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Investigation of a Novel Type of Locomotion for a Snake Robot Suited for Narrow Spaces

M. Watanabe, M.R. Khan

Department of Mechatronics Engineering, Faculty of Engineering
International Islamic University Malaysia, Jalan Gombak, 53100 Kuala Lumpur, Malaysia
mluqmanw@yahoo.com, raisuddin@iiu.edu.my

ABSTRACT

In snake robot research, one of the most efficient forms of locomotion is the lateral undulation. However, lateral undulation, also known as serpentine locomotion, is ill-suited for narrow spaces, as the body of the snake must assume a certain amount of curvature to propel forward. Other types of motion such as the concertina or rectilinear may be suitable for narrow spaces, but is highly inefficient if the same type of locomotion is used even in open spaces. Though snakes naturally can interchange between the use of serpentine and concertina movement depending on the environment, snake robots based on lateral undulation to date are unable to function satisfactorily in narrow spaces. In undergoing concertina movement, the snake lifts part of its body off the ground to reduce friction; this cannot be reproduced in planar snake robots. To overcome the inability to adapt to narrow spaces, a novel type of a gait is introduced. With slight modifications to the members of the multi-link snake robot, the robot normally developed for lateral undulation is able to utilize the new gait to negotiate narrow spaces. The modifications include alterations to the snake segments as well elements that mimic scales on the underside of the snake body. Scales, often overlooked in locomotion research, play an important role in snake movement by increasing backward and lateral friction while minimizing it in forward direction. This concept provides the basis for movement in the proposed gait. Through kinematic studies the viability of this gait is illustrated.

1. INTRODUCTION

Having developed the active chord mechanism to model the movement of lateral undulation [1], Hirose went on to conduct further research on the same type of locomotion [2,3,4]. Numerous studies based on Hirose's work have also cropped up during the years. Initially Hirose used passive wheels on his snake robots, and Saito's research [5] looked as achieving the same locomotion without any such wheels, with the body of the robot in direct contact with the ground. Other variations include the application of the same type of locomotion to different surfaces such as a sloped surface [6] or uneven surfaces [7]. In recent years, Hirose teamed up with other Japanese researchers to develop a 3-D version his active chord mechanism [8]. However, all these works are principally based on one type of locomotion: lateral undulation.

This is not to say that other modes of locomotion have not been studied. Many years back, Burdick developed a model for the sidewinding movement [9], while somewhat more in the recent past a robot was developed based on rectilinear motion [10]. Even different gaits not found in natural snakes have been examined by the likes of Chen [11], where a movement known as lateral rolling is studied. Interestingly enough, studies on concertina locomotion is surprisingly absent.

Coming back to the application of snake movements, the advantages of the serpentine movement has been abundantly demonstrated. The movement is efficient and can be utilized in various environments. There is, however, a limitation. As Hirose evaluated, the snake is only able to propel forward when it assumes the serpenoid curve. Unlike a simple sinusoidal curve, the curvature of this curve changes sinusoidally over its length. Thus if the snake is to travel along a certain axis, then it must displace its body both above and below this axis to form the curve. The problem arises here, if the minimum perpendicular displacement is not maintained, the snake will not move forward. Even with the increase of links, the minimum perpendicular displacement will be much greater than the width of the body.

The immediate approach to solving the issue of narrow space may be to use a different type of locomotion. Two possible candidates come forth, the rectilinear and the concertina, since sidewinding also requires the body to undergo a curve of even greater amplitude. The movement of lateral undulation and rectilinear motion are completely different, and it would be unwise to try and implement both sets of movement in one robot. The concertina too has issues when considered in practical terms. Sinus-lifting is used in this type of motion, which means the robot must lift part of its body above the ground. To bypass this vertical degree of freedom, perhaps mechanisms could be added where friction could be controlled. Though it may be possible to design such a structure, it would hamper the ability of the robot to undertake lateral undulation. A robot developed exclusively for concertina motion would end up being highly inefficient in environs where space is not an issue.

