

# ASGUARD: A Hybrid -Wheel Security and SAR-Robot Using Bio-Inspired Locomotion for Rough Terrain

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## Abstract

For outdoor locomotion of mobile robots, one has to cope with different requirements for such systems. These robots have to be highly agile and fast on flat ground and, at the same time, should be able to deal with very rough terrain, e.g. rubble, gravel, and even stairs. This is particularly true for robots which are used for surveillance and search and rescue missions (SAR) in outdoor environment as well as for robots for remote inspection, such as CBRNE detection in crises situations. Tracked robots are currently regarded as the best trade-off between high velocity and mobility in rough terrain. Those systems have the drawback of high energy consumption due to friction and are generally not able to climb stairs or very steep slopes. In this paper we present a hybrid legged-wheel approach which is used for our outdoor security robot ASGUARD. The robot has four rotating wheels in the shape of a five-pointed star. Each point of the star serves as a leg during locomotion and is controlled using bio-inspired central pattern generators (CPGs). We will show in this work that with our approach, the robot can handle high velocities, is able to climb stairs, and can cope with piles of rubble without changing the hardware configuration.

## 1 Introduction

In this paper we present our fast and highly agile quadruped robot ASGUARD<sup>1</sup>(cf. Figure 1). The robot was designed to be used in harsh outdoor environment with a focus on security and outdoor surveillance as well as on disaster mitigation missions. For those applications, a robot has to transport a variety of mission-depending application sensors inside a difficult terrain. Those missions are commonly named “Three D” missions. “Three D” stands for dull, dirty, and dangerous and implies, e.g., tasks where rescue personnel must enter a collapse-endangered building in search for injured people, the acquisition of samples in contaminated areas or patrolling every day along the same fence of a security-relevant compound. For all those applications, the requirements for such an in-situ system are that it has to deal with obstacles or uneven and difficult outdoor terrain. Additionally, the robot has to move fast where the ground is leveled and easier to cross. In order to cope with those two requirements, the quadruped robot ASGUARD was designed, which makes use of multiple rotating legs along one hip shaft. In the last few years, some work regarding hybrid legged wheel locomotion approaches has been done. Sometimes in literature referred to as compliant legs [11] or spoked wheel [10], this approach makes often use of a very simple and therefore very robust locomotion principle. The key idea is to use one rotating actuator for driving one or more simple legs around one axis.

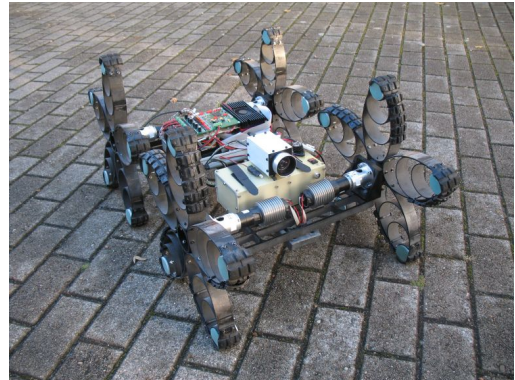


Figure 1: The quadruped robot ASGUARD

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<sup>1</sup>Advanced Security Guard

In [11] the hexapod RHex is described. The robot uses one rotating compliant leg per actuator and is able to ascend and descend stairs. RHex uses a fixed pattern for the trajectory of each leg. The locomotion is performed by a tripod gait, where the “retraction” and “protraction” phases are alternately triggered. For the stair climbing behavior of the RHex robot, six phases were defined, based on a fixed transition model [9]. The parameters for the single gait were defined, using empirical analysis. [8] describes an improvement on the prior RHex robot by introducing two additional behaviors based on proprioceptive sensing. One behavior is the adjustment of the compliant legs in direction of the gravity force by using an internal tilt-sensor. The behavior ensures an optimal position in the stance phase of the legs while climbing a slope. The second behavior introduced is the “pronking” controller, enabling a jumping behavior which can be found in hooved mammals, like the springbok. For synchronising, the trajectories, the proprioceptive data from six ground contact sensors are used. Another proprioceptive information of the robot is used in [4], where the motor current is used to detect the contact with a flight of stairs. In this case, the tripod gait changes to a metachronal wave gate. In contrast to our approach, the trajectories of the legs are based on a fixed, hand-adjusted gait configuration. The proprioceptive information is used to trigger the transition between those two gaits.

