Effects of Wheel Synchronization for the Hybrid Leg-Wheel Robot Asguard

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Abstract

Hybrid Leg-Wheel Robots have gained increasing popularity over the last years, as they can combine the terrain negotiation ability of legged systems with the efficiency and simplicity of wheeled systems. In this paper, the effects of locomotion patterns on the system’s efficiency are studied for the legged-wheel robot Asguard. The locomotion pattern is controlled by setting the motion offsets between the wheels, and maintaining the synchronization during the motion using a cascaded position-velocity controller. The front-back and left-right wheel offsets are changed to generate different patterns. The efficiency of locomotion for these offsets, defined by specific resistance, is experimentally determined at different speed and terrain configurations. Experimental data was gathered with the help of a motion tracker system, to also analyze the vibration of the robot. The locomotion offsets showed a significant impact on the efficiency, especially at low speeds.

1 Introduction

The Asguard system (Figure 1) was developed at German Research Center for Artificial Intelligence (DFKI) with the purpose of being able to traverse through unstructured and uneven terrains. Currently, the robot is part of the project Intelligent Mobility, which aims at giving the robot ability to autonomously explore planetary or lunar surfaces. The robot’s innovation lies in the hybrid leg-wheel (Figure 2) design, which is formed of five spike-like structures. The novelty of this design generates the need for an extensive study of the body configuration in order to develop a good understanding of the abilities and control requirements.

Leg-wheel hybrid designs have certain advantages over pure leg or wheel designs. First, its design is simple and sturdy, and is inherently stable compared to walking robots. Indeed, the robot, even without power, can stay standing as is the case with wheeled robots. Second, it can handle more difficult terrain than wheeled systems, as its leg-wheel has a better ground contact in most situations.

However, the mechanical linkages between the four legged-wheels removes the flexibility in foot placement that legged systems have. It also has some impact on the way the wheels should be controlled, as will be explained later.

Researchers have always tried different models of locomotion, mostly taking inspiration from the biological world. Study on the motion gait pattern of Pika [8] shows how gait pattern is used in locomotion. There is a noticeable change in locomotion pattern with change in speed in animals. This gait pattern and the angle of attack [2][8] transforms to the synchronization between the wheels in Asguard. The angle of attack is the angle at which the leg hits the ground. It becomes more important at higher speeds, at which the amount of bounce in the robot determines the optimum angle of attack. It might be possible to control the bouncing behavior and the angle of attack through the synchronization. A bad synchronization could result in a higher angle of attack and thereby reducing the forward momentum. The scope of this paper is limited to lower speed ranges (0.2 to 0.5 m/s). At these speeds, the bouncing of the robot and the effect of angle of attack is low.

Several works in the direction of locomotion study of robots have been previously undertaken. A preliminary controller for six-legged RHex is designed in [13]. An au-
Table 1. Specifications of Asguard

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Length</td>
<td>95 cm</td>
</tr>
<tr>
<td>Width</td>
<td>51 cm</td>
</tr>
<tr>
<td>Height</td>
<td>44 cm</td>
</tr>
<tr>
<td>Leg length</td>
<td>19 cm</td>
</tr>
<tr>
<td>Mass</td>
<td>12.9 kg</td>
</tr>
<tr>
<td>Motors</td>
<td>4× 24 V DC motor</td>
</tr>
<tr>
<td>Gears</td>
<td>46:1 planetary gears</td>
</tr>
<tr>
<td>Body joint limit</td>
<td>-40° to +40°</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>2 m/s</td>
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</table>

tomated gait adaptation of RHex has been studied in [16]. [12] depicts the bounding locomotion of Scout II. These locomotions and controller are not directly applicable to Asguard, due to the design differences. All of these publications use the dimensionless term specific resistance to assess the locomotion performance. The Gabriellivon Karman diagram [7] compares the specific resistance of a wide range of land vehicles.

Asguard has been the basis for numerous publications and theses. [3], [4] discusses the motivation and design of the robot. [5] proposes a compliance control architecture based on proprioceptive data, giving the robot ability to adapt automatically to different slopes. [11] studies the bounding behavior of the robot. [9] analyzes and optimizes the legged-wheel design.

This paper studies the locomotion of the robot with the objective of developing effective control strategies. The wheel design requires adapted control strategies, as simple velocity control designed for a wheel system works, but is not optimal. The challenge lies in trying to get a good performance by understanding the inherent physical abilities of the robot. Analytical analysis possibilities are limited due to several system complexities and nonlinearities. Experiments are performed here to gain an insight into the system properties.

The remainder of the paper is arranged as follows. Section 2 gives details of the mechanical, hardware and software design of the robot. Section 3 describes the locomotion principle and possible opportunities for improvement. Section 4 explains the experimental setup. Finally, the experimental results are presented in section 5.

