Bounding With Active Wheels and Liftoff Angle Velocity Adjustment

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April 3, 2009

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Abstract

The bounding gait for the Platform for Ambulating Wheels (PAW), a new and unique hybrid wheeled-leg system is presented here. Two hypotheses are tested and discussed: first, that the robot’s forward speed can be increased by increasing the leg liftoff angles and, second, that addition of distally-mounted actuated wheels can be used in running gaits such as the bound. Both hypotheses were tested experimentally and found to be valid.

1 Introduction

1.1 Legged and Hybrid Wheeled-Leg Systems

As an alternative to traditional wheeled and tracked ground vehicles, biologically-inspired legged systems are becoming increasingly common. This work examines a particular form of legged locomotion, the bounding gait, which is common in the animal world, making it a reasonable locomotion mode to better understand the design and implementation of artificial quadrupeds. However, given that the dominant method for ground-based mobile robot locomotion is wheeled or tracked, future deployment of legged systems may be preceded by hybrid wheeled-leg technology. This is the primary motivation behind the development of the robot presented here.

While the most prevalent legged designs are slow moving statically stable systems [Hirose, 2001, Song and Waldron, 1989, Bares and Wettergreen, 1999, Fujita, 2001] this paper focuses on dynamically stable systems related to the original work at the CMU and MIT Leg Labs [Raibert, 1986].
Recently, simpler controllers, which do not require task-level or torso-state feedback, have successfully stabilized running gaits such as the bound [Poulakakis et al., 2005, Iida et al., 2005]. Many of these systems rely on underactuation for reliability and tractability.

Minimally actuated systems [Poulakakis et al., 2005, Saranli et al., 2001, Cham et al., 2004, Poulakakis et al., 2006, Wisse et al., 2007] have allowed researchers to examine fundamental elements of legged locomotion which were not easily studied in earlier systems with more actuated degrees of freedom and have led to the study of climbing [Autumn et al., 2005] and aquatic [Prahacs et al., 2004] modes of locomotion.

![Figure 1: The Platform for Ambulating Wheels (PAW) quadrupedal robot. The PAW robot is shown in the flight phase of the bounding gait while using active wheel control on an outdoor concrete surface. [Photo courtesy of Defence R&D Canada – Suffield]](image)

Wheels and legs are not mutually exclusive. The Platform for Ambulating Wheels (PAW, shown in Fig. 1) [Steeves, 2002] approaches the issue of ground mobility by combining wheels and legs – similar to Sojourner’s bogies [Mishkin, 2003] and PackBot’s tracked paddles [McBride et al., 2003]. The Roller-Walker robot [Endo and Hirose, 2000] uses distally-mounted passive wheels on actively-controlled legs to roll along a surface. The Shrimp system negotiates terrain with actuated wheels and a passive adaptation mechanism [Estier et al., 2000]. The Hylos system uses active posture control to adapt to irregular terrain [Grand et al., 2004]. None of these systems, however, have demonstrated dynamically stable legged gaits in addition to their wheeled modes of locomotion.

### 1.2 Quadrupedal Running: The Bounding Gait

In addition to work on monopods and bipeds, the CMU and MIT Leg Labs developed controllers for trotting, pacing and bounding gaits in quadrupeds [Raibert, 1990]. Since then, a number of leg, body and controller designs for dynamically stable running systems have been put forward. These include the segmented-leg Scamper bounding quadruped [Furus sho et al., 1995]. Scamper’s controller divided one running cycle into eight states and switched the two joints per leg between three control modes: free rotation, position control and velocity control. Following a different approach, the Patrush quadruped implemented bounding by transitioning from pronking based on principles from
neurobiology, [Kimura et al., 1999]. It combined compliant legs with a neural oscillator network, the frequency of which matched that of natural hopping frequency of the spring-loaded mass. The Scout II robot, developed at McGill University, [Poulakakis et al., 2005] demonstrated a power and computationally autonomous state-machine-based bounding gait. The PAW robot succeeds the Scout II system for the examination of fixed-toe and active wheel legged locomotion studies.

A variety of leg designs for quadrupedal locomotion have been proposed, most involving more actuators than the platforms used in this research – Scout II with one actuator per leg (four in total) and PAW (Fig. 1) with two actuators per leg (eight in total). In contrast, the OSU-Stanford KOLT quadrupedal robot has twelve proximal leg actuators [Palmer and Orin, 2005, Estremera and Waldron, 2008]. Similarly, the Boston Dynamics BigDog [Kirsner, 2004] houses at least twelve actuators.

Unlike these other designs, the Scout II robot houses only a single actuator per leg and uses one of the simplest controllers proposed to date [Poulakakis et al., 2005]. It has been demonstrated experimentally that dynamic running on flat ground via a bounding gait is possible by merely positioning the legs at a body-relative fixed desired touchdown angle during flight, and commanding a motor torque during the stance until a sweep limit angle is reached. The most striking feature of the controller is that it requires minimal sensing and feedback – touchdown/lift-off detection and local feedback of the leg angles relative to the body. The resulting motion is largely caused by the interaction between the actuators and the natural dynamics of the mechanical system. This has led to the realization of different dynamically stable gaits such as dynamic walking [de Lasa, 2000], pronking [Talebi, 2000], bounding [Papadopoulos and Buehler, 2000, Poulakakis et al., 2005] and – uniquely in Scout II and PAW – galloping, [Smith and Poulakakis, 2004, Smith, 2006].

