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Robot Design and Control Algorithm Development for Wheeled Mobility Behaviours

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Technical Memorandum
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Abstract

This paper discusses current wheeled mobility research on a hybrid wheeled-leg robot called PAW. In addition to providing design details, controllers for wheeled modes of locomotion including inclined turning and sprawled braking are presented. These controllers are designed to take advantage of the hybrid nature of the platform to enhance the wheeled behaviour stability and locomotive performance of the robot. Experimental results are presented and discussed. Four basic results have been obtained, including a maximum cruising speed, an operational range, initial turning tests, and a demonstration of a sprawled rolling and braking posture. Power consumption values for a number of its basic behaviours are also presented.

Résumé

Cet article discute de la recherche actuelle sur la mobilité à roues d'un robot hybride monté sur jambes roulantes appelé PAW. Il fournit des détails quant au concept et présente aussi des unités de contrôle pour des modes de locomotion à roues dont la prise de virage et le freinage étalé sur plan incliné. Ces unités de contrôle sont conçues pour tirer profit de la nature hybride de la plate-forme afin d'améliorer la stabilité du comportement roulant ainsi que le rendement locomotif du robot. Des résultats expérimentaux y sont présentés et discutés. Quatre résultats de base ont été obtenus dont un régime optimum de navigation, une portée opérationnelle, des essais initiaux de prise de virages et une démonstration en position de roulage et de freinage étalé sur plan incliné. Des valeurs de consommation d'électricité pour un certain nombre de ses comportements sont aussi présentées.

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Executive summary

This paper presents current wheeled mobility research of a hybrid wheeled-leg robot called PAW. In addition to providing design details, controllers for wheeled modes of locomotion, including inclined turning and sprawled braking, are presented. These controllers are designed to take advantage of the hybrid nature of the platform to enhance the wheeled behaviour stability and locomotive performance of the robot. In this paper experimental results are presented and discussed. Four basic results have been obtained, including a maximum cruising speed, an operational range, initial turning tests, and a demonstration of a sprawled rolling and braking posture. The robot demonstrates an ability to travel in a straight line at an average speed of 1.4 m/s. Power consumption values are also measured and an operational driving distance of over 2500 m in the span of approximately one hour was determined. The robot performs turns by executing controllers that exploit the robot's ability to reconfigure wheel placement. In addition, through appropriate wheel placement and low controller gains, the robot demonstrates the ability to brake without tipping over.

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Sommaire

Cet article discute de la recherche actuelle sur la mobilité à roues d'un robot hybride monté sur jambes roulantes appelé PAW. Il fournit des détails quant au concept et présente aussi des unités de contrôle pour des modes de locomotion à roues dont la prise de virage et le freinage étalé sur plan incliné. Ces unités de contrôle sont conçues pour tirer profit de la nature hybride de la plate-forme et améliorer la stabilité du comportement roulant ainsi que le rendement locomotif du robot. Des résultats expérimentaux y sont présentés et discutés. Quatre résultats de base ont été obtenus dont un régime optimum de navigation, une portée opérationnelle, des essais initiaux de prise de virages et une démonstration en position de roulage et de freinage étalé. Le robot démontre une capacité à se déplacer en ligne droite à une vitesse moyenne de 1,4 m/s. On a mesuré les valeurs de consommation d'électricité et on a déterminé la distance opérationnelle de conduite comme étant supérieure à 2 500 m durant un intervalle d'environ une heure. Le robot exécute des virages au moyen de contrôleurs d'exécution qui exploitent la capacité du robot à reconfigurer le placement des roues. De plus, le robot démontre sa capacité à freiner sans se renverser au moyen du placement approprié des roues et des gains faibles de l'unité de contrôle.

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1. Introduction

The objective of the Autonomous Intelligent Systems Section (AISS) of Defence R&D Canada – Suffield (DRDC Suffield) is best described by its mission statement, which is ”to augment soldiers and combat systems by developing and demonstrating practical, cost effective, autonomous intelligent systems capable of completing military missions in complex operating environments.” The mobility requirement for ground-based mobile systems operating in urban settings must increase significantly if robotic technology is to augment human efforts in these roles and environments. The urban setting, both indoor and outdoor, poses numerous unforeseeable mobility challenges for robots. It includes trenches, berms, abandoned vehicles, rubble, wire barricades and operation in buildings with tight confines designed on a human scale. In order to achieve this objective, AISS is pursuing Intelligent Mobility research that explores the use of novel mobility platforms incorporating intelligent mobility algorithms designed to improve robot mobility in unknown highly complex terrain. The algorithms seek to exploit the inherent capabilities of the platform and available world representations of the environment to allow the robot to interact with its surroundings and produce locomotion in complex terrain. As a result, the mobility characteristics of robots designed in this manner will outperform larger systems without these capabilities.

