Estimation of the Contact Forces Between the Hexapod Legs and the Ground During Walking in the Tripod Gait

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Abstract

The paper is devoted to the dynamical modelling of the hexapod robot walking on a flat and hard ground. The main goal is to determine time series of reaction forces acting on individual legs of the robot during tripod gait often used both by the six-legged insects as well as mobile walking robots found in engineering applications. The movement of the considered robot is realized by the kinematic excitation of its legs using the so-called Central Pattern Generator (CPG) method. The paper demonstrates that there are different contact forces and overload acting on the robot, resulting from different models working as a CPG. The mentioned forces belong to the important issues that should be taken into account when the robot locomotion on the unknown terrain is planned.

Keywords: Multi-legged robot, six-legged robot, hexapod, tripod gait, contact forces, reaction forces

1. Introduction

Legged locomotion is the most common locomotion form in nature and numerous animals species use this method for travelling on our planet. For many researchers, it became the inspiration for the construction of walking machines for engineering applications [1,2]. It should be noted that there are lots of biological inspirations and constructed robots in the scientific literature (including hexapod-type robots), and interesting state-of-the-art in this area can be found in recent paper [3]. Lately, also eight-legged robots have become popular, for instance a biomimetric robot called Scorpion [4], or searching and rescuing robot Halluc II [5]. The mentioned eight-legged robots are popular and usually studied based on the six-legged walking machines. Hexapod robots, due to their simplicity, statical and dynamical stability as well as due to large configuration of various possible gaits (described by the so-called MhGee formula [6]) have been studied by many researchers over the past decades. However, in comparison to the wheeled vehicles, legged locomotion is characterized by more nonuniform distribution of reaction forces acting between the mentioned mobile machines and the ground. Namely, in the case of wheeled motion, usually all the wheels touch the ground at the same time, and the appropriate contact pressure distribution is almost the same in each phase of the machine movement. In turn, in the case of the legged locomotion, reaction forces between the ground and legs forming the support polygon of the robot vary in a periodic manner. In addition, fluctuations of the robot gravity center have a significant impact on the reaction forces between the legs of the robot and the ground, due to present additional dynamic load resulting from the movement of the individual elements of the robot in the gravitational field of the Earth. In the case of relatively small contact surfaces of the robot leg tips with the ground and the simultaneous transport of an additional mass by the robot, the problem of the reaction forces acting on the ground may be significantly important for this system. In engineering calculations, the appropriate mathematical models are rarely used, since engineers usually employ commercial software, such as SimMechanics module of MATLAB [7,8]. This is why in this paper the mentioned problem has been considered in more detail by adopting the appropriate dynamic robot model, taking kinematic excitation of the robot legs, and focusing on the reaction forces acting along the direction of the gravity field. The problem of controlling individual robot legs has been presented in our previous paper [10] and in this work is not considered in detail.

2. Model of the Hexapod Robot for the Tripod Gait

Figure 1 shows a model of the considered hexapod robot embedded in the gravity field with coefficient g, supported by three legs forming the support polygon. The robot consists of a body with mass M_B and six identical legs denoted as L1, L2, L3 (on the left) and R1, R2, R3 (on the right). Each leg of the robot contains three links with masses m_1, m_2 and m_3, respectively. In the case of the tripod gait, the robot legs are divided into two groups, i.e.: the group A (solid legs L1, L3 and R2) and group B (dashed legs R1, R3 and L2). The movements of all robot legs are controlled by the same CPG model, however, the signals applied to the group B of the legs (joint angles $\varphi_{1B}(t)$, $\varphi_{2B}(t)$, $\varphi_{3B}(t)$) are out of phase with respect to signals applied to the group A (joint angles $\varphi_{1A}(t)$, $\varphi_{2A}(t)$, $\varphi_{3A}(t)$), with shift phase equal to 180°, and vice versa. For this reason, in one phase the robot is supported by the legs from group A, and in another phase - by the legs from group B. As a result, ground reaction forces to respective foot robot appear on different legs. In addition, due to the symmetry of the considered system, we can assume that the reaction forces in legs L1 and L3 are the same, as well as are the reaction forces in legs R1 and R3. In the considered case we assume that the robot walks on a relatively hard ground. This is why it can be assumed that there is no rotation of the robot body, and therefore the corresponding rotational movements and moments of inertia of the robot body can be neglected. The presented robot consists of many connected parts (including six identical legs). Without loss of generality, and to increase transparency of illustration, only one leg has been precisely described in Fig 1.