[10] and [1] use a design of a multi-spoked wheel for their hexapod Whegs, which comes closer to our design of our quadruped ASGUARD. The bio-inspired mechanical design is derived from an analysis of the cockroach gait. In contrast to other research regarding legged wheel approaches, Whegs uses no sensor information to adjust the tripod gait. It uses only the compliant legs design to adapt to different types of terrain. Whegs uses only one DC motor for locomotion and one servo for active steering.

To our knowledge, all locomotion concepts for hybrid legged wheel approaches are based on fixed motion patterns which are controlled in open-loop manner. In all research we found, only inclination and ground contact were used to change the pattern of the trajectory, which is then again done in open-loop control. In our research we mainly focus on a robust stair-climbing behavior based on a behavior-based closed-loop approach. We will use the information of the measured motor current and the shaft encoders in order to change the behavior of each leg.

The remainder of the paper is arranged as follows: The robot platform ASGUARD is described in Section 2. The control approach and its implementation in FPGA hardware design is described in Section 3. In Section 4 we present the results of our algorithm, with the robot climbing a flight of stairs. In Section 5 we will discuss our results and give some ideas about our future research direction.

## 2 Platform Description

The long-term goal of our research is to develop a robust outdoor platform which is suitable to be included in disaster mitigation as well as in security and surveillance missions. The platform should be able to transport application sensors to areas that are dangerous for humans to access, e.g. a collapse-endangered building or an industrial compound after a chemical accident. In those cases, before they enter, the rescue personnel might need some information about the air contamination or the whereabouts of people inside an area. The robot should be upgradeable with a variety of application sensors, e.g. cameras, thermal vision, or chemical sensors. To be usable in any search and rescue or security context, the robot has to be operational without changing batteries for at least two hours. All those requirements were specified with potential end users beforehand.

This defined the minimum size of ASGUARD, as well as the energy budget and the minimum payload. To be usable for a variety of missions, the robot has to be able to carry sensors to areas which are normally not accessible to wheeled and tracked robots.

### 2.1 The Physical Robot ASGUARD

The robot ASGUARD is a hybrid quadruped outdoor robot which was inspired by insect locomotion, as described in [10] and [1]. The first prototype of our system is driven by four directly actuated legs with one rotational degree of freedom. In Figure 2 three aspects of the robot frame are shown; in Table 2.1 the dimensions and other physical data are given. After testing the ground traction with a rigid corpus, we found out that we could increase ground contact by adding an additional rotational degree of freedom along the body axis, serving as an elastic spinal column (cf. Figure 2(b)). By this we could increase the ground traction significantly. For the low level control of the robot, a custom-designed FPGA motor control board (MOTCON6) is used which controls the four motors in a closed-loop manner. The

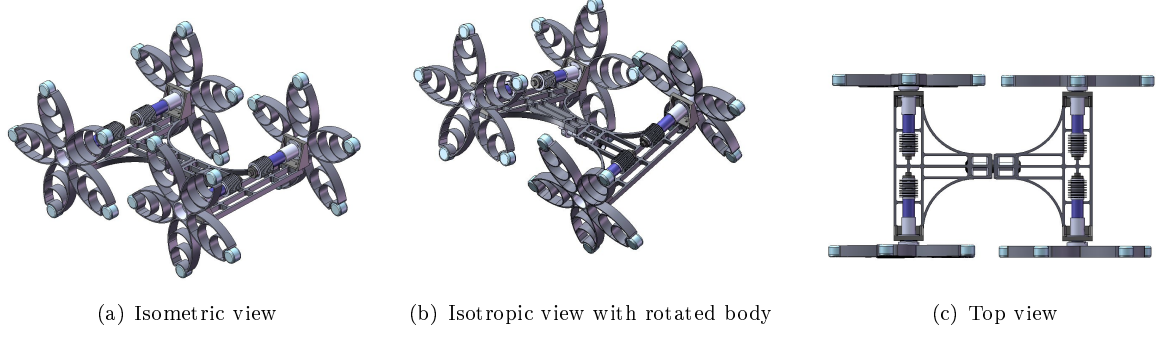


Figure 2: The CAD design of the quadruped robot ASGUARD

Height	44cm
Length	95cm
Width	50cm
Wheelbase	51cm
Weight	11.5kg
Motors	4x Faulhaber 24V DC motors with 46:1 planetary gear
Motor Power	4x 83W
Battery	10Ah/30V, Lithium Polymer Batteries
Battery Weight	1.6kg

