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Analysis of Contact Forces Between the Ground and the Hexapod Robot Legs During Tripod Gait

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Abstract
The aim of the study is kinematic and dynamic simulation of a hexapod robot walking with a classical tripod gait on a flat surface. To drive robot legs, a novel central pattern generator is applied. Time series of the robot's kinematic and dynamic parameters are reported to assess the applied control method. Ground reaction forces and overloads acting on the hexapod legs are estimated on the basis of the inverse dynamics concept. For better analysis and illustration of the studied hexapod, the simulation model of the robot, suitable for virtual experiments on the locomotion process, is developed in Mathematica software. The obtained results indicate some advantages of the applied central pattern generator.

Keywords: hexapod, multi-legged robot, central pattern generator.

1 Introduction

Multi-legged walking machines belong to the one of the most important groups of mobile robots in engineering applications. Due to unique advantages, such as overcoming obstacles and executing tasks in a wild environment, biologically inspired multi-legged robots are better at adapting to unknown and unstructured environments in comparison to wheeled vehicles. However, during the movements, the feet of a legged robot interact frequently with the ground in different ways. It means that the demand for drive unit includes not only characteristics of response ability and high control accuracy, but also dynamic compliance (Ba et al., 2017). Therefore, the impact on the driving systems implemented in the joints of the robot legs should be reduced, which can protect both individual components and the whole mechanical structure of the robot. Moreover,it wouldimprove stability of the robot during walking.

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The selection of control methods of the movements of the robot legs directly affects the ground reaction forces and overloads acting on robot feet. A brief literature review on some existing control methods widely applied to variuos motor-driving legged robots is presented in the paper (Ba et al., 2017). For instance, the impedance control method has been widely employed both to motor-driving (Poulakakis et al., 2005; Kimura et al., 2007) and hydraulic-driven legged robots (Rong et al., 2012; Semini et al., 2015).

The appropriate choice of the robot legs movements can have a positive influence on the kinematics, dynamics and energy demand of the walking robot . In our previous investigations, we proposed a novel central pattern generator (CPG) based on the stick-slip oscillator (Grzelczyk et al., 2016). Using the constructed prototype of an insect-inspired six-legged robot, we obtained numerical and experimental results which showed some analogies between the characteristics of the investigated robot and insects met in nature. In other paper (Grzelczyk et al., 2017), using the same control method, we conducted kinematic, dynamic and power consumption analysis for an improved version of the six-legged robot. In contrast to the aforementioned works, this paper deals with kinematics and dynamics of other construction of the hexapod robot, controlled by different central pattern generator based on a sine function. This generator has been previously applied in the control system of a human lower limb exoskeleton, and it can be used in other multi-legged robots (Grzelczyk et al., 2018).

The paper is organized as follows: section 2 deals with the robot and its simulation model developed in Mathematica; section 3 contains a brief review of using CPGs to control a motion of a walking robot and the proposed CPG model; simulations of kinematic and dynamic parameters of the robot are reported and discussed in Section 4 and conclusions of the study are outlined in Section 5.

2 Model of the robot

The simulation model of the considered hexapod robot implemented in Mathematica is shown in Fig. 1. The robot consists of a body and six identical legs (denoted respectively as $L1, L2, L3$ on the left, and $R1, R2, R3$ on the right side of the robot). The created model was used for design and virtual experiments of its motion during walking. Figure 1 also shows a scheme of a single robot leg.