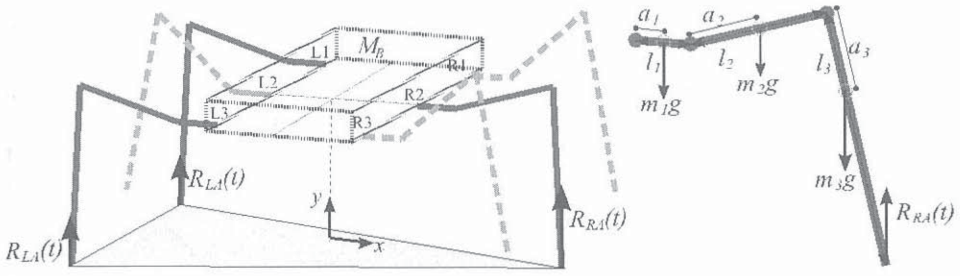

Figure 1. Model of the considered hexapod robot

Equations of motion of the hexapod robot considered in Fig. 1 in y direction can be written as follows

$$\begin{gathered}2R_{LA}(t)+R_{RA}(t)=\left(6\sum_{i=1}^{3}m_i+M_B\right)g+M_B\ddot{y}_C(t)+\\+2\sum_{i=1}^{3}m_i\ddot{y}_{iLA}(t)+\sum_{i=1}^{3}m_i\ddot{y}_{iRA}(t)+2\sum_{i=1}^{3}m_i\ddot{y}_{iRB}(t)+\sum_{i=1}^{3}m_i\ddot{y}_{iLB}(t)\end{gathered} \tag{1}$$

if $h_A(t)\geq h_B(t)$, and

$$\begin{gathered}2R_{RB}(t)+R_{LB}(t)=\left(6\sum_{i=1}^{3}m_i+M_B\right)g+M_B\ddot{y}_C(t)+\\+2\sum_{i=1}^{3}m_i\ddot{y}_{iLA}(t)+\sum_{i=1}^{3}m_i\ddot{y}_{iRA}(t)+2\sum_{i=1}^{3}m_i\ddot{y}_{iRB}(t)+\sum_{i=1}^{3}m_i\ddot{y}_{iLB}(t)\end{gathered} \tag{2}$$

if $h_A(t)<h_B(t)$, where

$$h_A(t)=\left|l_2\sin\varphi_{2A}(t)-l_3\sin(\varphi_{3A}(t)-\varphi_{2A}(t))\right|, \tag{3}$$

$$h_B(t)=\left|l_2\sin\varphi_{2B}(t)-l_3\sin(\varphi_{3B}(t)-\varphi_{2B}(t))\right|, \tag{4}$$

$$y_C(t)=\begin{cases}h_A(t) & \text{if} \quad h_A(t)\geq h_B(t)\\ h_B(t) & \text{if} \quad h_A(t)<h_B(t)\end{cases}, \tag{5}$$

$$y_{1RA}(t)=y_{1LA}(t)=y_{1RB}(t)=y_{1LB}(t)=y_C(t), \tag{6}$$

$$y_{2RA}(t)=y_{2LA}(t)=y_C(t)+a_2\sin\varphi_{2A}(t), \tag{7}$$

$$y_{2RB}(t)=y_{2LB}(t)=y_C(t)+a_2\sin\varphi_{2B}(t), \tag{8}$$

$$y_{3RA}(t)=y_{3LA}(t)=y_C(t)+l_2\sin\varphi_{2A}(t)-a_3\sin(\varphi_{3A}(t)-\varphi_{2A}(t)), \tag{9}$$

$$y_{3RB}(t)=y_{3LB}(t)=y_C(t)+l_2\sin\varphi_{2B}(t)-a_3\sin(\varphi_{3B}(t)-\varphi_{2B}(t)). \tag{10}$$

