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COMPUTER ANALYSIS OF INSECT-LIKE ROBOT LEG STRUCTURE – PART 2 – KINEMATIC AND DYNAMIC ANALYSES

The aim of this paper is to present the effect of a chosen gait algorithm on the forward speed of the robot and on the joint load values. To this end a motion simulation study was carried out using Solidworks software package, comprising kinematic and dynamic analyses. It also presents the forward and reverse kinematics solutions for the insect-like walking robot leg.

1. INTRODUCTION

The walking robot motion study consist in analysing either a single step or a sequence of steps called gait cycle. Gait is defined as the form of locomotion effected by cyclic transferring of legs in a desired direction, sometimes assisted with the motion of the robot's body. Gait is the only mode of locomotion available to walking machines, understood as a change of position of the centre of gravity in a plane parallel to the ground. The centre of gravity can change its position also vertically or sideways as a side effect of such motion. There are a number of gait types, classified on the basis of observation of the animal world. The most important characteristic used to discriminate the different gait types is the sequence of leg transfer and not the gait speed. Some sequences of leg transfers correspond to specific speeds for specific animal species. Gait types include trot, leisurely walk, jumping, fast walk,

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etc. Trot is a specific kind of walking, which includes moments with all feet lifted off the ground [Friedrich and Zielińska 2004, Piątek 2012, Wojtkowiak 2015, Zielińska 2014].

For the walking robot gait analysis it is necessary to define the following basic notions: anterior extreme position (AEP), posterior extreme position (PEP), step, gait cycle, load factor, protraction, retraction and relative phase. The leg transfer process together with the characteristic parameters is presented in Fig. 1.
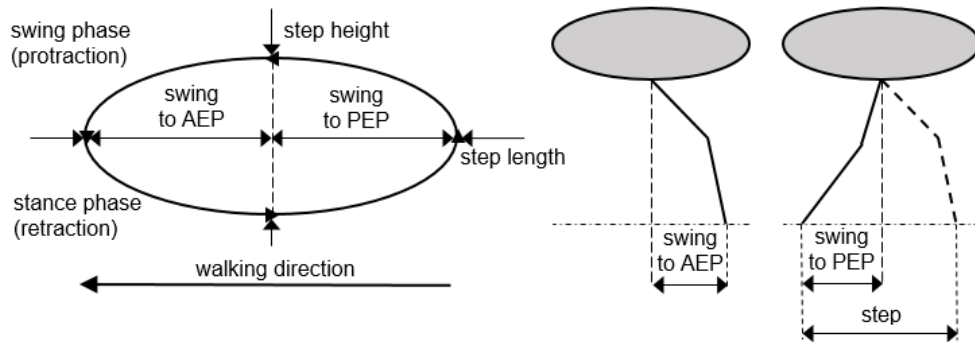

Fig. 1. Step diagram showing characteristic parameters

A step is the process of transferring a single leg of a walking robot. The step is described by the following parameters: length, height, trajectory and direction. The length of step is measured between two successive placements of one leg (treated as points). The step height is the difference between the highest and the lowest position of the leg tip during a step. The step trajectory is an ellipsoid-like curve of the foot travel path, drawn in the plane normal to the ground and parallel to the walking direction. A step consist of two phases: protraction and retraction. The protraction phase (lifting the leg off the ground) is the part of the leg walking during which it remains off the ground. The retraction (stance) phase is the part of walking when the leg rests on the ground. This phase causes the centre of gravity of the machine to move forward. In the protraction phase the leg returns to the initial position before the actual walking during the retraction phase. There are two main parameters related these phases: Anterior extreme position (AEP) and posterior extreme position (PEP). AEP is the point reached by the leg in the forward direction and PEP is the point reached by leg in the backward direction in relation to the robot body moving in the walking direction. The distance between AEP and PEP is the step length [Piątek 2012, Wojtkowiak 2015, Zielińska 2014].

Fig. 2 presents a 3D model of a six-legged insect-like walking robot. The robot body is composed of three segments: front body segment, middle body segment and rear body segment. Each segment has only one pair of legs attached to it. Front pair of limbs are used for locomotion and manipulation, while other limbs are used only for generating motion. Segments of the robot body are connected with each other by

using proper joints – single axis joint between rear and middle segment and double axis joint between front and middle trunk. This joints provides possibility of obtaining two different configurations: HEXAPOD and QUADRUPED. In this way the construction combines the advantages of six- and four-legged robots. The change between main configuration (HEXAPOD) and alternative configuration (QUADRUPED) is realized by lifting up front segment to a right angle.