To overcome this conflict between the mechanics of concertina and lateral undulation, a completely different type of locomotion is introduced. The directional friction element of the snake is in fact provided by the scales on the underside of the body. The scales are arranged in a manner such that friction in low in the forward direction while high in reverse and lateral directions. This is achieved by the scales effectively digging into the ground. Using this idea and adding additional elements to the generic design of the serpentine robot, a strategy for a novel type of locomotion is proposed. The strategy is evaluated through kinematic studies, and its viability supported.

2. STRUCTURE OF THE SNAKE SEGMENT

The proposed structure is based on links which have cross-members. Each link is designed in the shape of cross with its vertical member having the same dimensions at the horizontal member, and intersecting at the midpoints of both. In the figure below a five-link structure is exemplified.

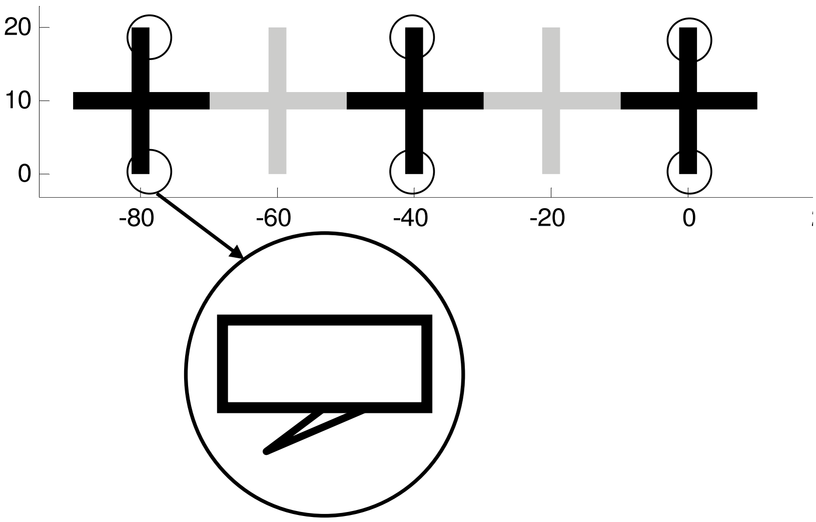

Fig. 1. Top view of the five-link model with an enlarged side view of the frictional elements

The circles in the diagram represent the ends of the cross-members where the directional friction elements are added. Much like the scale this addition at the underside of the designated end of these members will result in low friction in the forward motion and high friction in other directions. One way this could be achieved would be fixing a sharp nail-like object with its pointed end sticking out at an angle. If it is attached at an incline with the pointed end heading backwards, this end could move forward without generating the "digging in" effect, while in the backward direction this effect would be great. In the lateral directions too, though not as great as in backward, the pointed object would tend to restrain movement. Another important factor is that these nail-like protrusions are added only to alternating links. In the above illustration this is indicated by the difference in shade: black representing the links with frictional elements and gray without.

3. THE INVERSE KINEMATICS

In ascertaining the inverse kinematics, the first three links are considered as in the figure below. Let point (a, b) denote the position of the bottom end of the cross-member of the first link, (d, e) the position of its counterpart on Link 3, and (h, k) the position of the joint between Link 1 and 2. If actuated in the right direction, both the frictional elements at (a, b) and (d, e) will dig into the ground and the respective link will experience a moment about that point, hence rotating with those points as the centers. The horizontal length of each member is $2l$ and the vertical width $2w$. And since $w = l$, the two can be used interchangeably. The dimension r therefore denotes the base of the isosceles triangle with sides w and l. And φ denotes the angle between the x-axis and the line connecting points (a, b) and (h, k).

