Nonlinear Dynamics and Systems Theory, **15** (1) (2015) 63–72

Six-Legged Robot Gait Analysis

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Received: March 31, 2014; Revised: December 23, 2014

Abstract: This paper includes results of investigations of real six-legged robot. By the name of hexapod we call a robot that walks on six legs. Due to specific construction of legs, each leg has 3 degrees of freedom, prototype constructed by us allows to model gait of reptiles and insects. Presented system of rotation angle of each of the cells (servos) allows to analyze every single type of the movement. Applied measurement system allows also to measure current, and use it for calculation of power generated by motor. It allows to calculate power necessary for each type of the robot movement. Applied mathematical model allows for identification and check of the angular velocity, acceleration and moments generated by each of the robot cells separately. As a result it is possible to determine quality coefficients of different gait patterns of the robot, i.e. maximal speed or maximal load depending on the number of working legs. Obtained results were confronted with theoretical model of differential equations regulating gait of our hexapod.

Keywords: *hexapod, control, servo, gait, micro control.*

Mathematics Subject Classification (2010): 70E60.

1 Introduction

Nowadays mobile robotics is based mainly on the wheeled devices [1]. Due to the difficulties in the construction and control walking robots are much less common. Also, the equations used to describe the movements of the robot are less complicated for wheeled robots than in the case of the devices with legs [1]. However, due to the rapid development of technology, miniaturization and continuous growth of microcontroller productivity, robots with legs appear more and more frequently. Due to the desire to expand knowledge of the human gait most of robots subjected to the analysis are anthropomorphic, therefore in literature test results and structures of the two-legged robots are most

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common (i.e. see [2]). However, as far as we know there is no research on robots multi revenues in the six-legged.

In this paper, we present the results of real prototype of the six-legged (Hexapod) robot. Hexapod is a mobile robot, that is a vehicle equipped with electric motors by means of which it is capable of walking on its feet. In our case it is a design resembling insects (see Figure 1) and it moves using 18 engines. To maintain the balance only three legs are required, however for walking four are necessary. Additional two legs allow some leeway in walking and increase the reliability of the robot movements. Robot control is via a mobile phone equipped with a specially designed program that uses the serial data and Bluetooth networks. Originally developed software allows one to send movement data and then receive the information gathered by the sensors. Our robot is equipped with a wireless color camera with microphone, which is placed on the tail and is also controlled using a mobile phone. A special electronic system based on the ATmega128 microcontroller with 6 channels with pulse module which is programmable resolution from 2 to 16 bits, but now uses only two 16-bit channels to control 24 servos, enables separation of servo control signals.

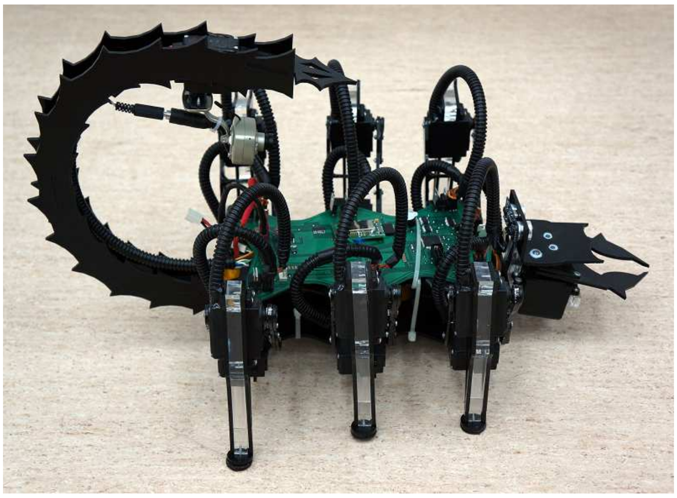

Figure 1: View of the built walking six-feet mobile robot (hexapod).