The main element which allows to perform a given locomotion function is the robotic leg called pedipulator. In presented construction each limb consists of three links: hip segment L_1 – 35 mm long, thigh segment L_2 – 80 mm long and shank segment L_3 – 140 mm long. The robotic leg is an open kinematic chain, where each link is connected with the preceding link with an articulated join. This joints permits rotation about horizontal axis by creating kinematic pairs of class 5. Hip segment is coupled with the robot body by an articulated joint permitting rotation about vertical axis and also has one degree of freedom. Shank segment is ended with the foot. All the three links are situated in a single plane, which is called „leg plane". The geometry of each of the three links is based on simple shapes, like bent cranks or a pair of curved cranks. They are connected by the driving mechanisms.
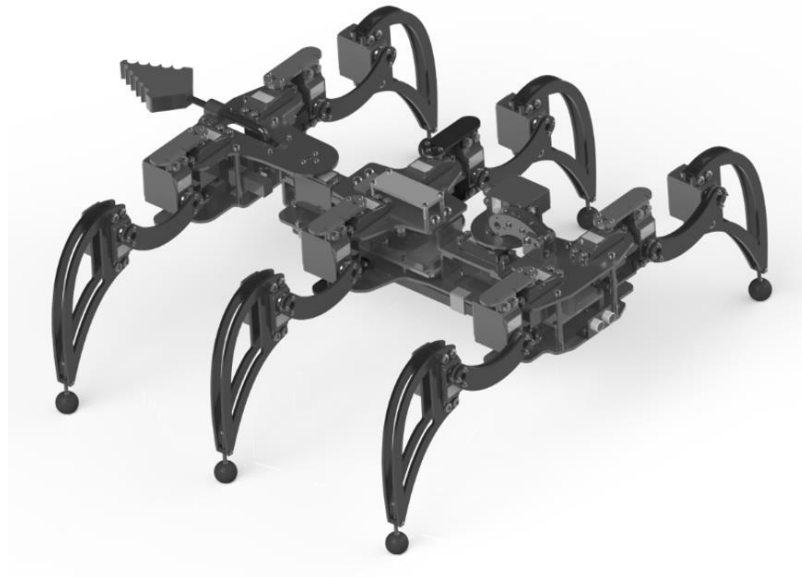

Fig. 2. 3D model of insect-like walking robot

2. KINEMATICS OF AN INSECT-LIKE ROBOT LEG

For analysing the basic kinematic parameters of a given system, such as position, velocity and acceleration vectors it is necessary to solve forward and inverse kinematics problems. These results are used for determining the robot's working space and the walking control algorithms. The first step is to prepare a kinematic diagram (Fig. 3), including determination of the global, local and generalised coordinates in the form of linear or angular displacements.
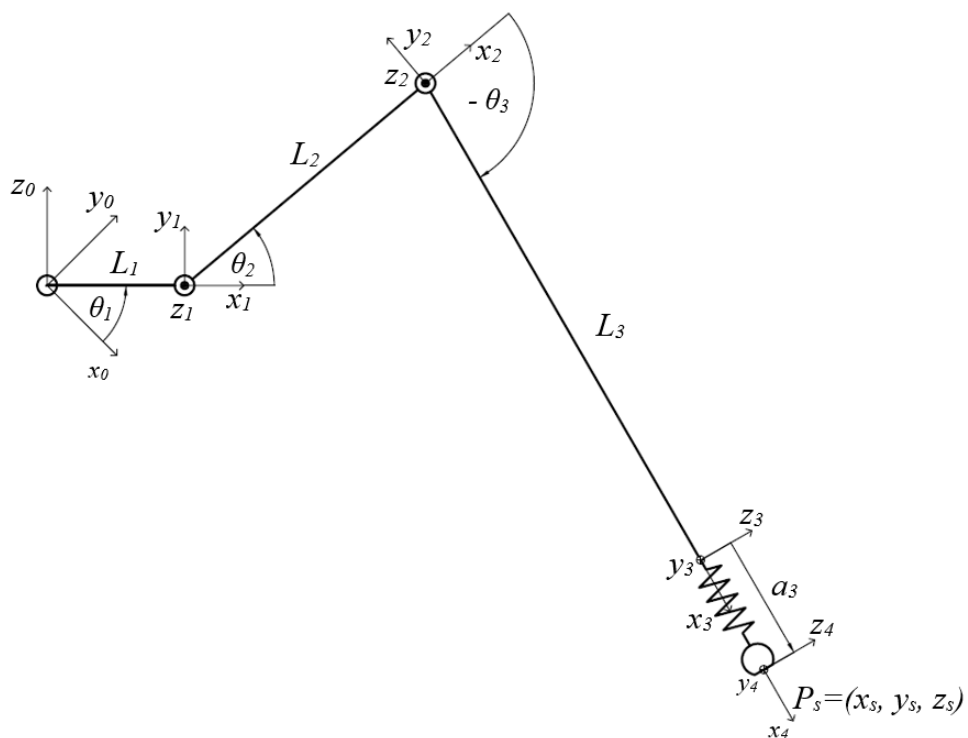