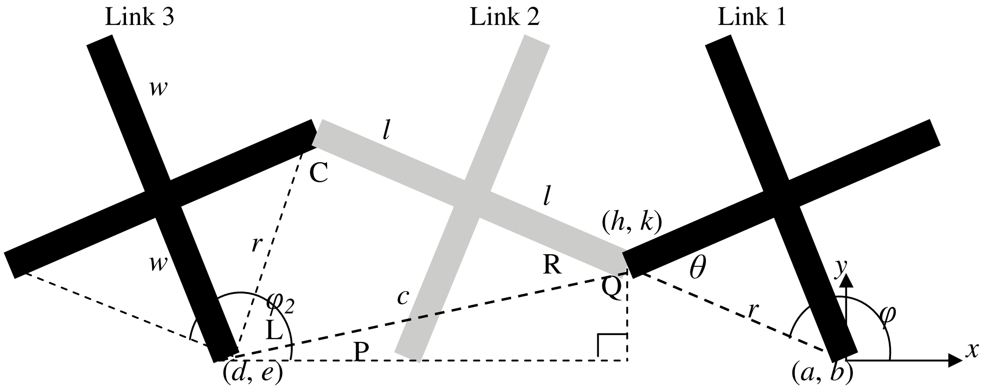

Fig. 2. Graphical approach to solving the inverse kinematics

The coordinates of (h, k) would therefore be

$$\left(r\cos\varphi + a, r\sin\varphi + b\right)$$

The length of segment c connecting (d, e) and (h, k) would be given by the expression

$$c = \sqrt{(h-d)^2 + (k-e)^2}$$

Using the cosine rule on the triangle formed between the points (d, e), (h, k), and the joint between Link 2 and 3, the three angles R, C, and L can be determined as

$$R = \cos^{-1}\left(\frac{4l^2 + c^2 - r^2}{4lc}\right)$$

$$C = \cos^{-1}\left(\frac{4l^2 + r^2 - c^2}{4lr}\right)$$

$$L = \cos^{-1}\left(\frac{r^2 + c^2 - 4l^2}{2rc}\right)$$

Drawing a right triangle with its hypotenuse as segment c, two more angles are obtained:

$$Q = \tan^{-1}\left(\frac{h-d}{k-e}\right)$$

$$P = \tan^{-1}\left(\frac{k-e}{h-d}\right)$$

From all this, θ, the angle between the lengthwise members of Link 1 and 2, is evaluated as

$$\theta = \left(\varphi + R + Q - \frac{5\pi}{4}\right)$$

Similarly, φ_2, the Link 3 equivalent to the angle φ for Link 1, is

$$\varphi_2 = \left(L + P + \frac{\pi}{2} \right)$$

The angles for the following links can then be calculated using the same method on φ_2 as was illustrated here with φ. Thus from the first angle φ, all other positions and angles between links can be determined. However, this still constitutes as inverse kinematics, since the angle that is actuated in the model is θ, and the resulting configuration and position of the structure is denoted by φ. Thus to anticipate the position of the members from the actuated angle θ, a forward kinematics needs to be developed. However, though the forward kinematics is not readily apparent, the maximum angle for θ is evident. For the links to avoid singular positions and keep moving forward, at maximum deflection, the segment *r* of Link 1 must be in line with, i.e. parallel to, the lengthwise member 2*l* of Link 2. Keeping this in mind, it becomes clear that the range is

$$-\frac{\pi}{4} \le \theta \le \frac{\pi}{4} \tag{1}$$

4. THE FORWARD KINEMATICS

As is apparent from the above the variable φ is embedded deep into the equation. It appears in three separate places each time within an inverse trigonometric expression. To arrive at an expression with φ as a function of θ requires one to solve six quadratic equations simultaneously using a method involving resultants of polynomials. However, when the two variables are plotted on a graph within the range stated in (1), the curve does not appear too problematic. Thus, using regression techniques, a six-order polynomial equation is developed to estimate the relationship between the two variables.