Robot is equipped with a system for measurement of the rotation angle for each of the servos, what enables analysis of the individual movements. It also provides possibility of measurement of current through the motors, what can be used for approximation of the energy necessary for each type of the movements.

Pulse-width modulation (PWM), which is suplied to the controler of the servo has a constant frequency 50Hz and duration varying in a range of 0-13% (0-2,5MS), what allows to control all eight servos using single signal PWM, as shown in Figure 3.

According to equation (1), constructed robot can realize up to 11! different types of movements, what was initial point of the investigations of different gait possibilities.

$$N = (2k - 1)!, \tag{1}$$

where k denotes number of the legs, and N represents number of the movement types.

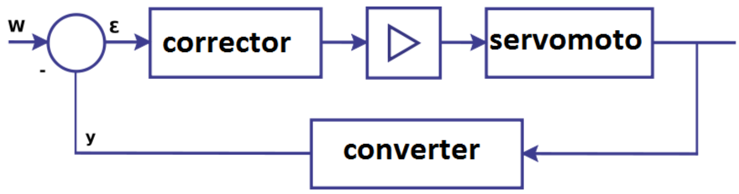

Figure 2: Block diagram of the servo.

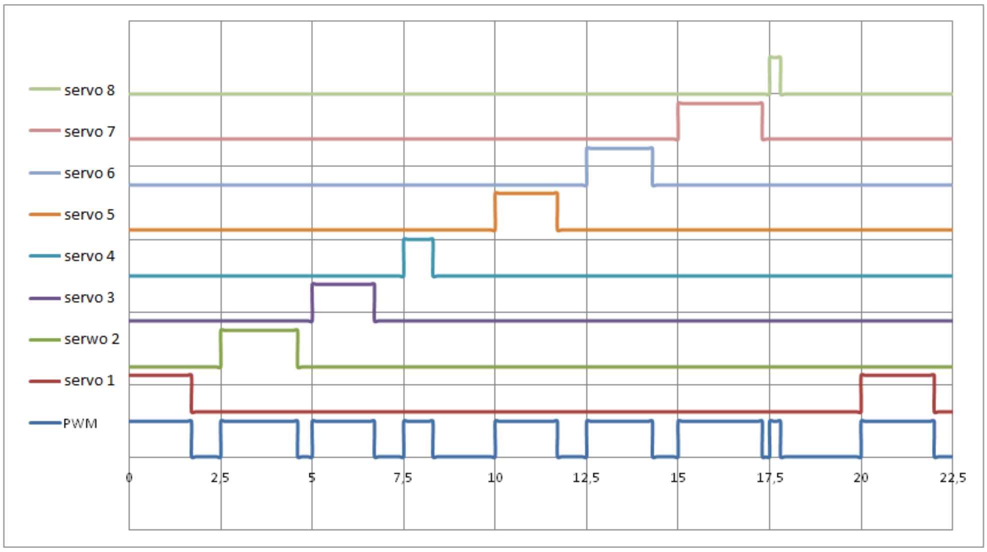

Figure 3: Division of the PWM control signal in dependence of designated servo.

2 Limbs Construction

Construction of the robot's leg is based on the classical kinematic scheme of the insect. This pattern was chosen for its versatility and possibility to apply for investigations of the gait of both arthropods and reptiles. Moreover, chosen construction enables also to overcome wider range of the obstacles than in case of application of reptile or mammal kinematics. Figure 4 presents the scheme of the kinematic systems of mammals, reptiles and insects.

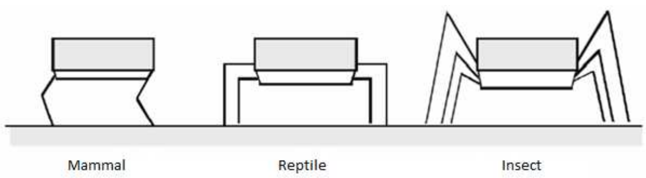

Figure 4: Possible configurations of robot legs.

