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Dynamic Analyze of Snake Robot

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***Abstract*—**Crawling movement as a motive mode seen in nature of some animals such as snakes possesses a specific syntactic and dynamic analysis. Serpentine robot designed by inspiration from nature and snake's crawling motion, is regarded as a crawling robot. In this paper, a serpentine robot with spiral motion model will be analyzed. The purpose of this analysis is to calculate the vertical and tangential forces along snake's body and to determine the parameters affecting on these forces. Two types of serpentine robots have been designed in order to examine the achieved relations explained below.

***Keywords*—**Force, Dynamic analyze, Joint and Snake robot.

I. INTRODUCTION

SERPENTINE robots are made by interconnecting components called module. Modules can include electronic components, actuators, processors, etc. Modules are connected by joints, which considering the deployment of modules toward each other can have two DOF.

Articulation of robot body has facilitated the increase or decrease in body length and assembly of components [1]. High level of DOF increases the power and controllability of the robot [2]. The short transverse and altitude of the robot has made it possible for it to move in narrow routs such as pipes and also has provided it with camouflage ability. There are no balance or stability problems in such a robot. By stabilizing the robot's end component, it can be used as a manipulator with high DOF [3]. The drive in such a robot is not a wheel or other similar components, but it is possible to motivate it by using a number of angular drives and creating coupling at joints [4]. In controlling the robot movement, it is possible to determine the robot's path by controlling its head in a way that other components follow that [5]. Serpentine robots designed by inspiration from nature and movement of snakes, were made for first time by Hirose [6]. Serpentine robots' applications include mine detecting [7], inspection of oil and gas pipes [8], submarine inspection, bridge inspection, surgery [9], assistant robot [10] and identification operations in battlefields.

In this article, motive mechanisms of serpentine robot will be examined first. Then we will discuss about how tangential, vertical, parameters affecting the forces and serpentine efficiency are measured. Then, two types of new designed robots will be explained.

II. BIOLOGICAL SNAKE LOCOMOTION

A. Lateral Undulation

Commonly used by biological snakes, the lateral undulation gait produces propulsion, by simultaneously moving body sections. The sections continuously move from side to side perpendicular to the direction of forward motion. This oscillation, as a directional vector has both a tangential and a normal component relative to the forward direction. The lateral, side-to-side, direction is defined as normal to the forward direction. By assigning a positive, conventional direction to one side and a negative direction to the other, the net result of the lateral oscillation cancels the normal force. The tangential components for both sides are in the same direction, parallel to the direction of forward motion. The tangential forces created by these components drive the body forward. The motion requires three points of contact. Two points for forward pressure and a third for balance. Dependent on sliding friction, lateral undulation is not successful on low-friction surfaces. Also, the motion is less effective with shorter body lengths and heavy bodies [11].

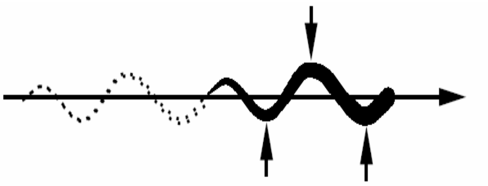

Fig. 1 Lateral Undulation Motion [12]

B. Concertina

Unlike the continuous, simultaneous body movements in lateral undulation, the concertina gait uses a progressive, body extension pattern. The body starts compressed, folded in a posture similar to an accordion. Extending a front section, the snake reaches forward a distance, while the back sections remain stationary. The stationary sections provide a foundation for the moving section. The moving sections use the foundation for leverage to extend forward. The extension is undone, as the snake begins to refold its body, by drawing its back section forward. In this phase the front section acts as the foundation, while the back section is in motion. The pattern results in a series, alternating between pushing against a back foundation and pulling against a front foundation. Static friction is the key; thus, this gait is more useful on Low-friction surfaces [12].

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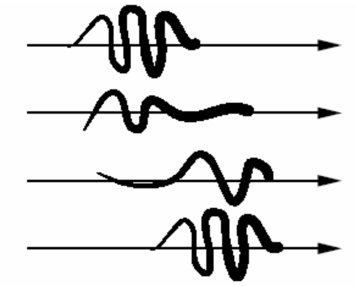

Fig. 2 Concertina Motion [13]

C. Side Winding

Most useful on low-friction surfaces, the side-winding gait utilizes continuous waves of lateral bending. Only two points of contact are maintained with the ground. The segments not in contact with the surface are lifted and move to the side. They then become the new contact points. The previous contact point is then lifted and moved. Repeating this pattern, the snake moves in a direction to its side. Since sections must be lifted, the snake moves in both horizontal and vertical planes. Lateral undulation and concertina only necessitate horizontal mobility; thus, the side-winding gait requires more complex muscular and skeletal structures to facilitate the two degrees of freedom [14].