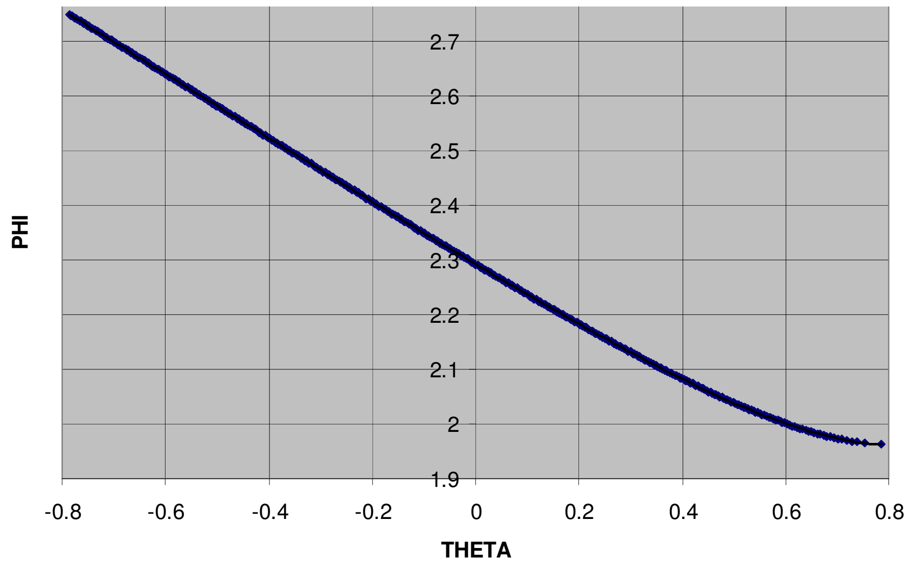

Figure 3: Estimating the curve from the φ vs. θ graph

The forward kinematics is thus estimated as

$$\theta = 0.065\varphi^6 + 0.0708\varphi^5 + 0.0302\varphi^4 + 0.0537\varphi^3 + 0.059\varphi^2 - 0.5613\varphi + 2.2924$$

Over the range mentioned in (1), this approximation has a maximum error of 0.08% and an average error of 0.004%.

5. IMPLEMENTING THE NOVEL GAIT

Given the kinematics, the control algorithm for the joint actuators may be developed to push the robot forward. In this first example only the first two joints are actuated to achieve motion.

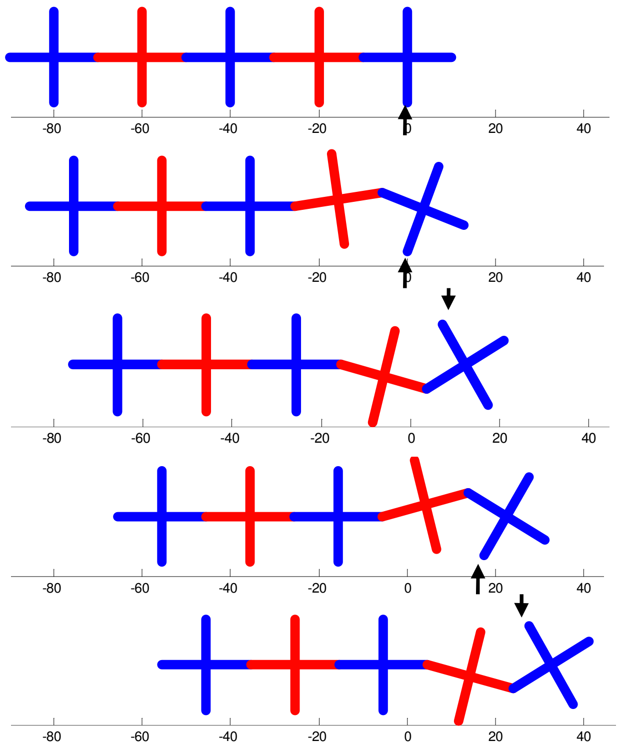

Fig. 4. The first example of the novel gait

As displayed in the figure above, actuating the first joint creates a moment on the first link. This moment then translates into the ends of the cross-members, and the side that tends to move backwards would "dig in" and thus the whole link would rotate about that point. In the diagram, the "dug in" ends are marked with arrows. The joint between Link 2 and 3 is actuated in the opposite direction so as to neutralize the effect of the moment on Link 3 from Link 1. The positions of the angles are also coordinated such that Links 3, 4, and 5 remain in line and only move forward along the axis of the lengthwise members.