Fig. 3. Kinematic diagram of an insect-like walking robot leg: L_1, L_2, L_3 – lengths of links (limb segments), $(KS)_0$ – global Cartesian system, θ_1, θ_2, θ_3 – angles of rotation of the respective links (generalised coordinates), a_3 – the distance between the foot tip and the point of attachment of spring along the axis of L_3 link (generalised coordinate), P_s – foot tip position

A forward kinematics problem is solved by giving equations of position vector in the global system of coordinates in relation to generalised coordinates (angles θ_1, θ_2, θ_3) . These equations can be found by using geometric method based on geometric relationships, such as the laws of sines and cosines or the Denavit–Hartenberg method relating different coordinate systems by transformation matri-

ces [Frączek and Wojtyra 2008]. The position vector coordinates of the leg tip schematically presented in Fig. 3 are given in equations (1), (2) and (3). The coordinates of the velocity and acceleration vectors are obtained by calculating subsequent derivatives of the position vector coordinates [Wojtkowiak 2015].

$$x_s = L_1 \cdot \cos\theta_1 + L_2 \cdot \cos\theta_2 \cdot \cos\theta_1 + (a_3 + L_3) \cdot \cos(\theta_2 + \theta_3) \cdot \cos\theta_1 \qquad (1)$$

$$y_s = L_1 \cdot \sin\theta_1 + L_2 \cdot \cos\theta_2 \cdot \sin\theta_1 + (a_3 + L_3) \cdot \cos(\theta_2 + \theta_3) \cdot \sin\theta_1 \qquad (2)$$

$$z_s = -L_2 \cdot \sin\theta_2 - (a_3 + L_3) \cdot \sin(\theta_2 + \theta_3) \qquad (3)$$

The problem of inverse kinematics consists in finding the angles of rotation of the respective links using the known coordinates of the leg tip position. The methods used to solve this problem are the same as in the forward kinematics problems. However, calculations are much more complicated in this case and analytical methods can be used only for less complex kinematic structures [Heinmann Gerth and Popp 2001]. The solution of the inverse kinematic problem formulated for the leg tip schematically presented in Fig. 3 is given by equations (4), (5) and (6). As previously, the component angular velocities and accelerations are obtained by calculating subsequent derivatives of the angles θ_1, θ_2 and θ_3 [Wojtkowiak 2015].

$$\theta_1 = arctg\left(\frac{y}{x}\right) \qquad (4)$$

$$\theta_3 = \pm\, arccos\left(\frac{x_s{}^2 + y_s{}^2 + z_s{}^2 + L_1{}^2 - 2L_1\sqrt{x_s{}^2 + y_s{}^2} - L_2{}^2 - (a_3 + L_3)^2}{2L_2 \cdot (a_3 + L_3)}\right) \qquad (5)$$

$$\theta_2 = \pm arcsin\left(\frac{z_s}{\sqrt{x_s{}^2 + y_s{}^2 + z_s{}^2 + L_1{}^2 - 2L_1\sqrt{x_s{}^2 + y_s{}^2}}}\right) \mp$$

$$\mp arcsin\left(\frac{(a_3 + L_3)\cdot\left(1 - \left(\frac{x_s{}^2 + y_s{}^2 + z_s{}^2 + L_1{}^2 - 2L_1\sqrt{x_s{}^2 + y_s{}^2} - L_2{}^2 - (a_3 + L_3)^2}{2L_2 \cdot (a_3 + L_3)}\right)^2\right)}{\sqrt{x_s{}^2 + y_s{}^2 + z_s{}^2 + L_1{}^2 - 2L_1\sqrt{x_s{}^2 + y_s{}^2}}}\right) \qquad (6)$$