The Platform for Ambulating Wheels (PAW) robot is one research vehicle testbed developed to investigate how the inherent dynamic capabilities of a platform can be exploited to produce improved mobility characteristics. The PAW robot combines aspects of legged and wheeled locomotion in order to achieve greater mobility. In wheeled modes of operation, it is able to take advantage of locomotive efficiencies of ground traversal, especially in conditions where the terrain is flat. In legged modes of operation, the dynamic behaviours of the robot including jumping and bounding, allow the robot to operate in increasingly complex terrains where conventional rolling is prohibitive. Thus, the PAW robot has the potential to outperform conventional vehicles of much larger geometric scale in its ability to overcome obstacles and negotiate unstructured terrain.

While this research represents a potentially significant contribution to the state of the art, it alone does not fully solve the mobility problem for UGVs operating in unknown terrain. Any of the resulting mobility behaviours of the robot must be mated with relevant world representation information of the environment so as to allow the UGV to interact intimately with its surroundings. Given this context, the focus of this paper is to present the current work in developing the primarily kinematic wheeled aspects of PAW’s locomotion behaviours only. The results described in this paper have implications for high speed locomotion in which vehicle dynamics play a role, such as in braking and high speed turning.

Section 2 provides a brief overview of mobile robotics research and examples of robots for each area that represent the state-of-the-art. This background provides the context for the PAW research introduced in Section 3. It discusses the formulation of the PAW concept and provides detail of the final design, which serves as a platform for the study of both wheeled and dynamically-stable-legged locomotion. Two types of control algorithms are discussed in Section 4, which are designed to enhance the wheeled behaviour capabilities of the PAW robot. Experimental results of these control algorithms are presented in Section 5 including discussion of wheeled behaviour performance. The paper concludes with a summary of the experimental results and discussion of the resulting improvements to vehicle stability and performance.

2. Background of Mobile Robotics

In this section, a brief overview of mobile robotics research is presented including small/medium wheeled and tracked mobile robots, legged robots, and articulated suspension systems. Examples of robots representing the state-of-the-art in each of these research areas are also presented. This background provides the context for the research direction of the PAW robot.

2.1 Small/Medium Wheeled and Tracked Mobile Robots

Traditionally, designers of ground-based mobile systems tend to create vehicles which use wheels or tracks for locomotion. These vehicle designs can take advantage of a large accumulated knowledge base, they have very good performance characteristics, and methods for maintenance, construction and manufacturing are well established and tested [1] - [3]. These vehicles offer an efficient and often rapid method of ground traversal, especially in conditions where the terrain is flat. Of particular relevance to the mobile robotics community, a number of studies have been performed on relatively small tracked or wheeled platforms (e.g. [4, 5]), of which iRobot's Packbot [6] is one of the more successful and widely deployed examples.

2.2 Legged Robots

As mobile robots are required to operate in increasingly challenging environments, the limitations of traditional wheeled and tracked vehicle designs become increasingly apparent: their simple and robust design does not provide sufficient versatility and adaptability for many real-world terrain conditions. Design modifications, which add passive or active degrees of freedom with or without compliance, can be made to make these vehicles better suited to rough terrain. Packbot's foot-like tracked paddles and NASA's Sojourner rover's bogies [7] are examples of modifications made to traditional tracked and wheeled vehicles. The result of these modifications are vehicles that possess enhanced mobility relative to traditional small/medium wheeled and tracked systems.

In an effort to provide the required versatility and adaptability, legged locomotion is commonly cited as an alternative to traditional wheeled and tracked designs. The biological world is filled with a multitude of *incredibly complex* legged locomotion examples that have inspired many scientists and engineers. Although not as broad as the literature available for wheeled or tracked vehicles, knowledge about the analysis and synthesis of legged systems is available [8] - [10]. In general, legged systems are mechanically more complex, less efficient, have smaller operational ranges, require more complex control, and have higher peak power and torque requirements than wheeled or tracked systems. Their payloads and sensors must often be designed to withstand or compensate for oscillatory motion.

For all of these disadvantages, legs still have potential advantages. Biological examples of legged systems that readers are familiar with reinforce the notion that legs provide versatility, redundancy and potential adaptability that simple wheeled and tracked systems cannot. Wheeled and tracked vehicles require, for the most part, continuous contact surfaces whereas legged systems can locomote on terrain with isolated footholds. Legged robots, such as those developed within the RiSE project, can be designed specifically for environments where foothold selection is critical, such as vertical surfaces [11].

