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A New Approach to Kinematics Modelling of Snake-Robot Concertina Locomotion

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Abstract. In this paper, for the first time, kinematics modelling of snake robot travelling with concertina locomotion is presented. Next a novel kinematics modelling method is presented which has an advantage of allowing natural snake like locomotion. During concertina motion, certain parts of the body contract, expand or do not change their shape. This results into having different body curves for different parts of a snake. To simulate this, first we introduce a mathematical equation, called dynamic function, in which by varying a certain function parameter, body curve during motion is realized. To obtain concertina gait, the snake body is divided into three different modules, head module, tail module and main body module that connects the head to the tail module. Each module forms a specific curve which can be modelled using the proposed dynamic function. At each moment during snake locomotion, the kinematics of different links can be derived by fitting links to the body curve. Finally concertina locomotion is simulated using Webots software. Results indicate concertina locomotion can be obtained. Furthermore, the proposed dynamic function requires relatively lower computation requirement. Therefore, adaption of body curve to other real snake like gaits as well as mixed type locomotion is made possible. This works represents a first approach to a simulation of a snake-like mechanism in order to get basic characteristics of such locomotion and to enable our future research.

Introduction

Snake can adapt their movement modes according to the different grounds and conditions. They have many movement modes to choose from and thus can move well on almost all grounds even on water. Based on studies in exiting literature, snake movement can be divided into four main categories: Serpentine movement; Rectilinear movement; Concertina movement and Sidewinding movement. Each movement, also called gait or locomotion, has its own characteristic and is used for different grounds and conditions. In this paper, Concertina locomotion is investigated

The first qualitative research on snake locomotion was made by J. Gray in 1946 [1] and the first snake robot was built by Hirose [2]. Hirose studied kinematics of Serpentine gait and proposed a 'Serpenoid curve' as a means to generate Serpentine locomotion. M. Walter [3], J. Gray, C. Gans [4], [5] are, among many others, biologists specialized in limbless locomotion who tried to explain the principles of the snake locomotion and to model it. However among these works, there aren't any detailed geometrical approaches to the describe body forms and trajectory characteristics. Klaassen and Paap [6] have presented a new snake-like robot (GMD-SNAKE2) and an algorithm for curvature controlled path calculation. Mathematically it is based on an enhancement of the well-known clothoid curve. Saito et al [7] made a snake robot without wheels and analyzed the optimally efficient Serpentine locomotion. More recently Sh. Hasanzadeh and A. Akbarzadeh [8] presented a novel gait, forward head Serpentine (FHS), for a two dimensional snake robot. They use Genetic Algorithm (GA) to find FHS gait parameters. J. Safehian[9] proposed a novel kinematics modeling method for Travelling Wave locomotion..

Concertina Locomotion Mechanism

The word Concertina represents a small accordion instrument. This name is used in snake locomotion to indicate that the snake stretches and contracts its body to move forward. This motion is similar to the motion of the concertina instrument. Concertina movement occurs in snakes and other legless organisms and consists of gripping or anchoring section of the body while pulling/pushing other sections in the direction of movement [1]. In Concertina locomotion parts of the body stop while other parts move forward. The sequence repeats and the snake moves forward. The key element of Concertina locomotion is the utilization of the difference between higher forces resulting from static coefficient of friction and lower forces resulting from the dynamic coefficient of friction along different parts of the body. Fig. 1 shows the snake moving forward into the pipe by using Concertina locomotion. As shown in this Figure, the snake keeps the end parts of its body in contact with the pipe wall. Then gradually expand its body.