2 Design of the robot

The robot body is 50 cm long with leg length of 19 cm. It can attain a maximum speed of 2 m/s. The robot is designed such that the weight distribution on the front axle (60%) is higher than in the rear axle (40%). The specifications of the robot are given in Table 1.

2.1 Mechanical and Hardware Design

The key components of the system are the legged-wheels, motor drives and the robot body. Two main sources of flexibility in the system are the legged-wheel and the flexible motor coupling. The legs have flexibility, both in linear and radial directions (Figure 3). In certain scenarios this results in bumpy behavior at higher speeds. The linear and radial spring constants and damping parameters are optimized in [9]. The flexible coupling acts as a shock absorber, reducing the jerks affecting the robot body.

The robot is also equipped with a passive joint, connecting the front part and the rear part of the body. This additional degree of freedom allows the robot to maintain contact with the ground with all four wheels even on uneven surfaces, which improves overall traction. The leg tips are connected to a soft foot, which is designed to increase longitudinal friction and reduce transverse friction, to improve skid-steering abilities.

The robot is fitted with PC104 stack and various sensors (IMU, cameras, laser scanners and time-of-flight cameras). Moreover, a differential GPS provides a ground truth from which it is possible to validate localization algorithms. The robot can operate autonomously or can be controlled manually with a custom designed control-pad.
or a joystick.

The wheel motors are 24 V brushed DC motors with 46:1 planetary gear systems. Custom designed H-Bridge motor boards are used to drive the motors. The drives are connected with incremental encoders for feedback control, which give a tick resolution of around $70 \mu$rad on the wheel side. The motor is connected to the wheel through a planetary gear system and a flexible coupling (Figure 4), which makes the estimation of the actual wheel position very difficult. The coupling also introduces additional motion effects between the motor and the wheel.

2.2 Software

The control loop is implemented on the embedded PC104 system, implemented in the Orocos real-time framework, on top of a Linux with RT-PREEMPT patches. The communication between the PC104 and the H-bridge hardware (which controls the motors) is using a CAN-bus. Latency measurement showed that the control loop latency (between the sensors and the actuator) is below 3 ms for a control frequency of 1 kHz.

The software also includes a complete realtime data logging part, which allows to save all the evolution of the control loop at its running frequency (1 kHz).

2.3 Motion Controller

Proportional Integral Derivative (PID) based velocity controllers tend to unintentionally change the wheel synchronization due to load disturbances. It tries to maintain the speed of the wheel, but fails to account for the effect of disturbances on the position. So, the asguard motor is controlled by using cascaded position and velocity controllers known as the PIV controller [10]. The position controller helps in maintaining the synchronization between the wheels. The reference position and velocity profiles, generated by the trajectory generator, acts as the input to this controller. Additionally, it is provided with a first order velocity smoothing. Provisions for velocity and acceleration feed-forward are also given. This controller allows us to study the effect of inter-wheel synchronization on the overall locomotion performance, which is presented in the paper.

PIV controller consists of three cascaded control loops. The outermost position loop, inner velocity loop and the innermost current control loop (inherent in the motor). The position loop works with a proportional gain and the velocity loop with a proportional-integral gain. The controller outputs the Pulse Width Modulation (PWM) command to the H-Bridge board, which drives the motor. The feedback obtained is the position information from the incremental motor encoders. The advantages of PIV controller are as follows.

1. Non-linearities in the inner loop does not affect the outer loop
2. Good disturbance rejection capabilities
3. Easy to tune

The synchronization is performed by starting the robot with all wheels in the same position to calibrate the wheel position. The position offsets are then applied to the individual trajectories. The tuned PIV gains are given in Table 2.

2.4 Effect of Wheel Synchronization

If from the controller point of view, the robot is considering a wheeled system, neglecting its legged properties, the result is a vibrating system with inefficient locomotion. The wheels can be synchronized to have a particular relative orientation at an instance in time, thereby emulating gait patterns of legs. This influences the energy transfer between different parts of the robot, effectively smoothening the locomotion and improving its efficiency.

<table>
<thead>
<tr>
<th>Table 2. PIV controller gains</th>
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<tbody>
<tr>
<td><strong>Position proportional</strong></td>
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<tr>
<td><strong>Velocity proportional</strong></td>
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<tr>
<td><strong>Velocity integral</strong></td>
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<tr>
<td><strong>Integral windup</strong></td>
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<tr>
<td><strong>Velocity smoothing</strong></td>
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<tr>
<td><strong>Velocity feed-forward</strong></td>
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<tr>
<td><strong>Acceleration feed-forward</strong></td>
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3 Locomotion of the robot

In legged robots, the leg motion alternates between **swing** phase and **stance** phase. Simple velocity controllers
for Asguard occasionally resulted in stance phase and swing phase blocking [4] each other and at times flipping the robot. Asguard can have these two phases simultaneously. Primarily, the legged-wheels have two alternating positions:

1. **Vertical stance**
2. **Double-contact stance**.