In addition, artificial legged systems are no longer limited to quasi-static motion, as was demonstrated in the 1980s at Carnegie Mellon University and Massachusetts Institute of Technology Leg Labs where simple controllers were made to stabilize high speed motion of monopedal, bipedal and quadrupedal robots [10]. Even simpler controllers for high speed quadrupedal locomotion have recently been implemented on the Scout II robot at McGill University's Centre for Intelligent Machines. the [12]. The six-legged RHex platform [13] was shown to be largely as capable as the commercially developed PackBot platform under difficult outdoor conditions [5].

2.3 Articulated Suspension Systems

It is possible to obtain many of the advantages of both traditional wheeled and legged systems by combining aspects of both into a single articulated suspension platform. Examples of these are the Shrimp and Hylos platforms. The Shrimp system, developed by the Autonomous Systems Lab at the Swiss Federal Institute of Technology Lausanne, negotiates terrain with actuated wheels and a passive adaptation mechanism [14]. In contrast, the wheel-legged robot Hylos at the Laboratoire de Robotique de Paris uses active posture control to adapt to irregular terrain in order to maintain stability and traction [15].

3. The PAW Robot: a Hybrid Wheeled-Leg System

The PAW robot depicted in Fig. 1 is an active research project between McGill University's Centre for Intelligent Machines and DRDC Suffield. PAW has been designed as a platform for the study of both wheeled and dynamically stable legged modes of locomotion and to be power and computationally autonomous. Like the

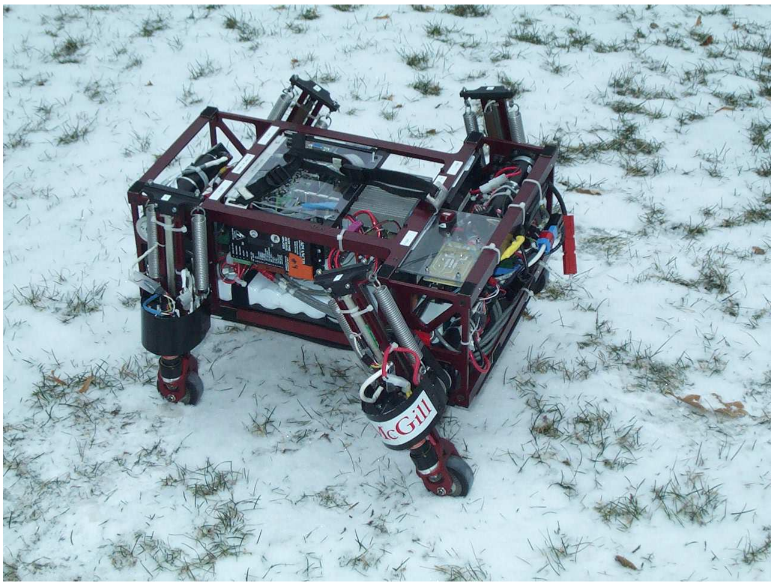


Figure 1: *The PAW Robot*

articulated suspension systems mentioned earlier, it combines aspects of legged and wheeled locomotion in order to achieve greater overall mobility. This section describes the mechanical, electrical, and sensor design of the robot. It also discusses the control scheme for the motor actuators that produce both wheeled and legged locomotion for the robot.

3.1 Mechanical Components

The body of the robot consists of a T-shaped aluminum frame, as shown in Fig. 2. The robot has four compliant legs and an active wheel placed at the foot of each leg. Thus, each leg has three degrees-of-freedom: an actuated joint at the hip, a passively compliant telescoping leg, and an actuated wheel joint. The basic parameters of the PAW robot are listed in Table 1.

The hip joints of the four legs are each driven 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. A toothed belt and pair of sprockets provide a further 1.33:1 reduction ratio.

Each leg is equipped with a pair of extension springs rated at 3200 N/m. At the end of each leg is 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 0.0633 m. diameter wheel. The wheel motors' quadrature encoders are identical to those of the hip motors. Selection of the hip motor, planetary gearbox, and sprocket combination was made to maximize available hip torque. The availability of high hip torque is especially important when the robot stands up or carries a payload.

