Leg's Tip-Ground Contact Detection Based on Drive Currents in a Real Walking Robot

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Marek Wąsik

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Abstract:
To ensure an effective walking over uneven terrain for multilegged walking robots, there is necessary to detect the contact between the leg's tips and the ground. It is essential to determine the moment when we should end the swing phase of the leg. This paper presents a method of detecting contact with the ground based on total current drawn by the servomotors of each robot's legs. The method was developed using a 4-legs supported gait on 5-legged walking robot – PentOpiliones. This detection method has been tested and positively verified on a real robot. Also there has been tested the limitation of above method using a gait with different robot postures and different speeds.

Keywords: *5-legged walking robot, walking on uneven terrain, 4-legs supported gait, ground contact detection, servomotor current, load estimation*

1. Introduction

To allow the robot to move over an uneven terrain it is necessary to detect the moment when the leg is landing on the ground [11]. This detection can be realized in many ways, using different sensors, typically located at the leg's tips:

— mechanical switches – the simplest sensors, which under the load are mechanically switched, close the circuit and signalize the collision. They return a binary signal; are easy to use but often sensitive to mechanical damage. They are used for example in many hexapod robots [6]
— strain gauges – depending on the number of sensors, they allow to measure forces and torques along many directions [5]. They perform an accurate measurement, but usually are larger and more expensive than mechanical switches.
— sensors that measure mechanical deformation – while placing the leg, its tip is deformed, what can be measured for example with a potentiometric displacement sensor. It is particularly suitable for solutions where the leg tip must be elastic for example to absorb the impacts.
— proximity sensors – depending on the ground properties in robot's environment, there can be used a capacitive proximity sensors, inductive or reflective infrared light sensors. They detect the proximity between the ground and leg's tip, however, they require that the ground must have some specific properties, for which the sensor is sensitive.

Another method to detect the leg contact with the ground can be realized base on measurement of supply current drawn by the servomotors in each of the robot's legs. Such a possibility was decided to consider in this paper. The remainder of the paper is structured as follows: section 2 describes the outline of the robot construction, section 3 presents the 4-legs supported gait used during this research, while section 4 provides a detail description of legs current measurements. The algorithm of ground detection is described in section 5 and in section 6 it is verified during the gait on uneven terrain. Section 7 shows the efficiency of ground detection in gait with various parameters. The paper is concluded in section 8 with a short film presented the results of a developed gait with a ground detection.

2. Robot Platform Used in the Research

As a platform for research a 5-legged walking robot – PentOpiliones was used [9]. It is a robot with five legs and a radial symmetry (Fig. 1a). The legs are positioned at 72 degrees to each other, similarly like in other 5-legged robots [2]. This solution allows moving legs in each direction with the same simplicity [4].

The construction is driven by a standard servomotors, like these used in remote control models, and have a torque of 1.0 Nm. Legs have a classical kinematics scheme with three degrees of freedom and insect-like structure [3]. The two main segments of a leg (femur and tibia) have length of 150 and 250 mm, respectively. The legs in robot were indicated with a consecutive number from 1 to 5 (Fig. 1b).

3. Gait used in the research

During the research, there was used a 4-legs supported gait. The goal was to develop a method of the effective detecting the contact between the leg's tips and the ground during the landing phase of the leg. This is necessary to provide the gait on an uneven terrain where the level of the ground is uncertain.

