Development of a Novel Locomotion Algorithm for Snake Robot

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Abstract. A novel algorithm for snake robot locomotion is developed and analyzed in this paper. Serpentine is one of the renowned locomotion for snake robot in disaster recovery mission to overcome narrow space navigation. Several locomotion for snake navigation, such as 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 resulting friction reduction which make difficulties for snake movement. A novel locomotion algorithm has been proposed based on the modification of the multi-link snake robot, the modifications include alterations to the snake segments as well elements that mimic scales on the underside of the snake body. Snake robot can be able to navigate in the narrow space using this developed locomotion algorithm. The developed algorithm surmount the others locomotion limitation in narrow space navigation.

1. Introduction

The calamitous earthquake (Sendai Earthquake) that ruined chaos Japan in 2011, tsunami hit Indonesia several times in 2012 and the terrorist attacks on the World Trade Centers in 2001 are clear sign that we are not prepared for disaster recovery at all. In all cases the infrastructure could not withstand the fury of nature, even in the case of WTC the NYPD was not prepared for such gigantic task of disaster recovery. The conventional reaction to such disaster is not adequate; a new paradigm shift is needed to address such calamities utilizing all resources at hand. Disaster recovery is defined to be the emergency response function which deals with the collapse of manmade structures. In any disaster either man made or due to Mother nature, the elementary tasks at hand are: (i) reach the affected hazardous field (ii) find and get information about victims, and (iii) rescue as many of them as possible. It is possible for robot to reach any hazardous field unlike who have limited mobility in such missions. Nowadays legged and wheeled robots are involved in such mission, but limbless robot like snake robot bring a great advantages to overcome navigation over the very narrow space in disaster area. Few researches have been conducted on snake robot locomotion unlike narrow space consideration [1-5]. 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].

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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 side-winding 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 the limitations of serpenoid motion, a completely different type of locomotion is introduced in this paper [12]. 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 is low in the forward direction while high in reverse and lateral directions. 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 kinematics and kinetics studies.

2. Materials And Method

2.1. Snake Robot Mechanism

In Fig. 1 mechanical skeleton of a conceived snake robot is shown where each link consists of a solid cross. The legs of the cross, connected in a chain fashion are called centre legs, while the other legs are called transverse legs. Edges of the alternate transverse legs have got snake scale like protrusions that give low frictional resistance during forward motion and high resistance during backward motion. In figure 1 link 1, 3 have got such snake scales. Link 2 acts as a connector between the alternate links with scales. The transverse legs of link 2 are used to make the link symmetric and to reduce complexity of calculating its mass moments of inertia.

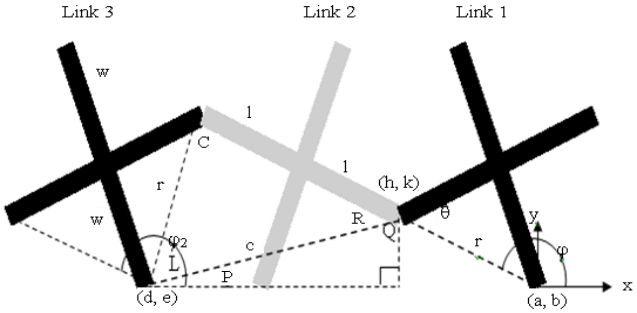

Figure 1. Figure with Coordinate System for a Five-Link snake Structure

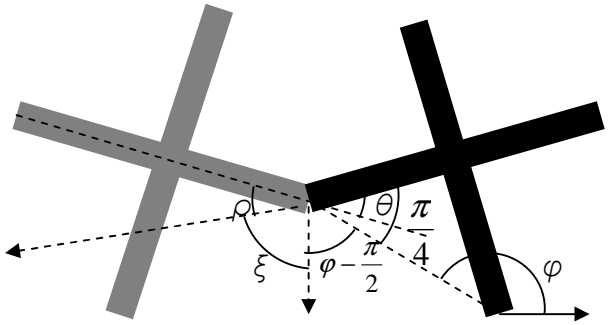

Figure 2. Exaggerated view of a general geometry at a joint

2.2. Kinematics for snake robot with scales underneath

In Fig.1, Link 1 and Link 3 rotate in arcs about point (a, b) and (h, k) respectively. Link 2 on the other hand does not move in a defined arc about a fixed point, and hence must be free to move. To facilitate this unimpeded movement, no frictional appendages are added.

Moving on with the kinematics, following the geometric relations in Figure 1, the coordinates of (h, k) would be

$$\left(r\cos\varphi + a, r\sin\varphi + b\right) \tag{1}$$

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

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

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 ρ, γ, and λ can be determined as

$$\rho = \cos^{-1}\left(\frac{4l^2 + c^2 - r^2}{4lc}\right) \tag{3}$$

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

$$\lambda = \cos^{-1}\left(\frac{r^2 + c^2 - 4l^2}{2rc}\right) \tag{5}$$

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

$$\xi = \tan^{-1}\left(\frac{h-d}{k-e}\right) \tag{6}$$

$$\psi = \tan^{-1}\left(\frac{k-e}{h-d}\right) \tag{7}$$

From all this, θ, the angle between the extension of the lengthwise axis of Link 1 and the central member of Link 2, is therefore evaluated by adding the angles concentric to point (h,k). It would be important to note that though this angle appears to simply be $\frac{\pi}{4}$ in the initial configuration, as Link 1 rotates about (a,b) in the clockwise direction.