Table 1: Physical dimensions of the robot

locomotion of the robot is performed by central pattern generators, which describe the trajectory of each leg within the phase of  $[-\frac{1}{5}\pi, \frac{1}{5}\pi]$ . The detailed pattern generator approach is described in Section 3 and works as an independent low level controller. With the MOTCON6 board, we are also able to measure the power consumption as well as the position of each leg in real time, providing us with important proprioceptive information about the system.

With the actual motor-gear configuration and with the current weight of the robot, we measured a maximum speed of around  $2m/s$  on flat ground. For each leg we can individually define the trajectory of a leg, allowing us to synchronise or asynchronise the legs with each other. We found out that the maximum speed is depending on the used gait and gait transitions during movement. An analysis of different gaits in terms of energy efficiency and velocity will be done in the near future.

## 2.2 The Multi-Legged Wheel Design

Our design of the legged wheel consists of five compliant legs which are assembled as shown in Figure 3(b). Each individual leg is designed as shown in Figure 3(a). They are arranged around the hip shaft,



Figure 3: Design of the legged wheel

with an angular distance of  $\frac{2\pi}{5}$ . Because of the symmetry of the legs, we have only to consider the phase

between  $[-\frac{1}{5}\pi, \frac{1}{5}\pi]$  (cf. Figure 3(c)). By this configuration we can assure that we have a minimum of four legs on the ground, which ensures a stable configuration of the robot. The outer radius of the legged wheel is  $22\text{cm}$ . The inner radius (i.e. the height of the hip joint shaft, if two legs have ground contact) of the legged wheel is  $18\text{cm}$ . In order to decrease the physical shock during locomotion, shock-absorbing leg tips were used.

As described already in [10], a compliant leg design is able to overcome obstacles which are higher than the wheel axis. A theoretical value for our legged-wheel approach can be calculated by

$$c = a * \sin(\alpha) + a * \cos(\beta) \quad (1)$$

with  $a$  naming the minimum height of the legged wheel. The angles  $\alpha$  and  $\beta$  are shown in Figure 4(a). For our current wheel configuration the maximum height of an obstacle that can be overcome is  $33.85\text{cm}$  for the values of  $a = 22\text{cm}$ ,  $\alpha = 36^\circ$ ,  $\beta = 18^\circ$ . Practically, ASGUARD can climb on a plateau with a height of  $25\text{cm}$ , which is well above the height of the hip shaft. The limit of  $25\text{cm}$  is not depending on the wheel design but limited by the robot's overall physiognomy (i.e. wheelbase, center of gravity, etc.). In contrast to that, a wheeled robot would only be able to go on a plateau of a height which is much less than the height of the wheel shaft. While driving with high velocities, only the leg tips have direct

