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# On Locomotion Control Using Position Feedback Only in Traversing Rough Terrains with Hexapod Crawling Robot

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**Abstract.** In this paper, we report on our results on improved locomotion control of small and affordable hexapod crawling robot using only position feedback from the utilized servo motors. Multi-legged robots represent complex mechanical systems with many degrees of freedom from which they can benefit in traversing rough terrains. However, the crucial ability of multi-legged robots is maintaining stable locomotion over irregularities of the terrain which makes the locomotion control complex and requires reliable and timely detection of the leg contact point with the ground. Such detection may require additional sensory equipment which can increase the cost of the multi-legged platform. Therefore, we focus on exploiting capabilities of nowadays intelligent servo motors with position feedback to develop a minimalistic set up in which the robot uses solely the position feedback of the servo motors to sense the ground reaction force. The first achievements enable a small hexapod crawling robot to navigate rough terrains using stable pentapod gait, where only one leg moves at a time, and five legs support the robot. Later on, we improved the locomotion control to enable faster locomotion using three simultaneously moved legs in the so-called tripod motion gait. This paper reports on further advancements with a faster control loop enabled by hardware based acceleration of the communication latency with the utilized Dynamixel AX12 servo motors that improve the locomotion capabilities of the robot. The reported results indicate the robot locomotion with the used adaptive motion gait is speeded up by a factor of 1.4 with the same stability in traversing the rough terrain of the experimental laboratory mock-up.

## 1. Introduction

Multi-legged robots can overcome terrains that are impassable by wheeled or tracked platforms at the cost of complex mechanical construction and locomotion control. The crucial property that enables to traverse rough terrains with the minimal possible stress on the robot construction is timely and reliable detection of the leg(s) contact with the ground and obstacles. If foot-contact events are not appropriately detected, the robot construction is put under a stress because of increased load and torque at the joints. Moreover, the stability of the robot posture can be lost, and high torque values in the joints may overheat or even damage the actuators. Therefore sensory feedback is utilized to supply tactile information, and thus negotiate the terrain and cope with its irregularities. However, additional sensory equipment may increase the cost and complexity of the robotic platform.

In our previous work [1], we focus on minimalistic approach of the locomotion control for hexapod crawling robot to enable traversing rough terrains using only the position feedback provided by the utilized servo motors. Such a minimalistic setup is suitable for affordable robots with minimal sensory equipment as the robot consists only from the servo motors that form the robot legs, the body frame,

and a control board, see Figure 1. The idea of the developed adaptive motion gait [1] is based on the interpolation of the leg motion into small steps during the swing-down phase of the moving leg and evaluating the difference between the expected position and real position of the actuator read from the servo motor. However, the number of simultaneously controlled actuators (that also provide the required feedback for the control) limits the speed of the locomotion because of the limited bandwidth of the communication channel between the control board and the servo motors. The communication issues have been addressed by developed model of the actuator controller that enables to predict the position of the actuator, and thus compensates the experienced communication latency. Usage of the predicted position improves the reliability of the ground detection and also enables usage of the so-called tripod gait, where three legs provide support and the other three legs are simultaneously moving in the swing phase.
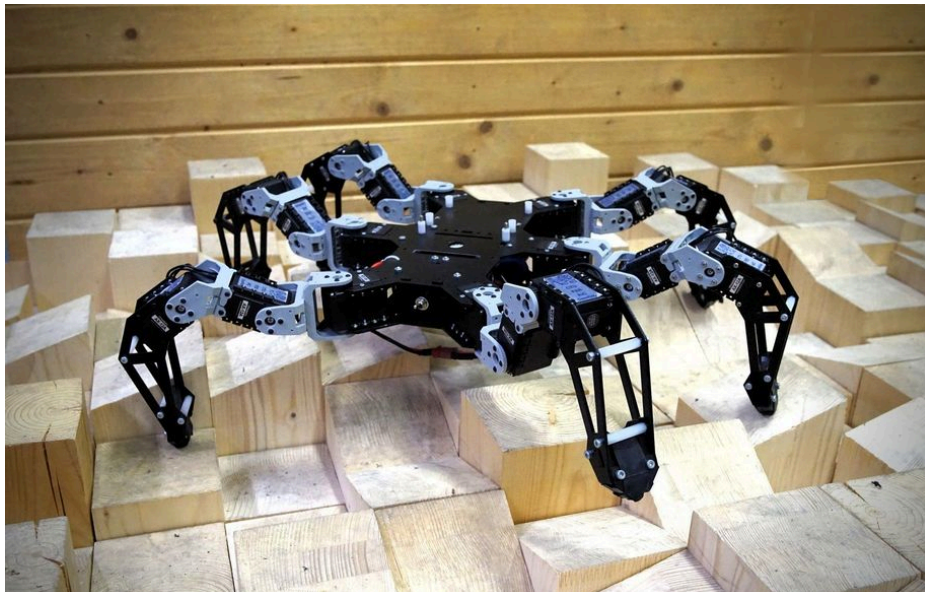