The robot is located in the global coordinate system $0xy$ which is fixed to the ground. The centre of the local coordinate system $0'x'y'$ (see Fig. 1) has the coordinates $0'(x,L)$ with respect to the global coordinate system, where L means the distance between the ground and the point and the leg is attached to the robot body when the robot is in its initial configuration). Links l_i (i = 1,2,3) with joints j_i (i = 1,2,3) form a kinematic scheme of a robot limb. The function $h(t)$ is a time-varying function responsible for vertical fluctuation of the joint j_1, i.e. the pivot point of the

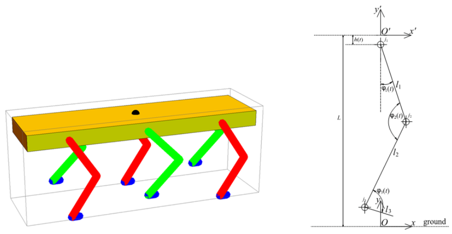

Fig. 1. The investigated hexapod robot implemented in Mathematica software and a schematic configuration of a single robot limb.

whole robot leg. Moreover, the definitions of the angular positions $\varphi_i(t)$ (i = 1,2,3) of the segments l_i in the local coordinate system $0'x'y'$ are also visible in Fig. 1. The considered hexapod robot is embedded in the gravitational field with the coefficient $g = 9.81\ \mathrm{m/s^2}$. The mass of the body of the robot without legs equals M. Each of the robot limbs contains three links with masses m_i and distances a_i between the coordinates of the joints j_i and the mass centres of the mentioned links, respectively.

In this study we are most interested in obtaining time histories of the angular positions $\varphi_1(t)$ and $\varphi_2(t)$ which correspond to the joints j_1 and j_2, respectively. As a supporting point of the robot leg we choose the joint j_3. Therefore, forward kinematics for the mentioned point has the following form:

$$\begin{cases} x'(t) = l_1 \sin\varphi_1(t) - l_2 \sin(\pi - \varphi_1(t) - \varphi_2(t)), \\ y'(t) = -h(t) - l_1 \cos\varphi_1(t) - l_2 \cos(\pi - \varphi_1(t) - \varphi_2(t)), \end{cases} \tag{1}$$

whereas inverse kinematics is given as

$$\begin{cases} \varphi_1(t) = \mathrm{atan}\left(\frac{-x'(t)}{y'(t)+h(t)}\right) + \mathrm{acos}\left(\frac{l_1^2+(x'(t))^2+(y'(t)+h(t))^2-l_2^2}{2l_1\sqrt{(x'(t))^2+(y'(t)+h(t))^2}}\right), \\ \varphi_2(t) = \mathrm{acos}\left(\frac{l_1^2+l_2^2-(x'(t))^2-(y'(t)+h(t))^2}{2l_1 l_2}\right). \end{cases} \tag{2}$$

In our model, we assume that the segment l_3 is always paralell to the ground in each phase of the robot gait. Thererfore, we take the time history of the angle $\varphi_3(t)$ in the following form

$$\varphi_3(t) = \varphi_1(t) + \varphi_2(t) - \pi/2. \tag{3}$$

3 Control of robot legs

In contrast to numerous methods applied in the literature, in this study we have used a relatively simple method to control the movement of robot legs by using a concept of central pattern generator. In general, central pattern generators are biological neural networks that produce rhythmic outputs in the absence of rhythmic input (Kuo, 2002). As a result, they are the source of the tightly-coupled patterns of neural activity that

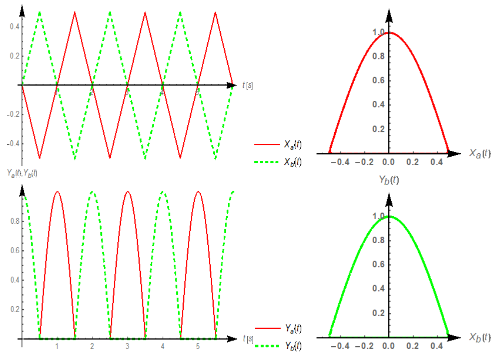

Fig. 2. Time histories and phase trajectories of the applied CPG model.

drive rhythmic motions in different biological processes like breathing, chewing or walking. Studies have shown that CPGs have been detected in numerous vertebrate species investigations (Hultborn and Nielsen, 2007), including human (Danner et al., 2015). Since 1980s this concept has been widely used to control different multi-legged robots, and an interesting literature review in this area can be found in (Buchli and Righetti, 2006; Ijspeert, 2008; Chen et al., 2012).