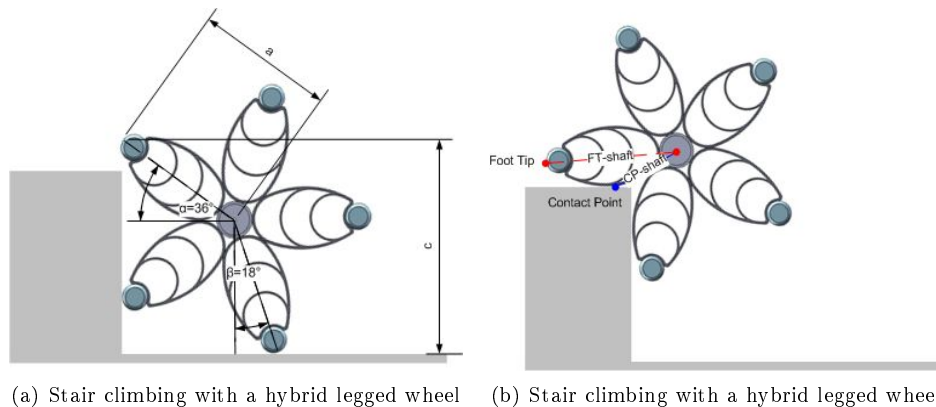


Figure 4: Climbing an obstacle with a legged wheel

contact to the ground. In this case, ASGUARD behaves like a wheeled system, with the radius  $b$  (cf. Figure 3(c)), reaching velocities of around  $2\text{m/s}$ . If the robot climbs a flight of stairs (cf. Figure 4(b)), an increase of leverage implies more power to climb it, because the ground contact point moves further to the axis of the leg. This is comparable to gear changing, but without any additional actuation.

### 3 Bio-Inspired Locomotion Control for Legged-Wheel Robots

#### 3.1 Central Pattern Generation in Walking Robots

The concept of using CPGs (Central Pattern Generators) is well known and utilized in the area of ambulating robots. Central Pattern Generators (CPG) are the major mechanisms in animals to control and to produce rhythmic motion. They are characterized by the ability to produce rhythmic motion patterns via oscillation of neuronal activity without the need of sensory feedback [16]. However, sensory feedback is normally integrated into the CPG-control. Mostly load and position data of the controlled limb/joint are fed back into the CPG-network, which is used to implement a closed-loop control of the rhythmic motion of the system actuators. To modulate the controlled rhythmic patterns, the CPG can change its frequency, phase, and amplitude [12]. For the use in robots it is reasonable to develop an abstract CPG model which inherits only the basic principles of the CPG's functionality.

Many different ways to achieve this have been proposed and tested, e.g. [2, 7, 5, 17]. In [15] our approaches for controlling walking robots are described in detail. Our model consists of a controller module (using a PID-controller) and a unit to produce rhythmic trajectories in the joint angle space. To

produce the rhythmic trajectories, we describe a CPG-pattern as a function of part-wise fitted together third-order Bezier polynomial (for details see [13]). This CPG-approach allows very easy adaptation of rhythmic walking patterns as well as the overlaying of different CPG-patterns. For example, our approach enables the Scorpion robot to walk omni directional by overlaying a forward and a lateral rhythmic walking pattern[14]. Together with an implemented posture and reflex module, our walking robots are able to walk very robust in an adaptive way through rough terrain.

Thus, implementing this control approach on a hybrid legged wheel system looks very promising. First steps in that direction have already been done, which are described in the next section.

### 3.2 Using CPGs for Hybrid Legged Wheel Approach

In order to control our robot ASGUARD, we are facing two control requirements. On one hand, we have to control the velocity, i.e. the rotational speed of each of the legs. On the other hand, we have to control the position of each leg of the quadruped robot. For controlled obstacle and stair climbing we have to assure certain positions over time. From the CPG control methods, used in a variety of walking machines (cf. Section 3.1), we learned an efficient approach to control such systems by using trajectories in the time-angle space. In contrast to many pure legged robots, which have generally more than one degree of freedom for each leg, we have only one angle to control over time. As described in Section 2.2, we only have to consider the angular space between  $[-\frac{1}{5}\pi, \frac{1}{5}\pi]$ . The patterns are generated by our custom-designed FPGA-based MOTCON6 board. From our high-level controller we can modify the pattern parameters by changing the pattern frequency, the direction of the generated pattern as well as a phase offset. By this phase offset we can change the stance phase, i.e. the time in which a leg has ground contact. Figure 3.2 shows the typical trajectory of the front left leg in time-angle space. Because we use more than one leg per wheel, we can make use of a simple saw tooth pattern in time-angle space. The actual velocity of the robot is controlled by the frequency of the trajectory in the internal control loop. A P-Controller, which is implemented in MOTCON6 control board, is used to follow the trajectory generated by the internal pattern generator.

In Figure 3.2 PAR gives the actual trajectory, the variable PSR names the target trajectory. The figure shows also the error between PAR and PSR as well as the power consumption of the motor.

