Bionic movement algorithms implemented in mechatronic robots

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Abstract: This paper addresses the problem of bionic movement algorithms of two types of limbless species: serpentes and geometridae. Bionic aspects seem to play important role in the processes of designing and development of new mechatronic systems and in modeling of their movement patterns. Evolution of the biological systems and resulting benefits cannot be neglected as the nature has created a lot of very complicated but specialized and effective systems. This gives an opportunity to observe, examine, modeling, and design via adjustable mechatronical systems. In this work we are presenting a way of implementation undulatory and inch-worm like movement locomotion algorithms based on examples of the manufactured two different robots.

1. Introduction

Bionics is a relatively new branch of science, however mankind has a tendency to mimic or copy the biological solutions probably at the beginning of our civilization development. This trend is visible in all fields of our life and we are in habit of looking for solutions to complex problems from different fields of science, engineering and daily life in the surrounding us nature [1]. It is quite popular to introduce naturally occurring behaviors in designing, construction and control of new mechatronics devices [2, 3]. In this work we are focusing on construction and implementation of the bionic movement algorithms in two types of robots. They are inspired by snake and inchworm and can serve as examples of transfer of living organisms structure and movement algorithms to the mechatronic structures. The movement patterns applied in this study were created on the basis of Hirose [4] and Saito et al. [5] results with assumption, that generated control signals can be treated as simplified Central Pattern Generator signals [6].

We begin with a short introduction to a biological aspect of the snake motion. Among the limbless animals there is a wide diversity of the movement patterns but, in general, the possibility of movement is caused by friction force created between the body and the ground. One of the examples of the limbless animals are serpents. Different movements patterns are not only caused by their structure (size), but also by environment, way of hunting, available space for movement and types of barriers they have to overcome [10]. Therefore, in the case of snakes, we can differentiate the following types of motion: serpenoid, concertina, rectilinear or sidewinding (see Fig. 1) [7]. The belly scales occurring in varied shapes depending on the natural animals natural environment [9] stand for useful tools helping with increasing the friction force (friction coefficient) in an intended direction of movement [8].

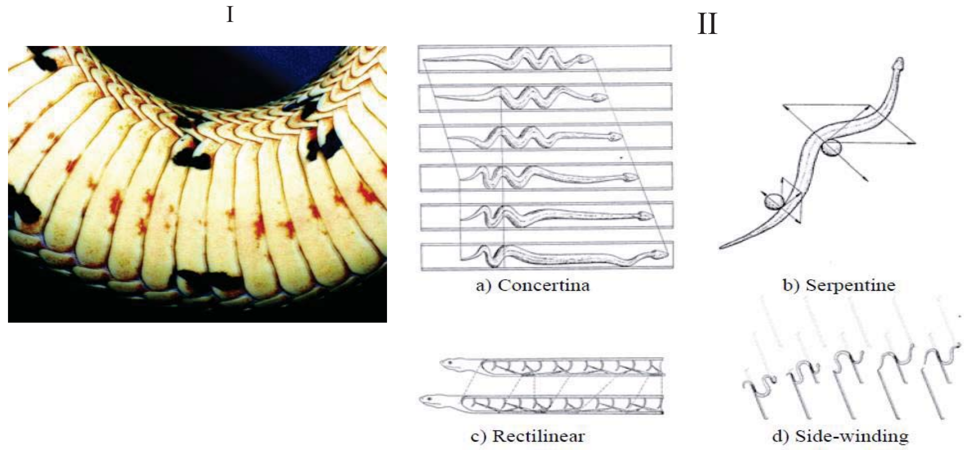

Figure 1. Snake appearance and main gaits of snakes. I – Belly scales of snake, II – Types of movement: a) Concertina, b) Serpentine, c) Rectilinear, d) Side-winding [7]

The inchworms also known as *Geometridae* caterpillars belong to a multispecies group [11]. Dimension of their body length is rather small and fluctuates from 10 to 50 mm. Significant role in caterpillar movement play prolegs, thanks to them the inchworms can attach to the ground [12]. Fig. 2 presents four phases of inchworm movement.