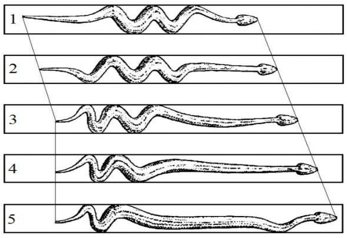


Fig. 1. Progression stages of real snake Concertina Locomotion

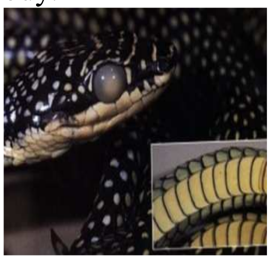


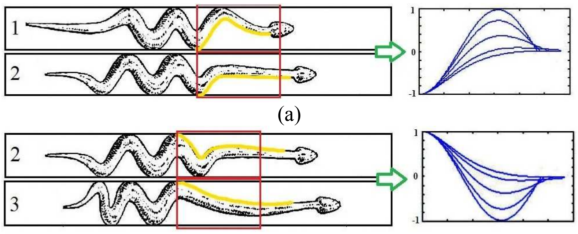
Fig. 2. Scales covered the snake body

Forward motion occurs because of the passive action of the ventral scales. The posterior edges of the scales cause the static resistance due to backward motion. This resistance is four or five times greater than the resistance due to forward motion [10]. As shown in Fig. 2, the directions of the scales are so that snake moving forward will face less friction than moving backward. Jayne claims that Concertina is seven times less efficient when compared to other kinds of locomotion used by real snakes [11]. However, snakes use Concertina only when other options of locomotion are ineffective such as traversing tight spaces with high friction. Due to momentum changes, static friction, and slower speeds, Concertina is a relatively inefficient mode of locomotion [12]. However, Concertina allows motion not otherwise possible, such as moving along wires and cables as well as through tree branches.

A Novel Curve Fitting to Snake body shape

Because the snake body is string like, it can be likened to a curve. The curve attributed to the snake body is called body curve. The spine of the snake is along the body curve. Therefore, links of a snake-like robot that imitate the movement of a real snake should fit the body curve. In this section, for the first time, Concertina curve is defined and explained. To do this, the snake body curve is assumed to include several modules. A simple dynamic curve will be fitted to each module.

Consider snake moving in Concertina locomotion as shown in Fig. 1. This figure shows 5 stages of progression. The more details of progression from stage 1 to stage 3 are shown in Fig. 3. Consider a frame that encompasses part of a snake body. This frame is also shown in Fig 3. As shown in this Figure, a part of the snake body curve within the frame can be likened to the curve shown in diagram on the right side. As snake body changes from stage 1 to stage 2, the curves in the diagram on the right side also change. The two variations between snake body curve and the other curve are in accordance with each other. The two stages, 1 to 2 and 2 to 3 are repeated for the other parts of snake body. Therefore, the snake movement may be simulated using these curves. In following, we introduce a curve which allows modeling snake body Concertina locomotion. The Concertina curve is made by combining several curves, each called *dynamic curve*.



(b)

Fig. 3. Accordance snake body part to dynamic curve

Dynamic Curve

Equation for the dynamic curve representing any section of the Concertina curve, may be written as:

$$F_{concertina}(x) = \frac{e^{-\alpha x}}{\beta}\sin(\delta x + \theta) \quad (1)$$

$$\theta = \cos^{-1}\gamma, \alpha = \gamma\omega_n, \beta = \sqrt{1-\gamma^2}, \delta = \omega_n\sqrt{1-\gamma^2}$$

where $\gamma = [0,1]$. The dynamic curve for $\omega_n = 1$ and different values of γ is shown in Fig. 4.

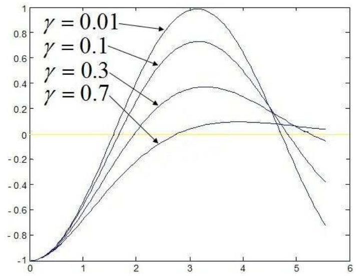


Fig. 4. Variation of dynamic curve

As can be seen from this figure, as parameter γ increases the high peak of the curve flattens and it seems like the curve is stretched. The stretched mode of the curve is similar to the case when the snake extends its body onward and thereby advances forward. When $\gamma = 1$, most stretching mode of the curve occurs. Referring to equation 1, when the value of γ move towards zero ($\gamma \to 0$), the curve obtained from dynamic function becomes similar to the Serpenoid sine curve. Serpenoid curve is known as the most similar curve to the snake body [8]. Thus far, only a section of a Concertina snake body curve is simulated by using the dynamic curve. In the following section, several combination of the dynamic curves is used to simulate the entire snake body curve, the Concertina curve

Composition of Dynamic Curves

Consider a snake moving in concertina locomotion as shown in Fig. 5. The developed concertina curve, made of connecting several dynamic curves, is also shown in this figure. As can be seen the developed concertina curve closely matches the real snake body curve. Next consider Fig. 6. To develop the Concertina curve, the snake body is divided into tail, body and head modules.