**Figure 1.** Utilized hexapod crawling robot with 18 Dynamixel AX-12A servo motors and Odroid XU-4 control board.

Based on our first results, we consider the influence of the bandwidth and latency of the readings important to the reliability of the ground detection, the achievable speed of the locomotion, but also to the smoothness of the locomotion itself. Therefore we investigate the influence of the control loop period to the locomotion of hexapod crawling robot in the experimental setup with our hexapod robot (shown in Figure 1) traversing rough terrains of the experimental laboratory mock-up. In this paper, we report on the achieved results and found insights because we believe that such an evaluation is of the significant importance to provide condensed insights on influencing factors of the locomotion stability and design guidelines for developing affordable robotic platforms capable of traversing rough terrains.

The rest of the paper is organized as follows. Section 2 overviews different architectures and approaches to locomotion control of multi-legged robots. The problem statement within the context of the hardware used and the used groundwork is introduced in Section 3. A discussion how latency can affect the locomotion stability is provided in Section 4. The achieved results of the experimental evaluation are reported in Section 5. Concluding remarks are in Section 6.

## 2. Related work
Locomotion control of multi-legged robots is a problem studied for many years, and therefore, there can be found numerous contributions in the literature. Deployment of the multi-legged platforms in rough terrains is mainly enabled by improvement (and also cost reduction) of the necessary sensory

equipment that allows for sensing and negotiating the terrain. Two complementary types of sensors can be used in the locomotion control: the exteroceptive and proprioceptive sensors. The exteroceptive sensors allow taking measurements remotely without a direct visitation of the particular location, and the already reported deployments with hexapod robots include LIDARs [2, 3], stereo [4], and RGB-D cameras [5, 6]. These sensors are used to build the spatial awareness of the robot by creating a local map of the environment that is then utilized to steer the robot to avoid obstacles [4] or select individual foothold positions [7]. However, online built maps tend to suffer from artifacts and inaccuracies causing foothold selection to be unreliable. Besides, further processing techniques might be necessary for, e.g., soft terrains, to distinguish vegetation and the actual supportive soil [8]. Hence, additional information is desirable to improve the accuracy of the build maps [9].

The proprioceptive sensing such as the tactile feedback aims to detect the moment of the leg contact with the ground. A straightforward approach is to place a contact sensor at the leg foot tip [10]. Another method is to estimate or measure ground-reaction forces or joint torques. The joint torques can be measured directly at each joint [11], but they can be estimated using a linear model of the servo motor current [12]. Besides, other existing approaches employ strain-gauges [13] and force-sensitive resistors [14] to build a more affordable solution than using expensive force-torque sensors [15] to measure the ground reaction force at the leg foot-tip. But all these approaches rely on the particular servo motors accompanied with the selected sensor, which increase the cost and complexity of the robot construction and needed electronics. A minimalistic approach based on additional compliant actuator added on each leg is proposed in [16] to measure the ground reaction force in the kinematic chain. Using the ground reaction force, Palankar et al. [17] propose a force threshold-based position controller for crawling over irregular terrains.