In 4-legs supported gait at any time exactly one leg is moved, while the others support the robot. It consists for each of the legs from following phases:

- *Swing phase* – on flat terrain it lasts exactly 20% of time (1/5 gait cycle) and is divided into:
  — leg rises up – the leg's tip is constantly raised up to desired level,
  — leg floats to the front – the leg's tip is constantly

carried along the half-circle trajectory to the front (in direction of movement),
 - leg lands – leg's tip is constantly lowered until the contact with the ground is detected (if the robot is walking on uneven terrain we don't know on which level is the ground),
 - leg's correction, trunk carried – there can be a delay in the ground detection and leg's tip can override the real level of the ground. In this situation it is necessary to move the leg's tip back to the position where the ground contact was really detected. It is necessary to align the load among all legs. Additionally in this phase, the trunk is constantly transferred to the front relative to the ground, with a distance of 1/5 step length. This ensure the moving of the robot and is realized by moving the leg's tips constantly to the back with a distance of 1/5 step length.
- *stance phase* – the leg end is on the ground and supports the weight of the robot. During this phase, all other legs are consecutively performing a swing phase.

The above phases for any two legs lying side by side are shifted with 144 degrees in phase to each other. This means that after the swing phase of any leg, the leg on the opposite side of the robot starts the swing phase (they moves in the following order: leg number 1, 3, 5, 2, 4, 1.... The 4-legs supported gait can be realized without detecting the ground contact

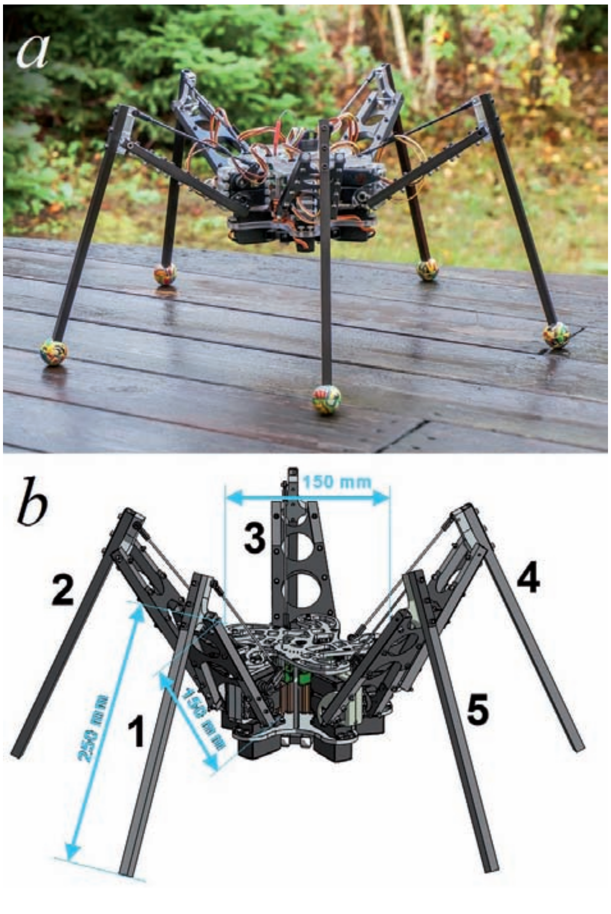

Fig. 1. PentOpiliones – 5-legged walking robot used for a research

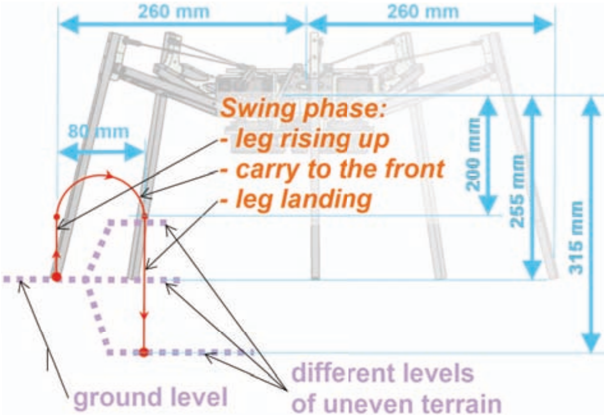

Fig. 2. Leg trajectory in 4-legs supported gait

only on a flat terrain, because only then we can exactly determine when the leg should ends its swing phase without using any additional sensors.

