In addition, the hypothesis that forward speed can be regulated by solely varying leg takeoff angles has been verified to work in both versions of the bounding gait presented.

Future work will investigate alternative methods of wheel control to improve performance. Other legged locomotion gaits, such as the rotary gallop, will be implemented as well.

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