In [1], we consider the same affordable servo motors as Palankar et al., but we propose an even more minimalistic approach that directly utilizes position feedback of the active actuators without the need of additional compliant actuators as in [17]. Thus, the proposed approach does not rely on any additional sensory equipment, and it solely uses the actuators that form the hexapod robot legs. Therefore, the developed locomotion control enables an affordable solution for the multi-legged robot capable of locomotion over rough terrains. However, the stability of the motion is influenced by the communication bandwidth and latency between the control board and the utilized servo motors. Therefore, we investigate the effect of the control loop period on the overall performance of the locomotion, and the achieved results are reported in the following sections of this paper.

## 3. Position-based Adaptive Locomotion

The problem addressed in this paper is to show an influence of the control loop period, e.g., defined by the communication bandwidth and latency, of the adaptive motion gait to the performance of the locomotion in crawling rough terrains. In particular, the reported experimental evaluation is based on our groundwork [1] that proposes a minimalistic control system for a hexapod crawling robot using only the position feedback of the utilized servo motors. In this section, we briefly introduce the underlying adaptive locomotion control that is essential for the elaboration of the control loop period influence on the locomotion performance.

### 3.1. Hexapod Robot Platform

The utilized affordable hexapod crawling robot is assembled from off-the-shelf components, and it consists of six electrically actuated legs, each with three joints, attached to the trunk which hosts the control board. Each leg follows a yaw-pitch-pitch kinematic chain, where each joint is motorized with the Dynamixel AX-12A intelligent servo motor with position feedback. All servo motors are connected in a daisy chain over a half-duplex serial bus with a bandwidth up to 1 MBaud and communicate using a master-slave protocol with the control board. Each servo motor has a P-type position controller and provides the control unit with its current position on demand. In the default configuration, the robot dimensions are approx. $45 \times 40$ cm, see Figure 1.

### 3.2. Adaptive Locomotion Control

The utilized adaptive locomotion control [1] split the motion of the legs into swing phase and stance phase. The individual legs alternate the phases according to the prescribed motion gait [18], and the legs in the swing phase are reaching new footholds while the legs in the stance phase support the robot body. In the employed locomotion control, the swing phase is further divided into three individual parts with the ground contact detection only in the swing-down phase of the motion as it is visualized in Figure 2a. Moreover, the robot motion is divided into reaching new footholds and body leveling parts because of the proposed ground detection using the position feedback.
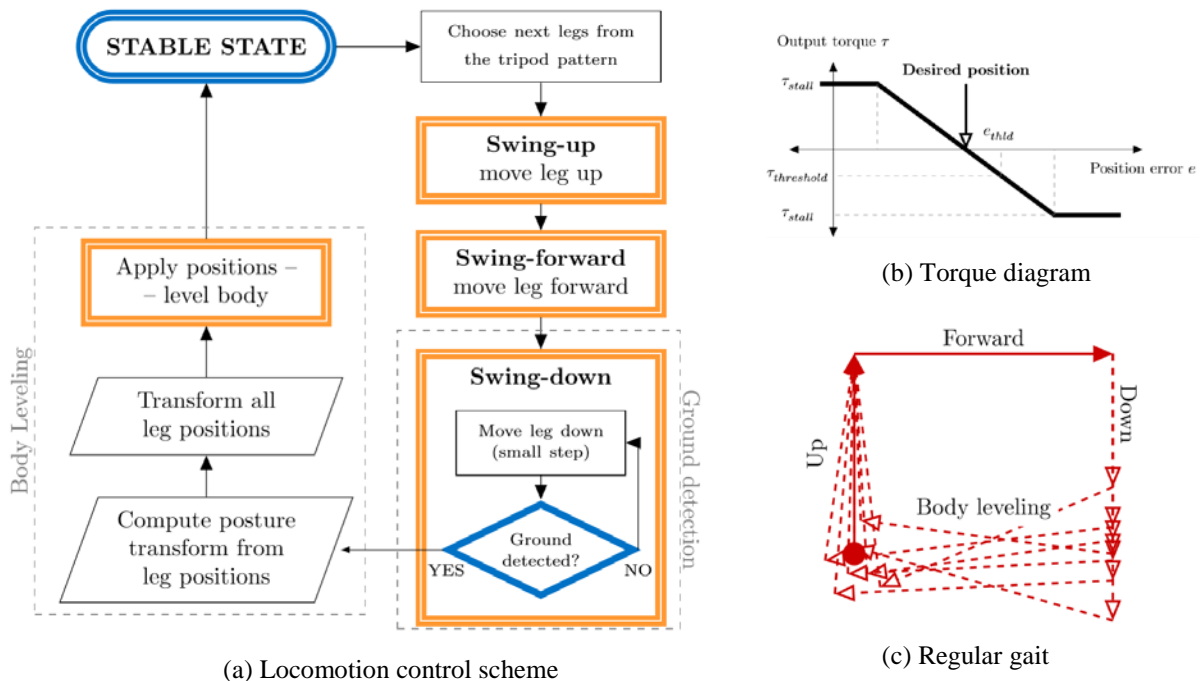