During the research there was used a 4-legs supported gait with a legs trajectory shown in Figure 2 and with the following specification [10]:
- step length: 80 mm,
- maximal height of legs lift up: 200 mm below the trunk,
- average height of trunk above the ground: 255 mm,
- maximal height of legs put down: 315 mm below the trunk,
- duration of one step: 3.5 sec,
- distance between the leg neutral support point and the robot's center: 260 mm.

The analysis of the legs load was performed 50 times per second, what is sufficient due to the dynamics of the robot.

4. Measure of the Current Consumed by the Robot's Legs

In PentOpiliones robot simple servomotors without the possibility of current measurement are used. Nevertheless, in electronic circuit was considered the possibility to measure a total current drawn by each of five robot legs. These five currents signals drawn by each of the leg are the only information used during this research to determine the load of the legs. We proved that this is sufficient information to detect the moment when the leg has a contact with the ground and to allow walking on uneven terrain.

The supply current drawn by all three servomotors in each leg is measured basis on voltage drop on a shunt resistor with a resistance of 10 mOhm (Fig. 3). This voltage is amplified 50 times and shifted to the ground level by the INA168 amplifier [8]. Next the signal is converted by a 12-bit analog to digital converter in a main robot microcontroller: STM32F407 [7]. The above measurement method allows the measure up to 3 Amps with an absolute error smaller than 30 mA. As confirmed by further tests, this accuracy is sufficient enough.

The electronic circuit in servomotor is a switching regulator and it controls the motor with a frequency of 1000 Hz, so it draws a pulse current. To allow the

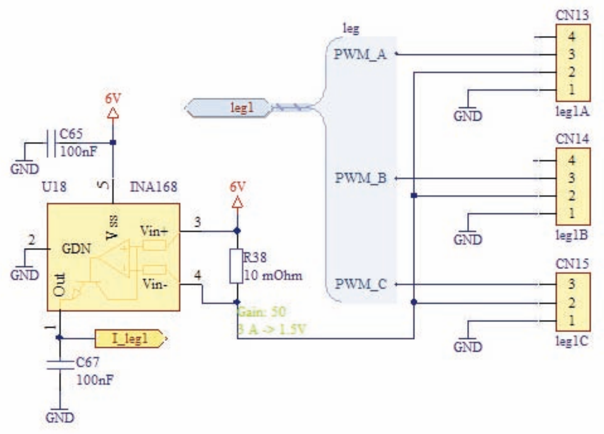

Fig. 3. Part of an electronic schematic which measure the supply current in one of the legs

estimation of leg load base on drawn current it is necessary to average it. Therefore, the microcontroller samples the current at a frequency of 50 kHz and averages it with the digital FIR filter:

$$P = \sum_{i=0}^{1999} (2000 - i) \cdot z[i] \tag{1}$$

where: P – value of averaged current, $z[i]$ – measuring sample delayed by i measurements relative to the most recent.

According to the above formula (1), the filter works on the last 2000 samples (40 ms of time) and as was validated by the practical tests this filter behaved the best among several tested filter. The results of filtering was wirelessly sent to the computer and analyzed in a real time in the robot control application to verify the quality of all tested filters.

5. Analysis of Legs Load

The first test was executed to familiarize oneself with a correlation between the value of measured current in each of the legs and a legs load. There was used a 4-legs supported gait on a flat terrain, but legs were not stopped when they touched the ground, and they were farther moved down, up to the end of their working space. That means that during the leg landing in a swing phase, the leg was lowered so low, that after the collision with the ground there was a big overload on its servomotors. It can be observed in the Fig. 4 of legs current consumption. In the presented case the robot was moving in the direction of the leg number 1.

The supply current consumed by each of the legs during the landing phase varies considerably among them. This is because the legs are not always arranged ideally symmetrically (in regular pentagon) and at various moments, some of the legs are more loaded.