Similarly, speed regulation has recently been demonstrated on a hip-actuated quadruped with compliant legs using a single control parameter, [Iida et al., 2005]. In particular, rather than use the touchdown angle for speed control, as is the case for Scout II [Papadopoulos, 2000] and the CMU and MIT Leg Labs Quadruped [Raibert, 1986], the commanded input to this quadruped is either the stride frequency or the leg phase difference. It is interesting to note that [Estremera and Waldron, 2008] uses control over hip radial velocity at liftoff to regulate the pitch. This is closely related to our control over the liftoff angle, the difference being that we use it to control forward speed instead.

1.3 About This Paper

Two hypotheses are tested here: first, that wheels can be used in a running quadrupedal robot and, second, that liftoff angles can be used to change the forward speed of the quadruped. In this manuscript, it is conclusively demonstrated that dynamic legged gaits such as the bound are not only possible but realizable in systems that incorporate wheels, such as the hybrid PAW robot. Of particular importance is the fact that a stable bounding gait is possible given the fact that the wheels, while actively controlled and not mechanically blocked, rotate a non-negligible amount during the stance phase. This is the first time that such experimental results, comprising over 100 separate trials, have been presented in the literature to date. These results form a baseline for future work on the development of more complex hybrid legged and wheeled behaviours, and provide a valuable reference for the validation of simulated models.
2 Robot Design

The PAW robot’s design is based on an approach which emphasizes simplicity to achieve performance, reliability, and research objectives. The design is characterized by limited actuation, minimal sensing, no task-level feedback, and no elaborate state feedback scheme; this is similar to the approach taken in [Poulakakis et al., 2005] and [Saranli et al., 2001]. The motion of the robot is, however, anything but simple, relying on underlying natural dynamics and resulting in gaits such as the bound and gallop which are similar to those found in nature, for instance squirrels and dogs [Gambaryan, 1974].

2.1 The PAW Robot

The PAW robot, Fig. 2a., has a T-shaped body and compliant legs. PAW’s legs are equipped with actuated hard rubber wheels instead of fixed toes. In wheeled modes of operation the four hip motors can reposition the wheels with respect to the body of the robot. As it combines aspects of legged and wheeled locomotion in order to achieve greater mobility, PAW resembles other articulated suspension systems, [Endo and Hirose, 2000, Estier et al., 2000, Grand et al., 2004]. Many of PAW’s wheeled behaviours are primarily kinematic, but they have implications for high speed locomotion in which vehicle dynamics play a role, such as in braking and high speed turning, [Smith et al., 2006]. In legged modes, the wheels may be actively controlled, allowing dynamic behaviours such as jumping and bounding. A list of inertial, geometric and actuation parameters for PAW is found in Table 1.

![Figure 2: PAW CAD model and leg schematic](image)

The PAW robot uses AMC 25A8 motor amplifiers and 90 Watt brushed DC Maxon motors and gearboxes at the hips. Each of PAW’s legs has 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 0.066 m diameter wheel. The wheel motors’ quadrature encoders are identical to those of the hip motors. The wheel motors are driven by four Apex SA60 amplifiers on a custom-made device, the RHex
Table 1: PAW Inertial, Geometric, Actuation and Leg Compliance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Length</td>
<td>0.494 m</td>
</tr>
<tr>
<td>Front Body Width</td>
<td>0.366 m</td>
</tr>
<tr>
<td>Rear Body Width</td>
<td>0.240 m</td>
</tr>
<tr>
<td>Front Leg-to-Leg Width</td>
<td>0.478 m</td>
</tr>
<tr>
<td>Rear Leg-to-Leg Width</td>
<td>0.352 m</td>
</tr>
<tr>
<td>Hip Separation</td>
<td>0.322 m</td>
</tr>
<tr>
<td>Body Height</td>
<td>0.168 m</td>
</tr>
<tr>
<td>Body Mass</td>
<td>15.7 kg</td>
</tr>
<tr>
<td>Body Moments of Inertia ((I_{xx}, I_{yy}, I_{zz}))</td>
<td>(0.170, 0.470, 0.372) kg m(^2)</td>
</tr>
<tr>
<td>Body Products of Inertia ((I_{xy}, I_{xz}, I_{yz}))</td>
<td>(0.00061, -0.00064, 0.00665) kg m(^2)</td>
</tr>
<tr>
<td>Leg Length</td>
<td>0.212 m</td>
</tr>
<tr>
<td>Leg Mass</td>
<td>1.3 kg</td>
</tr>
<tr>
<td>Leg Spring Constant</td>
<td>2000 N m(^{-1})</td>
</tr>
<tr>
<td>Hip Gear Ratio</td>
<td>73.5:1</td>
</tr>
<tr>
<td>Hip Gear Efficiency</td>
<td>72%</td>
</tr>
<tr>
<td>Hip Pulley-Belt Ratio</td>
<td>4:3</td>
</tr>
<tr>
<td>Hip Pulley-Belt Efficiency</td>
<td>96%</td>
</tr>
<tr>
<td>Hip No-Load Speed</td>
<td>74 RPM</td>
</tr>
<tr>
<td>Hip Stall Torque</td>
<td>64 Nm</td>
</tr>
<tr>
<td>Wheel Gear Ratio</td>
<td>4.3:1</td>
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<tr>
<td>Wheel Gear Efficiency</td>
<td>80%</td>
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<tr>
<td>Wheel Bevel Gear Ratio</td>
<td>3:1</td>
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<tr>
<td>Wheel Bevel Gear Efficiency</td>
<td>n/a</td>
</tr>
<tr>
<td>Wheel No-Load Speed</td>
<td>715 RPM</td>
</tr>
<tr>
<td>Wheel Stall Torque</td>
<td>&lt;2.5 Nm</td>
</tr>
</tbody>
</table>
Motor Driver Board (MDB), originally developed for the RHex hexapod robot [McMordie, 2002]. Other sensors include linear potentiometers for measuring leg length and a BAE SilMU-01 Inertial Measurement Unit (IMU) [Systems, 2003] which transmits roll, pitch and yaw information to the onboard PC/104 stack via a serial data line.