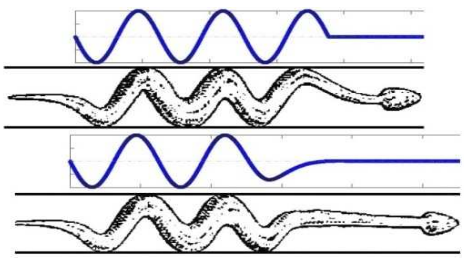


Fig. 5. Accordence of snake body curve to Concertina curve

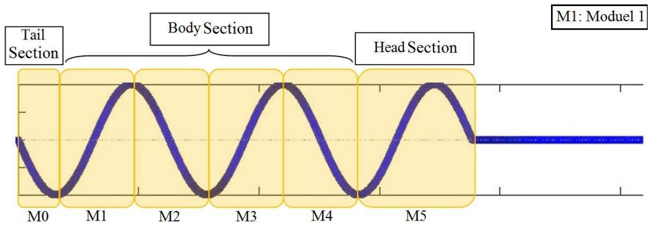


Fig. 6. Modules of concertina curve

A. Tail Section: The left segment of the snake body is called tail module. A simplified dynamic curve is used to represent the tail section. This function is presented by equation 2 as,

$$y_{Tail\,Module}(x) = -\sin(\omega_n x),\ where\ x \in [0, \frac{\pi}{2}]] \quad \& \quad \omega_n = 1 \tag{2}$$

To define a reference point, we designate point (0,0) as the start point for the tail section. Further the start configuration for the snake body is assumed to be in the contracted mode. This configuration represents the condition where snake will start stretching. Note that in this paper $\omega_n = 1$.

B. Body Section: The body section, connects tail section to head section. In this paper, the number of body modules that is considered four. If the modules were numbered from left to right, and the zero number is allocated to tail module, then the equation for each body module would be determined using equation 3 as,

$$\begin{aligned} & y^{(i)}_{Body\,Module}(x) = (-1)^{i+1} F_{Concertina}(x - x_{Body\,Module}) \\ & where \\ & i = The\,number\ assigned\ to\ body\ module \\ & i = 1,2,\ldots,N_B\ \ (N_B : Number\,of\,Body\,Modules) \\ & x^{i}_{Body\,Module} = (\frac{\pi}{2} + (i-1)\pi)/\omega_n \\ & x^{i}_{Body\,Module} \le x \le x^{i}_{Body\,Module} + \pi/\omega_n \end{aligned} \tag{3}$$

where $F_{Concertina}$ is defined by dynamic curve in equation 1. Also, for body section shown in Fig. 6, $\omega_n = 1$ and $\gamma = 0$.

C. Head Section: During the locomotion, the most forefront Concertina curve section is the head module. The curve of the head module is developed by equation 4.

$$\begin{aligned} & y_{Head\,Module}(x) = F_{Concertina}(x - x_{Head\,Module}) \\ & where \\ & x_{Head\,Module} \le x \le x_{Head\,Module} + \pi, \\ & x_{Head\,Module} = \frac{\pi}{2} + N_B \times \pi \end{aligned} \tag{4}$$

An appropriate dynamic curve for head module is a curve that its end always remains on line y=0, and this is matched with the curve of moving snake body. To keep fixed the end of head module on the line y=0, the equation 4 is changed as following equation,

$$\begin{aligned} & y_{Head\,Module}(x) = \begin{cases} F_{Concertina}(x - x_{Head\,Module}), & x_{Head\,Module} \le x \le x' \\ 0, & x' \le x \end{cases} \\ & where,\ x_{Head\,Module} = (\frac{\pi}{2} + N_B \times \pi)/\omega_n \ \ \& \\ & x' = \frac{(N_C\pi - \theta)}{\omega_n\sqrt{1-\gamma^2}} + x_{Head\,Module} \\ & N_C = 2, (N_C : Intersection\,Number) \end{aligned} \tag{5}$$

In this change, the output of head module for values greater than x' is considered zero. Now the important point is to find a suitable point for x'. To find the most appropriate point of x', the behavior of dynamic curve should be examined. In Fig. 7 the dynamic curve is plotted for different values of γ in interval [0,10]. In this Figure it is observed that the dynamic curve for different values of γ will have intersect by line y=0 in different points. The place of intersections are obtained by equalizing the dynamic function to zero, equation 6.