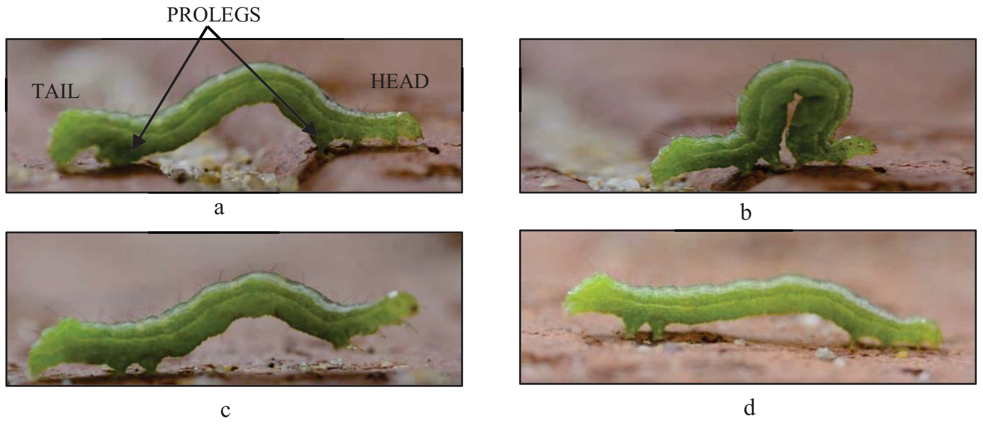

Figure 2. Four phases of inchworm movement [14]: a) Thorax part with head is attached to the ground by prolegs; b) Thorax part with tail is lifted upward and attracted to head; c) Thorax part with tail is attached to the ground by prolegs; d) Thorax part with head is lifted and shifted to forward direction.

When inchworm wants to change the direction of motion, it stops in the position shown in Fig. 2c and turns thorax part with head to new direction. It should be pointed out that the angle of turning is limited, as a result this type of species cannot turn back in one step.

2. Mechanical structure of biology inspired robots

This subsection includes examples of the snake robot and the inch-worm robot. Presented in this study snake-robot (Fig. 3) was designed and constructed by authors. It consists of eleven segments printed at 3D printer from durable acrylonitrile butadiene styrene (ABS) material. Six of them are able to move in vertical and five in horizontal plane. They are placed alternately, what allowed to achieve the rotation angle up to 40° for each of the joints. This construction of 0.97 m length and 1.7 kg weight is powered by servomotors with maximum torque of 1.32 Nm placed in each of the segments. Its remote control is realized by means of the microcontroller (programmable Arduino M0) located in the tail-segment of the robot.

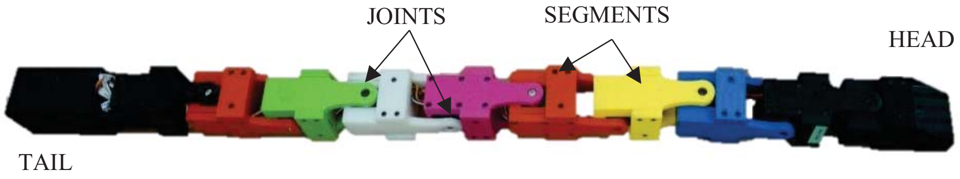

Figure 3. Horizontal view of the designed snake robot

The designed inch-worm robot (Fig. 4) consists of four segments printed on the 3D printer from ABS material with total length of 0.32 m and total weight of 0.53 kg. Its first (head) and last (tail) segments are additionally equipped with suction cups acting as the prolegs. Suction cups are connected to ejectors which using compressed air to produce vacuum pressure, allowing robot to attach to the ground. Two middle segments allow lifting non-attached segment and attracting/repulsing it. In the tail there is located stepper motor which can rotate the robot and change its motion direction. Servomotors are used for drive. The main simplifications of the proposed model, in comparison to the real inch-worms are exhibited by its much bigger size and significantly decreased number of the segments.