After analyzing the data we decided that it is worth to add an additional parameter to easier determine the moment of leg tip contact with the ground. Let's call this parameter as an *overload current* in putting the *i*-th leg (K_i):

$$K_i = 5 \cdot I_i + I_{(i+2)\bmod 5} + I_{(i+3)\bmod 5} - 2 \cdot I_{(i+1)\bmod 5} - 2 \cdot I_{(i+4)\bmod 5} \tag{2}$$

where: I_k – current consumed by the *k-th* leg.

The overload current is defined as a weighted arithmetic sum of supply current consumed by consecutive legs. It is due to the fact that in the leg which has a ground contact, the load will increase the most

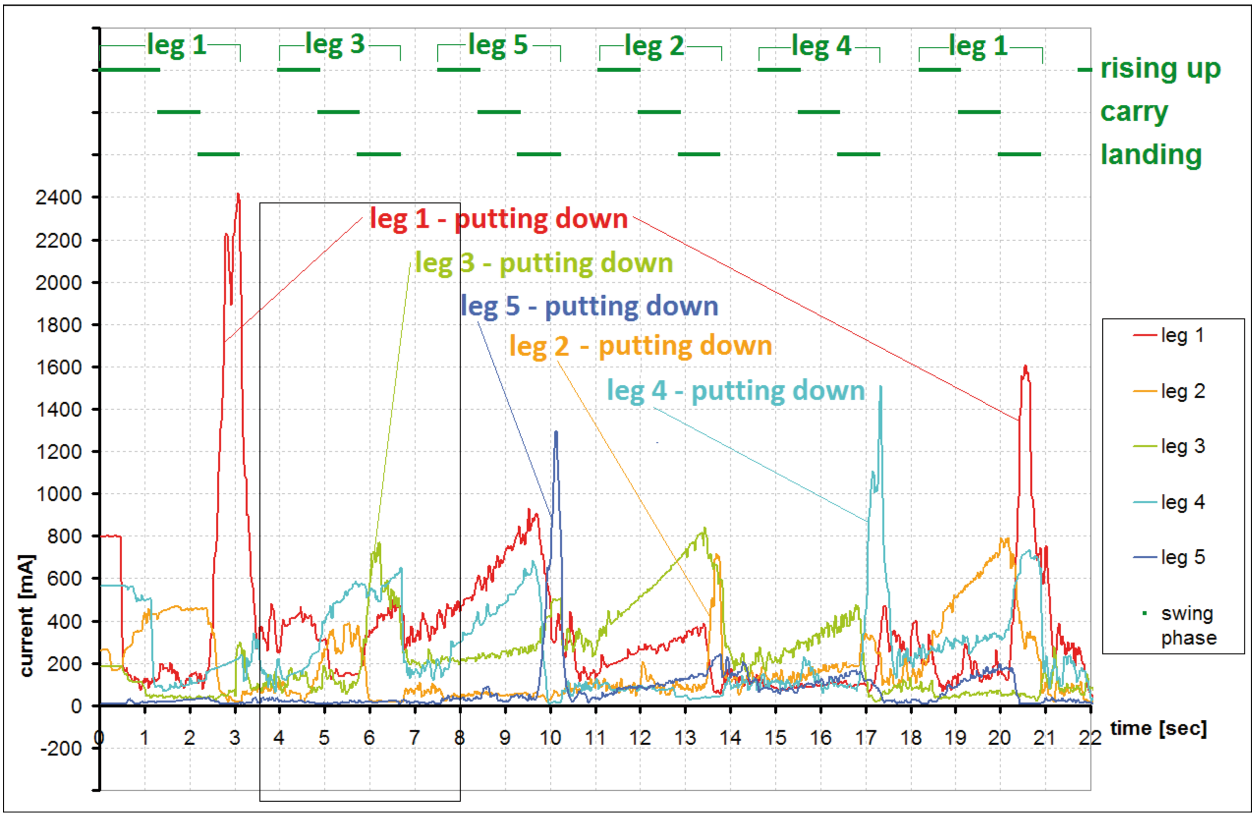

Fig. 4. Legs consumed current during the walk without ground detection

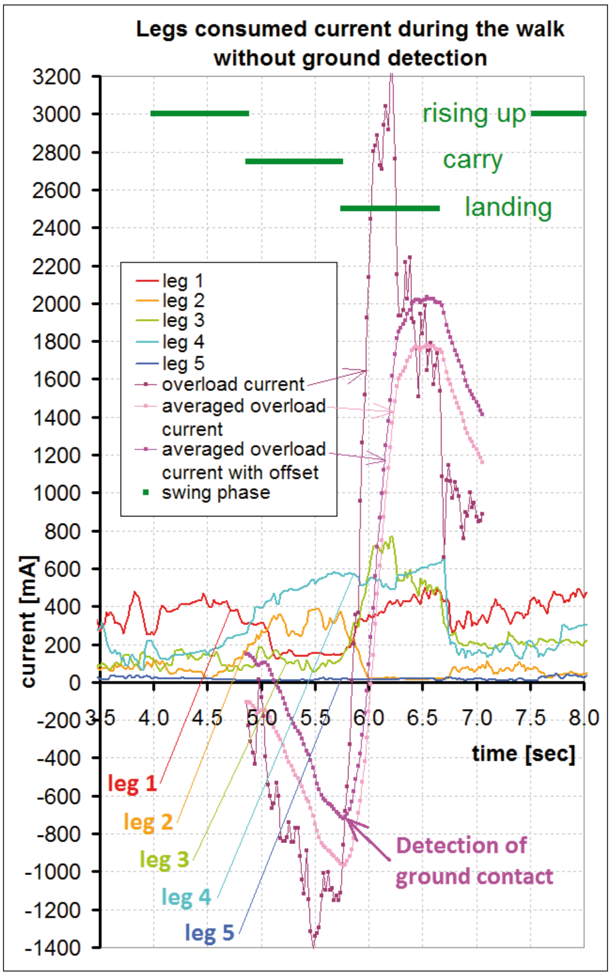

Fig. 5. Chart with an overload current of the leg number 3 during the swing phase. This is enlarged chart fragment indicated in Fig. 4 with a black frame

after this contact (weight 5). Simultaneously in two nearest legs the load will decrease (weight -2) and in two legs on the opposite side the load will also increase (weight 1). The above coefficients were determine experimentally. Such defined parameter of an overload current is appropriate to determine the moment when the leg had a contact with the ground and it was shown in Fig. 5 during the situation of landing leg number 3 from the Fig. 4.

Based on increase of the overload current, there is a possibility to detect a leg contact with the ground. After some tests, to resist the detection to the external disruptions, it was decided that the ground contact will be approved if the instantaneous overload current exceeds the average overload current more than the offset of 375 mA (Fig. 5). An average overload current is averaged by a digital low pass filter with a time constant of 250 ms.

6. Verification Developed Method of Ground Detection

To expand the 4-legs supported gait on a flat terrain to a gait on an uneven terrain it is necessary to detect the moment of leg contact with the ground to ends the landing phase of the leg [1].

In the previous section, after ground contact detection, the leg landing phase was not stopped. This was because we wanted only to observe the behavior of the overload current. In this section, the algorithm will stop the leg landing phase immediately when the ground contact is detected.

Above method based on overload current is sufficient for ground detection. It was verified in practice on an uneven terrain. Recorded measurements of cur-