Vertical stance is the position where only one leg is in contact and is perpendicular to the ground. At double stance two legs are in contact with the ground at the same instance. The blocking of the swing phase happens at the double-contact stance. The impact of this blocking can be reduced using effective synchronizations.

### 3.1 Improving locomotion

The locomotion can be improved by maintaining a smooth flow of energy within the system. We consider two scenarios to explain the principle behind the locomotion improvement.

In the first scenario, assume the leg-wheels are moving in perfect synchronization (no offsets). At the vertical stance, there is an additional potential energy in the robot owing to its height. This potential energy is converted to kinetic energy as the legged wheel rotates further. But this kinetic energy is abruptly removed when it reaches the double contact stance, creating unnecessary vibrations. Additionally, to move from the double stance to the vertical stance, the motor should provide additional energy and lift the robot up.

In the second scenario, assume the Front-Left wheel is offset to Back-Left by $\xi$. Similarly, Front-Right wheel is offset to Back-Right wheel. When the front wheels are in vertical stance, the back wheels are in double stance. As the wheels rotate the potential energy from the rear part gets transformed to kinetic energy. This kinetic energy assists in overcoming the double stance block and also to gain the potential energy for the vertical stance of the front part. The transfer of energy between the states should have an impact on locomotion efficiency, which is also likely to change depending on system velocity and surface material properties. The same principle might be applied for left and right wheels.

We define three sets of offsets (Figure 6).

1. Front and Back wheels $\phi_{FB}$ (FB-offset)
2. Left and Right wheels $\phi_{LR}$ (LR-offset)
3. Left and Right cross wheels $\phi_{LR}$ (LR-cross-offset)

The FB-offset is the difference in angle between the front wheel and the rear wheel (Figure 6: top-left). LR-offset is the offset between left and right wheels (Figure 6: top-right). LR-cross-offset is same as the LR-offset, though in different directions (Figure 6: bottom).

It is not possible to maintain a left-right synchronization while turning using skid steering. So, more importance is given to front-back offsets. The aim is to find the most efficient front-back offset and study the change in efficiency for different left-right offsets.

### 3.2 Locomotion Efficiency

Locomotion can be evaluated using specific resistance or Froude number. The term specific resistance for locomotion was introduced in [6]. It is defined as the energy consumption per unit distance per unit weight[14] [7].

$$\epsilon = \frac{E}{Mgd}$$

where $E$ is the energy consumed, $M$ is the mass of the vehicle, $g$ is the acceleration due to gravity and $d$ is the distance traveled. It has since been used in numerous literatures to compare wide range of locomotions.

Froude number [14] is usually used to characterize animal locomotion. It is calculated as

$$F_r = \frac{V^2}{gh}$$

where $V$ is the velocity of walking or running, $g$ is the acceleration due to gravity and $h$ is the height of the hip joint from ground.

Specific resistance is more suited for analyzing robot motions and hence will be used in this work. To put the
specific resistance ($\varepsilon$) values in perspective [14], cars have a specific resistance in the range 0.07 to 0.4. Specific resistance for a human walking is between 0.02 to 0.1. RHHex robot using automated tuning methods obtained a specific resistance of 0.6 [16]. Quadruped Robot running with Bounding Gait [15] had a specific resistance of 0.32. McGeer’s gravity walker [14] shows the lowest specific resistance among walking robot at 0.01. Among powered legged robots, ARI Monopod [7] with $\varepsilon$=0.7 shows the lowest specific resistance.

The energy consumed in our case is calculating the integral of power consumed by the motor. So the total energy is given by

$$E = V_{app} \int I(t)PWM(t)dt$$  \hspace{1cm} (3)

where $V_{app}$ is the battery voltage, $I(t)$ is the current measured at the motor and $PWM(t)$ is the PWM input given to the motor. When the current is measured at the source, the equation becomes,

$$E = V_{app} \int I(t)dt$$  \hspace{1cm} (4)

### 3.3 Error propagation in Specific Resistance

The equation for specific resistance (1) can be used to estimate the error propagation due to measurement inaccuracies. Error propagation[11] for multiplication is given by

$$(x \pm \delta x)(y \pm \delta y) = xy \pm \sqrt{x^2\delta y^2 + y^2\delta x^2}$$  \hspace{1cm} (5)

and error propagation for division is given by

$$\frac{x \pm \delta x}{y \pm \delta y} = \frac{x}{y} \pm \sqrt{\left(\frac{1}{y^2}\right)\delta x^2 + \left(\frac{1}{x^2}\right)\delta y^2}$$  \hspace{1cm} (6)

Average value and expected errors for energy = 300.0 $\pm$ 30.0 Nm, distance = 8.0 $\pm$ 0.25 m and mass = 13.0 $\pm$ 0.1 kg. Using (5), (6) and the average values given above, the error propagation was estimated to be approximately 10.0%.