Fig. 3 Side Winding Motion [14]

III. DYNAMIC ANALYZE OF SNAKE ROBOT

A. Measurement of the Force Exerting on Snake Body with Spiral Paradigm

In this section, forces exerted on snake body are calculated. These forces are used to make movement. First, snake's integrated body is modeled by some jointed connectors with length δs. In the connection of J_i joints, actuators with $T_i.ds$ torque are located. T indicates torque distribution in snake body. θ_i is the angle between two consecutive connectors. T_i torque can be substituted by a couple of f_i forces. This force is gained in below.

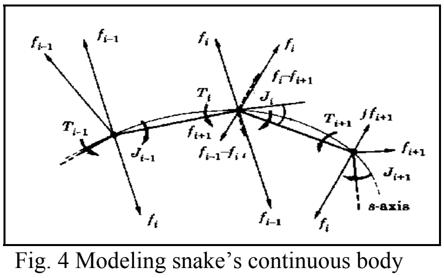

Fig. 4 Modeling snake's continuous body

$$f_i = \frac{T_i}{\delta s} \tag{1}$$

If we consider snake body spindle (S) as the coordinate axes, the density of forces in both vertical and horizontal directions will be:

$$f_{ti} = \{(f_i - f_{i+1}) + (f_{i-1} - f_i)\} \sin\left(\frac{\theta_i}{2}\right) \tag{2}$$

$$f_{ni} = \{(f_i - f_{i+1}) - (f_{i-1} - f_i)\} \cos\left(\frac{\theta_i}{2}\right) \tag{3}$$

If p_i is snake body's curvature in joint i the following proximities can be considered. With these proximities, the equations are written in the following forms.

$$\rho_i \approx \frac{\theta_i}{\delta s},\ \sin\left(\frac{\theta_i}{2}\right) \approx \frac{\theta_i}{2},\ \cos\left(\frac{\theta_i}{2}\right) \approx 1$$

$$f_{ti} = -\frac{T_{i+1} - T_{i-1}}{2\delta s} \rho_i \tag{4}$$

$$f_{ti} = \frac{dT(s)}{ds} \rho(s) \tag{5}$$

$$F_t = \int_0^L \frac{dT(s)}{ds} \rho(s) ds \tag{6}$$

Also, vertical force is gained through the following equation,

$$f_n = \frac{d^2T(s)}{ds^2} \tag{7}$$

$$F_n = \int_0^L \left| \frac{dT(s)}{ds} \right| ds \tag{8}$$

in which F_n Fn is the pure force exerted on body.

Considering the above equations, curvature function, and torque distribution function should be calculated in snake body. First, the curvature function and then torque distribution function are calculated.

B. Function Consistent with Biology of Snake Body

In order to gain curvature distribution and torque functions, it is necessary for us to be aware of muscle contraction along snake body. By now, several models have been offered for this purpose, the most consistent of which with snake body biology is the model offered by Hirose [16]. Hirose, offered serpnoid curve the curvature of which changes in sine way along snake body.

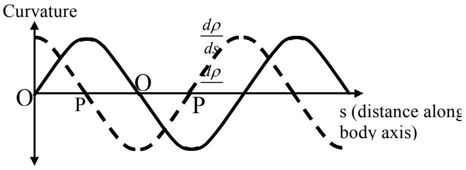

Fig. 5 Serpnoid Curve [16]

Bend angle in serpnoid curve *θ(s)* varies in sine direction from zero in point *O* to its maximum at *P* and can be indicated in the following equation:

$$\theta(s) = A.\sin\{(\pi/2).(s/l)\} \tag{9}$$

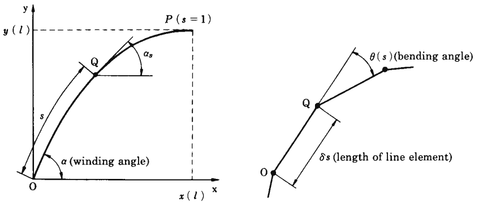

Fig. 6 Naming different parts of Serpnoid curve [16]

Mathematical relations of serpnoid curve are as follows:

$$x(s) = sJ_0(\alpha\alpha + \frac{4l}{\pi}\sum_{m=0}^{\infty}\frac{(-1)^m}{2m}J_{2m}(\alpha\alpha\sin(m\pi\frac{s}{l})) \tag{10}$$

$$y(s) = \frac{4l}{\pi}\sum_{m=1}^{\infty}\frac{(-1)^{m-1}}{2m-1}J_{2m-1}(\alpha\alpha\sin(\frac{2m-1}{2}\pi\frac{s}{l}) \tag{11}$$

X and Y stand for coordinates such as S.
In this equation, angle α indicates the spiral angle and is illustrated in Fig. 6. S is location parameter along snake body. Assuming that α is constant; the following relation exists between muscle forces and joint torque.

$$Ti = fm \tag{12}$$

Therefore, in order to calculate the torque, only muscle forces should be calculated.

