Paper: E11_245

The 4th KKU International Engineering Conference 2012 (KKU-IENC 2012)
"Driving together towards ASEAN Economic Community"
Faculty of Engineering, Khon Kaen University, Thailand, May 10-12, 2012

A Snake Robot with Mixed Gaits Capability

Md. Raisuddin Khan, Mad Helmi Ab Majid, Shahrul Na'im Sidek
Department of Mechatronics Engineering, Faculty of Engineering,
International Islamic University Malaysia,
Kuala Lumpur 53100
E-mail: raisuddin@iium.edu.my, helmi_mjd@yahoo.com, snaim@iium.edu.my

***Abstract*—Snake robots are mostly designed based on single mode of locomotion. However, single mode gait most of the time fails to work effectively when they are required to work in different cluttered environment with different measures of complexity. As a solution, mixed mode locomotion is proposed in this paper by synchronizing serpentine gait for unconstricted workspace and wriggler gait for narrow space environment through development of a simple gait transition algorithm. This study includes the investigation on kinematics analysis followed by dynamics analysis while considering related structural constraints for both gaits. This approach utilized speed of the serpentine gait for open area operation and exploits narrow space access capability of the wriggler gait. Hence, this approach in such a way increases motion flexibility in view of the fact that the snake robot is capable of changing its mode of locomotion according to the working environment.**

Keywords–mixed mode; serpentine; wriggler; transition algorithm; motion flexibility

I. INTRODUCTION

The characteristic of highly articulated body allows a snake robot to traverse in difficult terrains such as under a collapsed building or any chaotic environment which consists of different measure of workspaces complexity. Snake robot also offers high stability compares to wheeled and legged mobile robot. Moreover, the exterior of the snake robot body could be sealed completely to allow movement in the fluids or any environment that could damage the electronic parts. On the other hand, modular design of a snake robot provides simplicity in fabrication and consequently reduces time taken for replacing faulty parts. However, to successfully deploy snake robot for a real task, motion flexibility is fundamental as shown in a real snake. Thus, the only way to improve motion flexibility is to incorporate as many gaits as possible to suit varieties of working spaces and the robot should effectively change its gait to adapt to the change of the environment.

Snake robot has been studied in [1] quite extensively. There are four most common gaits found in the biological snake namely serpentine, concertina, sidewinding and rectilinear [2].

Serpentine is known as the most prominent and the simplest form of snake robot gait found in literature inspired from nature. It is a sinusoidal form of locomotion and conventionally generated by approximating a serpenoid curve [3]. Recently, some modification has been made to improve the workability of the conventional serpentine gait. The serpentine gait with variable bending angles observed in natural snake was introduced in [4]. The results show that the proposed gait achieved better motion efficiency compared to the one that used constant bending angles. Moreover, since conventional serpentine model is based on fixed parameters, a modified serpenoid curve was developed by using variable parameters [5]. These parameters ensured that the motion is optimal and no side slip occurs during locomotion. Traveling wave locomotion (i.e. vertical form of serpentine gait motion) has been presented in [6]. A complete description of mathematical modeling and experimental validation was discussed. The authors found that through combination of both serpentine and traveling wave locomotions, a 3-D locomotion may be achieved.

Sidewinding is another type of snake gait usually observed in the desert snakes. A novel kinematics model of a sidewinding gait is found in [7]. The locomotion was generated by repetitive traveling wave of bending mechanism. The robot could travel either in a uniform direction or turning motion by using algorithm generated by using backbone curve model. In addition, simulation study of the sidewinding locomotion has been conducted using genetic programming and the empirical results showed that the emergence of the sidewinding as the fastest locomotion gait [8]. In the latest work, stability conditions were identified for sidewinders on a slope and a solution for a minimum aspect ratio of the sidewinding pattern needed to maintain stability is also presented [9]. It is also important to note that, sidewinding locomotion involves sinus lifting where the snake robot lifts some parts of its body above the ground and switches grounded parts of its body dynamically [10].

Rectilinear locomotion is known as the slowest among the four primary types of snake robot gaits. In [11], a snake robot that used shape memory alloy (SMA) as actuators and move in a similar way to rectilinear locomotion was introduced. However, this snake robot locomotes at a very low average speed (0.025 cm/s). Furthermore, a kinematic and dynamic model for a rectilinear gait has been developed considering changes of mechanism topology over the course of the gait [12]. In other work, a simplified model of rectilinear gait was proposed where a simple two-mass model was employed to analyze the motion and the damping coefficient is varied to change the speed [13].