The movement is clearly a stop-and-go movement, and not continuous nor as efficient as the serpentine locomotion. Nevertheless, even the concertina is stop-and-go, and as for narrow spaces, this gait hardly occupies more space then the width of its body. The above gait presents a few drawbacks, however. The entire movement rests on the action of only two actuators. Perhaps for a five-link robot the load may be bearable, but as the number of links increases, two actuators would not be able to carry the load and move forward.

5.1 ALL JOINTS IN MOTION

For this gait to be viable, all actuators must contribute to the forward movement. The same type of movement as the above is implemented here but repeated with all links. As is apparent from the first two links in the simpler version, the first joint traverses the full range of motion, while the second joint does not. To achieve maximum forward displacement on each thrust it would be wise to actuate the joints through its full range. Thus, the robot does not begin with a linear configuration, but rather in an oblique zigzag formation where the joint angles begin at their maximum or minimum values.

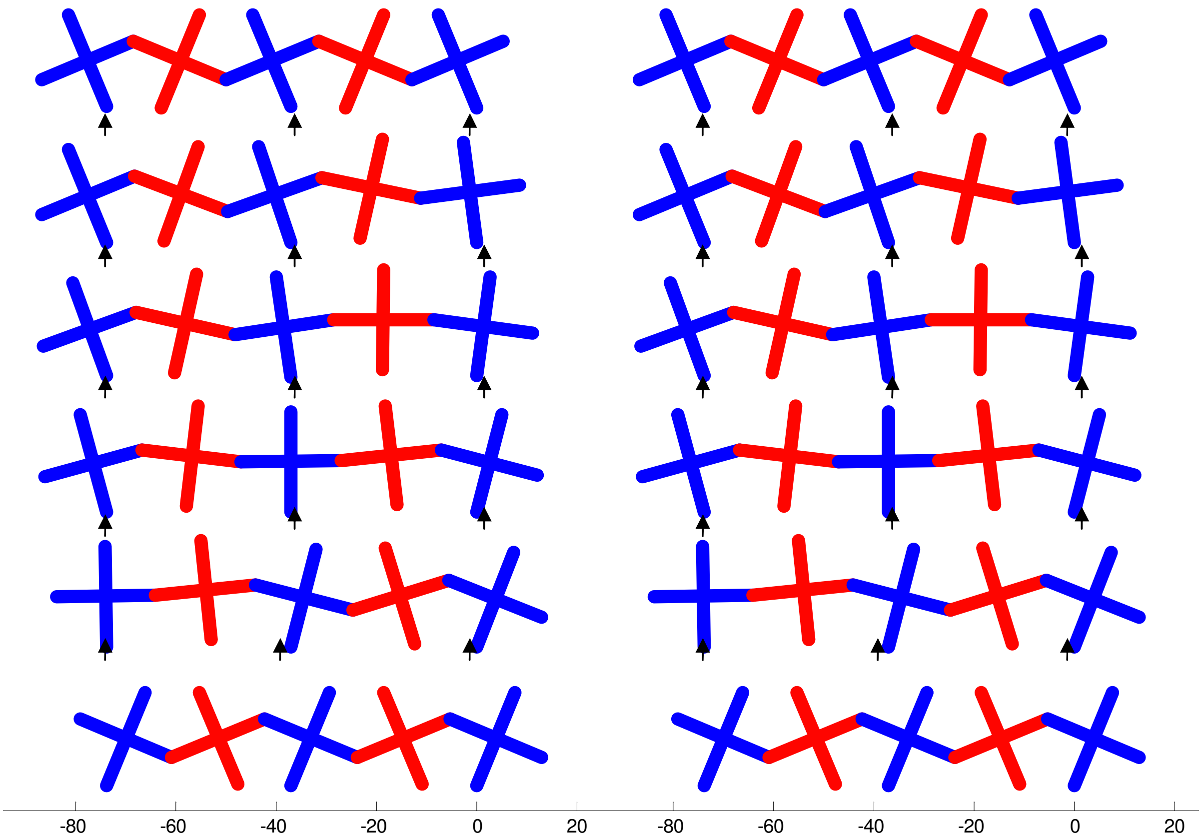

Fig. 5. The novel gait with arrows pointed to ends that have "dug in"

Again, the correct direction of actuation on the joints would produce a moment allowing the nail-like protrusions to "dig in." As this occurs, the links would rotate about their respective centers. However, the links will not rotate at the same speeds. Due to geometrical constraints, the latter links can only begin to turn after the earlier leading links have started to undergo rotation. The leading first link will be the quickest to start the rotating process, and slow down as it reaches the end of its range, while the latter links will start off slow and speed up as it approaches its final position. The position and speed of the changing joint angles are plotted against the constant change in the base angle φ.