(a) Locomotion control scheme

(b) Torque diagram

(c) Regular gait

**Figure 2.** (a) Schema of the adaptive locomotion control [1] with the divided swing phase with the ground detection and body leveling. The ground is detected only in the swing-down phase of the leg motion using position error $\epsilon$ and its relation to the joint torque $\tau$ of the utilized servo motor shown in (b) torque diagram. (c) Leg trajectory in the hexapod body reference frame.

The ground detection is based on the relation of the position error and the torque that acts on the joint as it is depicted in Figure 2b. When the swinging leg touches the ground, the ground reaction force causes an increase of the load applied to the individual leg joints. Therefore the position error is increased, and if it reaches a specific threshold, the leg contact with the ground can be detected [1]. Once all legs in the swing-down phase reach the ground, and thus the foothold positions are acquired, the robot body is moved into an equilibrium position to distribute the weight of the robot evenly among its legs, which increases the robot stability. This motion is called body leveling by which the robot reaches a stable position from which it can easily move in any direction. As the equilibrium position is always given by the new footholds, it makes the whole robot thrust forward. Therefore the resulting trajectory of the leg in the robot body reference frame during several gait cycles may look like in Figure 2c.

The essential part of the timely detection of the foot contact with the ground is an interpolation of the swing-down trajectory of the leg into small incremental steps $\Delta\theta$ that are given according to

$$\Delta\theta = \frac{\theta_{\text{fin}} - \theta_{\text{init}}}{t_{\text{des}}/t_{\text{con}}} \tag{1}$$

where $\theta_{\text{init}}$ and $\theta_{\text{fin}}$ are the initial position and the desired final position of the joint, respectively, $t_{\text{des}}$ is the requested time to finish the motion, and $t_{\text{con}}$ is the control cycle period, which is limited by the minimum period in which the servo motors can be polled for the position of the joint and which

depends on the used communication chain. The ground is detected by the adaptive controller as follows.
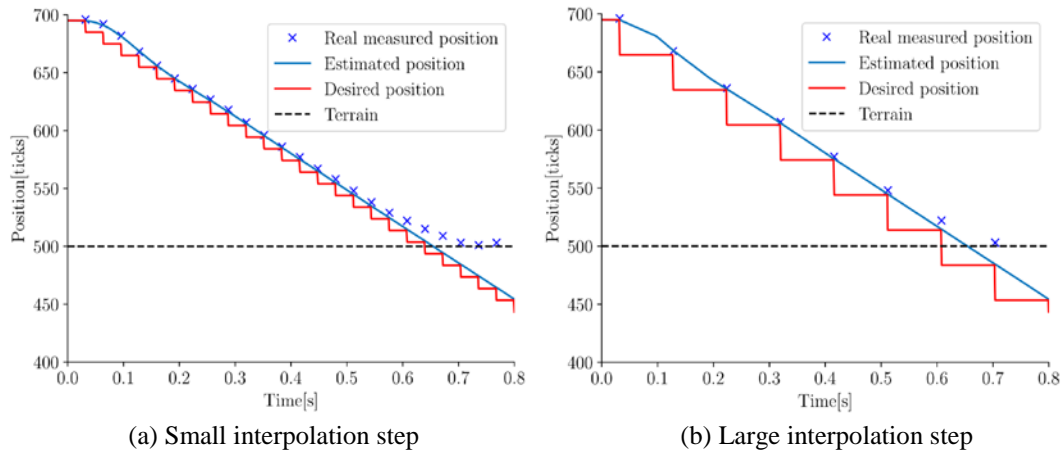