Presented in Figure 5 scheme of the robot's leg is composed of three rotary cells (A, B, C) and three arms (of lengths l_1, l_2, l_3). The first cell (A) is attached to the robot's body and is perpendicular to its surface, what allows for forward-backward movements. Next cell is attached to the arm of length l_1. This cell is responsible for up-down movement. Cell C is attached to the end of the arm of length l_2 in such a way, that its rotation axis is parallel to the axis of rotation of the cell B. To cell C attached is also additional arm, that serves as foot.

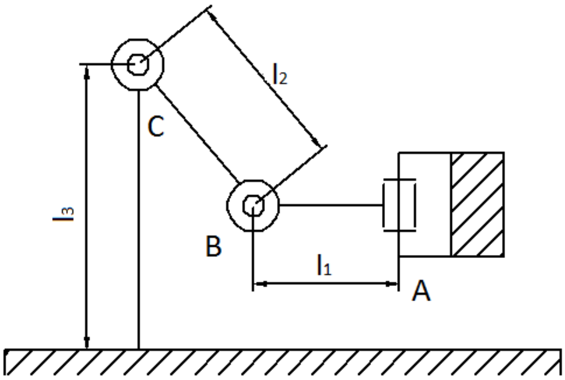

Figure 5: Scheme of the robot arm.

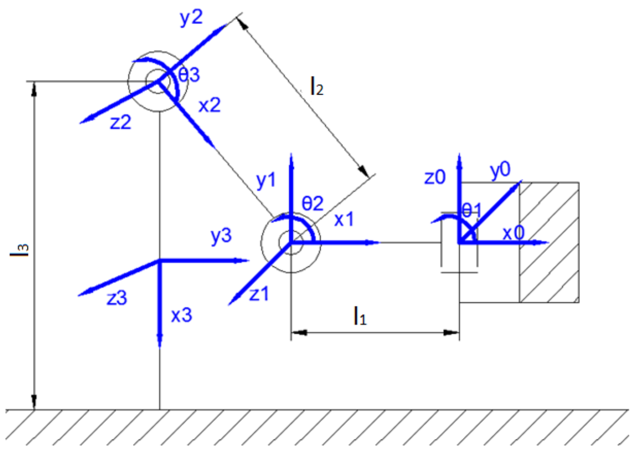

Figure 6: The kinematic scheme and arrangement of the coordinates.

Introduction of the articulated variables yields kinematic scheme of the robot's arm presented in Fig. 6. It is easy to notice, that it is similar to articulated scheme of the anthropomorphic manipulators (OOO). Application of the Denavit-Hartenberg theory allows for easy determination of the location of the end of the arm with respect to its attachment point and, what follows, for description of the gait sequences.

	Θ_{i-1}	λ_{i-1}	l_{i-1}	α_{i-1}
$0-1$	Θ_1	0	$-l_1$	90°
$1-2$	Θ_2	0	$-l_2$	0°
$2-3$	Θ_3	0	$-l_3$	0°

Table 1: Denavit-Hartenberg data (l_i - distance from the axis of Z_i to Z_{i+1} measured along the axis X_i; α_i - angle between the axes Z_i and Z_{i+1} measured about X_i; λ_i - distance from the axis X_{i-1} to X_i measured along Z_i; Θ_i - angle between the axes X_{i-1} and X_i measured about Z_i) .

Table 1 presents dependence between variables necessary for transition between coordinate systems. It was applied to derive the following matrices governing transition of variables between cells:

$$A_{0-1} = \begin{bmatrix} \cos\Theta_1 & 0 & \sin\Theta_1 & -l_1\cos\Theta_1 \\ \sin\Theta_1 & 0 & -\cos\Theta_1 & -l_1\sin\Theta_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{2}$$

$$A_{1-2} = \begin{bmatrix} \cos\Theta_2 & -\sin\Theta_2 & 0 & -l_2\cos\Theta_2 \\ \sin\Theta_2 & \cos\Theta_2 & 0 & -l_2\sin\Theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{3}$$

$$A_{2-3} = \begin{bmatrix} \cos\Theta_3 & -\sin\Theta_3 & 0 & l_3\cos\Theta_3 \\ \sin\Theta_3 & \cos\Theta_3 & 0 & l_3\sin\Theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{4}$$