An advantage of our design is that we can modify the amplification factor of the proportional control term of the inner control loop at runtime. By changing those parameters on-line, we allow a larger error between the current leg position and the target trajectory. This is an important factor because we are using the proprioceptive information of the applied force to change those parameters. For left/right control of the robot, we use a differential steering approach by individually controlling the speed and the direction of movement for each side of the robot. By this, we save additional actuators for steering, thus saving weight and energy.

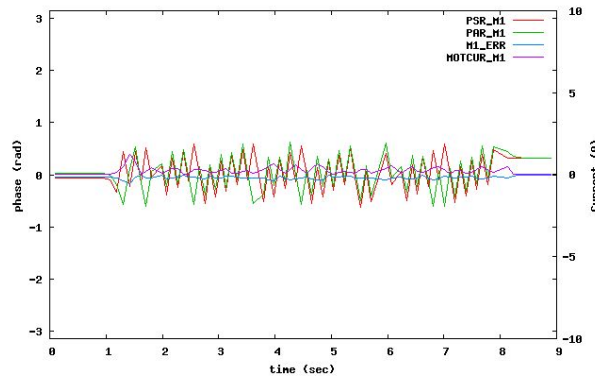


Figure 5: Proprioceptive data of the legs on flat ground

### 3.3 Implementing Timed Motion Pattern in FPGA

The low level control concept of the ASGUARD robot is centered around a newly developed electronic control board named MOTCON6. This control board features autonomous position and motion control for up to six independent DC actuators. The power electronics can drive DC motors within a voltage range of 12-35V and can deliver 4(8)A current continuously as well as 80A peak current for each motor with high efficiency around 99%. To control DC-motor driven legs, several functional blocks are required. These are (cf. Figure 6):

- Power electronics for driving the electrical motors
- Data acquisition of sensor signals
- Position control for each motor
- Limited protection (leg position, peak current values, power consumption, and temperature)
- Communication between the low level control and higher control levels

Several special purpose peripheral circuits are required to interface the power electronics, the data acquisition blocks, and the communication blocks. Generic microcontrollers deliver some of the required peripherals, but not all. Therefore, customized digital logic featuring system-on-chip architecture is preferred. For rapid prototyping, Field Programmable Gate Arrays (FPGA) are best suited for this

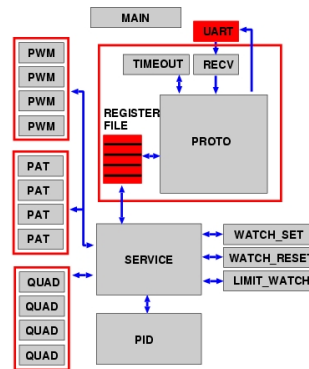


Figure 6: Functional blocks implemented with concurrent processes required for autonomous robot actuator control.

purpose. For reliability and for maintenance reasons, a motor control unit should be independent from a master controller, like a microcontroller or an embedded PC. Another important design aspect is power efficiency, regarding the power electronics and the power consumption of the analog and digital parts required for operation. The communication and the link technology must be independent of the target robot architecture and the main controller architecture, and must provide fault tolerance and reliability. The MOTCON6 board uses a register bank memory for data exchange between the controller and the host controller. The registers are read and modified by messages. All registers are mapped to controller parameters and sensor data tables. The control architecture is partitioned and modularized into different system blocks supporting independent leg actuator control, implemented with concurrent processes (see Figure 6):

1. Pulse-width-modulated (PWM) signal generators delivering drive signals for the H-motor-bridge power electronics with 8 bit pulse-width resolution
2. ADC device drivers providing an interface to three external ADC devices with 12 bit data resolution providing a total of 24 channels (not shown)
3. Quadrature signal decoder (rotational angle position measurement) with 12 bit resolution per turn and additional turn counter (QUAD)

4. Service controller for synchronizing processes and managing access to the 256 registers of (SERVICE). The register bank contains all parameters required for actuator control and all acquired sensor data.
5. Communication controller (PROTO) implementing a simple and fault-tolerant communication protocol stack, following a connectionless text-message based approach, independent of the underlying serial link controller.
6. Serial link controller unit (UART) attached to the communication controller.
7. The position controller for each actuator (PID), implemented using an optimized and fully developed Proportional-Integral-Differential term controller with 12 bit data resolution and 1kHz loop frequency.
8. Limit observation and regulation (LIMIT), for example over-current detection.
9. Parameterizable pattern generators (PAT) generating leg position patterns. The pattern leg frequency, direction, and a phase offset can be specified with parameters changeable during runtime.