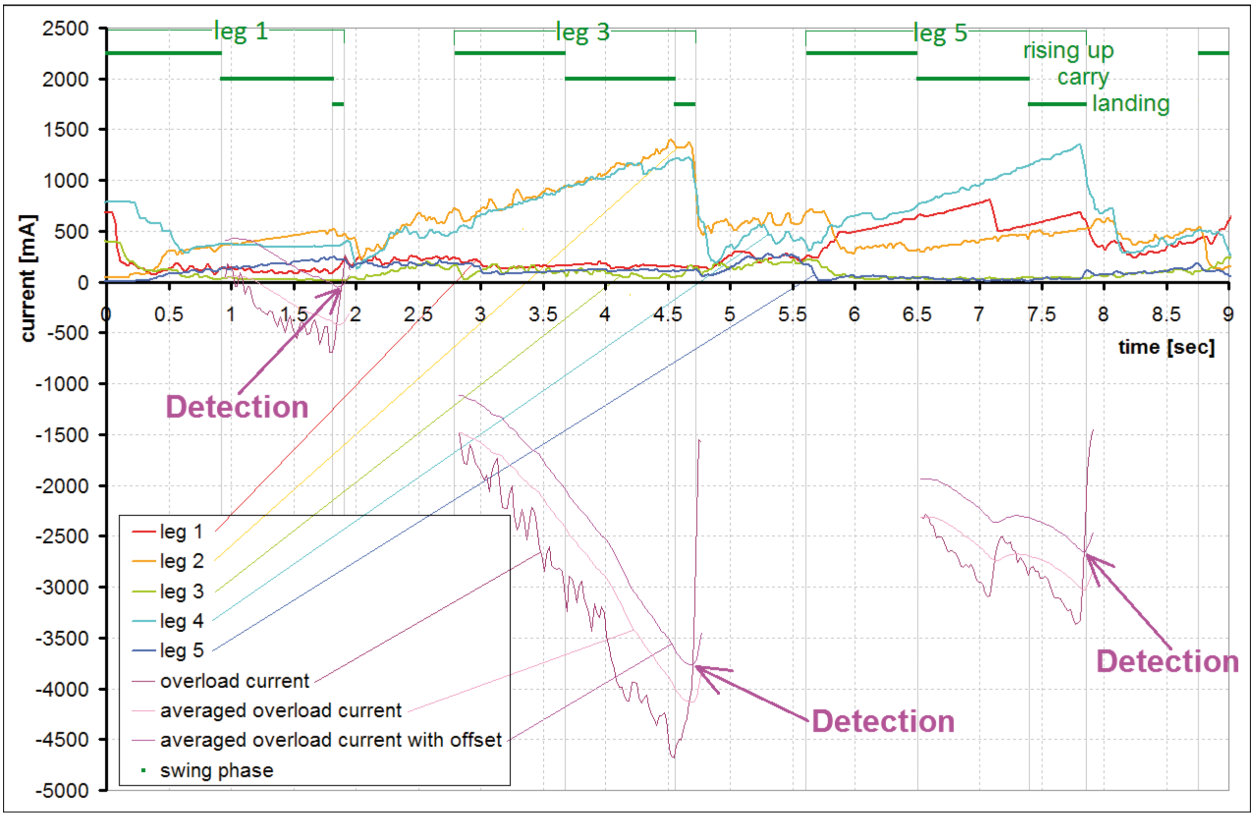

Fig. 6. Legs consumed current during the walk on uneven terrain with ground detection