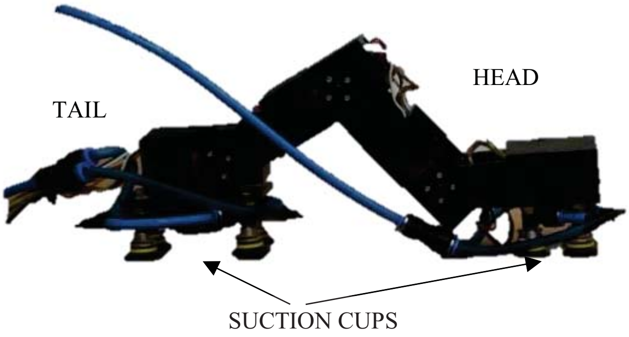

Figure 4. Horizontal view of the inchworm robot

3. Motion algorithm of two designed mechatronic robots

3.1 Snake robot algorithm

One of the most popular mathematical models of snake motion, describing its kinematics, has been created by Hirose [4]. The model assumes that the snake body is represented by continues curve and the coordinates are expressed by the following two equations:

$$x(s) = \int_0^s \cos[a \cdot \cos(b\sigma) + c\sigma]\, d\sigma,$$

$$y(s) = \int_0^s \sin[a \cdot \cos(b\sigma) + c\sigma]\, d\sigma, \tag{1}$$

where: s – length from start of the curve, a – parameter describing an undulation, b – parameter describing a frequency, c – parameter describing a deflection of curve.

The curve governed by two parametric equations (1) is called serpenoid curve. Fig. 5 presents influence of parameters *a, b* and *c* for the shape of serpenoid curve.

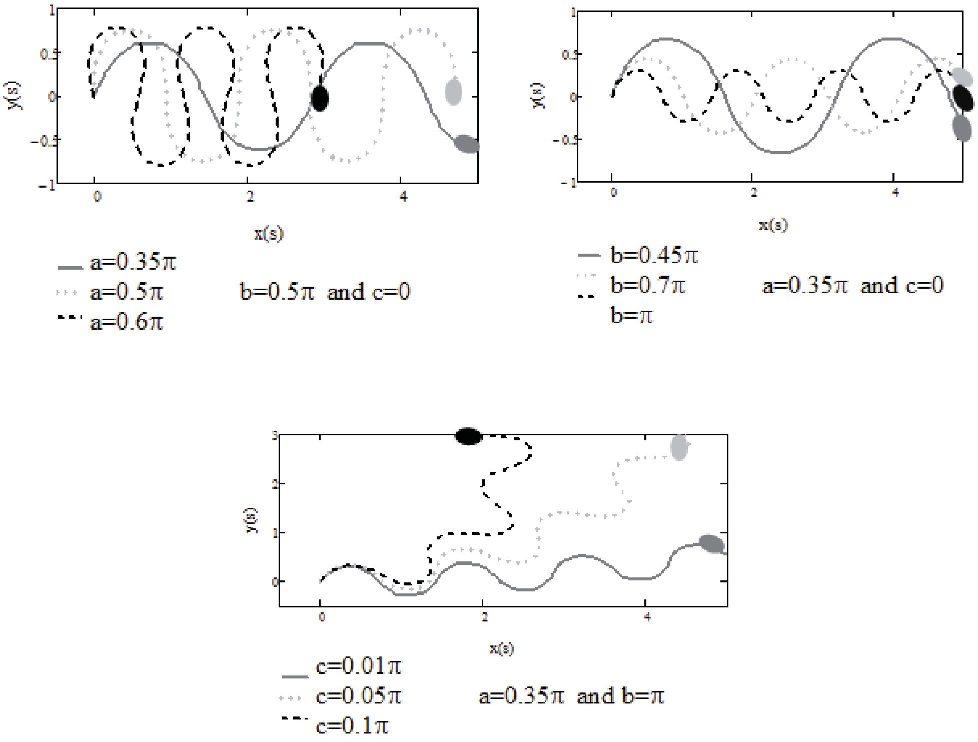

Figure 5. Shape of serpenoid curve for different parameters, (black dot denotes head of the snake).