3. GENERATING THE STEP OF THE WALKING ROBOT

The sequence of motions related to a single step is the same for all gaits. The algorithm for carrying out a single step is presented in Fig. 4.
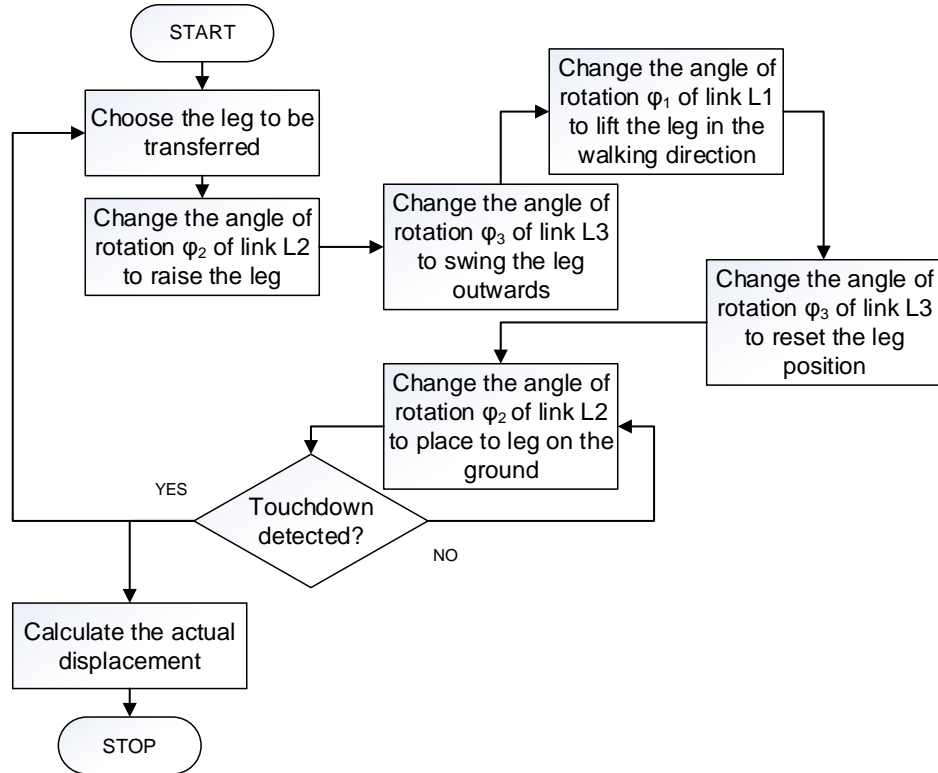
Fig. 4. Walking robot step generation algorithm

After the leg has been selected it is raised up by rotation of the servo propelling link L_2. Then link L_3 is rotated and the angle of rotation is such that the foot does not contact with any obstacle. The swing forward to AEP is effected by rotation of the servo coupled with link L_1. When the leg reaches the final position it is placed on the ground through rotating the distal link, followed by the middle link. When ground impact is detected (touchdown) the leg returns to the initial position. In this way the remaining legs are shifted backwards in relation to the robot body to the posterior extreme position (PEP). The length of displacement of the whole machine is calculated with forward kinematics equations. This information is used to determine the total displacement. The rotation angles in the above algorithm should be chosen to obtain the optimum conditions of walking. This can be achieved by performing a computer-assisted motion study. Two types of analyses can be performed [Heinmann Gerth and Popp 2001]:
− kinematic motion analysis − which predicts the walking on the basis of applied loads and actuations producing trajectories of points, displacements, velocities and accelerations.

− dynamic motion analysis which analyses the forces generated as a result of motion, as well as the motion itself, producing the reaction forces and moments, as well as all types of energy conversions, etc.