C. Kinematics of Regular Crawling Motion

Snake's body follows serpnoid curve in move. Therefore, curvature distribution function will be as follows.

$$\theta(s) = \frac{\pi}{2}.\alpha\alpha\frac{\delta s}{l}.\sin\left(\frac{\pi.s}{2l}\right) \tag{13}$$

The following assumptions were proposed by Hirose to calculate torque distribution factor.

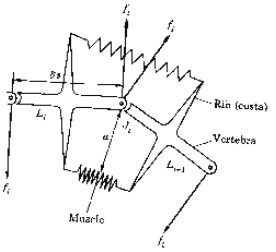

Fig. 7 Mechanical model of snake muscular system

1- Muscles exert the most force at point O and as they move toward point 0 the force exerted on them tends to 0.
2- Point P is a transition point in which motor muscles shift from extension to contraction.
3- At transition points, force shift occurs smoothly

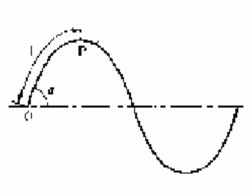

Fig. 8 A complete cycle of snake body

Based on the mentioned situations, F_m**(s)** is proposed for muscle force distribution along snake body. Parameter σ indicates muscle force distribution:

$$F_m(s) = f_{mO}\left\{1-\left(\frac{s}{l}\right)^{\sigma}\right\} \tag{14}$$

l is pivotal length of *OP* and f_{mo} stands fro force at point *O*. Distribution of muscle forces for different values of σ are indicated in the following figure.

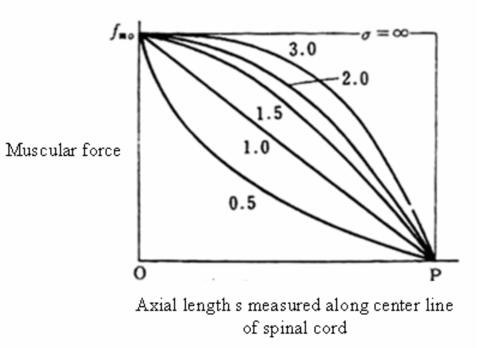

Fig. 9 Force variations with parameter σ

This diagram illustrates that when σ≤1, force distribution is uneven at point O. torque distribution along the body can be calculated from equation 8 and the above equation.

$$T(s) = a.f_{mO}\left\{1-\left(\frac{s}{l}\right)^{\sigma}\right\} \tag{15}$$

Using equations 11, 10, 8, 6, and 15, the following equations are gained for tangential force and vertical force.

$$f_t(s)=\sigma\frac{a\alpha}{l^2}\left(\frac{2}{\pi}\right)^{\sigma-1} f_{mO}\left(\frac{s}{l}\right)^{\sigma-1}\sin\left(\frac{\pi s}{2l}\right) \quad (16)$$

$$F_{tOP}(s)=\sigma\frac{a\alpha}{l^2}\left(\frac{2}{\pi}\right)^{\sigma-1} f_{mO}\int_0^l\left(\frac{\pi s}{2l}\right)^{\sigma-1}\sin\left(\frac{\pi s}{2l}\right)ds=\sigma\, Serp(\sigma e\frac{a\alpha}{l}f_{mO}) \quad (17)$$

In which:

$$\mathrm{Serp}(\sigma er)=\left(\frac{2}{\pi}\right)^{\sigma}\int_0^{\frac{\pi}{2}} x^{\sigma-1}\sin x\, dx \quad (18)$$

$$x=\frac{\pi.s}{2l} \quad (19)$$

in which vertical force equals with:

$$f_n(s)=\frac{\sigma(\sigma-1)a}{l^2}f_{mO}\left(\frac{s}{l}\right)^{\sigma-2} \quad (20)$$

$$F_{nOP}(s)=\sigma\frac{a}{l}f_{mO} \quad (21)$$

In desirable situation, the tangential situation should reach its maximum, and the vertical force should reach its least value. In the other words, if the ratio of tangential to vertical force increases the efficiency will be exceeding. Movement efficiency is defined as below.

$$\frac{F_t}{F_n}=\mathrm{Serp}(\sigma erp) \quad (22)$$

“Equation (22) indicates that in order to achieve high efficiency, α value should increase and σ value should decrease as much as possible”. On the other hand, σ >1 should be retained. Therefore, the optimum value for σ is one.

IV. NEW JOINTS DESIGN

1-in the first type, the purpose was to design a joint similar to snake muscles, namely has high flexibility in addition to having low weight can exert high force.

Muscles are flexible and only can exert force at the time of contraction. String or rope is mechanical components that in tolerate the force in tension, is flexible too.