Note that although various measured variables are used to study the properties of the bounding motion of PAW, the controller does not rely on all of them. For instance, the implementation of the $\varphi$-controller used in bounding relies only on measurements from the encoders and the leg length potentiometers.

### 2.2 Control

#### 2.2.1 The Bounding Finite State Machines

The high-level control of bounding, being a symmetrical gait about the sagittal plane\(^1\), can be simplified by considering a planar model of the robot where the front and rear leg pairs are replaced by the two corresponding virtual legs. Then, the bounding gait is controlled by two separate state machines, one for the rear virtual leg and one for the front, as illustrated in Fig. 3. These separate state machines do not communicate with one another, meaning that the bounding gait is a result of the action of two separate sagittal plane monopods rigidly coupled by the mechanical chassis. The characteristics of this entrainment (e.g. phase, frequency, etc.) vary based on the control inputs (e.g. touchdown and liftoff angles) to the system.

The pair of Finite State Machines, $(S, s_0, \lambda, \wedge, T, G)$ used onboard the PAW robot are based on the Moore Machine model [Moore, 1956]. Here $\lambda$ refers to the input set, $S$ to a finite, non-empty set of states, $s_0$ is the initial state, and $\wedge$ to the outputs, while $T : S \times \lambda \rightarrow S'$ is the transition function and $G : S \rightarrow \wedge$ is the output function.

The state machine pair is shown in Fig. 3, where the input set is $\lambda = \{TD, LO, SW L\}$ and the set of states is $S = \{\text{Flight, Stance1, Stance2}\}$. $TD$ is short for “Touchdown”, $LO$ for “Liftoff” and $SW L$ for “Sweep Limit”. The set of outputs corresponding to actions taken by the hip actuators is $\wedge = \{Protract, Retract, Brake\}$.

The separate state machines affect the transitions between three robot states: Flight, Stance1 and Stance2. When leg touchdown (TD) occurs the Stance1 state results in Retraction (rearward) thrusting of the hips. When liftoff (LO) occurs the leg enters the Flight state, causing the hip actuator to Protract forward until it achieves the touchdown angle, $\varphi_{td}$, which it then holds until the transition to Stance1. A third state, Stance2, occurs when a sweep limit angle, $\varphi_{swl}$ is detected, resulting in the SWL input. If the leg passes $\varphi_{swl}$ then the Brake output attempts to hold the leg at that angle until the Liftoff (LO) event occurs. The angle at which liftoff occurs, $\varphi_{lo}$ is ideally equal to $\varphi_{swl}$. This sweep limit was introduced [Poulakakis et al., 2005] to prevent stubbing of the toes during the protraction phase by ensuring that the hips moved sufficiently high during the stance-flight transition; this can be used to adjust forward speed.

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\(^1\)The sagittal plane is a vertical plane that cuts through what could be considered the spine of the quadruped, dividing its body into left and right halves.
Figure 3: Bounding State Machine Transition and Output mapping. There is no controlled coupling between the two state machines.

2.2.2 Hip Actuator Control and Blocking of Wheel Actuator

At the heart of the control for each joint of the robot is a proportional-derivative (PD) controller which is responsible for maintaining a desired position at that joint. The equation for position control of a particular joint (hip or wheel) is described as:

\[ \tau_{jd} = k_P(\vartheta_j - \vartheta_{jd}) + k_D(\dot{\vartheta}_j - \dot{\vartheta}_{jd}) \]

where \( \tau_{jd} \) is the desired joint torque, \( (\vartheta_j - \vartheta_{jd}) \) is the error between actual and desired joint angle, \( (\dot{\vartheta}_j - \dot{\vartheta}_{jd}) \) is the error between actual and desired joint angular velocities, and \( k_P \) and \( k_D \) are the proportional and derivative gains, respectively.

In the case of controlling a desired position, such as during braking, a desired position value is given and the desired velocity is set to zero. Transitions between one set of desired velocities and positions and another is resolved using computationally-efficient cycloidal functions, [Angeles, 2002], which provide smooth motion.

The outputs of the PD controllers are torque commands to off-the-shelf amplifiers which regulate current to the DC motors at the hips. During the stance phase (between leg touchdown and liftoff events) a desired torque is transmitted to the hip amplifiers; velocity of the hip during stance retraction is not directly controlled and results from the internal dynamics of both the hip motor and amplifier. This is discussed in greater detail in [Poulakakis et al., 2005]. It should be noted, however, that the Scout II hip controller employed in [Poulakakis et al., 2005] modifies the desired torque based on the actuator and power supply model. The controller used in PAW’s hips does not use these models. The hip control gains for these controllers are set relatively high to ensure that the legs are held firmly at the touchdown and liftoff angles at the beginning and end of the stance phases.