All modules are connected using a System-On-Chip architecture and either shared register or queues or channels for data exchange, and mutexes or semaphores for interprocess communication.

The target technology used on the MOTCON6 board is a Xilinx Spartan-III FPGA with an estimated gate count of approx. 1M gates, with the highly optimized PID controller, the communication and main control blocks fitting well into the FPGA resources. The hardware design occupies 50 % of slice resources (about 300k equivalent gate count), longest path estimation predicts a maximal clock frequency of 140 MHz (20 MHz actually used), 25 FSMs were inferred. The hardware design was made using an imperative multi-process approach on system level (CONPRO silicon compiler, [3]), (about 1500 lines source code), synthesizing pure Register-Transfer-Logic and VHDL code (about 15000 lines), further synthesized to gate level with Xilinx ISE software.

The implemented leg position controller is a compact version of a traditional PID-controller. The input data is derived from the actual and past angular leg position sensor signal, and the scaled output signal  $U$  from the controller is fed directly into the PWM generators driving the motor voltage using highly efficient H-Bridge technology. The control function delivers three terms: a proportional, an integral, and a differential function term.

The actual measured leg position is  $P_A$ , the target leg position is  $P_D$ . The actual error value is the difference of these two values. An enhanced recursive and compact version of the controller algorithm was derived for efficient synthesis into digital logic concerning hardware resources and latency. Therefore, there is only one equation built from a linear superposition of the three terms. The control parameters  $K_P$  for the proportional term,  $K_I$  for the integral term, and  $K_D$  for the differential term must be transformed into the parameters  $K_0$ ,  $K_1$ , and  $K_2$  using the equation shown below, derived from [6].

$$U(n) = U(n-1) + \Delta U(n) \quad (2)$$

$$\Delta U(n) = K_0 E(n) - K_1 E(n-1) + K_2 E(n-2) \quad (3)$$

$$E(n) = P_D - P_A \quad (4)$$

$$K_0 = K_P + K_I + K_D \quad (5)$$

$$K_1 = K_P + 2K_D \quad (6)$$

$$K_2 = K_D \quad (7)$$

## 4 Using Proprioceptive Data for Changing Leg Trajectories on Stairs

When climbing a stair, we have to ensure in our control approach that the legs on the front axis are synchronized, i.e. that they have exactly the same pattern phase. The same is valid for the synchronization of the rear legs. An optimal behavior in climbing a stair would be to keep the tilt angle of the whole robot minimal and that all motors have more or less the same power consumption. By keeping the left and right wheels at the same phase through our CPG approach, on a stair, we can assume that the

energy consumption on the left and on the right side of each axis is about the same, given that we have the same motor configuration, mechanical friction within the system, and the weight distribution along the body axis.

In order to distribute the torque of each actuator, which is directly related to the measured motor current, we use an approach to modify the amplification of the P-Factor within the internal control loop, which is responsible for following the trajectory of the generated pattern (cf. Equation 8).

$$O_i = (\kappa_i - (cur_i - \frac{\sum cur}{n}) * \iota) * (PAR_i - PSR_i) \quad (8)$$

$O$  refers to the motor output of the controller; PAR and PSR name the actual position of the hip encoders and of the target position, respectively. The measured motor current in A ( $cur$ ) we assume to be in the interval  $[0, 10]$  for each motor. The constants  $\kappa$  and  $\iota$  are used to map the P-Factor within the limits of our P-Controlled, i.e. the interval  $[20, 100]$ .

For our test setup, we empirically determined the value for  $\kappa = 50$  and  $\iota = 5.5$ . To show the effect of our control approach, we logged several runs on a flight of stairs with a step height of  $18cm$ , a step size of  $27cm$ , and an inclination of  $34^\circ$  (75%). Figure 7 shows the data of a stair climbing run without our adaptive controller. Figure 8 shows our approach with a current adaptive control, using Equation 8.