Therefore using engine and string it is possible to make mechanisms, function of which resembles the muscle. When the motor rotates, considering the motor rotation direction, these strings are fastened and unfastened.

Rubber is used to connect the modules to each other, because it decreases the weight and increases the flexibility and simplifies the connection mechanism.

Usage of rubber causes that at the time of modules rotation, a point can not be determined as the rotation center.

In order to solve this problem, free length of the rubber should be limited as much as possible.

Hence two pierced redundancies are connected to both modules and the rubber is passed trough them.

The wheels used in this robot are not motives, but they are free wheels, decreasing the friction along the body and increasing that vertically so that they prohibit the robot body from sliding vertically.

Advantages of this design are the low weight, flexibility, and designing a mechanism similar to snake muscle.

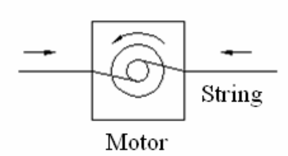

Fig. 10 Semi muscle actuator schematic

Fig. 11 Method of rubber use

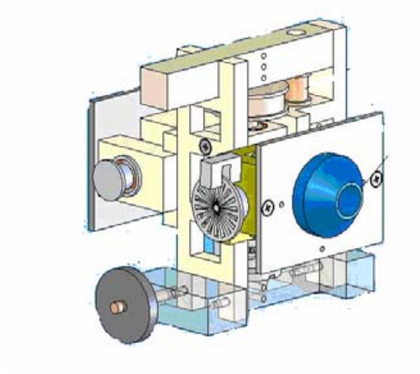

Fig. 12 New Joint design

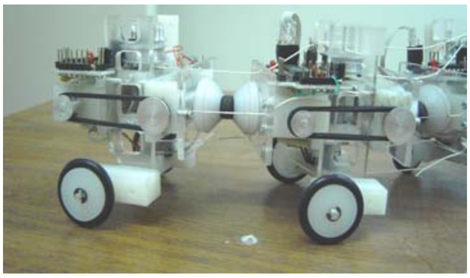

Fig. 13 Snake like robot with muscle joints

2- The second group of the joints was designed in order to install the robot on a fixed support and to use that as the manipulator. These robots consist of similar parts called module.

Modules consist of electronic boards, engines, and processors. Modules are connected be joints and considering the position of two modules toward each other can have two DOF.

Modules are connected to these joints with phase variance of 90° As the robot support, is fixed, the motion should be transferred upward. In the other word each joint should move its above module.

Therefore a universal joint is used that the bar of one has the ability of rotation in the other. a gear is mounted on any bar of this joint, involved with the spiral teeth mounted on engine's up and down shafts.

Rotation of the down engine moves the up module along X and rotation of up engine moves the up module along Y.

Two motor are located in every module positioned in two opposite directions, driving down and up modules.

A space has been considered in each module for accommodating an electronic board, duty of which is to motivate and control the motors.

How to install the gear on the universal joint is very important. One of the gears is connected to the universal joint's central shaft which has more width and accommodates the bearings, and the other one is connected to the module body.

Thus modules can not have relative motion toward each other.(Modules can move only when the engines rotate.)

The advantages of this design include low weight, keep rotation and the ability of to independent bend motion. Its disadvantages are relatively low efficiency and speed, as a result of using spiral gearwheels.

Joint specifications are as follows:

Module height is 65mm, and their diameter is 50mm.

Weight of each module is 420g.

Fig. 14 Hyper redundant manipulator with new joint

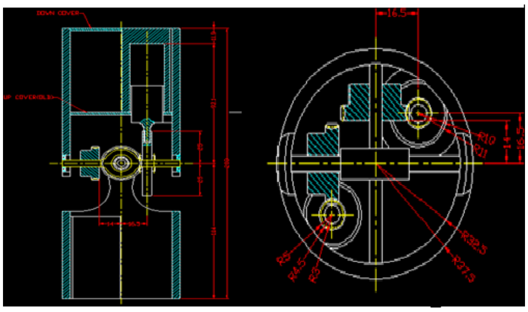

Fig. 15 Assembly plan

V. RESULTS

This study has examined a crawling robot with serpnoid curve. After determining the kind of moving curve and the model consistent with snake body biology, tangential and vertical forces exerted to snake body was gained. Considering the fact that movement efficiency is the result of the difference between tangential and vertical forces exerted on snake body, the parameters affecting on efficiency and the way they affect are explained below. In order to test the gained results two types of robots with semi-muscle joints and plain muscles was designed.

TABLE I
LIST OF SYMBOLS

SYMBOL	QUANTITY	UNIT
L	Snake body length	m
F_t, F_n	Tangential and vertical forces	N
f_m	Muscular forces	N
T	Torque	Nm
ds	Element Length of snake body	m
θ	Angle between two consecutive equations	Degree
m	Location parameter	S
α	Spiral Angle	Degree
ρ	Snake body curvature	mm

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