Next, taking into account symmetrical distribution of the robot legs and partial compensation of their mutual movements, we assume that $R_{RA}(t)\approx 2R_{LA}(t)$ and

$R_{LB}(t) \approx 2R_{RB}(t)$. The exact solution to this problem requires consideration of additional equations for moments of the forces generated by the individual reaction forces, gravity forces acting on the mass centers and inertial forces resulting from movements of individual elements of the robot legs in the considered coordinate system. This problem requires more complicated numerical algorithm and will be the subject of our further research.

3. Numerical Results

This section presents numerical simulations obtained with the use of Mathematica 10 software. Parameters of the considered robot gait are the same as in our previous paper [10], namely: the stride length of 60 mm, the stride height of 30 mm. However, the mentioned simulations have been obtained for two different periods of the single robot stride equal to 2 s and 1 s, respectively. In the first case the average velocity of the robot movement in the forward direction is 30 mm/s and in the second one is equal to 60 mm/s. This approach allows for additional investigation of the influence of robot velocity on the estimated contact forces. The aforementioned kinematic excitation of the robot legs is realized using four different CPG models based on simple mechanical oscillators, namely: Hopf oscillator, van der Pol oscillator, Rayleigh oscillator as well as oscillator describing stick-slip vibrations (further referred to as a stick-slip oscillator) [10]. Other parameters required for numerical simulations are presented in Table 1.

Table 1. Parameters of the considered hexapod robot

Quantity	Symbol	Unit	Value
Mass of the robot body (without legs)	M_B	kg	2.00
Masses of the robot leg parts	m_1 ; m_2 ; m_3	kg	0.12; 0.05; 0.15
Lengths of the robot leg links	l_1 ; l_2 ; l_3	m	0.027; 0.07; 0.12
Displacements of the mass centers	a_1 , a_2 , a_3	m	0.0135; 0.035; 0.04
Gravity coefficient	g	m/s^2	9.81

Figure 2 depicts the trajectories plotted by the robot gravity center (fluctuations $y_C(t)$ of the robot gravity center in the vertical direction) and trajectories plotted by the tips of the robot legs (group A - solid line, group B - dashed line). As can be seen, in the case of first three oscillators controlling robot legs, considerable fluctuations of the robot gravity center can be observed. These fluctuations have a great impact on the contact forces acting on the individual legs of the robot due to its acceleration/deceleration in the vertical direction.