(a) Small interpolation step                    (b) Large interpolation step

**Figure 3**.Visualization of the servo trajectory interpolation for settings $\theta_{init} = 700$, $\theta_{fin} = 300$, $t_{des} = 1$ s and (a) $t_{con} = 32$ ms, and (b) $t_{con} = 96$ ms.

In each incremental step of the swing-down motion, the actuators of the currently swinging legs (given according to the motion gait) are set with a new position and their current position is fetched by the controller. The trajectory interpolation for a single actuator swinging between the current position $\theta_{init} = 700$ and the final desired position $\theta_{fin} = 300$ that is expected to be reached in $t_{des} = 1$ s is shown in Figure 3. Note, the reported values of the position are in ticks because the measured angular position of the actuator is discretized. Given the control cycle period $t_{con}$, each interpolation step corresponds to a single write and a single read of the servo position. When the leg touches the ground, the ground-reaction force starts to act on the robot leg causing the torque in the joints is increased that further propagate into the position error, which is in the case of the utilized Dynamixel AX12 servo motors, approximately proportional to the torque according to the curve depicted in Figure 2b. Hence, if the read position differs in more than $\epsilon$ threshold ticks from the expected estimated position of the joint, i.e., the position in which the servo should be at the given time without any external influence, the foot-strike is detected, and the leg motion is stopped.

The length of the interpolation step significantly influences the reaction time of the controller. For longer steps, there are fewer readings throughout the leg swing-down phase, and thus a higher ground reaction force can arise which can further cause, e.g., overheat of the servo motors, but it primarily affects the stability of the locomotion. An example of a large interpolation step for a longer period $t_{con}$ is visualized in Figure 3b. The large interpolation step causes an increased latency of the ground detection process as it makes a longer time to satisfy the threshold condition.

## 4. Ground Detection, Latency, and Motion Stability
Sensory feedback is necessary to maintain the stability of the multi-legged robot in crawling rough terrains. In the utilized adaptive locomotion control [1], the position feedback of the servo motors is sufficient for the timely stopping of the leg movement in the case of the foot-strike event. However, the position readout latency and other related communication and signal processing factors may further significantly influence the stability of the robot during locomotion over rough and irregular terrains. The main identified influencing factors are as follows.

**Robot topology** influences the placement and connection of the sensors, and thus it influences the information gain that can be obtained by reading data from the particular sensor. In the utilized adaptive locomotion control [1], the actuators are the sensors that are connected in a tree-like topology

with a single communication channel to the control board. The servo motors are connected via a half-duplex serial interface which has to be utilized for both setting the desired pose and reading the current pose. The adaptive locomotion control uses three sub-phases of the swing phase that is split into up, forward, and down parts. Together with the design of the robot leg, it is sufficient to read the position information only from the middle servo of the leg (called femur) as the main portion of the ground reaction force acts on to this servo during the swing-down phase.

**Latency of the communication channel** is mainly influenced by the utilized communication interface, but it is also related to the topology and connection of the sensors. Besides, the particular communication protocol and the delays caused by both hardware and software level may cause significant latency issues. For example, it is reported that the used Dynamixel AX12 servo motor suffers from 16 ms period latency for serial communication under Windows and Linux-based operating systems [19]. Hence, real-time operating systems, tailored drivers or dedicated hardware solutions might be necessary to speed up the communication further and overcome the boundary conditions, which may further increase the cost of the complete solution for a multi-legged robot capable of traversing rough terrains. The latency of the communication channel is directly expressed by the control cycle period $t_{con}$ as the maximum reading speed influences the overall trajectory interpolation process.