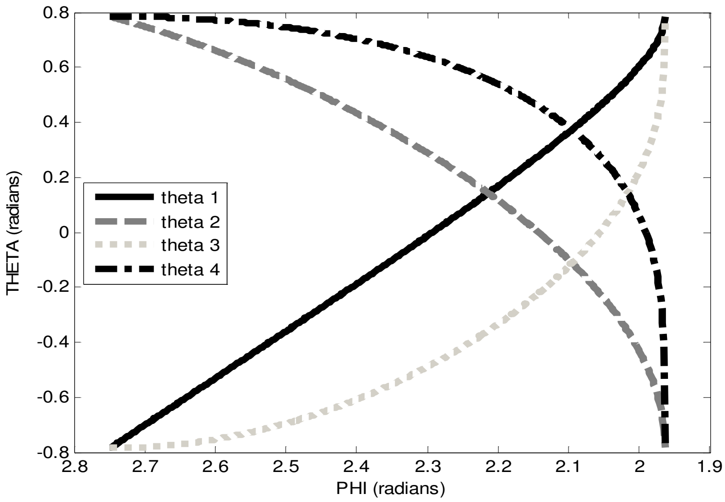

Fig. 6: Difference in movements of the joint angles

As these are the initial kinematic investigations, dynamic analysis is yet to be conducted, and hence φ is assumed as decreasing at a constant rate. Clearly this may not be the case when conducting dynamic analysis since the speed would depend on the maximum actuator speed achievable, and even then each of the joint actuators would be achieving maximum speeds at different times. In fact, other motors would have to slow down to coordinate its movement with the fastest moving motor at that instance in time. The graph may be misleading, and thus it is important to note that the x-axis does not represent time but simply a correlation to the controlling angle φ. Hence, the slope of the graph does not represent angular velocity which may appear to incorrectly approach infinity. What can be deduced from the graph, then, is the fact that each angle is at a different position as the robot moves forward. This graph shows the kinematics of the structure, i.e. the exact angles that the four joints must assume to produce the desired angle φ.

6. CONCLUSION

Kinematic investigations have shown that this "wriggler" gait is theoretically feasible. Strategies for forward motion have been corroborated, and the joint angles for each step along the process have been determined. It has been shown kinematically that the desired locomotion can be achieved thorough the computed joint angles.

7. FUTURE WORKS

The kinematic solution must be supported by dynamic analysis, and hence this must be added in further investigations. Moreover, even after the completion of dynamic analysis, the strategy must be tested on a prototype to evaluate its practical applicability.

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