The following transfer matrix (5) allows for mathematical description of the location of the end of the limb with respect to the coordinate system of attachment limb plane (it was calculated using Denavit-Hartenberg theory as a product of equations (2)–(4)):

$$T_{0-3} = A_{0-1} * A_{1-2} * A_{2-3} =$$
$$\begin{bmatrix} c\theta_1(c\theta_2 c\theta_3 - s\theta_2 s\theta_3) & c\theta_1(c\theta_2 c\theta_3 - s\theta_2 c\theta_3) & s\theta_1 & c\theta_1(l_3(c\theta_2 c\theta_3 - s\theta_2 s\theta_3) - l_1 - l_2 c\theta_2 \\ s\theta_1(c\theta_2 c\theta_3 - s\theta_2 s\theta_3 & -s\theta_1(c\theta_2 c\theta_3 + s\theta_2 c\theta_3) & -c\theta_1 & s\theta_1(l_3(c\theta_2 c\theta_3 + s\theta_2 s\theta_3) - l_1 - l_2 s\theta_2 \\ c\theta_2 c\theta_3 + s\theta_2 s\theta_3 & c\theta_2 c\theta_3 + s\theta_2 s\theta_3 & 0 & l_3(c\theta_2 s\theta_3 + s\theta_2 c\theta_3) - l_2 s\theta_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{5}$$

3 Research and Analysis of Operation Servo

In order to carry out preliminary research on the robot gait and qualitative factors to determine the energy consumption, walking speed and capacity, it is necessary to analyze work of the applied servos. Servos characteristic, being an integral nature of the actuator exhibits dynamics that does not interfere with the regulation, but introduces non-linearity. It implies the use of proportional equalizers (P controller) with high gain.

Observe that integrating characteristics of the actuator ensures theoretically zero static error. High gain in the main control line improves monitoring of the system after changes in pattern but it reduces the stability margin. It can be partially corrected by a proportionally-derivational controller (PD), that plays a role of the corrector. Control module of the servo works with frequency 50 Hz, current provided to motor can be treated as a signal with constant frequency and varying duration, as shown in Figure 7. It can be noted, that in dependence on the load applied to the motor in servo, there is change in the duration of the current signal. Maximal current consumption by single servo is about 1,5 A with provided voltage 6 V.

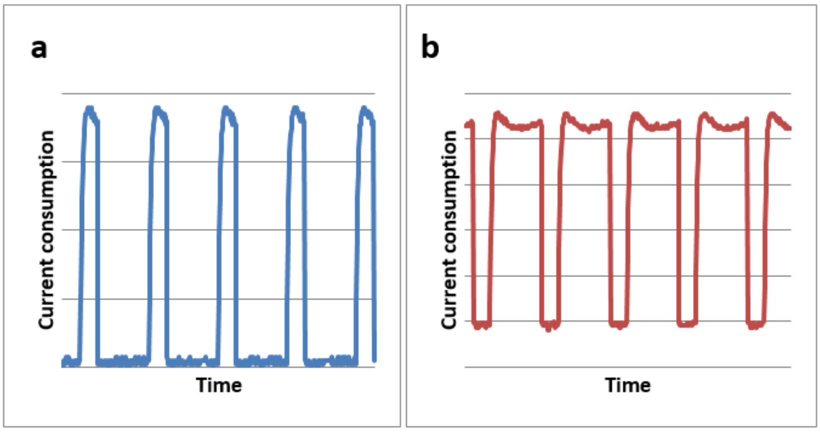

Figure 7: Change in the filling of a servos power signal for, low load on the servo(a), and high load on the servo(b).