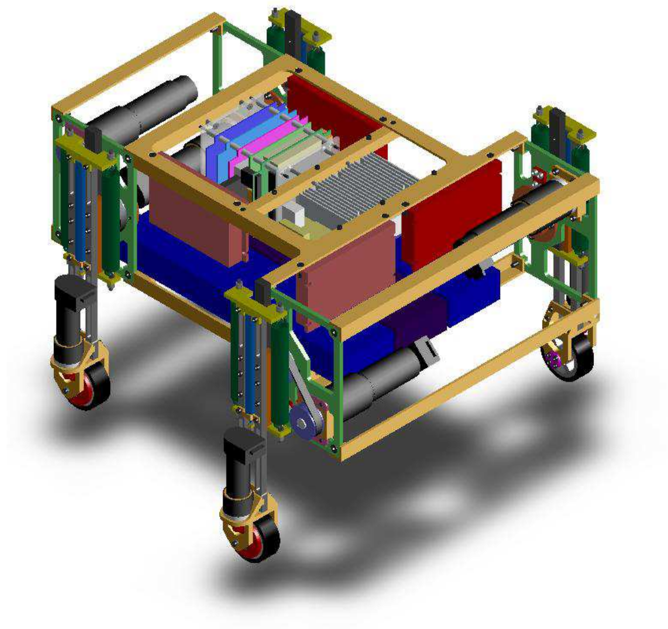


Figure 2: *The PAW Robot Solidworks CAD Model*

Table 1: *PAW Body Parameters*

Parameter	Value
front width	0.366 m
rear width	0.240 m
body length	0.494 m
hip separation	0.35 m
wheel diameter	0.0633 m
leg length	0.209 m
body height	0.170 m
max body clearance	0.124 m
leg mass (each)	1.2 kg
body mass	15.7 kg
leg spring constant	3200 N/m

Power and signal wires to the motors and sensors on each leg are passed through a hollow hip axle to the vehicle chassis. This prevents the cables from becoming entangled in the legs and results in a simpler and more compact solution than that which can be provided with conventional commercial slip rings. Unfortunately, this prevents the legs from continuous rotation, as is the case in robots such as RHex. The legs are equipped with actuated hard rubber wheels. In wheeled modes of operation, the four hip motors can position the wheels at various positions with respect to the body of the robot. In legged modes the wheels are actively locked, effectively making them compliant toes, and allowing dynamic behaviours such as jumping and bounding [16].

3.2 Electrical Components

Apart from the motors described earlier, other relevant electrical components on the robot include a PC/104 computer stack, four AMC 25A8 brushed DC motor amplifiers, a custom amplifier board containing Apex SA60 motor amplifiers, and three NiMH battery packs.

The PC/104 computer stack contains a Pentium-compatible processor board running the QNX 6.1 real-time operating system and control code, a PCMCIA board with wireless Ethernet card for teleoperation control, a power supply board, and a quadrature decoder board for obtaining motor angles.

The AMC amplifiers are set to deliver 10 A of continuous current (20 A peak) to drive each of the hip motors. The Apex amplifiers drive the wheel motors and are capable of delivering 10 A continuously.

Two different sets of NiMH battery packs, made up of industry standard D-cells, are used. The Twicell HR-D packs are manufactured by Sanyo and have a charge capacity of up to 7.5 Ah. The VH D cells are manufactured by Saft and possess a charge capacity of up to 9.5 Ah.

3.3 Proprioceptive Sensors

Currently, the PAW robot uses proprioceptive sensor information to control its locomotion behaviours. In addition to battery voltage and current sensors, the robot uses one quadrature encoder with 2000 counts per revolution effective resolution in each of its eight motors, one linear potentiometer with up to 0.10 m range in each of its four legs and a current sensor on each hip motor amplifier.

The motor encoders are used to determine the angle of the eight motor shafts (four hip, four wheel), while the linear potentiometers are used to measure leg compression.

By measuring current consumption and battery voltage, it is possible to determine power usage in various subsystems of the robot. In the case of the hip motor amplifiers, measurement of current provides a proportional estimate of motor torque applied to the hip.

Finally, a SilMU-01 Inertial Measurement Unit (IMU) is now available for measuring three axes of rotation and three axes of linear velocity. The IMU combines three micro-electromechanical system (MEMS) gyroscopes and three MEMS accelerometers. This IMU was chosen for its high angular velocity and linear acceleration ratings, high update rate, relatively small size, low drift rate and its ability to perform onboard integration of sensor readings yielding attitude values and linear velocity solutions of the vehicle without the need for additional data. The IMU has not been used in any of the vehicle behaviours to date, but will be used in the future for closed-loop control of the robot.