4. COMPUTER ASSISTED MOTION ANALYSIS OF A WALKING ROBOT LEG

4.1. Experimental procedure

The analysis was performed using SolidWorks 2012 software. The software includes the motion analysis model enabling assembly analysis together with defined contacts and bonded contacts. The model used in the analysis (Fig. 5) does not include the foot, which was omitted to simplify the computational model to exclude the effect of the foot elasticity. The step algorithm was modelled using the event-based programming method (Fig. 6) which enables defining the conditions for performing a given action on the basis of sensor outputs, time delays, preceding events, etc. Links are rotated by three rotary drives at servo horn locations, modelled as servo drives modelled by the position inputs. The model additionally includes two external forces to represent the actual motion resistance resulting the leg-ground contact (F_1) or forces of inertia during body motion (F_2). The forces are modelled as data segments vs. time curve. Moreover, these forces can be switched to on and off status by specific events. The point of attachment of force F_1 is the midpoint of the bottom wall of link L_3. The other force F_2 is applied at the side surface of link L_1. The values of these forces were calculated using the reaction to the pressure of 10 N applied by the robot on the surface when it is supported on only three legs and the previously calculated accelerations where the force of inertia equals the product of mass and acceleration along the relevant axis. Fig. 4 presents also the trajectory of robot leg tip when the robot carries out a step.
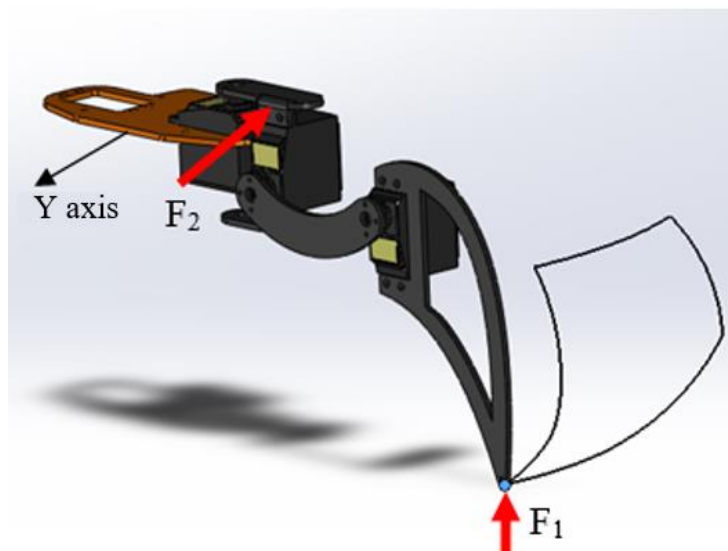
Fig. 5. 3D model of robot leg showing the leg tip trajectory during a step

Zadania		Wyzwalacze			Akcje					Czas	
Nazwa	**Opis**	**Wyzwalacz**	**Warune**	**Czas/Opóź**	**Operacja**	**Akcja**	**Wart**	**Czas trwa**	**Profil**	**Start**	**Koni**
Przenoszeni		Unieś L3	Począ	0.15s opóź	Siła1	Wyłąc				0.15s	0.15s
Unieś L3		Czas		0s	Napęd ob	Zmień	-30d	1s		0s	1s
Unieś L2		Czas		0.5s	Napęd ob	Zmień	45de	0.5s		0.5s	1s
Krok do prz		Unieś L2	Konie	<Brak>	Napęd ob	Zmień	30de	0.5s		1s	1.5s
Opuść L2		Krok do p	Konie	<Brak>	Napęd ob	Zmień	-45d	0.5s		1.5s	2s
Podparcie		Opuść L2	Konie	0.85s opóź	Siła1	Włącz				2.85s	2.85s
Opuść L3		Opuść L2	Konie	<Brak>	Napęd ob	Zmień	30de	1s		2s	3s
Obciążenie		Opuść L3	Konie	0.25s opóź	Siła2	Włącz				3.25s	4s
Ruchu korp		Opuść L3	Konie	0.25s opóź	Napęd ob	Zmień	-30d	0.75s		3.25s	4s

Fig. 6. Event-based robot step control algorithm

4.2. Kinematic analysis of pedipulator

The kinematic analysis was limited to the components along axis Y running in the robot's walking direction. Fig. 7 presents the curves of displacement, velocity and acceleration plotted against time for the basic gait mode. For the purposes of this analysis the basic gait is defined by 4 sec. duration of step and $45°$ angle of rotation of the leg about the vertical axis. One step results in 66 mm linear displacement of the robot in the walking direction. This gives the 16.5 mm/s forward speed which is considered quite slow. The velocity component in the Y direction of the leg tip is 0.3 m/s during leg transfer and 0.21 m/s during motion of the body. Acceleration values do not exceed 1.8 m/s^2. The acceleration peak at 2.85 sec.