The wheel motor controllers on the PAW robot do not have access to current-regulating amplifiers, so a more elaborate controller is used which takes into account motor back-EMF to estimate the
applied torque. This is based on the work conducted for the RHex robot [McMordie et al., 2003].

As a precursor to future work on acrobatic hybrid wheeled-leg behaviours, the experiments presented here compare simple active wheel control bounding to fixed-toe bounding. These baseline trials examine bounding with “mechanically blocked” wheels as well as with “active wheel control” where the wheels of PAW are commanded to zero motion during the stance phase of the bounding gait. Ideally, the control gains for the wheel motors during the active wheel control trials would be set arbitrarily high to accomplish this. Large controller gains used during stance would drive the wheels unstable when they unload during the flight phase. Therefore, relatively low wheel gains are used which result in the wheels acting compliantly as a torsional spring and damper pair during the stance phase of motion. This is reflected in the wheel response observed during experimental bounding in Section 4.1.

On the other hand, to perform fixed-toe bounding experiments without permanently changing the wheel drive mechanism, the wheels were blocked by pouring an adhesive between the teeth of the bevel gear pair to tightly 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, shown in Fig. 4.

Figure 4: The mechanically blocked wheel.

3 Models & Simulation

Here, two models are described: the first relates to the effect of wheel actuation on the bounding gait, and the second on the role played by liftoff angles on the bounding gait. These models play a supportive role in the examination of the experimental results later.
3.1 A Simplified Single-Leg Model for Hip-Wheel Operation during Stance

To better understand the experimental bounding gait with active wheels, presented later in this paper, it is helpful to examine the operation, in simulation, of a single leg during stance phase with hip and wheel actuation.

At a fundamental level, the effect of interaction of two actuators at the proximal (hip/body) and distal (wheel/ankle) ends of the leg can be investigated by using the simplified Revolute-Revolute Monopod (R-R monopod) model of Fig. 5a, comprised of two rigid links subject to applied torques at the two revolute joints. The torque at the distal end, $\tau_2$, is applied to link 1 and represents the reaction torque from the wheel actuator; hence the wheel torque is $-\tau_1$. Similarly, the torque shown at the proximal end, $\tau_1$, is that applied at the hip to the body and is the reaction of the torque applied by the hip actuator to the leg. The first link represents the stiff version of the PAW leg, while the second link stands for PAW’s body (with appropriate mass, inertia and length). Note that in this simplified model, we are treating the distal end as a ground-constrained pin joint, thereby neglecting the effect of the wheel rolling. This does not compromise the results of our dynamics analysis, assuming the wheel’s inertia is negligible and the wheel is rolling so that the friction at the wheel is small. However, this simplification has an effect on the velocity kinematics of the resulting motion.

The equations of motion for the system in Fig. 5a are as follows:

$$\tau_1 = I_{l1} + m_{l1}l_1^2 + I_{l2} + m_{l2}(a_1^2 + l_2^2 + 2a_1l_2\cos(\theta_2))\ddot{\theta}_1 + (I_{l2} + m_{l2}(l_2^2 + a_1l_2\cos(\theta_2)))\ddot{\theta}_2 - 2m_{l2}a_1l_2\sin(\theta_2)\dot{\theta}_1\dot{\theta}_2 - m_{l2}a_1l_2\sin(\theta_2)\dot{\theta}_2^2 + (m_{l1}l_1 + m_{l2}a_1)g\cos(\theta_1) + m_{l2}l_2g\cos(\theta_1 + \theta_2)$$

$$\tau_2 = (I_{l2} + m_{l2}(l_2^2 + a_1l_2\cos(\theta_2)))\ddot{\theta}_1 + (I_{l2} + m_{l2}l_2^2)\ddot{\theta}_2 + m_{l2}a_1l_2\sin(\theta_2)\dot{\theta}_1^2 + m_{l2}l_2g\cos(\theta_1 + \theta_2)$$

Here $\theta_1$ and $\theta_2$ are the angles of the first and second joints, $\tau_1$ and $\tau_2$ are the torques applied to these joints; $m_1 = 2.6$ kg and $m_2 = 15.7$ kg are the masses of the leg and body, while $I_{l1} = 0.004618$ kg m$^2$ and $I_{l2} = 0.372$ kg m$^2$ are their respective rotary inertia. The length of the leg is $a_1 = 0.179$ m, while the length of the body is $a_2 = 0.322$ m (the distance between the two hip joints on the robot). The distance from the distal joint to the distal link’s centre of mass is $l_1$, while the distance from the proximal joint to the body link’s centre of mass is $l_2$. These correspond to the half-way points on the leg and body, respectively. The gravity constant, $g$, is set to 9.81 m/s$^2$. Torques are limited to the stall torques available to the PAW robot’s sagittal plane wheel and hip motor pairs (5 Nm and 130 Nm).

The results from this model are examined under the following conditions. The stance phase is assumed to end when the final angle is $\theta_{1,f} = 180^\circ - \theta_{1,i}$, where the initial angles are $\theta_{1,i}$ and $\theta_{2,i}$. The output of interest is the change in the velocity at the hip joint, that is $v_f - v_i$. 
As can be seen from Fig. 6, highest forward speeds are achieved with negative torque applied to the proximal joint and positive torque applied to the distal joint. This in turn results in a retracting torque on the leg and a negative torque driving the wheel, making it roll backwards, and thus offsetting some of the velocity gain. However, for negative torques at the distal joint, the wheel would be driven forwards, hence augmenting the velocity increase of the robot. It is noted that the effect of varying wheel torques (at a constant hip torque) appear small in the figure due to the wheel torque, $\tau_1$, having approximately one thirtieth the torque of the hip motor, $\tau_2$. Nevertheless, in the ideal case where the wheel actuation is taken advantage of to assist the forward motion, some improvements in speed performance should result. The experimental results presented in Section 4 are obtained by employing wheel motors to simply prevent the wheels from moving and this results in decreased performance compared to the fixed-toe case.