3.4 Motor Control Design

Control of the wheeled behaviours presented in this paper is achieved through the use of proprioceptive sensor information only. Specifically, measurements of motor position, voltage and current are used for control feedback. At the heart of the control for each joint of the robot is a proportional-integral-derivative (PID) controller that is responsible for either maintaining a desired position or a desired velocity at that joint. The equation for position control of a particular joint is described as:

$$\tau_{desired} = k_p \Delta_{position} + k_i \Sigma_{\Delta_{position}} + k_d \Delta_{velocity} \tag{1}$$

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

The desired motor torques are converted into control signal voltages which are then fed into one of two types of amplifiers. AMC 25A8 amplifiers are used in closed-loop current/torque control mode for the hips. The control signal voltage for the hip amplifiers is set to be proportional to the desired amplifier current using the manufacturer specified conversion factor, while the resulting amplifier current is directly related to the motor shaft torque using conversion factors and efficiency values provided by Maxon Motors.

Apex Microtechnology SA60 amplifiers are used to drive the wheel motors operated as open-loop PWM amplifiers. By estimating current draw by the motors driven by these amplifiers, it is possible to obtain a reasonable estimate of the applied torque at each wheel. Details on motor current estimation without direct measurement, using a motor model, battery voltage measurements and motor speed measurements, are explained in [17].

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. In the case where the controller is required to maintain a particular velocity, a constant desired velocity is set and a matching desired position trajectory is computed. Alternatively, PID controllers can be set up using wheel velocities and accelerations. This method has the disadvantage of using a double derivative in the form of the motor acceleration, which is susceptible to large transient values due to time measurement errors. Transitions between one set of desired velocities and/or positions and another is resolved using cycloidal functions, [18], which provide smooth motion and are relatively computationally efficient.

Because the robot is redundantly actuated during wheeled modes of locomotion, it is not possible to have overly high gains on all joints since there is no coordination between individual motor controllers. High gains are set on the hip actuators to ensure that the wheels are properly positioned with respect to the body and lower gains are used at the wheels, resulting in relatively compliant wheel motion. This active compliance tends to smooth out wheel velocity transitions.

4. Wheeled Behaviours: Turning and Braking Controller Design

Two types of controllers are introduced in this section, which are designed to enhance the wheeled behaviour capabilities of the PAW robot. The first describes a method for turning, while the second describes a method for braking. Both controllers take advantage of the ability to reposition the wheels with respect to the body of the robot. The current work discussed in this section is limited to developing the primarily kinematic wheeled aspects of PAW's locomotion behaviours. However, the results described in this paper have implications for high speed locomotion in which vehicle dynamics play a role, such as in braking and high speed turning.

4.1 Inclined Turning Controller

Turning of the robot is achieved through a modified version of the standard differential / skid steering approach. Rather than applying differential wheel speeds on either side of the robot with the legs fixed, the legs are used to reposition the wheels to reduce shear forces at wheels and bending moments on legs. Effectively, this means that while the legs on the outside of the turn are kept vertical with respect to the body, the legs on the inside of the turn are brought together, lowering the center of mass (COM) and leaning the robot *into* the turn.

Given a desired turning radius for the ground-projected centre of mass, two concentric circles are determined which share the same centre as the turning radius of the COM but which intersect either the inner or outer wheel pairs. Wheel speed is then set in a proportional fashion to the desired ground-project centre-of-mass speed.

For the following calculations the robot is assumed to be rectangular and contact between the wheels and the ground are point contacts. Given a desired COM height, H, a known maximum leg length, l, and a known body width, W, and a requirement that