reaching 8.6 m/s^2 results from a sudden application of loading force F_1 introduced to represent the stance stance phase.
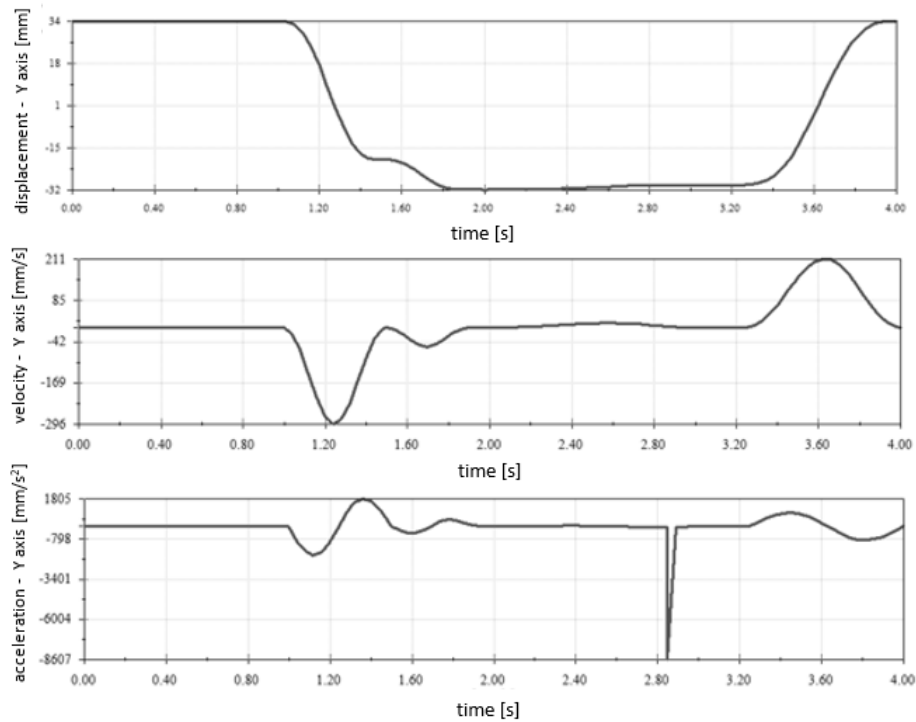

Fig. 7. Curves of displacement, velocity and acceleration of the leg tip along the Y axis (basic gait) plotted against time

Taking into account the driving systems used the minimum step duration would be ca. 0.8 sec. This would give 82.5 mm/s. forward speed of the robot. Unfortunately, this would generate very high accelerations resulting in high forces of inertia. These undesired accelerations can be mitigated by limiting the step duration to 2 seconds producing forward speed of ca. 33 mm/s. This is called fast gait and the results of kinematic analyses performed for such configuration are presented in Fig. 8.

The velocity of the leg swing in the walking direction is ca. 0.6 m/s with 0.44 m/s. velocity of the body motion. With double decrease of time the velocity increased two times which gives approximately linear and inversely proportional relationship. The accelerations in this configuration are ca. 7 m/s^2 in the case of the leg and ca. 4 m/s^2 in the case of the robot body. Here, instead of linear we obtain approximately quadratic relationship.
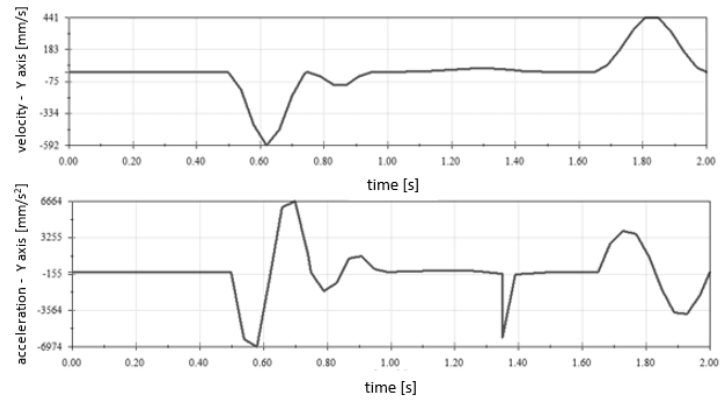
Fig. 8. Velocity and acceleration of the leg tip along the Y axis (fast gait)