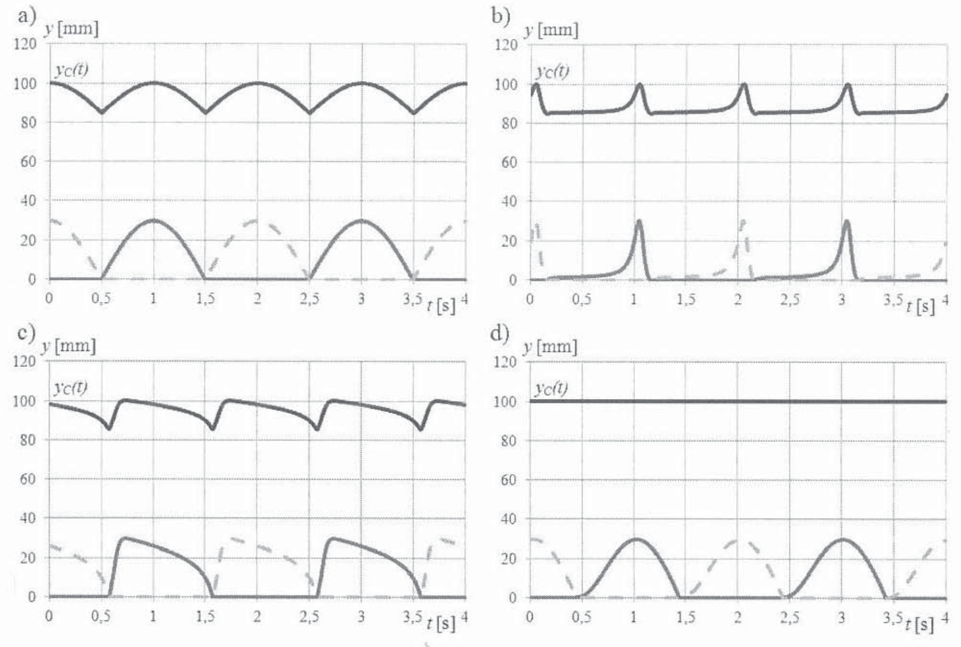

Figure 2. Fluctuations of the robot gravity center $y_C(t)$ and trajectories plotted by the robot legs for the period of the single robot stride equal to 2 s: a) Hopf oscillator; b) van der Pol oscillator; c) Rayleigh oscillator; d) stick-slip oscillator. Solid line - group A of the robot legs; dashed line - group B of the robot legs

Figure 3 shows time series of contact forces acting on the robot legs for the period of the single robot stride equal to 2 s. Due to the previously adopted assumptions, the largest contact reactions forces between the legs and the ground occur in the central legs (L2 and R2), and this is why only these reactions are presented (reaction forces in the lateral robot legs are two times smaller). The presented curves show that the appropriate reaction forces oscillate (increase and decrease) around the reaction force resulting from the weight of the robot (when none of its components is moved). As can be seen, the most frequent oscillations (overloads) occur in the case of using van der Pol oscillator and the Rayleigh one as a CPG model. In turn, the lowest fluctuations exist when the stick-slip oscillator is applied. Similar conclusions can be achieved considering the reaction forces shown in Fig. 4, where the appropriate curves have been obtained for two times larger velocity of the robot movement. However, for larger velocities of the robot movement, there are larger dynamic overloads and the appropriate reaction forces. This occurs due to faster and more frequent oscillations of the robot gravity center and other elements of its legs. As can be seen, the stick-slip oscillator does not have this disadvantage (there is only slight dynamical overload in comparison to other CPG models).

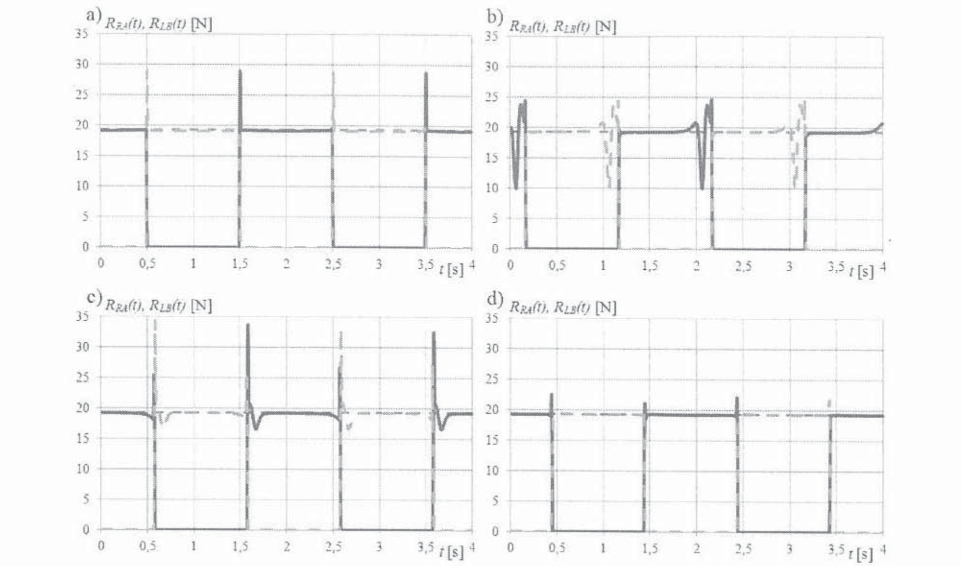

Figure 3. Time series of the reaction forces for the period of the single robot stride equal to 2 s: a) Hopf oscillator; b) van der Pol oscillator; c) Rayleigh oscillator; d) stick-slip oscillator. Solid line denotes $R_{RA}(t)$, whereas dashed line denotes $R_{LB}(t)$