Increasing of the parameter *a* implies increase of curvature of the serpenoid, while the parameter *b* is responsible for the period of the serpenoid and parameter *c* for the direction of the curve propagation.

To enable application in a microcontroller, the algorithm (1) can be simplified to achieve a sinusoid function [8]. Equations of angles in joints for the snake robot are as follows

i. Motion in a vertical plane (see Fig. 6) is described by the function

$$\xi_i(t) = A_\xi \sin\left(\frac{2\pi}{T} \cdot t + \psi_i\right) + \gamma, \tag{2}$$

ii. Motion in a horizontal plane is governed by the following formula

$$\Omega_i(t) = A_\Omega \sin\left(\frac{2\pi}{T} \cdot t + \omega_i\right) + \delta, \tag{3}$$

where: i – number of joint, ξ_i, Ω_i – angles of rotation in i-th joint for each segment, t – time, A_ξ, A_Ω – amplitudes, T – period, ψ_i, ω_i – phase shift for next link, γ, δ – vertical shift.

Scheme model of the snake robot in vertical plane is shown in Fig. 6.

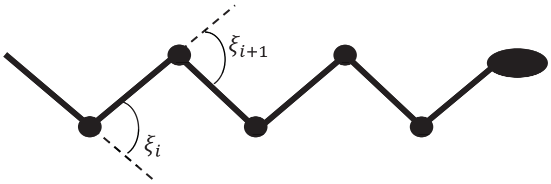

Figure 6. Model of the snake robot in vertical plane

In Fig. 7 examples of the changing angles in joints during snake-robot horizontal motion are presented. As it can be observed, signals have the same amplitudes and periods but they are shifted in phase for different segments, what creates a proper intersegmental coordination during their movement.

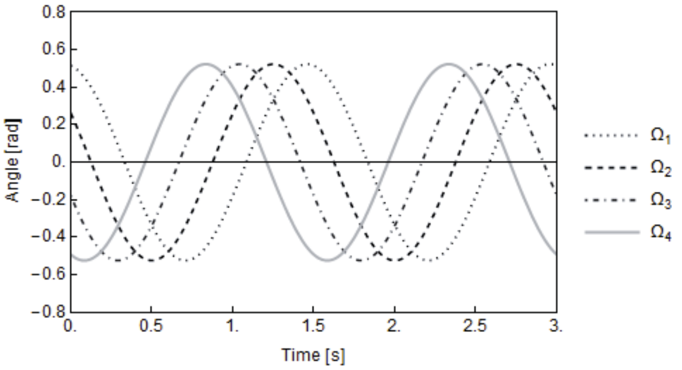

Figure 7. Control signals for serpentine motion for *i*-th segment

3.2 Inch-worm robot

Inchworm robot can move only in a vertical plane but the scheme model of the movement pattern is generated in the same way as for the snake robot in vertical plane (Fig. 6). The main difference is that a number of segments is limited to four. In contrary to the previous case, the algorithm is not continuous function but discrete changing sequence of the values of the angles in joints [13]. These sequences of angle values are shown in Fig 8. One can see that the values have sinusoid trend and oscillate above zero, the periods and phase shifts are the same for all of them but the amplitudes are different. It also creates a proper intersegmental coordination. Because the discrete algorithm of angle in joint has the sinusoid trend, it can be replaced by a continuous function expressed by modified Eq. 2 with a positive vertical shift. Fig. 9 shows sinusoidal wave fitting to angle values generated during the robot motion.