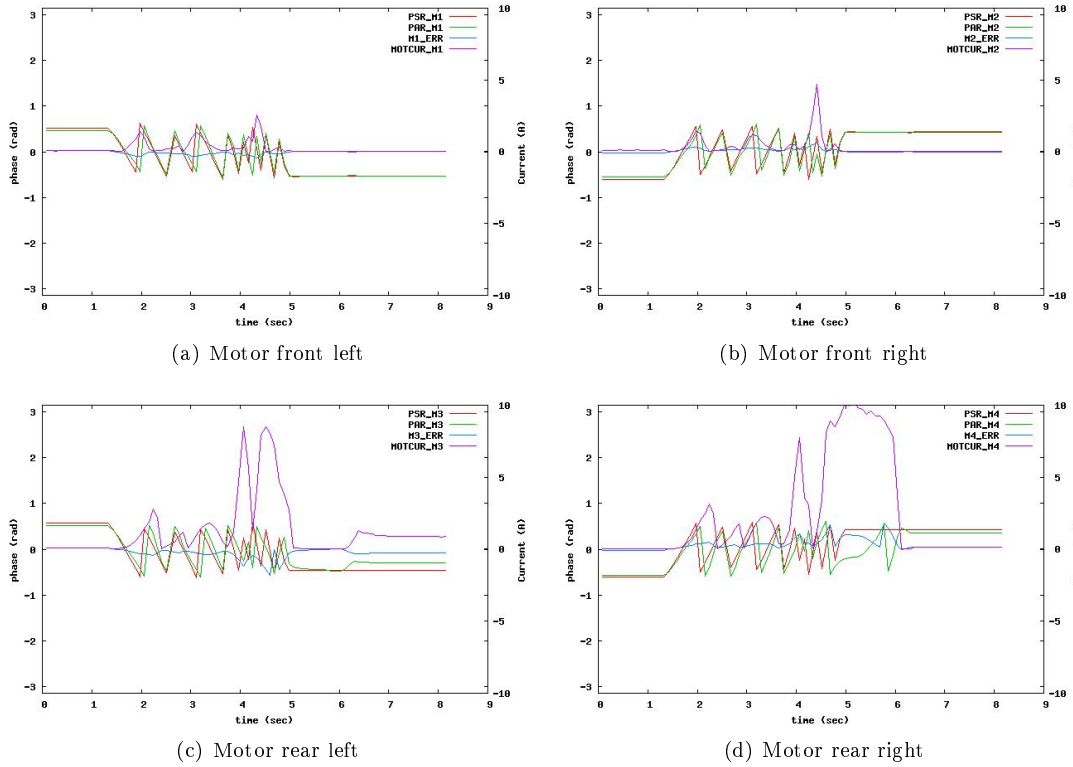


Figure 7: Proprioceptive data of the legs on stairs without adaptive control. The robot did a backflip on the stairs before reaching the landing.

What can be seen in those figures is that we could reduce the load on the rear legs (motor 3 and 4) significantly. Without the adaptive control, the drawn current reached easily 8-10A. This occurs if the rear legs erect the whole robot on the stairs, causing it to flip backwards. With the adaptive controller, the peak values were around 5A in Figure 8. Because of the actual weight distribution of the robot, we were not able to properly balance the current on each motor, the rear legs had still to carry the main load.

To assess the robustness of our approach, we did ten runs on the same stairs without manual interference. The speed was set to 10% of the maximum speed. The phase offset for each leg was set to zero in the run. By dynamically changing the P-factor of the internal control loop, the rear legs went out of synchronization because a smaller P-factor allows a greater error within the phase. By using our