**Motion gait** prescribes the order in which the individual legs are moved. When multiple legs are swinging simultaneously, e.g., for the tripod gait with three legs in the swing phase, synchronized transmission of the desired poses and readings of the current poses for all the involved servo motors is necessary. Managing multiple servo motors and sensors has a multiplicative effect on the overall latency, and thus the control cycle period $t_{con}$. Therefore it is desirable to write all the requested commands to the servo motors synchronously, but the readouts from the servos can be performed sequentially because of, e.g., half-duplex serial interface; hence, the control cycle period has to be prolonged appropriately.

**Locomotion speed** can be considered as the user-defined parameter $t_{des}$; however, it cannot be set arbitrarily as it should cope with the communication constraints imposed by the above influencing factors. Besides, too low $t_{des}$ may influence the reliability of the ground detection, and therefore, the appropriate value has to be set according to the expected performance of the locomotion.

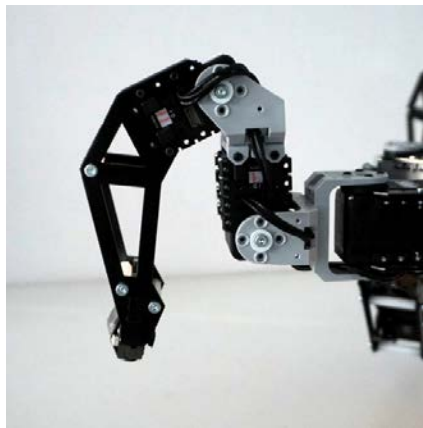### 4.1. Ground Detection and Control Cycle Period

An example of the influence of the communication latency given as the control cycle period $t_{con}$ on the servomotor motion is visualized in Figure 4., where a development of the position error between the desired and the actual position of the joint is shown for $t_{con} \in \{4\,\text{ms}, 16\,\text{ms}, 32\,\text{ms}, 48\,\text{ms}\}$. The values of $t_{con}$ have been selected as the representatives of the real latencies in the used hexapod crawling robot as follows.

- 16 ms is the period of the serial communication reported for Linux-based operating systems [19].
- 32 ms as the double of the communication period in the case of reading two servos in every interpolation step.
- 48 ms is the triple of the communication period needed in the tripod gait where three positions are read in each interpolation step because of simultaneous moving of three legs.
- 4 ms represents the minimal control cycle period for tripod gait achieved by the hardware accelerated communication.

For each $t_{con}$, the same setup with a single leg that swings down and reaches a ground has been utilized, see Figure 4a. The leg, i.e., the femur joint, is initially set to the position $\theta_{init} = 700$ and it is requested to reach the position $\theta_{fin} = 300$ in $t_{des} = 1$ s with the obstacle corresponding to the joint angle $\theta = 500$ that corresponds approximately to the time 0.6 s, when the leg hits the ground.

The results in Figure 4b indicate that shorter interpolation steps induced by the shorter $t_{con}$ reduce the overall torque in the leg as the servo P-type controller does not have to handle large jumps in the

desired position. Moreover, a short interpolation step allows for faster detection of the ground contact event. The overall effects of the lower latency (shorter control cycle period) on the actual locomotion control are discussed in the following section.
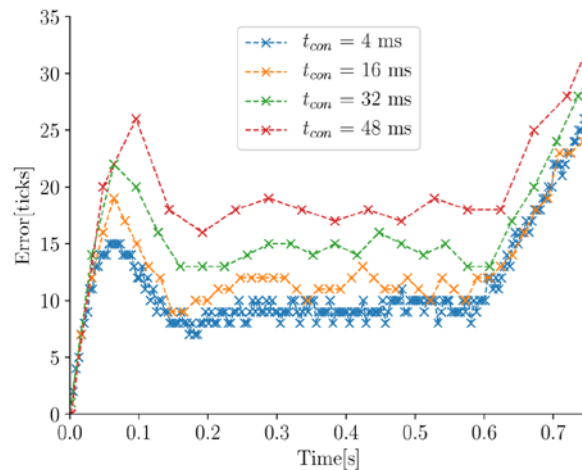


(a) Single leg setup                (b) Position errors for different control cycle period $t_{con}$

**Figure 4**. (a) Single leg of the hexapod crawling robot in experiment measuring the effect of sensor reading latency on the terrain contact detection; (b) Visualization of measured position errors for experiment with different values of $t_{con}$ and fixed obstacle that is hit at around 0.6 s.