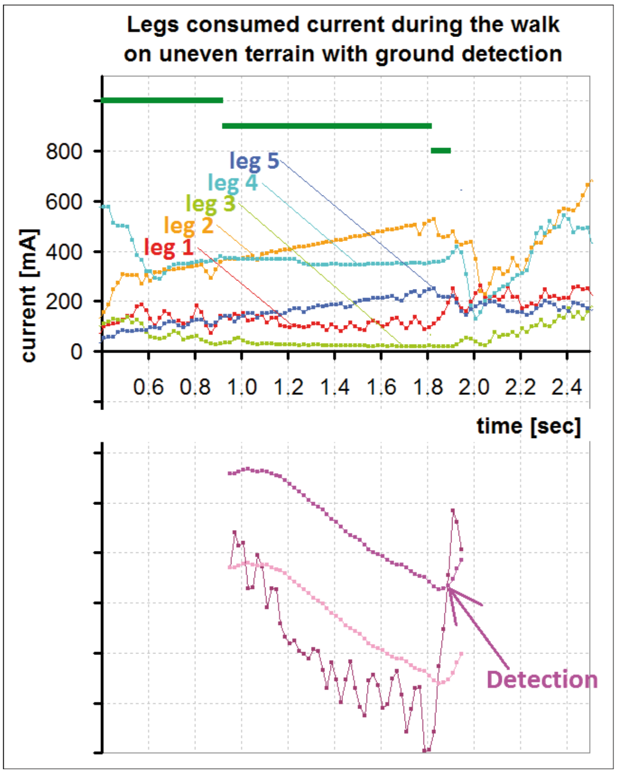

Fig. 7. Enlarged fragment from the Fig. 6 (landing phase of the leg number 1)

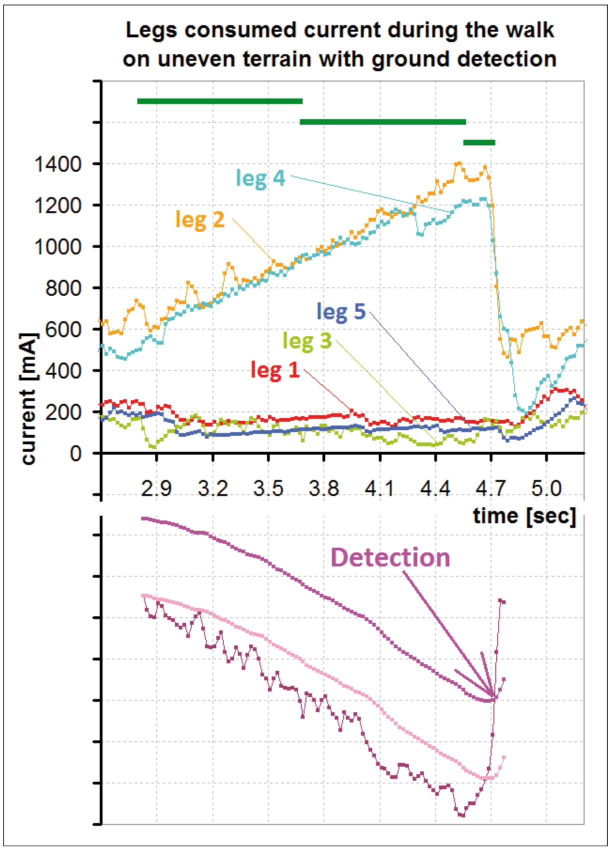

Fig. 8. Enlarged fragment from the Figure 6 (landing phase of the leg number 3)

rents are illustrated in Fig. 6. There are 3 steps performed consecutively with the leg number 1, 3 and 5. For each of these steps, there is also marked a calculated overload current.

We can see that unlike the Fig. 4, in Fig. 6 leg landing phase is much shorter. It lasts only to the moment when a leg contact with a ground is detected.

The above algorithm has an assumption that the leg end hit on the ground during its landing phase. Otherwise, the leg will be lowered until the end of its working space, and will stop over the ground (in case of very deep holes in the ground).

In Fig. 6 we can also see the constantly growing current for some of the legs (leg 2 and 4 from 3.0 to 4.5 second or leg 1, 2 and 4 from 6.5 to 7.9 second). It is caused by a poor quality of servomotors. The control error in servomotor regulator is slowly increasing, while the servomotor does not react by some friction on the gear and this cause the increasing of the current. Nevertheless, the above situations do not have an influence to the ground detecting, because landing the leg on the ground cause more significant changes in measured currents.

Two fragments from Fig. 6 (which shows the landing phase of the leg number 1 and 3) were enlarged and are shown in Fig. 7 and Fig. 8. The overload current in this figures was scaled to increase the clarity.