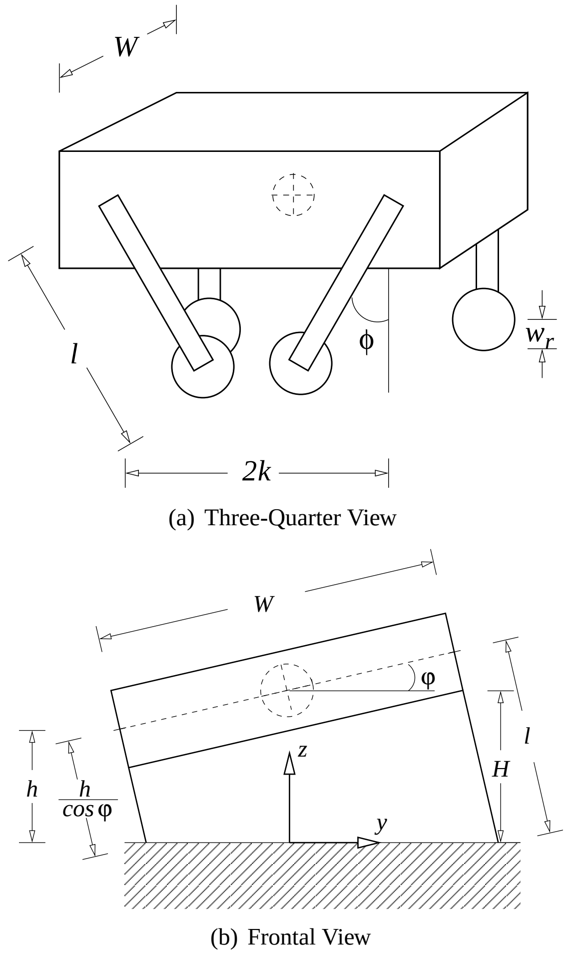


Figure 3: *Simplified views of PAW illustrating some important variables used in calculating hip angles for the turning algorithm.*

one pair of legs must remain vertical with respect to the body's local coordinate frame, a roll angle, φ, can be determined:

(2)
$$\varphi = acos(\frac{H}{\sqrt{l^2 + \frac{W^2}{4}}}) + atan(\frac{2l}{W}) - \frac{\pi}{2}.$$

Next, the height of the hips of the inner legs, h can be determined:

(3)
$$h = lcos(\varphi) - Wsin(\varphi).$$

The angle, ϕ, at which the hip angle is set with respect to the body can now be calculated:

(4) $$\phi = acos(\frac{\frac{h}{cos\varphi} - w_r}{l'})$$

where w_r is the radius of the wheel and l' is the length of the leg from the hip to the wheel axle, $l - w_r$. The second hip's angle is simply set to $-\phi$, resulting in the inner hips being in a tucked configuration, as seen in Fig. 3a.

In order to determine the inner and outer turning radii, one must determine the location of one of the wheels in the inner pair and one in the outer pair with respect to the COM of the robot. Defining x and y axes to form a plane parallel to the ground, whose origin is located directly below the COM, yields:

(5) $$x_{inner} = -l'sin(\phi) + k$$

(6) $$y_{inner} = -\frac{W}{2}cos(\varphi) + hsin(\varphi)$$

(7) $$x_{outer} = k$$

(8) $$y_{outer} = \frac{W}{2}cos(\varphi) + lsin(\varphi)$$

where k is half the hip spacing. Given a desired turn radius for the COM, r_{COM}, the turn radius for the inner legs can be found as follows:

(9) $$r_{inner} = \sqrt{(x_{inner})^2 + (-y_{inner} + r_{COM})^2}$$

while the turn radius for the outer legs is

(10) $$r_{outer} = \sqrt{(x_{outer})^2 + (y_{outer} + r_{COM})^2}.$$

With the radii of the inner and outer wheels determined, the wheel speeds are set so that the difference between the COM speed and inner and outer wheel speeds is proportional to corresponding radii differences.

4.2 Sprawled Braking Controller

Another important aspect of wheeled locomotion that must be considered is stopping. While driving forwards or backwards, it is important to apply braking action in such a way as to prevent the robot from pitching over. Pitching motion can result from braking too suddenly or by angling the legs either vertically or in a tucked configuration. During forward and reverse driving, the robot places its legs in a sprawled posture, at about 11.5 degrees with respect to the body's vertical reference. When a brake command is issued, the motors are used to dissipate the kinetic energy of the robot through the use of low gain PID controllers, as described in Section 3.4. This also prevents wheel slip.

5. Experimental Results

In this section, experimental results are presented and discussed. Four basic results have been obtained, including a maximum cruising speed of 1.4 m/s, an operational range of over 2500 m achieved in approximately one hour, initial turning tests with a radius of approximately 1 m, and a demonstration of a sprawled rolling and braking posture.

5.1 Cruising Speed Experiments

The predicted maximum loaded rolling velocity for the robot has been discussed in [16] to be approximately 2 m/s. The highest straight-line speed attempted on the robot to date is 1.4 m/s, although slightly higher speeds (1.7 m/s) have been observed on the outer wheels during turning behaviours. At these speeds it has been found that the robot's wheel motors warm up only slightly, indicating that they are not being overdriven.