Angle θ can then be evaluated by adding the following angles:

$$\rho + \xi + \left(\varphi - \frac{\pi}{2}\right) + \frac{\pi}{4} \tag{8}$$

and then subtracting π from the result

$$\rho + \xi + \left(\varphi - \frac{\pi}{2}\right) + \frac{\pi}{4} - \pi = \theta \tag{9}$$

Which rearranged would give the final equation of

$$\theta = \varphi + \rho + \xi - \frac{5\pi}{4} \tag{10}$$

Similarly, referring back to Figure 1, φ2, the Link 3 equivalent to the angle φ for Link 1, is

$$\varphi_2 = \lambda + \psi + \frac{\pi}{2} \tag{11}$$

The angles for 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. As mentioned earlier, 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 2l of Link 2. Keeping this in mind, it becomes clear that the range is

$$-\frac{\pi}{4} \le \theta \le \frac{\pi}{4} \tag{12}$$

2.3. Tables for Actuators value calculated from equations

Table I lists the necessary angles that need to be tracked. The table really consists of six rows as the seventh row is just a repeat of row one. What are deducible from the table are the varied differences in angles from one row to the next. Take the difference from row one to two for example: θ_1 has increased by 42° while θ_4 decreases by only 7°. All the angles in each row must be met before continuing on to the next row, and the angles must traverse their respective displacements and arrive at the next configuration at the same time. Thus, in the example, θ_1 must deflect 42° in the same amount of time θ_4 moves just 7°. It becomes clear that the speeds of the servo motors must also be controlled.

Table 1. Angular positions for gait sequence

Sequence Number	θ_1 (°)	θ_2 (°)	θ_3 (°)	θ_4 (°)
1	-45	45	-45	45

2	-3	19	-30	38
3	35	-25	13	3
4	45	-45	45	-45
5	1	-17	28	-37
6	-36	27	-16	0
7	-45	45	-45	45

For the purpose of controlling the servo motors using the microcontroller, rather than building the board and interface in the lab, a servo controller board as well as a microcontroller interface is procured from the same source as the servo motors themselves. The servo controller is able to control both position and speed, and uses values from 0 to 1454 to control the position which spans a range of 180°, and uses values of 0 to 63 for the speed, where 63 is the maximum controlled speed, and 1 is the slowest speed achievable. Using both the data sheet provided by the source as well as experimental data taken from the completed prototype, the following conversion tables are deduced (table 2 and table 3).

Table 2. Simple conversion table for servo motor position

Angular Displacement (°)	Controller Value
-45	420
0	811
45	1202

Table 3. Conversion table for angular velocity of servo motor

Angular Velocity ($°s^{-1}$)	2	13	26	43	50	64	82	95
Controller Value	1	10	20	30	40	50	60	63

For both the conversion tables, all the middle values are determined through linear interpolation. One of the necessary preparations is that of controlling the speed, as mentioned earlier the structure is required to traverse each sequence in the same amount of time. Thus, firstly the differences in angular displacement from the first position to the next must be determined. Applying this to table 1 the results obtained are shown in table 4:

Table 4. Angular displacement from one row to the next

Difference	θ_1 (°)	θ_2 (°)	θ_3 (°)	θ_4 (°)
From Row 1 to 2	42	-26	15	-7
From Row 2 to 3	38	-44	43	-35
From Row 3 to 4	10	-20	32	-48
From Row 4	-44	28	-17	8

to 5				
From Row 5 to 6	-37	44	-44	37
From Row 6 to 7	-9	18	-29	45

From each row of the table above, then, the maximum absolute value is identified, which in the case of "From Row 1 to 2" would be 42°, and in the case of "From Row 4 to 5" this is 44°. This maximum absolute value is then assigned the maximum velocity of $95°s^{-1}$. The other values in the same row are assigned proportionally slower velocities such that if those very displacements are traversed according to the assigned speeds then all the angles would arrive at their respective positions in the same amount of time.

Continuing with the example from the first row, since 26° is 1.62 times smaller than the maximum of 42°, its speed would also be 1.62 times slower at $59°s^{-1}$. The corresponding speeds can then be expressed as shown in table 5:

Table 5. Associated angular velocities for the sequence

Sequence Number	Angular Velocity ($°s^{-1}$)			
	θ_1	θ_2	θ_3	θ_4
1	95	59	34	16
2	82	95	93	76
3	20	40	63	95
4	95	60	37	17
5	80	95	95	80
6	19	38	61	95

3. Results and Discussions

As displayed in the figure 4 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.

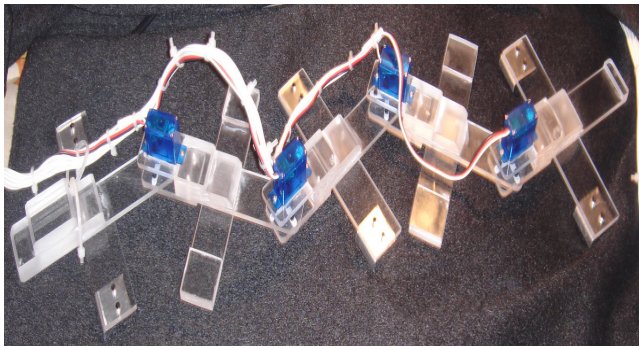

Figure 4. Snake robot navigation (top view)

4. Conclusion

A novel gait for snake robots with scales underneath has been successfully implemented using stand alone hardware. This algorithm requires less transverse movement of the snake body compared to the traditional algorithms based on serpenoid curve. Traversing narrow spaces would be possible for snake robots using this new gait.

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