## 5. Experimental Results

In this section, we report on the experimental evaluation of the adaptive locomotion controller [1] with the settings of the control cycle period $t_{con} \in \{4 \text{ ms}, 16 \text{ ms}, 32 \text{ ms}, 48 \text{ ms}\}$ to demonstrate an effect of the communication latency. The selected periods correspond to the adaptive tripod gait with and without the hardware acceleration of the communication with the servos. The evaluation is organized in two experiments. The first experiment is focused on the stability of the platform and reliability of the ground detection for the given $t_{con}$ and requested locomotion speed defined by the period $t_{des}$ according to (1). The second experiment benchmarks the performance of the controller in crawling a rough terrain mockup consisting of wooden blocks with the identical dimensions $10 \times 10$ cm, but with variable height and slope, see Figure 1.

### 5.1. Locomotion Stability

The stability of the platform and reliability of the ground detection is measured by observing the body motion during the locomotion on the flat surface. The stability is measured as smoothness of the locomotion using an inertial measurement unit (IMU) attached to the robot trunk. In a case of the miss detection of the ground contact, the hexapod robot trembles which cause vibrations measured by the IMU. Therefore, the body orientation (pitch and roll angles) and the linear acceleration in the vertical direction ($Acc_z$) are measured as the stability and reliability indicators during a course of 20 gait cycles of the tripod gait for the control cycle period $t_{con} \in \{4 \text{ ms}, 48 \text{ ms}\}$ and $t_{des} \in \{0.5 \text{ s}, 1 \text{ s}\}$. For each setup, a suitable error threshold $\epsilon$ for the ground detection has been determined experimentally as the median value of the position error (described in Section 4.1 with the evolution of the error depicted in Figure 4b) increased by three additional ticks. The indicators are measured at 400 Hz using the XSens MTi-30 Attitude Heading Reference System (AHRS). Then, the mean value of each variable is subtracted from the readings, which cancels systematic amplitude displacements, and the five-number summary for all the indicators is calculated.
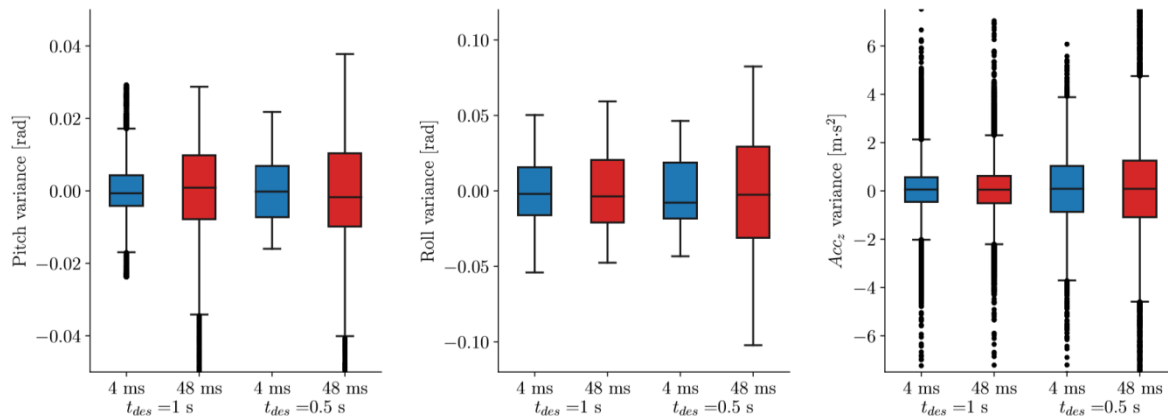
**Figure 5**. Stability and reliability indicators of the ground-detection according to $t_{con}$ and $t_{des}$.