![Diagram](image)

Figure 5: The R-R monopod whose two revolute joints are actuated, is a stiff model of one leg pair in the PAW robot. Forward speed of the body is compared at the two angles shown in (b). The simulation was run for variable torques at the two joints, standard gravity, an initial 300 deg/sec rotation about the distal joint and starting angles of 70 and -65 degrees for the distal and proximal joints, respectively. Similar results occur under different settings.

### 3.2 Effect of Liftoff Angles on Forward Speed: an MSC.ADAMS Model

While attempts have been made to control forward speed of the bounding gait using stance-retraction velocity such as with $\dot{\varphi}$-controller on Scout II [Talebi, 2000] or similar controllers on the PAW and RHex robots [Campbell and Buehler, 2003], it is the touchdown angles with respect to the body frame, $\varphi_{td}$ of the $\varphi$-controller, as discussed in [Poulakakis et al., 2005], which are used as the dominant control parameter for bounding speed control. Up to a certain limit, larger touchdown angles are required to accommodate higher running speeds. Here, the hypothesis that liftoff angles can be used to change forward speed is tested, first in simulation and then in experiment.

If one varies the liftoff angle, $\varphi_{lo}$, of the front and rear legs of a bounding quadruped it is also possible to adjust the forward speed without explicitly modifying the hip’s torque, $\tau$, or angular speed, $\dot{\varphi}$. Since the hip speed is not explicitly changed any reduction in the liftoff angle requires the leg to brake prior to the liftoff condition, as described in the state machine of Section 2.2.1. As
Figure 6: The R-R monopod simulation was run for variable torques at the two joints, standard gravity, an initial 300 deg/sec rotation about the distal joint and starting angles of 70 and -65 degrees for the distal and proximal joints, respectively. Similar results occur under different settings.
liftoff angle is made to be closer to the body’s vertical reference the robot is forced to increase its apex height during the flight phase. Likewise, if the liftoff angle is increased, the robot is brought closer to the ground during ballistic flight and increases its forward speed proportionally. As can be seen in Fig. 7 the trajectory becomes shallower as the liftoff angle is increased. This proposed method of speed adjustment is verified in the experiments presented in the following section. A more in-depth discussion of how this can be used for closed-loop speed regulation is a matter for future work.

![Diagram](image)

Figure 7: Varying the liftoff angle allows a tradeoff to be made between maximum apex height and forward speed. Liftoff angles are calculated relative to the body frame and not to a fixed global frame.

### 3.2.1 MSC.ADAMS Model

Using a numerical model programmed in MSC.ADAMS and a coupled Mathworks Matlab - Simulink controller, the above hypothesis was tested. The MSC.ADAMS model was created by disassembling the robot, weighing individual components (frame members, computer boards, actuators, cables, etc.), assigning the measured values into the Solidworks CAD model which had been used to originally construct the robot, and then obtaining the lumped body and leg segment masses and moments of inertia. Cables were modelled as straight cylinders through the centre of the body. The controller was ported to Matlab and Simulink from the actual C-code which is currently used on the robot. Data processing routines for both simulations and experiments were nearly identical, with minor changes based on differences in data structures of the experimental and simulation platforms.

A key feature that was included in the MSC.ADAMS model was a motor model. The equations describing a standard brushed DC motor are:
$e_a = k_E \omega_m$

$v_a = e_a + R_a i_a + L_a \frac{di_a}{dt}$

$T_{em} = k_T i_a$

$\frac{d\omega_m}{dt} = \frac{1}{J_{eq}} (T_{em} - T_L)$

In the above $e_a$ is the Back (Counter) electromotive force (EMF) produced by rotation of the motor shaft at speed $\omega_m$. The motor is characterized by $k_E$ and $k_T$, the speed and torque constants, where $k_E = k_T^{-1}$ when SI units are used. The applied armature voltage is $v_a$, the armature current is $i_a$, while the resistance and inductance present in the armature are $R_a$ and $L_a$, respectively. Torque applied by the current flowing through the motor is $T_{em}$. The load torque is $T_L$ and the combined rotor and load inertia present on the shaft is $J_{eq}$. Given that a permanent magnet is used, no field windings are present, unlike other DC motor topologies (i.e. shunt- and series-fed). This model yields a well-known speed-torque characteristic which, given a specific armature voltage, limits the performance of the motor. This saturation effect can be seen in experimental data gathered during bounding on the PAW robot, as shown in Fig. 8.

Figure 8: Hip speed-torque plot during the bound gait for PAW with mechanically blocked wheels (Exp. 2, Table 2). Note the saturation in the first and third quadrants.
3.2.2 The Bounding Simulation

Figure 9 illustrates the forward speed of the modelled robot for changes in liftoff angles in the front and rear legs. Touchdown angles of {-23, -28} and {-25, -30} degrees were used for Fig. 9(a) and Fig. 9(b), respectively. Liftoff angles were varied between 10 and 18 degrees for the front legs and between 20 and 40 degrees for the rear legs. Results in which the simulation model flipped, crashed, toe-stubbed excessively, or failed to move forward a significant amount were classified as failures and do not appear in Fig. 9.