In order to conduct research on robot gait, it is necessary to convert the signal with variable duration to analog continuous signal. For this purpose, a low-pass filter was constructed on the basis of a resistor and capacitor (RC). Unfiltered signal is shown in Figure 8a while the effect of the filter application is presented in Figure 8b.

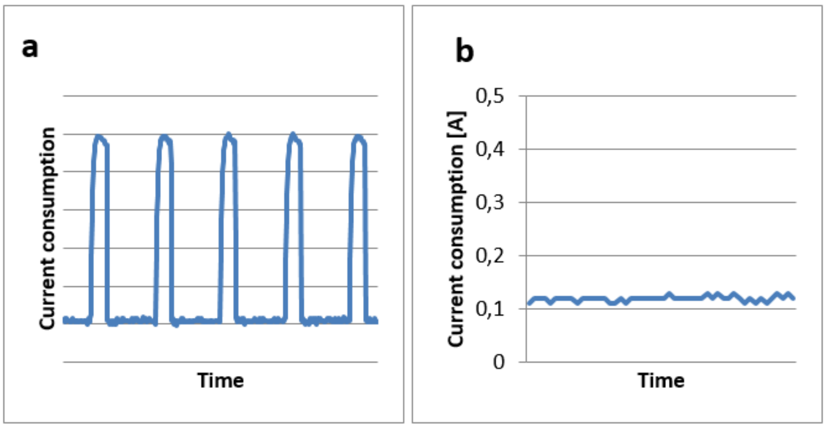

Figure 8: Conversion of the variable signal (a) to analog signal filling (b).

Introduction of signal filtration enabled to develop characteristics of dependence of the current drawn by a servo from the moment generated on the output of the transmission. The results of the servos tests for variable load are presented in Figure 9. The graph shows that with the load increase the current consumption by the motor also increases. It can be seen that the increase in torque increases the motor current consumption up to a value of 1.5 A. As can be seen in Figure 9, when generating the maximum torque by the servo there occurs an increase of the current drawn by the motor from the value 1A up to 1.5 A.

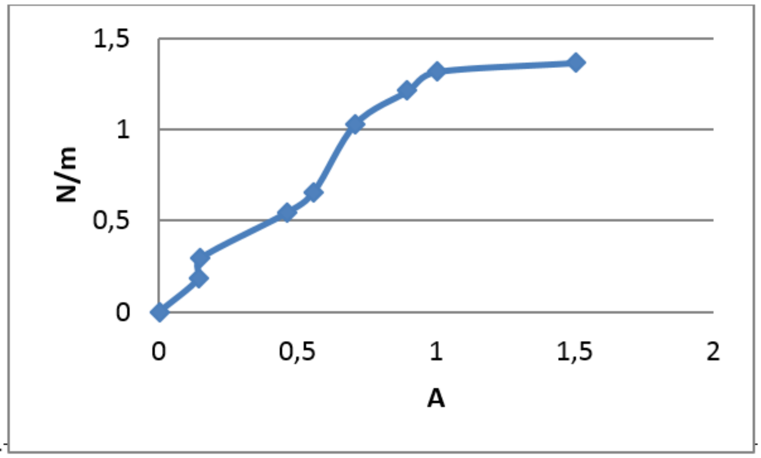

Figure 9: Measurement of intensity of the load servo.

With robot gait sequence as mentioned before, the robot having six legs is able to perform 11! different sequences of gait. First preliminary analysis has been subjected to a sequence of gait based on the movements of earth-boring dung beetle (Geotrupes stercorarius), because it has the same number of limbs as the constructed prototype robot. Constructed gait models are based on living organisms, what allows the analysis of movements created by millions of years of evolution. The quality of gait can be characterized by the use of qualitative indicators, such as minimum energy consumption, high speed and high performance. However, it is not always possible to get gait sequence that meets all the quality parameters. Therefore, analysis of relationships between different characteristics allows to choose the best solution for given situation.