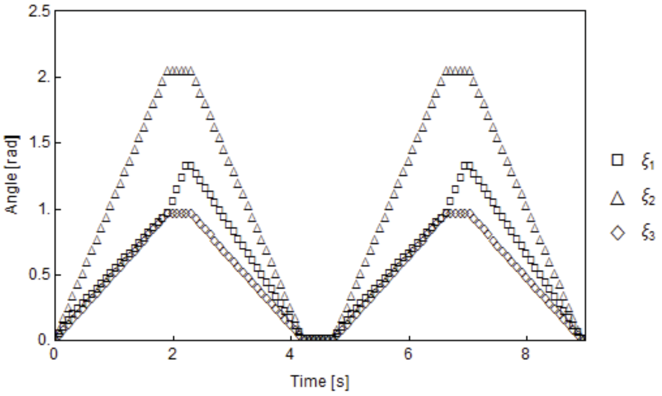

Figure 8. Discrete angle values in joints for the inchworm robot for the *i*–th segment

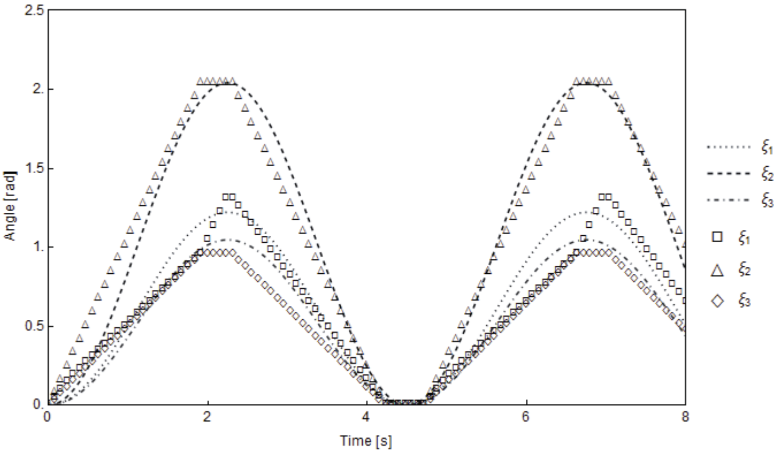

Figure 9. Curve fitting to discrete algorithm of the inchworm motion.

The angle signals are generated by microcontroller and send to servomotors located in rotation nods (joints).

4. Implementation of discrete algorithm

The results of the motion algorithms implementation are presented in a form of comparison of the real pictures which were done during motion recording versus the corresponding theoretical computation of the robots behavior. Coordinates of joint points for snake-robot have been obtained according to equations 2, 3, while for inch-worm robot according to Eq. 2 with the parameters chosen after curve fitting (Fig. 10). Theoretical results were plotted in global coordinates. Table 1 contains parameters of implemented algorithm for both robots. In case of snake robot the parameters have been defined experimentally.

Table 1. Motion parameters of discrete algorithm implemented in control algorithms

Snake robot		Inchworm robot
Vertical plane	Horizontal plane	Vertical plane
$A_\xi = 30°$, $T = 1.5\ s$, $\psi_1 = 160°$, $\psi_2 = 210°$, $\psi_3 = 320°$, $\psi_4 = 410°$, $\psi_5 = 500°$, $\gamma = 0°$	$A_\Omega = 30°$, $T = 1.5\ s$, $\omega_1 = 100°$, $\omega_2 = 150°$, $\omega_3 = 200°$, $\omega_4 = 250°$, $\delta = 0°$	$A_{\xi 1} = 32°$, $A_{\xi 2} = 58.5°$, $A_{\xi 1} = 27.°$, $T = 4.5\ s$, $\psi_1 = 270°$, $\psi_2 = 270°$, $\psi_3 = 270°$, $\gamma_1 = 35°$, $\gamma_2 = 58.5°$, $\gamma_3 = 30°$

Differences between theoretical and experimental results are caused mainly by a lack of precision in the servomotors, friction and dynamic processes. Also a control unit does not have a positive coupling, what yields lack of repeatability of movement cycles and what generates it differences between experimental and theoretical results. Implementation results are shown in Fig. 10 and Fig. 11 for the snake robot and in Fig. 12 for the inchworm robot.