It was found, via these simulations, that the general trend for increases in liftoff angle is an increase in forward speed as well. This is especially noticeable in the steep slopes on the left-hand sides, where small changes in rear liftoff angle provide large changes in forward speed. The changes in front liftoff angle provide more gradual changes in forward speed. The changes in forward speed which can be effected by the liftoff angles do have limits, as can be seen by the flattening of the curves in Fig. 9. At the highest values of rear liftoff angle this is due to motor saturation, whereby the leg cannot achieve the desired liftoff angle prior to the actual lifting off from the ground. At the highest values of the front liftoff angles, Fig. 9 also illustrates some slowing down of the model. This second type of saturation in speed increase due to liftoff angle changes is comparable to the saturation in speed increases observed when using touchdown angle control in Scout II [Poulakakis et al., 2005] and PAW [Smith, 2006].

4 Experimental Results

In this section, we present results for quadrupedal bounding. While a single type of bounding was obtained with PAW’s predecessor, Scout II, two variations of bounding and the new method of forward speed adjustment have been achieved on the PAW robot. In the Scout II experiments the liftoff angle was held fixed [Poulakakis et al., 2005], while the touchdown angle was adjusted to vary forward speed. In the PAW experiments, on the other hand, the touchdown angle was held fixed, while the liftoff angle was varied to adjust forward speed. The touchdown and liftoff angles were chosen after hundreds of preliminary experimental trials were performed to identify a significant region of control values which resulted in stable bounding. The PD controller gains, identified in the same trials, were kept constant throughout the experiments detailed here.

The bounding gait is explored using the distally-mounted wheels. The first bounding variation uses unactuated, mechanically blocked wheels. This provides a baseline set of results using passive, fixed toes. The second set of bounding results for PAW use actively controlled wheels.

4.1 Forward Speed Control Using Liftoff Angles

The hypothesis of increased liftoff angle resulting in increased forward speed was tested on the PAW robot with the mechanically blocked wheel configuration. The experimental results are summarized in Table 2. As shown in Fig. 10, the blocked wheel trials demonstrate an increase of speed with increased liftoff angle, confirming the forward speed versus liftoff angle hypothesis. Stride frequency increased with the speed increase, indicating that the apex heights were reduced and
Figure 9: MSC.ADAMS and Matlab-Simulink model simulation results showing the effect of changes in the commanded liftoff angles to the forward velocity of the robot. Touchdown angles where kept constant and equal to \{-23, -28\} and \{-25, -30\} degrees were used for Fig. 9(a) and Fig. 9(b), respectively. Liftoff angles were varied between 10 and 18 degrees for the front legs and between 20 and 40 degrees for the rear legs.
that an exchange between gravitational potential energy and kinetic energy levels was occurring as predicted by the model. This was confirmed through analysis of the video footage. Example still frames of related video footage are shown in Fig. 11.

Table 2: Experimental Results: PAW Bounding with Mechanically Blocked Wheels

<table>
<thead>
<tr>
<th>Exp #</th>
<th>Front Leg Touchdown, Lift-off Angles ($\varphi_{ftd}, \varphi_{flo}$) [deg]</th>
<th>Rear Leg Touchdown, Lift-off Angles ($\varphi_{rtd}, \varphi_{rlo}$) [deg]</th>
<th>COM Speed [m/s]</th>
<th>Stride Freq. (mean) [Hz]</th>
<th>Phase Diff. (mean) [%]</th>
<th>Strides To Converge.</th>
<th>Repeatability (Successful/Total Trials)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block1</td>
<td>(-20, 4)</td>
<td>(-22, 12)</td>
<td>0.87</td>
<td>3.3</td>
<td>19</td>
<td>5.6</td>
<td>10 / 10</td>
</tr>
<tr>
<td>Block2</td>
<td>(-20, 6)</td>
<td>(-22, 14)</td>
<td>0.99</td>
<td>3.5</td>
<td>19</td>
<td>3.8</td>
<td>10 / 10</td>
</tr>
<tr>
<td>Block3</td>
<td>(-20, 10)</td>
<td>(-22, 18)</td>
<td>1.18</td>
<td>4.2</td>
<td>16</td>
<td>8.8</td>
<td>10 / 11</td>
</tr>
</tbody>
</table>

4.2 Mechanically Blocked Wheels Versus Actively Controlled Wheels

The PAW robot was designed to evaluate the use of wheels during quadrupedal running gaits. The original hypothesis was that bounding could be accomplished with distally-mounted, actively-controlled wheels. To test this hypothesis two sets of experiments were conducted: the first with mechanically blocked wheels (described above) and the second with actively controlled wheels commanded to zero rotation. Similar front and rear touchdown ($\varphi_{ftd}, \varphi_{rtd}$) and liftoff angles ($\varphi_{flo}, \varphi_{rlo}$) were used in both cases, and the PD controller for both hip and wheel actuators were identical. In Fig. 12a one can see little measured wheel rotation when the wheels are mechanically blocked during bounding while, in Fig. 12b, wheels rotate to a greater extent during active wheel bounding. The results of these trials are summarized in Tables 2 and 3. Qualitatively, the bounding gait was similar in all trials, with the front legs touching down first after the ballistic phase, followed by the rear legs, as shown in Fig. 11. Quantitatively, it can be seen in Fig. 10 that the blocked wheel trials result in slightly faster bounding than the trials with actively controlled wheels.