Concertina is another type of snake robot locomotion gait. A mathematical model for concertina locomotion for climbing purpose is found in [14]. The optimum condition to reduce actuation torque during the locomotion was also investigated. Latest work on development of the kinematics model of concertina gait with advantage of closely following similar locomotion of real snakes for horizontal motion was presented in [15]. A new dynamic curve for modeling different parts of the snake robot was also presented.

Current research progress shows that many new gaits have been scrutinized apart from the main four types of locomotion. For example, in [16] a new gait called Forward Head Serpentine (FSH) was introduced while optimization of the FSH is presented [17]. FSH ensures that the head of snake robot always remains in the general direction of motion for easier sensing of obstacles in environment and significantly enhances the easiness of the information processing. In addition, a gait called a helical gait which defined as the locomotion of a snake-like robot convoluting around a pole or inside a pipe to propel itself forward has been introduced in [18]. Most recently, a snake robot is design with capability of moving in a small diameter pipe. For example, a KAEROT-snake IV robot could move in a sequence of holding motion as well as with a sinusoidal mode motion inside a vertical or horizontal small diameter pipe [19]. Another locomotion gait used inside a pipe is called as helical rolling motion and it make use of mathematical continuum curve model for body shape control [20]. Pedal wave locomotion with steering capability for narrow space application has been proposed and consequently tested as continuous snake robot model [21].

Mixed mode locomotion research still slowly progress as weigh against a unique locomotion type. In order to support multimode locomotion, a robot must have at least four capabilities [22]. First, it must be able to perform different locomotion mode. Second, it must be able to recover from unexpected locomotion failures. Third, it must be able to shift from one mode to another. Finally, it must be able to choose the correct mode for the correct environment. For example, a snake robot that capable of anguilliform swimming like sea-snakes and lampreys in water and lateral undulatory locomotion like a snake on ground found in [23]. The newest work on mixed locomotion was introduced in [24]. The proposed robot can realize both the serpentine and the rectilinear motion, and additionally the fusion of the two motions for higher adaptability to the environment.

II. GAIT KINEMATICS

In this paper, two distinct gaits namely serpentine and wriggler are synchronized together to form a mixed locomotion gait and is implemented on a snake robot prototype. Two different workspaces are considered namely the unconstricted workspace and the narrow workspace. The narrow space apart from open environment is the most common workspace faced by snake robot during its real application. For example, in a conduit, pipe, collapse building, bushes etc. Fig. 1 illustrates how a snake robot switches its gait to adapt to the type of the environment. In this work, serpentine gait is employed for open workspace while wriggler gait is used for narrow workspace.

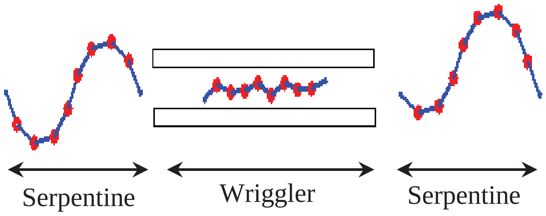

Fig. 1: Illustration of environment adaptation implementation

This paper presents a new form of gait combination for snake robots.

A. Serpentine Gait

The first gait to be considered in this paper is a discrete serpentine gait [25]. This gait is the most common gait found in the literatures. In the robot model, the joint angle is defined as a change of a sequence of absolute angles and it is given as,

$$\phi_i = \theta_{i+1} - \theta_i = \alpha \sin\left(i\beta + \frac{\beta}{2}\right) + \gamma \qquad (1)$$

where parameters α, β and γ are given as follows

$$\alpha = a\left|\sin\left(\frac{\beta}{2}\right)\right| \qquad (2)$$

$$\beta = \frac{b}{n} \qquad (3)$$

$$\gamma = -\frac{c}{n} \qquad (4)$$

As observed from (1), the shape of serpentine gait is in a sinusoidal form with amplitude of α and bias of γ. The relative angles which are adjacent to each other have phase difference of β. Moreover, values of α, β and γ could be controlled by adjusting the values of *a*, *b* and *c* respectively and as a result the shape of serpentine gait could be changed. Once the relative angles of the joint are known, it positions could be determined geometrically on Cartesian coordinate as illustrated in Fig. 2. From Fig. 2, the *x* and *y* coordinates of the joint could be tracked by using the following equations,