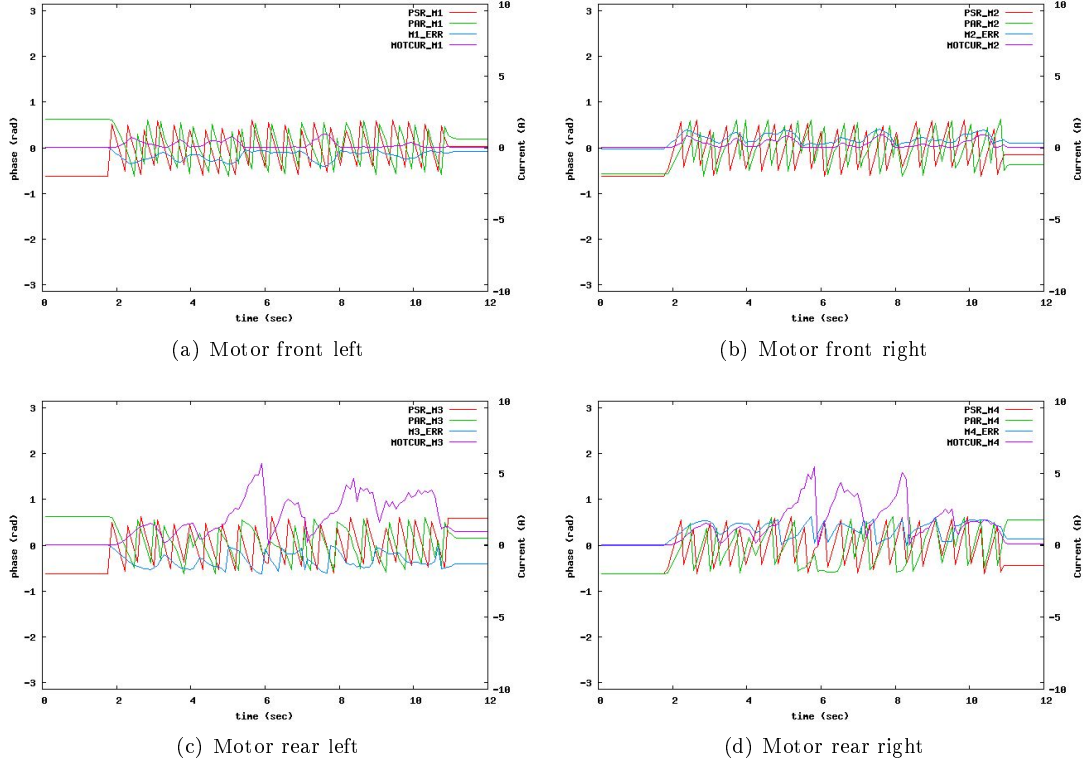


Figure 8: Proprioceptive data of the legs on stairs using adaptive P-factors. The robot reached the landing.

adaptive control approach, the robot was able to climb the stairs in 7 out of 10 trials. In two runs the robot skidded sideways. This could not be prevented because we did not use any IMUs to measure the unintended sidward skidding. In just one run the robot flipped back while climbing. We are optimistic that we can cover this occasional case by additional sensing of the robot’s inclination. This aspect will be included in the next step. Without an adaptive control the robot flipped back in almost every run.

## 5 Conclusion

In this paper we introduced for the first time our quadruped robot ASGUARD which will be usable for “Three D” missions. The robot uses a hybrid legged wheel approach for locomotion which is controlled using bio-inspired pattern generators. Similar pattern generators can be found in a variety of legged animals. We used the proprioceptive data from the actuators to implement an adaptive control mechanism. By this control approach, ASGUARD was able to climb a stair with an inclination angle of 75% at 70% reliability. This could be achieved without any additional exteroceptive data, like cameras or laserscanners. Additionally, the power consumption of the legs, especially of the rear legs, could be significantly reduced.

In future research we will add more proprioceptive sensors, like IMUs<sup>2</sup> and magnetic field sensors in order to estimate the pose on the stairs. By this we intend to improve our performance and prevent backflips and side skidding on stairs. We showed in this work the potential of a hybrid legged wheel locomotion and that our system using this approach is able to run at high speed as well as to overcome obstacle and climb stairs.

Another focus regarding our quadruped robot is the analysis of different walking patterns in terms of energy consumption and forward speed. Also the gait transition between different patterns needs some deeper analysis because we are using differential control for left/right steering. Therefore we must change the frequencies of the CPGs while maintaining the phases of the legs. Regarding the mechanical design,

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<sup>2</sup>Inertial Measurement Unit

we are currently working on an improved dust and waterproof version of ASGUARD in order to make the system usable under real outdoor conditions.

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