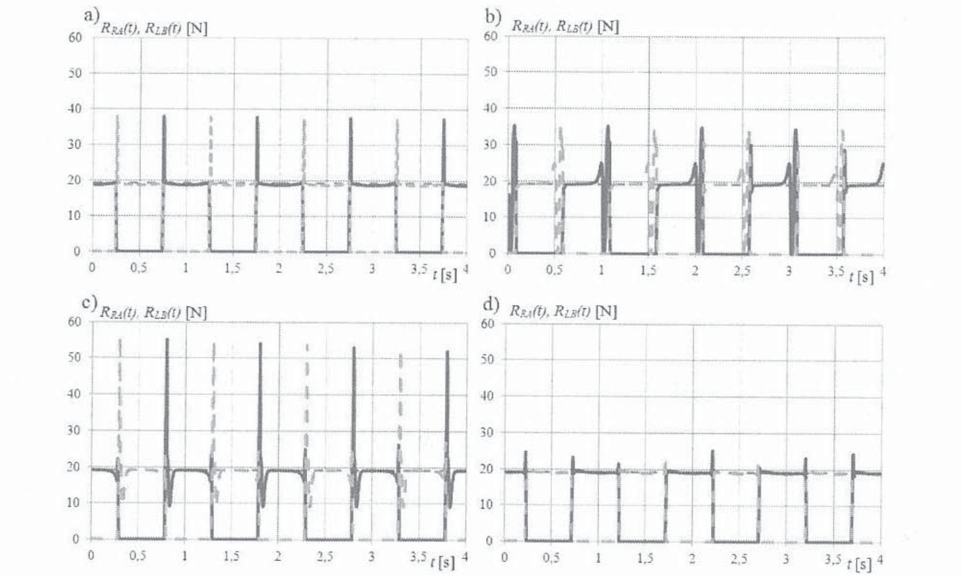

Figure 4. Time series of the reaction forces for the period of the single robot stride equal to 1 s: a) Hopf oscillator; b) van der Pol oscillator; c) Rayleigh oscillator; d) stick-slip oscillator. Solid line denotes $R_{RA}(t)$, whereas dashed line denotes $R_{LB}(t)$

4. Conclusions

In the paper, time series of the reaction forces acting on the individual robot legs and occurring undesirable dynamic overloads caused mainly by strong fluctuations of the center of gravity of the robot are obtained numerically. The robot movement has been kinematically excited by different well-known mechanical oscillators working as the CPG models, and to simulate the robot locomotion the tripod gait has been chosen. The choice of such a type of the robot gait has its justification. First, this type of gait is most commonly used by both the six-legged insects as well as six-legged walking machines in engineering applications. Second, in the case of the tripod gait, in general, at each moment of the robot movement the support polygon is formed only by three legs and the corresponding reaction forces are greater than in the case of other gaits (for instance, in case of tetrapod gait or wave gait). In addition, the choice of a relatively hard ground has also its justification, since this type of surface generates larger reaction force and correspondingly greater dynamic overload. In the considered type of gait and movement on the hard ground, the largest reaction forces and dynamic overload are expected, which justifies the choice to study this kind of the robot gait and this type of the ground. Different reaction forces and overload acting on the robot, being the result of using different CPG models to control its motion, have been illustrated and discussed. However, it should be noted that the obtained reaction forces have been obtained by double differentiation of displacements of the gravity centers of individual elements of the robot. The exact value of reaction forces at the moment of changing of supported legs depends strongly on the stiffness and damping of both the ground and construction of the robot. Nevertheless, the obtained simulations allow to compare the generated reaction forces for different CPG models which control the robot motion. The obtained information can be used in the future for analyzing the strength of the robot legs, being important for trouble-free uses and extension of life and operational time of the robot. Reaction forces occurring on the contact surfaces between the robot legs and the ground belong to one of the most important issues which should be taken into account.

Acknowledgments

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