The easiest way to present robots gait is to record the entire sequence (see Table 2). For simplicity, we assume that the first link takes only three positions and the second and third cells adopt the same angular position. Assumed positions are described below:

(i) the positions of movement for the first cell: 1 – Maximum withdrawal; 2 – middle position, 3 – maximum move forward;

(ii) the positions of movement of the second and third cell: 1 – maximum height, 2 – feet on the ground.

The legs move in pairs – the first motion is performed by legs 1 and 4, then 2 and 6, and finally 3 and 5. Data presented in table show that the movement of the robot is sequential, and always takes place in the same order. There are a number of limitations associated with the construction of the robot. The main limitation is the length of the movement depending on the dimension of the first robot arm and it is associated mainly

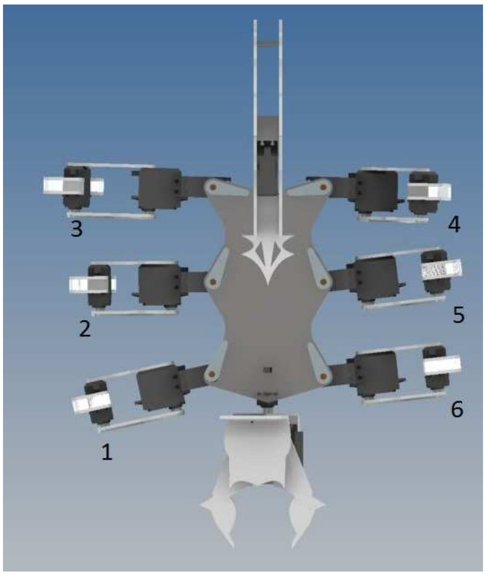

Figure 10: Order of robot limbs.

with the potential legs collisions.

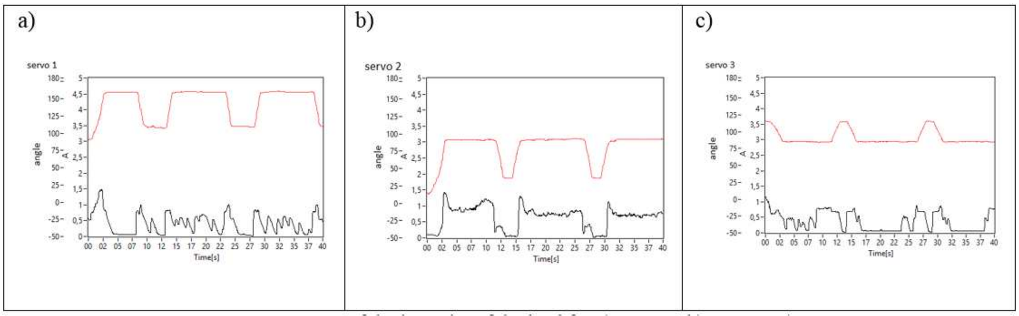

Figure 11: Measurement of the intensity of the load for a) servo 1, b) servo 2, c) servo 3.

Measurement of the intensity of the load for a) servo 1, b) servo 2, c) servo 3. In order to calculate the linear velocity of the end point of the robot leg, there should be introduced manipulator Jacobian. It is matrix J_0^N dimensions of $6xN$, where N is the number of segments of the kinematic system [8]. Such Jacobian may be introduced by the equation:

$$\begin{bmatrix} \vartheta_0^N \\ \omega_0^N \end{bmatrix} = J_0^N \dot{q}, \tag{6}$$

where: ϑ_0^N is a vector of linear velocity of the endpoint of the kinematic system in basic coordinate system (point of the foot attachment to the body), ω_0^N is the angular velocity vector for the end of a kinematic system in the basic coordinate system and $\dot{q}$ is velocity