$$F_{Concertina}(x) = \frac{e^{-\alpha x}}{\beta}\sin(\delta x + \theta) = 0 \rightarrow \delta x + \theta = N_C \pi$$
$$\rightarrow x = \frac{N_C \pi - \theta}{\omega_n \sqrt{1-\gamma^2}}, \ where$$
$$N_C = Intersection\ Number$$
$$\theta = \cos^{-1}\gamma, \alpha = \gamma\omega_n, \beta = \sqrt{1-\gamma^2}, \ \delta = \omega_n \sqrt{1-\gamma^2} \tag{6}$$

Regarding the snake body in Concertina locomotion, we consider the second intersection point of each curve with line y=0 as candidate for x'. Also, the vertical lines passing the points $x'(\gamma)$ is shown in Fig. 7. When the value of γ move toward one, the intersection of the dynamic curve with y=0 is placed in the infinity ($x' \rightarrow \infty$). So Concertina curve instead of being on the straight line of y=0, will place in asymptotic mode to y=0, it is demonstrated in Fig. 8. In this case, the robot links that are fit to Concertina curve will be out of the straight line. It will exert high torque on the robot links. To solve this problem, the interval of the γ variations can be limited. In this case, we change the maximum limit of the changes from 1 to γ_{Ext}. In this paper $\gamma_{Ext} = 0.8$. Hereafter the parameter γ will change only in $[0, \gamma_{Ext}]$.

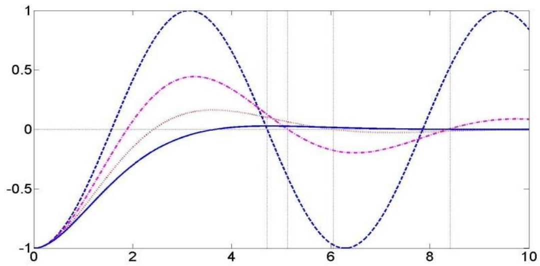


Fig. 7. Finding second intersection of dynamic curve to y=0

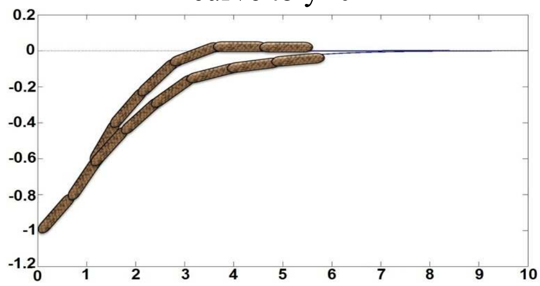


Fig. 8. In $\gamma = 1$ links do not place on y=0

Extention & Contraction of body

Thus far, the snake body curve in Concertina locomotion has been developed from combination of the tail, body and head modules. In following the way that modules change during Concertina locomotion will be explained.

Stretching of The Snake Body Curve

To model the Concertina locomotion, at first the head module should be stretched. Since all curve modules is made of dynamic function, by change of parameter γ from the value of 0 to γ_{Ext}, each module can be stretched. According to the number of modules types, the stages of stretching can be divided into three stages:

First stage (stretching of the head module): by change of parameter $\gamma : 0 \rightarrow \gamma_{Ext}$, the head module will stretched in the interval $x_{Head\ Module} \le x \le x'$. This stretching occurs while the other modules are fixed, Fig. 9.

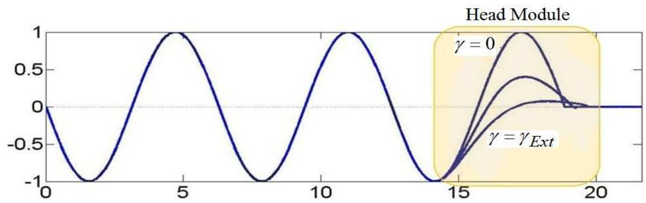


Fig. 9. Gradual stretching head module

Second stage (stretching of the body modules): similar to the stretching of the head module, by change of parameter $\gamma : 0 \rightarrow \gamma_{Ext}$, each one of the body modules will stretched in the interval $x^{i}_{Body\,Module} \le x \le x^{i}_{Body\,Module} + \pi$. To make coordination between stretching and full stretched modules (for example, as shown in Fig. 10, module 4 is stretching and module 5 is full stretched), the total value of full stretched module is multiplied in the value of stretching module in the junction of two modules (x_j).