In order to increase the forward speed of the robot without changing the step duration the angle of rotation of link L_1 must be increased two times in relation to the initial configuration. This kind of step is called long step as it produces big linear displacements. The curves of displacement, velocity and acceleration against time for such configuration are presented in the graphs in Fig. 9.
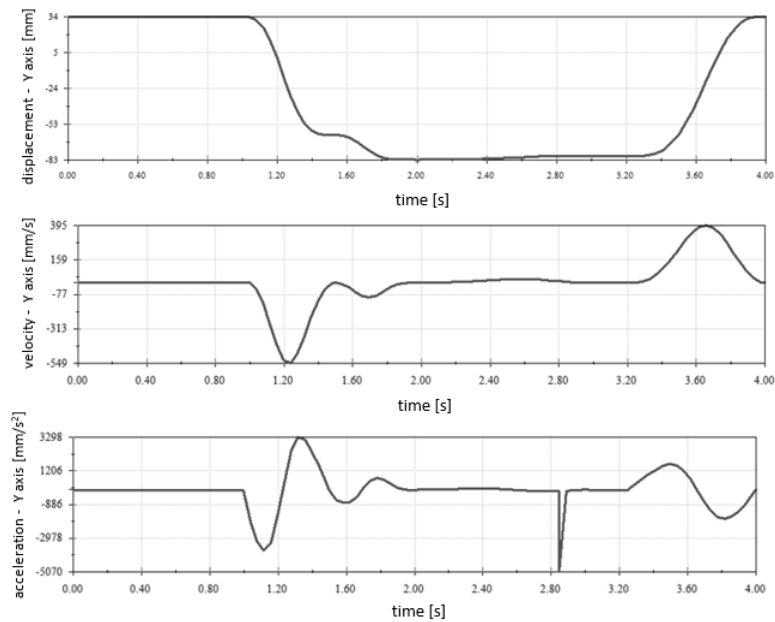
Fig. 9. Position, velocity and acceleration of the leg tip along the Y axis (long step gait)

Analysing the displacements for this case we note an increase of displacement to 117 mm. The linear velocities are: 0.55 m/s in the case of leg and ca. 0.4 m/s in the case of the robot body. The accelerations are ca. 3.3 m/s^2 and 1.5 m/s^2 respectively. All these values concern the components in the walking direction. Hence, increasing the leg swing angle while maintaining the step duration will increase the linear displacement during the gait cycle and thus the velocity of the robot. This change will, however, result in non-linear changes in the speed and acceleration values of a point.

4.3. Dynamic analysis of pedipulator

The output of the dynamic analysis was used to define the curves of reaction moments at all the joints of the robot leg for the basic gait (Fig. 10).
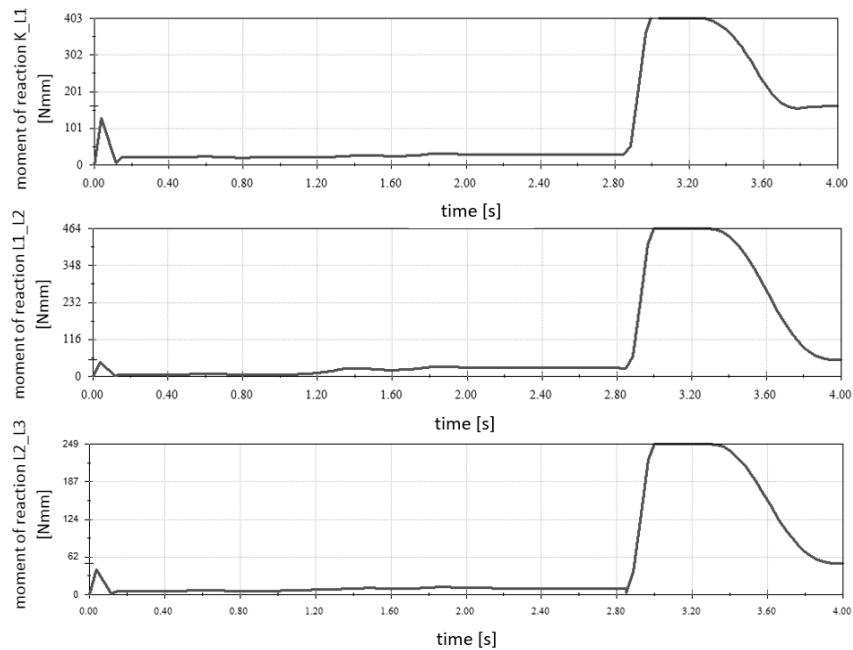

Fig. 10. Moments of reaction at the robot leg joints (basic gait)