Leg 1									
Cell 1	1	1	2	2	3	3	3	1	1
Cell 2, 3	1	1	1	1	1	1	2	2	1
Leg 2									
Cell 1	1	1	2	2	3	3	3	1	1
Cell 2, 3	1	1	1	2	2	1	1	1	1
Leg 3									
Cell 1	1	1	2	2	3	3	3	1	1
Cell 2, 3	2	2	1	1	1	1	1	1	1
Leg 4									
Cell 1	1	1	2	2	3	3	3	1	1
Cell 2, 3	1	1	1	1	1	1	2	2	1
Leg 5									
Cell 1	1	1	2	2	3	3	3	1	1
Cell 2,3	2	2	1	1	1	1	1	1	1
Leg 6									
Cell 1	1	1	2	2	3	3	3	1	1
Cell 2, 3	1	1	1	2	2	1	1	1	1

Table 2: Record of robot gait sequence.

vector in each of the joint in a natural coordinate system. For each component, $\dot{q}$ consists of the angular velocities (ω_i) in the case of joint rotation or linear velocities (ϑ_i) in the case of prismatic joints.

According to equation (6) the Jacobian is composed of the elements for the calculation of both linear and angular velocities. Therefore, introduced are the following two Jacobian parts: J_ω (the angular velocity) and J_ϑ (for flow velocity):

$$J_0^N = \begin{bmatrix} J_\vartheta \\ J_\omega \end{bmatrix}. \tag{7}$$

To apply this definition to our data, it is necessary to define Z_i as a unit vector in the Z axis for the i-th component of the system in relation to the basic coordinate system, and O_i as a vector derived from the basic coordinate system (O_0) to the i-th element of the coordinate system (O_i).

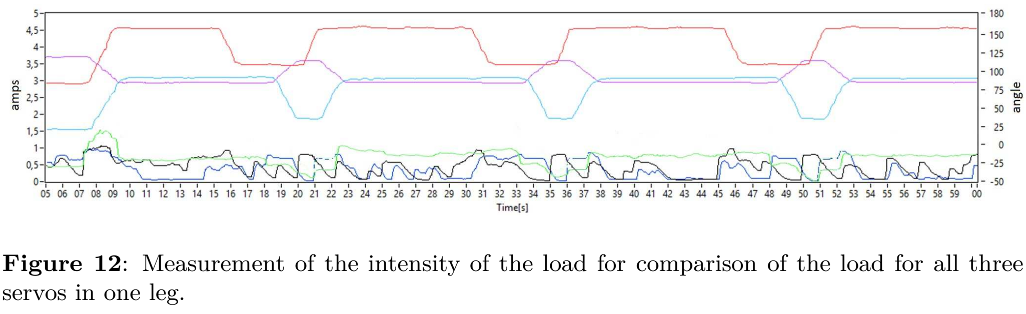

Figure 12: Measurement of the intensity of the load for comparison of the load for all three servos in one leg.

Figure 12 presents the analysis of walking robot in time with respect to the rotation angle of the servo and power consumption for all three cells in the one leg. Basing on equation (6) it is possible to numerically calculate that the theoretical speed of walking robot is approximately 0,006 m/s and a theoretical average power consumption is of the order of 0.6 A/h (0.0002 A/s). The obtained theoretical results were compared with the measured values, and the differences between real and calculated values were in a range of 6-10%.

4 Conclusions

Conducted simulations show similar theoretical and measurement results, leading to the conclusion that they are correctly performed. Preliminary results enable to determine the power consumption of working actuator. On the other hand, servo analysis is applied for determination of the speed of basic biologically inspired gait. As shown in Figure 11, the most loaded is servo 2. Further research on the robots potential movement possibilities will increase knowledge in this field and will allow for a better understanding of insects gait. This may lead to a better understanding of the advantages and disadvantages of each of the gait sequences and help to create an optimal solution for the most six-legged robots in dependence on their application.

Acknowledgment

This paper was presented during the 12th Conference on Dynamical Systems - Theory and Applications held in Lodz, Poland on 2-5 December 2013.

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