$$x_i = x_0 + \sum_{i=1}^{n} 2l\cos\theta_i \qquad (5)$$

$$y_i = y_0 + \sum_{i=1}^{n} 2l\sin\theta_i \qquad (6)$$

where (x_0, y_0) represents tail coordinate of the snake robot and θ_i is an absolute angle for *i*-th link which has equivalent length of 2*l*. Thus, once absolute angles are known and by using equations (5) and (6), the tracking of the snake robot coordinate on the x-y plane is possible.

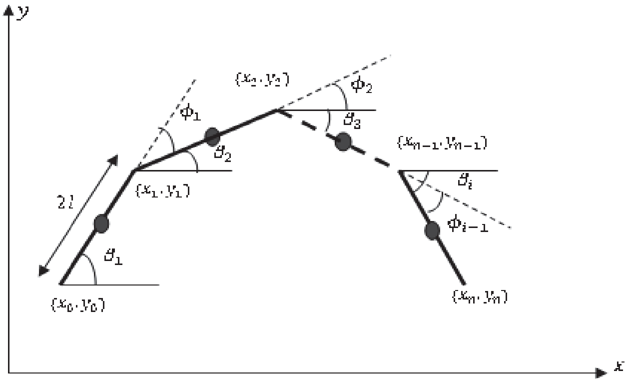

Fig. 2: Schematic of *n*-segment snake robot model

B. *Wriggler Gait*

The second type of gait being considered in this study is called wriggler gait [26]. This gait has been specifically modeled using cross link member to suit narrow space application. The derivation of the inverse kinematics model of this gait is based on cross link shown in Fig. 3 and Fig. 4 with length 2*l* and width 2*w*. From Fig.3, the first joint coordinate (h_1,k_1) is determined geometrically using equations (7) and (8).

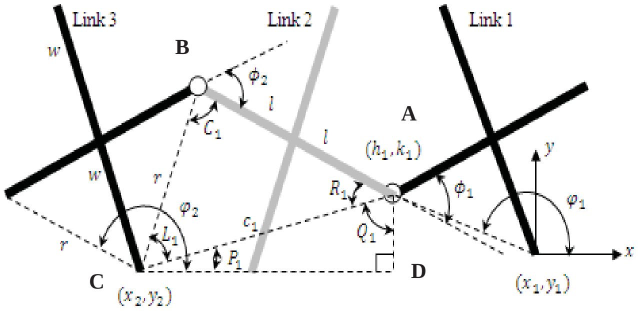

Fig. 3: Schematic for wriggler gait model

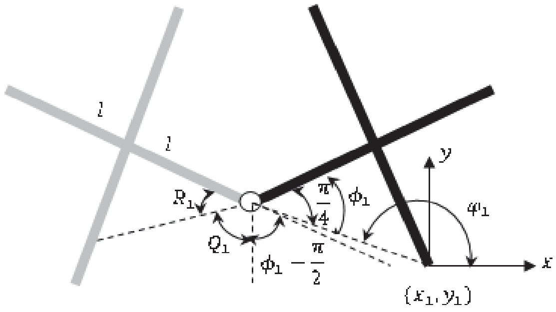

Fig. 4: Geometric relationship for even joint angle

$$h_1 = r\cos\varphi_1 + x_1 \tag{7}$$

$$k_1 = r\sin\varphi_1 + y_1 \tag{8}$$

Where the length of segment *r* and segment c_1 are given by

$$r = \sqrt{l^2 + w^2} \tag{9}$$

$$c_1 = \sqrt{(h_1 - x_2)^2 + (k_1 - y_2)^2} \tag{10}$$

By using cosine rule for triangle formed by joint $A(h_1,k_1)$ and second joint position, B and the second scale position $C(x_2,k_2)$, the three angles R_1, C_1 and L_1 are determined to be,