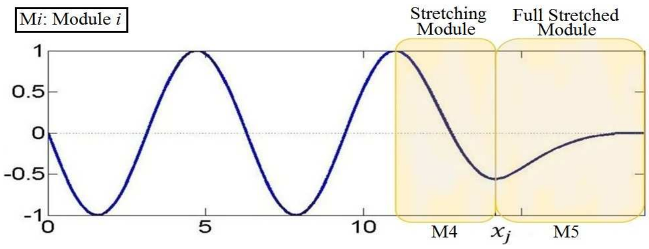


Fig. 10. Effect of active module on extended module

When the stretching module is completely stretched, its definition range will change from $x_{Body\,Module} \le x \le x_{Body\,Module} + \pi$ to $x_{Body\,Module} \le x \le \infty$.

Third stage (stretching of the tail module): after the complete stretching of all body modules and head module, by multiplying the numbers smaller than one, in tail module function, the high peak of the tail module curve will gradually flatten. With stretching of the tail module, snake body curve will stretch completely on the y=0 line.

Contraction of The Snake Body Curve

When the snake stretch its body enough, with anchoring of the head section, it pulls forward the rest of its body and contracts the body in front. By doing this it prepares its body for another kinematic cycle. Reverse of implemented stages to stretch Concertina curve would result the contraction of this curve.

Making More Natural of Locomotion Modeling

The snake gaits as a part of nature, is the result of long-term optimization of nature on the snake. Thus, more the modeling is close to the snake locomotion more it can be optimized. To model more natural Concertina locomotion, two terms are recommended:

A. Synchronicity of activity of two connected modules: Fig. 11 shows some stages of Concertina locomotion. It is observed that two elbow shapes in the snake body, stretch simultaneously. In fact, before the full stretching of an elbow, the next elbow begins to stretch, then for some moments both elbows are active simultaneously.

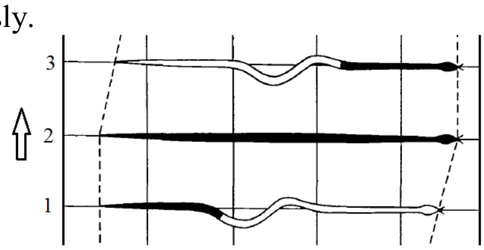


Fig.11. Simultaneity of two active module in snake

B. The simultaneity of stretching stages with contraction stages: If concertina locomotion occurs in a tunnel, when the snake body is still in contact with the tunnel walls, it should contact its stretched parts, with the tunnel wall so that it can move forward (or up) the end part of its body by creating an anchor. Therefore, it is better during stretching stage the contraction stage start simultaneously. To implement the mentioned problem, the Cooperation Number (CN) is defined as follows:

Suppose for Concertina curve, CN = 3. Then if three modules of the total number of Concertina curve modules stretch, the contraction stage would begin. Thus, the contraction and stretching stages will be done simultaneously. So if the total number of modules is 6 and CN = 6, then during a cycle, Concertina curve stretches completely. After the full stretching stage, contraction stage begins.

Kinematic

So far we have been able to present a new curve for modeling Concertina locomotion. But for creating Concertina locomotion by the snake robot which is made of some successive links, the angle of each link should be specified. In following, how to calculate the angle of robot links based on Concertina curve will be explained [9]. To fit the first link to the curve, we start at the beginning of the curve and draw a circle having a radius equal to the length of link. See Fig. 12. The center and the intersection of the circle with the body curve determine begging and end of the first link, respectively. Similarly, center of the next circle is placed at end of the first link and circle is drawn. This identifies begging and ends of the second link. The process is repeated for the remaining links. In this paper, we used the Secant method [10] to obtain the intersection of the circles with the body curve. Upon calculation of all absolute angles, the Five-Point Formula [10] is used to obtain corresponding angle velocity and acceleration.