From the results we see that during the stance phase the greatest reaction moments of ca. 0.15 Nm occur in the joint between the robot body and link L_1 The reaction moments in the remaining two joints are about 0.05 Nm. In the remaining phases of the leg motion the moments of reaction on all the joints do not exceed 0.05 Nm The reaction moment reaches the maximum during body motion when the leg is supported on the ground. The respective joints are loaded with reaction mo-

ments of 0.4 Nm, 0.46 Nm and 0.25 Nm viewing from the body to the foot. Thus it can be concluded that the most heavily loaded joints are the node between the body and link L_1 – when the leg rests on the ground and the joint between links L_1 and L_2 – during body motion. For the sake of comparison in Fig. 11 the same curves are presented also for the long step gait.
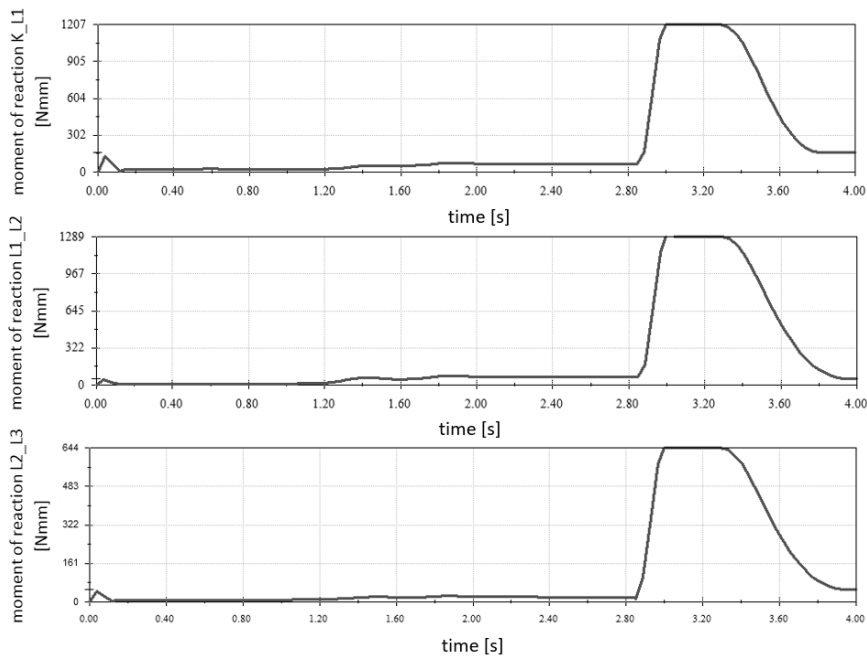

Fig. 11. Moments of reaction at the robot leg joints (long step gait)

The moment curves for long step gait are similar in shape to the basic gait curves. However, the values differ considerably. The maximum moments of reaction on the respective joints are: 1.3 Nm, 1.2 Nm and 0.64 Nm. This gives over 2.5 times increase in the moment, which entails a need for grater driving moment. The moment value does not change during the stance phase. This situation results in the influence of the force of inertia, whose high value results from high accelerations.

5. CONCLUSIONS

Use of computer analysis for studying motion enables finding favourable parameters of a step owing to easy modification of input parameters for different configurations. The outcome includes kinematic parameters, as well as information

on loading of joints and drives of the analysed walking machine. Thus the results influence both the robot's design and its control.

REFERENCES

Frączek J., Wojtyra M., Kinematyka układów wieloczłonowych – metody obliczeniowe, Warszawa 2008.

Friedrich P., Zielińska T., Walking: biological and technological aspects, Springer-Verlag, Wiedeń 2004.

Heinmann B., Gerth W., Popp K., Mechatronika: Komponenty metody przykłady, Wydawnictwo PWN, Warszawa 2001.

Piątek M., Problemy sterowania robotami kroczącymi – generatory chodu heksapod, praca doktorska, Kraków 2012.

Wojtkowiak D., Projekt koncepcyjny robota kroczącego wzorowanego na budowie owada, praca magisterska, Politechnika Poznańska, Poznań 2015.

Zielińska T., Maszyny kroczące – Podstawy, projektowanie, sterowanie i wzorce biologiczne, wyd. 2, PWN, Warszawa 2014.

KOMPUTEROWA ANALIZA KONSTRUKCJI NOGI ROBOTA KROCZĄCEGO WZOROWANEGO NA BUDOWIE OWADA – CZ. 2 – ANALIZA KINEMATYCZNA I DYNAMICZNA

Streszczenie

Niniejszy artykuł ma na celu przedstawienie wpływu wybranego algorytmu kroku na uzyskiwaną prędkość ruchu i obciążenia poszczególnych przegubów nogi. W tym celu wykorzystane zostało symulacyjne badanie ruchu wykonane w programie SolidWorks, które składa się z analizy kinematycznej i dynamicznej. Dodatkowo w artykule przedstawiono rozwiązanie zadań kinematyki prostej i odwrotnej dla nogi robota kroczącego wzorowanego na budowie owada.

Słowa kluczowe: robot kroczący, hexapod, quadruped, pedipulator, analiza kinematyczna