5 Discussion

5.1 Testing of the two hypotheses

The first hypothesis, that increases in liftoff angle can be used to increase the forward speed, has been verified experimentally in the blocked wheel case and to some degree with active wheels, backing up the general trends found in the model simulations.

The experiments on the bounding gait in both active wheel and blocked wheel cases, however, reveal some subtleties that require addressing. First, as shown in Fig. 10, the performance of active wheel bounding is consistently below that of fixed wheel bounding. Unlike the simulations of Section 3.1,

\[2\text{The wheel control was deactivated during blocked-wheel running.}\]
Figure 10: Comparison of forward speed for bounding as liftoff angles of front and rear legs are increased. The performance of active wheel bounding is consistently lower than bounding with fixed wheels.

Table 3: Experimental Results: PAW Bounding with Actively Locked Wheels

<table>
<thead>
<tr>
<th>Exp #</th>
<th>Front Leg Touchdown, Liftoff Angles $(\phi_{f td}, \phi_{f lo})$ [deg]</th>
<th>Rear Leg Touchdown, Liftoff Angles $(\phi_{r td}, \phi_{r lo})$ [deg]</th>
<th>COM Speed [m/s]</th>
<th>Stride Freq. (mean) [Hz]</th>
<th>Phase Diff. (mean) [%]</th>
<th>Max. Pitch [deg]</th>
<th>Strides To Converge.</th>
<th>Repeatability (Successful / Total Trials)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active1</td>
<td>(-20, 4)</td>
<td>(-22, 12)</td>
<td>0.83</td>
<td>3.4</td>
<td>23.7</td>
<td>15.6</td>
<td>4.9</td>
<td>12 / 17</td>
</tr>
<tr>
<td>Active2</td>
<td>(-20, 6)</td>
<td>(-22, 14)</td>
<td>0.83</td>
<td>3.4</td>
<td>20.1</td>
<td>14.9</td>
<td>6.6</td>
<td>11 / 11</td>
</tr>
<tr>
<td>Active3</td>
<td>(-20, 6)</td>
<td>(-22, 16)</td>
<td>0.83</td>
<td>3.4</td>
<td>17.0</td>
<td>13.7</td>
<td>6.6</td>
<td>13 / 15</td>
</tr>
<tr>
<td>Active4</td>
<td>(-20, 8)</td>
<td>(-22, 16)</td>
<td>0.91</td>
<td>3.5</td>
<td>17.0</td>
<td>13.4</td>
<td>6.5</td>
<td>12 / 12</td>
</tr>
<tr>
<td>Active5</td>
<td>(-20, 10)</td>
<td>(-22, 18)</td>
<td>1.00</td>
<td>3.6</td>
<td>18.3</td>
<td>11.2</td>
<td>5.8</td>
<td>12 / 16</td>
</tr>
</tbody>
</table>
Figure 11: Still frame images from PAW active wheel bounding experiments. Note the large apex height and toe clearance. The cloth safety tether attached to the rear of the robot did not provide any support or influence the gait. Video was captured with an off-the-shelf consumer-grade DV video camera.
the wheels do not act to reinforce the applied hip torques. This is not entirely surprising given that upon examination of the wheel torques, it was found that the majority of their operation during stance was either in forward or reverse braking modes. This is a direct result of using a traditional Proportional Derivative controller which only seeks to minimize position changes in the wheel during stance.

Examining the behaviour of the robot when liftoff angles are changed and wheels are actively controlled, it is apparent that the Active4 and Active5 experiments follow the forward speed versus liftoff angle relationship. Unfortunately, the Active1, Active2 and Active3 experiments do not. In these trials, the speed and stride frequency remain approximately constant. However, both the maximum pitch and front-to-rear leg phase difference are increased in the Active1 and Active2 experiments. What this indicates is that the wheels are responsible for an increase in pitching motion prior to the ballistic phase, altering the relationship between speed and liftoff angle. An examination of the rear wheel torque shows a noticeable increase in braking torque in both Active1 and Active2 trials prior to liftoff, as shown in Fig. 13, thereby supporting this explanation.

5.2 Energetics: Power and Specific Resistance

Power efficiency, as measured in terms of specific resistance $\varepsilon$, [Gabrielli and von Karman, 1950, Yong et al., 2005], is presented in Fig. 14 for PAW bounding and for comparison to Scout II bounding and PAW in rolling locomotion. The corresponding plots confirm the basic trend for energy efficiency which is: the robots become more efficient as they speed up. These results also indicate a very similar performance achieved with Scout II and PAW bounding with blocked wheels, despite some physical differences and differences in forward speed control methods (touchdown angle versus liftoff angle).

PAW bounding with mechanically blocked wheels is currently substantially more efficient than bounding with actively controlled wheels. This is to be expected since the wheels are not explicitly
Figure 13: Mean torque values for a rear wheel for all strides in the five different active wheel experiments. The flight phase, in which the leg is not in contact with the ground, occurs between 0% and approximately 60% of the entire stride cycle. Only the stance phase, from approximately 60% of the stride cycle, until liftoff from the ground at 100% is shown. The Active1 and Active2 experiments demonstrate the largest braking torques prior to liftoff.
used to aid in propelling the vehicle forward and there are presently significant energy savings by using blocked wheels during the stance phase. In addition, the use of the wheels slows the robot down given the same touchdown and liftoff angles, as indicated in Tables 2 and 3. As discussed earlier, given that the wheel control method is relatively simple and that the wheel motors do not saturate during bounding it should be possible to devise a method of control which can use the wheels to develop a more efficient gait. These baseline results should be viewed as a first step towards such a goal.