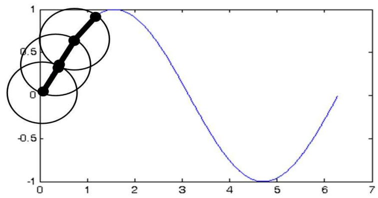


Fig. 12. Fitting snake robot links to body curve

Simulation

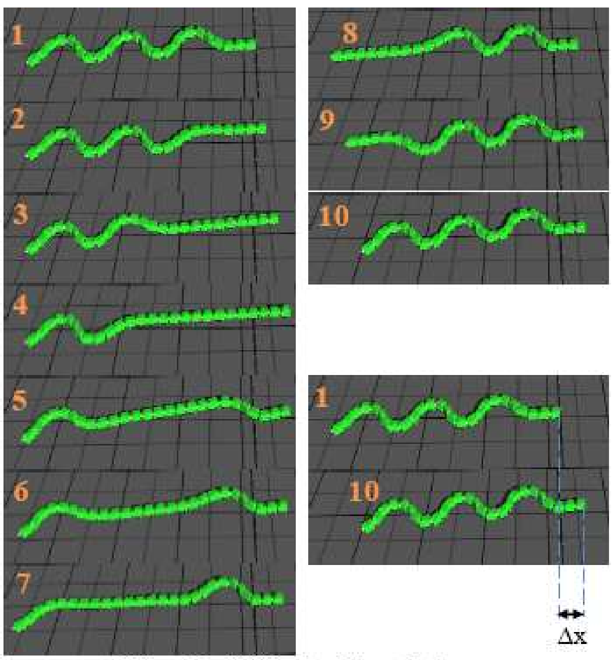


Fig. 13. Webots Simulstion

In this paper Webots^{TM} software is used for simulation. By using the method described in the previous sections, the absolute angles of a Concertina locomotion robot with 26 links are given as the input of a simulated snake-like robot by Webhost software. Results indicate Concertina locomotion can be obtained. Snap shots of simulated snake robot in Concertina locomotion is shown in Figure 13.

Conclusion

In this paper, for the first time, a novel method for kinematics modeling of Concertina locomotion which is very similar to Concertina locomotion of real snake is presented. To simulate this, we first introduce a mathematical equation, called dynamic function, in which by varying a certain function parameter, body curve in every moment of motion is realized. To obtain Concertina gait, we divide the snake body into three different modules, head module, tail module and main body module that connects the head to the tail module. Each module forms a specific curve which can be modeled using the proposed dynamic function. At each moment during snake locomtion, the kinematics of different links can be derived by fitting links to the body curve. Finally Concertina locomotion is simulated using Webot software. Results indicate concertina locomotion can be obtained. This works represents a first approach to a simulation of a snake-like mechanism in order to get basic characteristics of a such locomotion and to enable our future research.

References

[1] J. Gray, The Mechanism of Locomotion in Snakes. JOURNAL OF EXPERIMENTAL BIOLOGY, 1946. 23: p. No.2.

[2] Hirose, S., Biologically Inspired Robots (Snake-like Locomotor and Manipulator). 1993: Oxford University Press.

[3] Walter, M., On the Locomotion of Snakes. Science, 1932.

[4] Gans, C., Terrestrial Locomotion without Limbs. American Zoologist, 1962.

[5] B.R. Moon, C.G., Journal of Experimental Biology. Muscular Activity and Propulsion in Gopher Snakes, 1998.

[6] Bernhard Klaassen, K.L.P., GMD-SNAKE2: A Snake-Like Robot Driven by Wheels and a Method for Motion Control. Proceedings of the 1999 IEEE International Conference on Robotics & Automation Detroit, 1999.

[7] M. Saito , M.F., T. Iwasaki, Serpentine Locomotion with Robotic Snakes. IEEE Control Systems Magazine, 2002: p. 64-8.

[8] Shahir Hasanzadeh, A.A.T., Ground adaptive and optimized locomotion of snake robot moving with a novel gait. Auton Robot, 2010. 28 p. 457–470.

[9] D. Kornack and P. Rakic, “Cell Proliferation without Neurogenesis in Adult Primate Neocortex,” Science, vol. 294, Dec. 2001, pp. 2127-2130, doi:10.1126/science.1065467.

[10] J. Safehian, H.K., A. Akbarzadeh, Proceedings of the , , A Novel Kinematics Modeling Method for Snake Robot in Travelling Locomotion, in 10th Biennial Conference on Engineering Systems Design and Control, ASME, Editor. 2010: Turkey.

[11] Jayne, B.C., Kinematics of terrestrial snake locomotion. Copeia, 1986: p. 915–927.

[12] M. Walton, B.C.J., A.F. Bennett, The Energetic Cost of Limbless Locomotion. Science, 1990.

[13] Dowling, K., Limbless locomotion: learning to crawl with a snake robot, in Robotics Institute. 1997, Carnegie Mellon University: Pittsburg

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