In Fig. 7 and Fig. 8 we can clearly see the current consumed by each of the leg and the overload current during the practical test on uneven terrain. The landing phase of the leg is always ending, when the ground is detected. We can also observe that during the ground contact there is not any significant increase in current of leg which was putting down. Therefore, it was necessary to introduce and calculate an overload current, which allows to determine the moment of ground con-

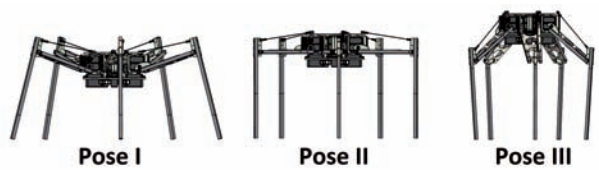

Fig. 9. Different poses used in robot gait

tact more precisely.

As practical tests have shown, the moment of ground detection determine on above method, existed almost exactly on the moment of a real support of the leg. There was only a slight delay from ground contact to detect it by algorithm. Nevertheless, the change in a leg's tip position during this delay was very small and comparable to the backlash which is a result of used servomotors quality. Therefore, this delay could be neglected and there is no necessary to correct the leg's tip position after ground detection.

7. Range of Applicability of the Developed Method

The developed method works effectively with the gait specified in section 3. It was a gait with a neutral robot poses, like Pose I in Fig. 9, and was relatively slow (3.5 second for 1 step). In further tests, the speed of gait was increased to determine the limitation of this method. The results are shown in Figure 10. With the faster speed there was more false detection of the ground. The time of one step was decreasing each 0.25 second from a 3.5 second, and for each try robots made 50 steps while there was counting the number

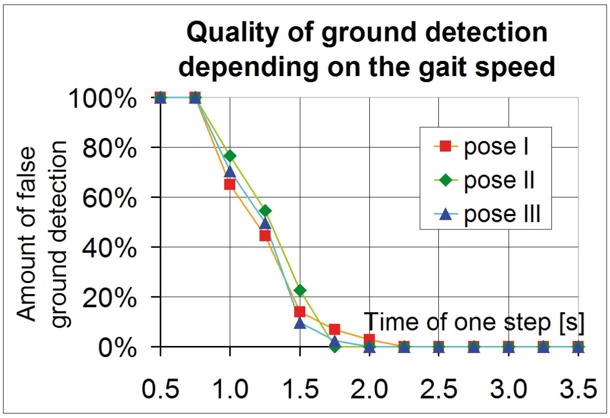

Fig. 10. Limitation of the ground detection according to the different poses and speed

of false ground detection.

The method of ground detection was also tested for a different poses: with a right angle in the last joint and with highly raised trunk (Pose II and Pose III in Fig. 9). These poses are less optimal in terms of motion range and stability, nevertheless it was expected that it may be better in contact detection. As shown by the tests (Fig. 10), the efficiency of ground detection is similar to each other. The maximal speed of a robot for proper ground detection is about 2.25 second per step and the robot pose does not have a big influent to it.

8. Conclusion

The measurement of the total current drawn by each of the legs provides a small amount of data. Despite this, it was proved in practice that it is sufficient for proper ground detection and to provide the gait on uneven terrain.

The developed method was shown on video[1]. It works successfully in 4-legs supported gait with a speed not faster than 2.25 second per step. During the higher speed, the algorithm begins to return some false ground detections. There were also tests to expand the above method to a 3-legs supported gait. Nevertheless it is more complicated task and this attempt was not successful.

The described method of ground detection has a big potential, especially in a small walking robots. In these robots often there is not enough space to mount a special contact sensor in the legs or limited funds does not allow to buy this sensors. This method could be also used as a redundant method to detect the ground in more sophisticated robots.

NOTES

A supplemental video is available at: http://lrm.cie.put.poznan.pl/JAMRISgaitMW.wmv

AUTHOR

Marek Wąsik – Poznan University of Technology, Institute of Control and Information Engineering, ul. Piotrowo 3A, 60-965 Poznań,
e-mail: wasik.m@gmail.com,
www: http://www.cie.put.poznan.pl/.

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