### 3.4 Vibrations

Vibrations on the robot body can affect the proper functioning of the robot sensors and can damage the components in the long run. Unnecessary vibrations reduce the efficiency of locomotion and is therefore an interesting parameter to investigate as it gives indications as to why some configurations are better than others. The amplitude and frequency of the vibrations should be as low as possible. In this work, the vibration was analyzed only for limited configurations and only important results are presented. This is due to the limited field of view of the motion capture system.

Figure 7 illustrates the experimental setup. Two time-synchronized cameras are used to measure the time difference between the start and finish. This time difference is used to extract the corresponding data from the log. The actual data extracted is the log from log start to log stop (Figure 7). The tests were performed on both hard ground and sand. Hard ground has low damping compared to the legs and sand has high damping effect compared to the legs. Robot forward velocities are taken in the the ranges low ($\sim$0.2 m/s), medium ($\sim$0.4 m/s) and high ($\sim$0.5 m/s). At velocities higher than 0.5 m/s, the robot tends to deviate from the designated track.

The offsets can range from $\pi/2$ to $\pi$, which covers the angle between two adjacent legs. Due to the symmetry of the robot, the range can be limited between 0 and $\pi/2$. For FB-offset and LR-cross-offset, the values 0, $\pi/8$, and $\pi/4$ were used. For LR-offset, the values 0, $0.25\pi/8$, $0.5\pi/8$, and $\pi/2$ were used. The offsets will be represented only as multiples of $\pi/8$ in the rest of the discussion and plots.

The robot logs the battery voltage, PWM input and current at 1 kHz frequency. The data logged during the time difference measured by the camera is used to calculate the specific resistance. The length of the track which is measured for each test setup, is approximately 8 m from start to finish.

Separate experiments were conducted using a 3D motion capture system to capture the vertical vibrations of the robot. The motion capture system from Qualysis captures the X-Y-Z motion of the robot at 100 Hz using a single marker. The three IR cameras are placed such that the cameras have an intersecting field of view along the track.

### 5 Results

In general, increasing the FB-offset and LR-cross-offsets resulted in improved efficiency. Figures 8 and 9 show the effect of increasing the FB-offset on sand and
hard ground respectively. At $0.2 \text{m/s}$ speed, increasing FB-offset, reduces specific resistance from 0.72 to 0.22 on sand. In similar situations on hard ground the value changes from 0.55 to 0.27. An exception to this trend was found on hard ground at 0.5 FB-offset and 0.2 ms speed (Figure 8). The specific resistance here is higher than the lower offset. This value seems to deviate from the trend and further investigation is required to determine its cause. Figures 10 and 11 show the effect of increasing LR-cross-offset. The trend here is similar to that of FB-offset.

The effect of change in specific resistance is dependent on speed. Lower speeds show higher response to change in offsets. But higher speeds are more efficient, with or without offsets.

Figures 12 and 13 show the effect of FB-offset=1.0 and varying the left-right offset. The results when FB-offset is 1.0 and varying left right offsets shows no appreciable change in efficiency. This shows that a FB-offset of 1.0 alone could be used to improve the locomotions efficiency.

The type of ground does not seem to significantly impact the specific resistance trends. Although hard ground slightly reduces the specific resistance compared to sand, due to the damping effect of the sand. The variance of the specific resistance was not determined and occasionally, some outliers were also found.

An example of the vibration differences is shown in Figure 14. At a LR-cross-offset of 1.0, the amplitude of vibrations is reduced to a great extend (25 mm lesser) when compared to 0.0 LR-cross-offset. But additional rotational motion (roll) is induced on the robot.

6 Conclusion

In this paper, we investigated a way to improve the overall locomotion efficiency at low speeds of a legged-
wheel system like Asguard. Our approach tried to reduce the energy loss during locomotion by improving the potential and kinetic energy exchange between parts of the robot. We achieved this by controlling the wheel synchronizations. The lowest specific resistance was achieved with a complete left-right-cross offset at 0.4 m/s speed on hard ground. The experimental results showed that it was possible to efficiently control Asguard in a way compatible with its skid-steering nature.

In future, automated method for determining efficiency could be developed to extend the study to higher speeds and different patterns.

7 Acknowledgment

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References