The results for the individual measured indicators and each particular setup are visualized in Figure 5, where it can be noticed that in all the cases, the ground detection with the shorter control period $t_{con} = 4$ ms provides smoother locomotion in comparison to the longer period $t_{con} = 48$ ms, and thus it seems to be more reliable. Besides, it can be seen that for the roll and pitch variances, the period $t_{con} = 4$ ms yields better stability even for faster locomotion in comparison to the adaptive tripod gait without the hardware acceleration of the communication.

*5.2. Rough Terrain Traversing*
The performance of the adaptive locomotion controller in traversing the rough terrain mockup has been experimentally verified to test dependency of the robot ability to crawl over rough terrains with different control cycle period $t_{con}$ and locomotion speeds defined by $t_{des}$. Also in this case, the tripod gait is considered with $t_{con} \in \{4$ ms, $48$ ms$\}$ and with the locomotion speeds $t_{des} \in \{0.5$ s, $1$ s$\}$. For each setup, the robot has been requested to traverse the experimental 2.1 m long mockup ten times. The average values of the time to traverse the mockup and the achieved velocities are reported in Table 1 and snapshots of the robot traversing the mockup are presented in Figure 6. The velocity has been estimated using an external visual localization system based on [20] running with 25 Hz according to $v = ds/dt$ where $dt$ is a fixed time window of 5 s and $ds$ is calculated from the robot's trajectory.

**Table 1.** Rough Terrain Traverse Times and Velocities

|  | $t_{des} = 1$s | | $t_{des} = 0.5$s | |
|---|---|---|---|---|
|  | $t_{con} = 4$ ms | $t_{con} = 48$ ms | $t_{con} = 4$ ms | $t_{con} = 48$ ms |
| Traverse time [s] | 58.6 | 62.3 | 47.3 | 83.1 |
| Velocity $\times 10^{-2}$[m · s$^{-1}$] | 3.6 | 3.4 | 4.7 | 2.9 |

The results indicate that using a short period of the control cycle enables faster but still stable locomotion. Overall, the speed of the locomotion in rough terrains is improved about 1.4 times in comparison to the original controller proposed in [1], which is represented by $t_{con} = 48$ ms and $t_{des} = 1$ s.
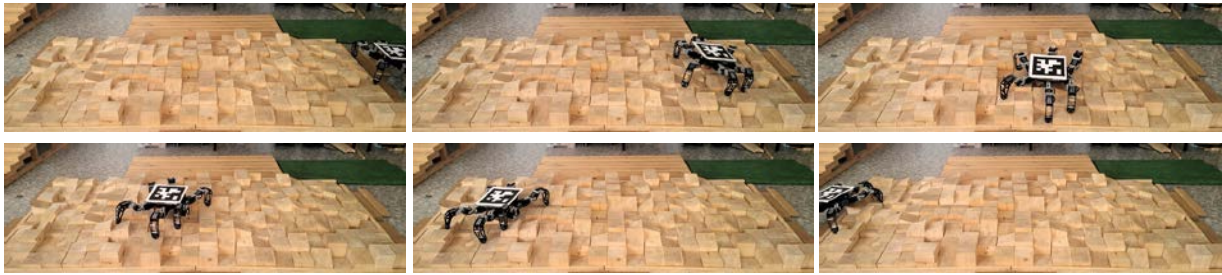
**Figure 6**. Snapshots of the robot traversing the experimental mockup with the rough terrain.

## 6. Conclusion

In this paper, we report on the experimental evaluation of the control cycle period influence to the locomotion of the hexapod crawling robot traversing rough terrains. The evaluation is based on measuring locomotion stability with different periods and locomotion speeds. Besides, we also report that by lowering the feedback control period (e.g., the latency), the overall torque in the servos is lower, and the stability of the locomotion in both flat and rough terrains is increased. Last but not least, we show that no additional sensory equipment is necessary for an affordable robot to overcome structured terrain and only the position feedback from the used servo motors is sufficient.

## Acknowledgments

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