In our study, the representation of the trajectory of the supporting point (joint j_3) is generated by the central pattern generator which is based on the sine function, previously presented in Grzelczyk et al., 2018. Time histories of the signals produced by the proposed CPG model and periodic orbits in the phase space for the period $T = 2$ s (which corresponds to the period of the single robot stride) are shown in Fig. 2.

In our model the variables $X_a(t), X_b(t)$ control the motion of the robot legs in the forward direction, whereas $Y_a(t), Y_b(t)$ are responsible for controlling the legs moving in the vertical direction. The subscript a corresponds to the legs $R1, R3$ and $L2$, while the subscript b corresponds to the legs $L1, L3$ and $R2$. It should be emphasized that in this study, we neglect the transient processes associated with the starting and ending phases of gait, and we focus exclusively on a completely rhythmic gait. These issues (i.e. transitions between different phases of the gait cycle) will be the goal of our future research.

Control parameters of a single robot stride can be obtained by the conversion of the applied CPG signals into the workspace of the mechanism of the robot leg in the local coordinate system $O'x'y'$ as follows

$$\begin{cases} x'_{a(b)}(t) = l_{\text{stride}} \cdot X_{a(b)}(t), \\ y'_{a(b)}(t) = h_{\text{stride}} \cdot Y_{a(b)}(t) - L, \end{cases} \tag{4}$$

where l_{stride} and h_{stride} are the length and height of a single stride of the robot, respectively. One can easily modify the shape of an orbit by changing the values of l_{stride}

M	m_1	m_2	m_3	l_1	l_2	l_3	a_1	a_2	a_3	T	l_{stride}	h_{stride}
kg	kg	kg	kg	m	m	m	m	m	m	s	m	m
1.0	0.1	0.1	0.01	0.12	0.12	0.02	0.03	0.03	0.01	2	0.1	0.03

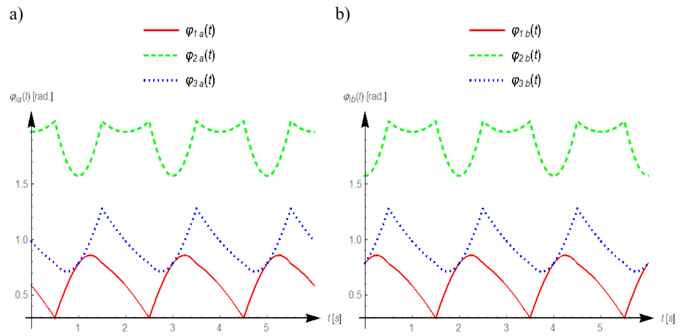

Fig. 3. Time histories of angles in individual joints of the robot legs R1, R3, L2 (a) and the angles in individual joints of the robot legs $L1, L3, R2$ (b).

and h_{stride}. Finally, the trajectories $x'_{a(b)}(t) - y'_{a(b)}(t)$ must be converted to the joints space of the legs by means of using the relations (2)-(3).

In this study, the function $h(t)$ is the same for all robot legs. However, tt is clear that the angular positions in the joints j_1, j_2, j_3 are not the same. In this study, we investigate tripod gait of the robot. It means that the legs of the robot are divided into two groups. Namely, the angles $\varphi_{1a}(t)$, $\varphi_{2a}(t)$ and $\varphi_{3a}(t)$ correspond to the legs $R1, R3$ and $L2$, whereas the angles $\varphi_{1b}(t)$, $\varphi_{2b}(t)$ and $\varphi_{3b}(t)$ correspond to the legs $L1, L3$ and $R2$.

4 Numerical results

The gait simulation model of the robot (previously presented in Fig. 1) was developed in Mathematica software. We used this model for virtual experiments and in order to obtain curcial parameters of the robot motion during walking. Initial parameters of the robot used in numerical simulations are presented in Tab. 1.

Table 1. Initial parameters of the investigated hexapod robot.