For mobile robots to be of practical utility, they need to be energy efficient and be able to operate in a power autonomous fashion for extended periods of time. An increasingly accepted measure of energy efficiency is the specific resistance - a measure originally proposed by Gabrielli and von Karman [19],

$$\epsilon(v) = \frac{P(v)}{mgv}$$

where P is the power expenditure, m is the mass of the vehicle, g is the gravitational acceleration constant, and v is the vehicle speed. With the ability to measure both battery voltage and the current consumption of the robot at any given instant, it is possible to calculate the average power consumed by the robot during operation. While sitting with its body against the ground, the robot has an average quiescent power consumption of 35.5 W. Comparatively, when placed on a 25 degree slope, with its legs locked perpendicular to its body and its wheels in active brake mode the robot consumes approximately 160 W.

Power consumption has also been measured for the robot rolling in a straight line at constant speed. At a speed of 0.47 m/s its average power consumption has been found to be 50.5 W, while at its maximum speed, 1.4 m/s, this is 60.8 W. This corresponds to a specific resistance of 0.53 at low speed and 0.22 at current maximum speed, indicating that the robot runs more efficiently at the higher speed. In comparison, legged robots such as Scout II have an unsurprisingly higher specific resistance: 1.4 while bounding at 1.3 m/s [12].

5.2 Operational Range

The robot uses three battery packs composed of a total of 30 NiMH D-Cells, as discussed earlier. At a top speed of 1.4 m/s, the robot draws approximately 1.6 A yielding a peak theoretical run-time of four hours using the HR-D battery packs mentioned in Section 3.2, and six hours with the VH D battery packs. On flat ground, this translates to a maximum theoretical distance of between 20 kilometers with the HR-D battery packs and 30 kilometers with the VH D battery packs. To test the maximum range of the robot under somewhat more realistic conditions than non-stop straight line motion, the robot was made to move back and forth on a three metre track with a maximum desired speed of 1.4 m/s until a critical (below 32 VDC) battery voltage was detected. Using a set of the VH D battery packs the robot travelled a total of 2562 m in 59 minutes. The test was terminated when the battery voltage dropped suddenly from above 32 VDC to 21 VDC during a deceleration. It should be noted that the robot was stopped once every 12 to 15 minutes to verify that the wheel motors had not warmed appreciably. In order to increase operational range the frequency of direction-of-travel changes could be lowered, deceleration and acceleration phases could be increased in length to decrease maximum current draw in the wheels, and the legs could be positioned more vertically to reduce current draw of the hip motors.

5.3 Turning

A series of tests were conducted on the turning behaviour. The first turn test performed involved lowering the center of mass height to 0.19 m by tucking the legs on one side of the robot to 37.4 and -37.4 degrees with respect to the body's vertical axis. To obtain a desired turning radius of 1 m the outer wheels were set to spin at 124% of desired centre of mass speed, while the inner wheels were set to 81%. Setting the desired speed of the centre of mass to 1.4 m/s an average resulting speed of 1.47 m/s was obtained on a circle with a radius of approximately 1.25 m. A second set of trials was performed with the same hip angles but for a desired turn radius of 0.5 m and a desired COM speed of 1.4 m/s. The result was a turn radius of approximately 0.9 m and a speed of 1.86 m/s. In the last set of experiments the hip angles were increased to nearly 65 degrees. With the desired COM radius set to 0.5 m and a desired COM speed of 1.4 m/s (inner wheel speed set to 65% and outer to 154% of COM speed), the robot followed a circle with a radius of 0.75 m at a speed of 1.77 m/s.

Roll-over stability is an important factor in the design of many wheeled vehicles [20].