![Electrical Specific Resistance vs. Speed](image)

Figure 14: Specific resistance of PAW while bounding with actively controlled wheels and mechanically blocked wheels. PAW’s rolling specific resistance, as well as Scout II’s bounding results are also provided for comparison. See Talebi [2000], Poulakakis et al. [2005], Smith et al. [2006] and Smith [2006] for specific resistance calculations.

5.3 Measuring Gait Success

In this section the quantifiable success of experimental gait trials is discussed. The first quantifiable measure of success presented is repetability in achieving a bounded limit cycle over a given number of trials. Then the quantization of the gait’s stability is discussed from the perspective of rate of convergence as well as the variability of a particular gait performance index via the measurement of its standard deviation.

5.3.1 Trial-to-Trial Repeatability

Most of PAW’s trials conducted using mechanically blocked wheels were successful, as shown in Table 2, yielding cyclic bounding gaits with no toe-stubbing or other non-trivial modes of failure. However, a few trials conducted for PAW’s actively controlled bounding experiments ended in critical failures. The higher failure rates seen at lowest and highest speeds are due to two factors. First, at the slowest speed the robot’s liftoff angles force it into higher ballistic phases, with a proportional decrease in stance time. Considering that much of the control effort which leads to stable motion occurs during the stance phase, this effectively means that the robot is spending more time in a mode where corrective action is not present, mostly with respect to pitching forward over its front
legs. Possible corrective action could be taken, for instance, through the use of a gyroscope and world-referenced touchdown angles. This sort of action is visible in videos of the CMU and MIT Leg Labs Quadruped, but were not designed into the PAW robot. Second, as the forward speed of the robot is increased, the apex heights it reaches during the ballistic phases of motion are decreased, making it stay closer to the ground. This increases its vulnerability to toe-stubbing when the legs are protracted, which in turn increases the chances of critical failure.

While several trials were voluntarily ended prematurely due to toe-stubbing, the PAW robot often recovered and continued bounding when it was permitted to continue without user intervention in preliminary trials. However, the authors set a high threshold for demonstration of gait success and, therefore, decided to classify even potentially recoverable trials as failures.

5.3.2 Quantifying Stability with Convergence Rate and Standard Deviation

The stride frequency easily lends itself to quantization from robot data. Changes in the stride frequency, such as during convergence to stable motion, have strong audible components that are immediately recognizable to the trained ear\(^3\), making evaluation of gait success relatively easy for the robot operator. Using the recorded stride frequency values one can measure both the rate of convergence as the number of strides to converge, and the variability of the gait as the standard deviation of the stride frequency during steady-state motion. These two values quantify the degree of stability of the system, with faster convergence rates and lower standard deviations being more desirable. These values are listed in Table 2 and 3 for PAW. While the average number of strides required for convergence is only slightly lower with mechanically blocked wheels on PAW, the standard deviation for actively controlled wheels is significantly higher.

6 Conclusions

In this paper, we presented experimental results obtained with PAW, exhibiting the bounding gait. The most unique contribution of the work presented here is the demonstration of the possibility of using actuated wheels as toes in a running system.

To test our first hypothesis that the forward speed could be increased by increasing the liftoff angle, a variation on the original $\varphi$-controller was proposed and experimentally demonstrated on PAW. The hypothesis was confirmed in both simulation and in experiment, establishing the liftoff angle, $\varphi_{lo}$, as a second parameter in addition to the touchdown angle, $\varphi_{td}$, for forward speed adjustment in the bounding gait. As with results for Scout II and PAW using touchdown angle for speed control, limits to maximum speed changes are also shown with respect to liftoff angle changes in PAW. This is most apparent in the simulation results of Fig. 9, but were also found in the limiting cases of the experimental trials.

Testing of the second hypothesis, that wheels can be used in a running quadruped robot, led to some interesting conclusions. First, the basic bounding gaits in both mechanically blocked and actively controlled wheel cases are similar enough that casual observers may not notice major differences.

\(^3\text{In the same way, the robot operator can hear changes in leg phase differences such as those between one-, two- and four-beat gaits.}\)
Upon closer inspection it was found that the bounding with actively controlled wheels is less efficient and exhibits relatively constant leg compression and duty factor values. Most important, not only is the reliability reduced, as shown in Tables 2 and 3, but forward speed is reduced by about 15% due to wheel usage. These results are not surprising since currently only a simple PD controller is used to prevent the wheels from significant rotation. We expect that further research in this direction will bear improved performance of the bounding gait when the wheels are controlled specifically with that goal.

Acknowledgments

The authors would like to thank a number of people who have been involved in the PAW projects, particularly Martin Buehler. Carl Steeves must also be acknowledged specifically for his initial work on the PAW robot. We also appreciate the help and support of Don Campbell, Dave Cowan, Philippe Giguère, Michelle Huth, Julien Marcil, Dave McMordie, Neil Neville, Chris Prahacs, Enrico Sabelli, Aaron Saunders, Shane Sauderson, John Sheldon, and Mike Tolley. James A. Smith’s work has been made possible through support from Defence R&D Canada. Special thanks go to the authors’ colleagues at Defence R&D Canada – Suffield for their support over the course of the PAW development.

References