Figure 3 shows time histories of the angles obtained by using relations (2) and (3) and applied to the joints of the robot legs, for $h(t) = 0$ and $L = 0.2$ m. As a result of applying the computed angular positions in the individual joints, the hexapod robot moves in the forward direction. Exemplary configurations of the whole robot at different stages of the gait are presented in Fig. 4.

As it can be seen, fluctuations of the position of the robot body in the vertical direction are not observed in any phase of the robot motion. The obtained time histories of kinematical parameters of the robot presented in Fig. 5 better illustrate this

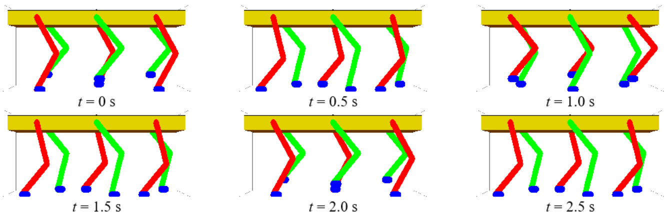

Fig. 4. Configurations of the robot legs at regular time intervals.

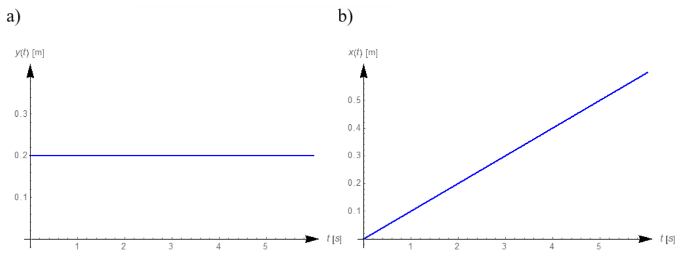

Fig. 5. Displacement curves of the position of the robot body in the vertical (a) and forward (b) directions.

observation. In comparison to other CPGs developed based on different nonlinear oscillators (Grzelczyk et al., 2016, 2017), the CPG model employed in this paper is more advantageous, because it allows keeping position of the robot body in the vertical direction at a constant distance over the ground, whereas the robot position in the forward direction changes linearly. As a result, the velocity of the robot body in the vertical direction equals zero, while the velocity of the robot body in the forward direction is constant (see Fig. 6).

It is known that fluctuation of the robot body can have a great influence on the ground reaction forces acting on the individual legs of the robot. Due to the lack of these fluctuations for the considered robot controlled by the employed CPG model, relatively small fluctuations of the ground reaction forces, in comparison to the force

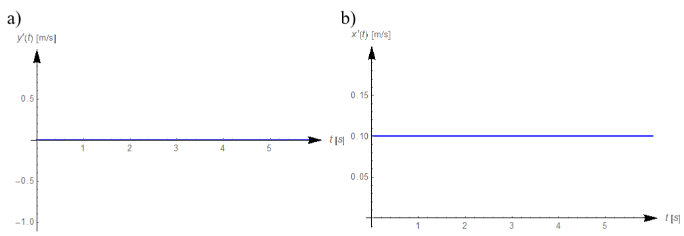

Fig. 6. Velocity curves of the position of the robot body in the vertical (a) and forward (b) directions.

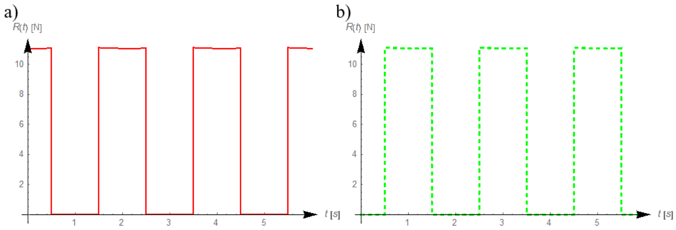

Fig. 7. Fluctuation of the ground reaction forces acting on the leg $L2$ (a) and the leg $R2$ (b).