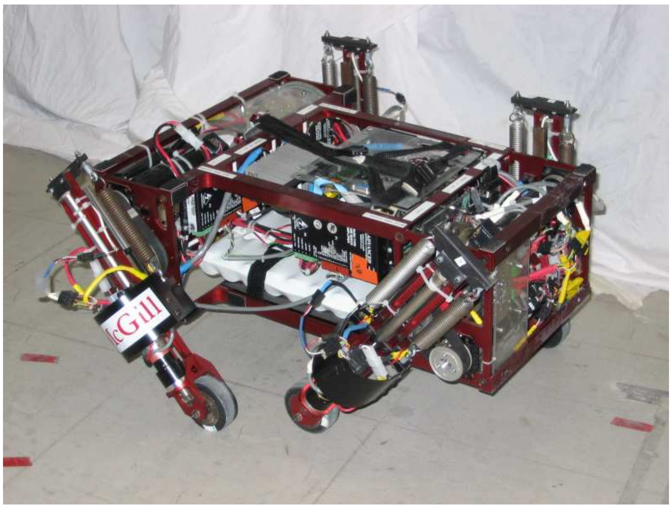


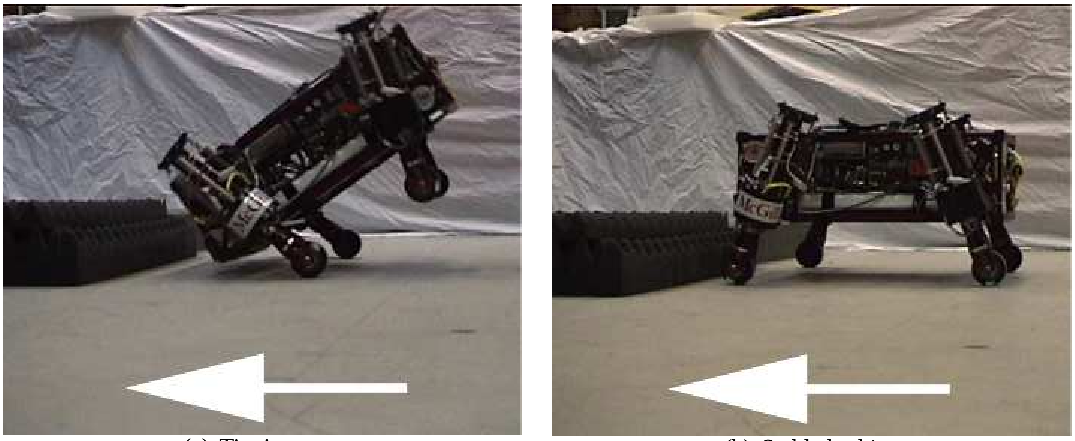
Figure 4: *The PAW robot executing an inclined turn.*

Experiments demonstrate that increasing the roll-over stability of the robot via the proposed and implemented turning algorithm is not critical at the speeds and radii of curvature it currently travels at. This would become more important at higher speeds for this or a scaled-up version of the vehicle.

5.4 Braking

To demonstrate the positive aspects of the braking algorithm described in Section 4.2, experimental trials were performed with the robot driving at 1.4 m/s with the legs initially tucked in and then with the legs sprawled out. These trials were carried out initially using high control gains and subsequently low control gains for the wheel motors (the hip motors used relatively high gains throughout). In the first set of trials, the legs were tucked in at 11.5 degrees. The robot was driven forward and a high gain braking command was issued once the robot had reached steady-state speed. This resulted in the robot pitching forward, as shown in Fig. 5a. In the second set of trials, the wheel controller gains were lowered, making the braking phase slightly longer. The result was that while the front of the robot dipped visibly with the legs compressing somewhat, it did not tip over. In the third set of trials, the robot attempted high gain stopping with the legs sprawled out at 11.5 degrees. While the robot stopped quickly and demonstrated no pitching motion, the wheels slipped along the linoleum floor. In the fourth set of trials, the robot's legs were sprawled outwards and the wheel controller gains set low, resulting in the robot stopping as shown in Fig. 5b, neither pitching forward nor slipping.

These experiments demonstrate that by combining a sprawled posture with relatively low wheel control gains it is possible to brake the robot's forward high speed motion without causing slip or pitching motion.



(a) Tipping over (b) Stable braking

Figure 5: *Two different braking methods, one which leads to tipping the other which is stable. The robot is travelling from right to left.*

6. Conclusions

This paper discusses current wheeled mobility work on a hybrid wheeled-leg robot called PAW. In addition to providing design details, controllers for inclined turning and sprawled braking for the robot were also presented. These control algorithms take advantage of the hybrid nature of the platform to provide improved stability and performance. Experimental results of these algorithms are presented and their enhancements to robot stability and performance are discussed. Specifically, the robot demonstrated an ability to travel in a straight line at an average speed of 1.4 m/s. It performed turns by executing control algorithms that take advantage of the robot's ability to reconfigure wheel placement. In addition, through appropriate wheel placement and low controller gains the robot demonstrated the ability to brake without tipping over. Power consumption values were also measured during experiments with the PAW robot. Experiments show an operational range for the PAW of over 2500 m in the span of approximately one hour.

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This paper discusses current wheeled mobility research on a hybrid wheeled-leg robot called PAW. In addition to providing design details, controllers for wheeled modes of locomotion including inclined turning and sprawled braking are presented. These controllers are designed to take advantage of the hybrid nature of the platform to enhance the wheeled behaviour stability and locomotive performance of the robot. Experimental results are presented and discussed. Four basic results have been obtained, including a maximum cruising speed, an operational range, initial turning tests, and a demonstration of a sprawled rolling and braking posture. Power consumption values for a number of its basic behaviours are also presented.

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