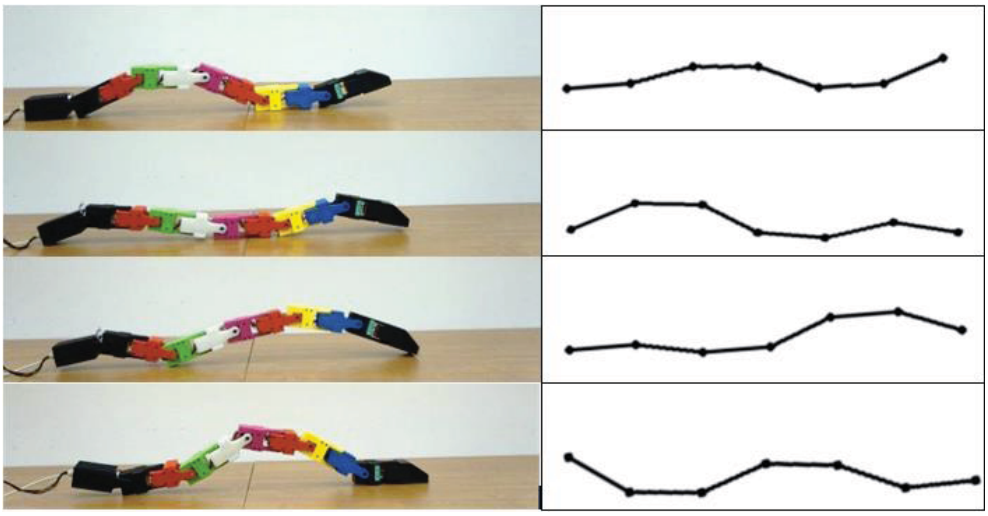

Figure 10. Snake robot motion – vertical plane

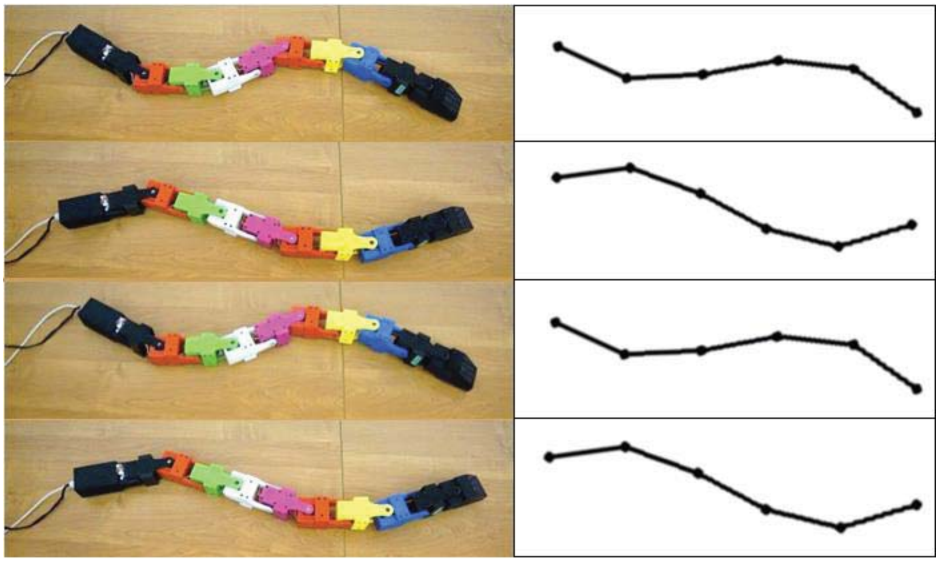

Figure 11. Snake robot motion – horizontal plane

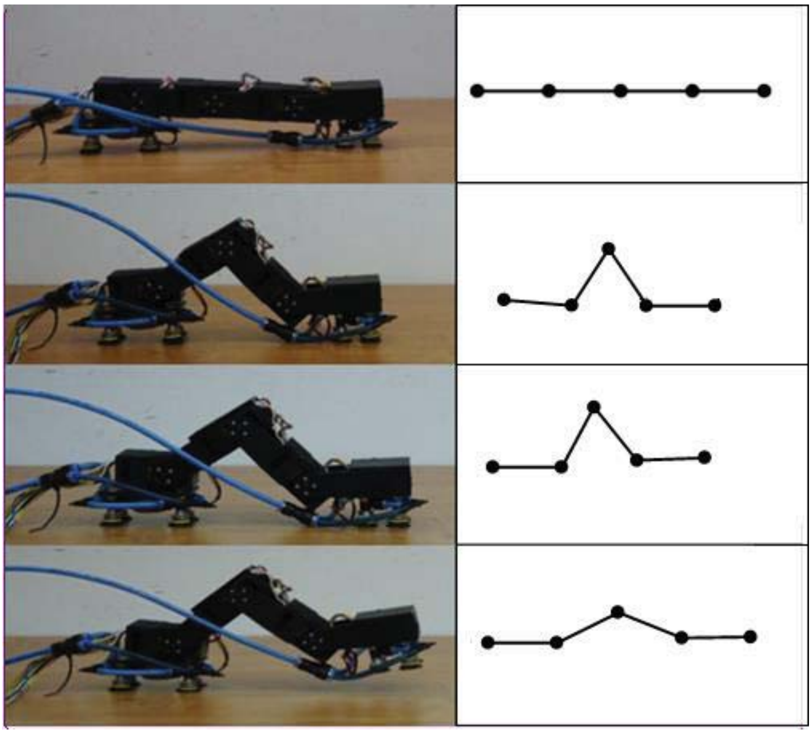

Figure 12. Inchworm robot motion – vertical plane

It was observed that for the uneven surfaces, decrease in the amplitude A_ξ results in shifting the mass center closer to the ground which implies stabilization of the robot. Main problem which occurred during realization of the motion of the snake robot is a sliding phenomenon appearing for the serpentine movement. In order to eliminate this harmful effect it is possible to apply material with directed friction force and/or increase the weight of segments.

The main disadvantage of the inchworm robot is its requirement of the smooth ground surface, as in other case the suction cups cannot create an underpressure, and hence a further motion is not possible. However, the robot can climb even on perpendicular wall if the surface of the ground is enough smooth and the vacuum pressure is high enough (see Fig. 13). There is also an option for replacing the suction cups by electromagnets, which allows the robot to move on ferromagnetic surfaces.

Figure 13. Climbing of inch-worm robot on the glass plate

5. Concluding remarks

Two unique bionic robots with which are able to imitate limbless animals: a snake and an inchworm are presented. Moreover, a control algorithm with proper parameter was implemented. Theoretical results were verified with experiments. It is assumed, that these robots can be useful as an inspection robots there, where is no room for wheeled or tracked vehicles. The main contribution of this paper is:

1. Presentation of movement algorithms creation for specific mechanisms.
2. Implementation of created algorithms to the robots control unit.

3. Comparison of theoretical results with robots behavior
4. Verification of the robots movement and its comparison to the biological structures movement abilities.

Moreover, it can be observed, that the robots dynamics have to be taken under consideration and this will be the subject of further study. Also some improvements in construction is necessary for a better imitation of the living animals like segments range of motion or stability control.

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