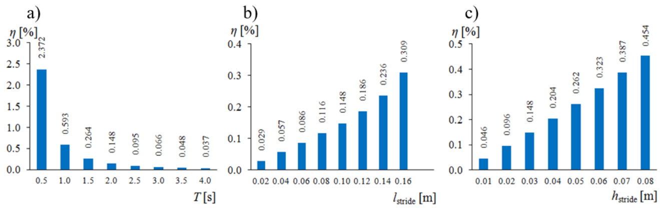

Fig. 8. Values of the parameter η characterizing overloads acting on central robot legs (legs $L2$ and $R2$).

resulting from gravity, can be expected. Figure 7 presents time histories of a contact force acting on the middle legs of the robot, i.e. legs $L2$ and $R2$. The presented forces have been estimated by using the method presented in Grzelczyk et al., 2017. It can be seen that the values of the presented forces oscillate around the reaction force resulting from the weight of the analysed robot (about 11.1 N). However, these oscillations are relatively small, especially in comparison to other well known CPG models.

In this paper, we investigate more carefully the influence of the parameters of the robot gait (i.e. the period T, the length l_{stride} and the height h_{stride} of a single stride) on the overloads acting on the robot legs during walking. Figure 8 presents maximum value of the coefficient η characterizing overloads with respect to the force resulting from gravity, defined as

$$\eta = \max\left(\frac{R(t) - R_{\text{gravity}}}{R_{\text{gravity}}} \cdot 100\%\right) \tag{5}$$

Values of the parameter were computed for the central robot legs (these values are the same both for legs $L2$ and $R2$).

In the last part of this work, we analyze also the problem of trajectory planning of the position of the robot body during walking process. From the viewpoint of the performed numerical simulations, the possibility of modification of the robot body position in the vertical direction seems to be the most interesting. The appropriate fluctuations of the robot in the vertical direction during walking can be preceded by

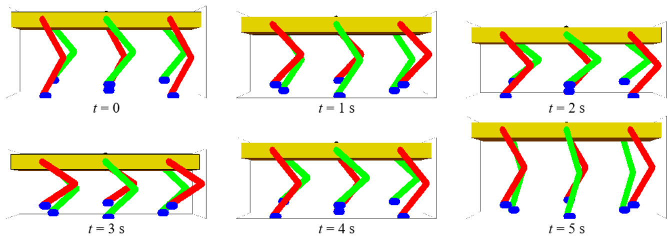

Fig. 9. C
onfigurations of the robot legs at regular time intervals in different phases of gait during walking according to the planned path in the vertical direction.

the relevantadjustment of the function $h(t)$ introduced in Section 2. As an example, we took the function in the form $h(t) = 0.1\, e^{-0.2t} \sin(0.05\pi t^2)$. Figure 9 shows the corresponding configurations of the robot during walking on a flat surface, resulting from the function $h(t)$ and the parameter $L = 0.2$ m. The presented snapshots were captured in regular time intervals. As it can be observed, at any presented stage of the robot gait, the supporting legs touch the ground, while the fluctuations of the posision of the robot are accurately reflected by means of the predefined function $h(t)$. It is realized by the appropriate changes in the configurations of the robot legs during walking. In this way, we can easily change the vertical position of the robot, for instance when the robot is walking under or over obstacles.

5 Summary and conclusions

In this paper, a simulation model of a hexapod robot developed in Mathematica software is investigated numerically by means of both kinematical and dynamical parameters characterizing robot locomotion process. To control the robot legs during walking in the tripod gait on a flat surface, a relatively simple central pattern generator is employed, which is based on the sine function. Advantages of the employed CPG model have been clearly emphasized, especially with regard to the kinematic parameters (i.e. displacement and velocity of the whole robot) and dynamic parameters (i.e. ground reaction forces and overloads acting on the robot legs).

The paper contains some information useful to control the robot legs and the whole robot with respect to their kinematic and dynamic parameters. The obtained simulation results can be treated as guidelines for further improvement of the employed CPG model and its applications in the control system of the multi-legged robot. Eventually, it should be noticed that it is possible to use this CPG for other puproses, including specialized control systems of bipeds, quadrupeds or octopods. In the future, it is also worth considering more detailed cases of robot walking and controlling its position while moving on irregular terrain.

Acknowledgments

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