$$R_1 = \cos^{-1}\left(\frac{4l^2 + c_1^2 - r^2}{4lc_1}\right) \tag{11}$$

$$C_1 = \cos^{-1}\left(\frac{r^2 + c_1^2 - 4l^2}{2rc_1}\right) \tag{12}$$

$$L_1 = \cos^{-1}\left(\frac{4l^2 + r^2 - c_1^2}{4lr}\right) \tag{13}$$

Next, using c_1 as hypotenuse for right triangle ACD, another two angles are obtained

$$Q_1 = \tan^{-1}\left(\frac{h_1 - x_2}{k_1 - y_2}\right) \tag{14}$$

$$P_1 = \tan^{-1}\left(\frac{k_1 - y_2}{h_1 - x_2}\right) \tag{15}$$

The relationship between the first joint angle, ϕ_1 and the first position of scales, φ_1 is

$$\phi_1 = \varphi_1 + R_1 + P_1 - \frac{5\pi}{4} \tag{16}$$

Finally, by referring to Fig. 4, the second joint position is obtained through

$$\phi_2 = L_1 + Q_1 + \frac{\pi}{2} \tag{17}$$

It should be noted that all subsequent angles could be derived in a similar manner repetitively. The length *l* and *w* could be set for any value. However, to maintain compatibility of the structure for narrow space application, *w* is set equal to *l*. Thus from the structure, it's clear that the all joint angles of the robot are limited within the range of

$$-\frac{\pi}{4} \le \phi \le \frac{\pi}{4} \tag{18}$$

As stated earlier, (16) and (17) are constituted as inverse kinematics. It is complicated to obtain forward kinematics equation straight away from the inverse kinematics. However, to arrive at the forward kinematics equations, curve fitting approximation method could be used by plotting the scales position against the joint angle within the range given in (18) and then applying curve fitting method.

C. *Gait Kinematics Constraints*

The two gaits discussed earlier have distinct kinematics structure where serpentine exhibits straight link structure while wriggler involves cross link structure. Gait kinematics constraint for both gaits under consideration is a key concept for designing a snake robot prototype. Thus, the prototype developed should satisfy both gaits design criteria.

III. ACTUATORS TORQUE

The main purpose of the dynamics analysis in our case is to determine the desired torque for each joint for prototype construction. Once the equation of motion for both gaits is obtained, trajectory planning is used to determine the desired torque. However, at least a set of data for each initial and final position should be known. These values could be obtained from the kinematics analysis discussed previously. Here, acceptable simulation time is selected based on the data sheet of the actuators' speed. A simple third order polynomial trajectory planning as in (19) is used. Thus, at least four initial conditions are required to solve for the coefficients *c* and consequently expression for angular velocity and angular acceleration could be obtained. Here we assumed the initial and final positions as in (20) and the initial and final velocities are zero as in (21).

$$\phi(t) = c_0 + c_1 t + c_2 t^2 + c_3 t^3 \quad (19)$$

$$\phi(t_i) = \phi_i \quad , \quad \phi(t_f) = \phi_f \quad (20)$$

$$\dot{\phi}(t_i) = 0 \quad , \quad \dot{\phi}(t_f) = 0 \quad (21)$$

The derivation of equation of motion is not shown but it is based on Recursive Newton Euler method. Once the torque for each joint for each gait is known, comparison is made to select the largest torque for each joint among the two gaits. Fig. 5 illustrates the overall process taken to compute the joint torques, and the results are shown in Table I before actuators size care selected.

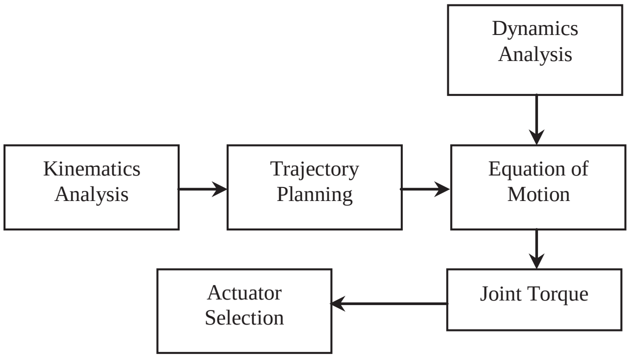

Fig. 5: Flow of torque computation

TABLE I. COMPARISONS OF JOINT TORQUE

Joint Number	Maximum Values of Joint Tourque (kgf.cm)	
	Serpentine	Wriggler
1	1.550	1.180
2	1.280	0.450
3	1.120	0.880
4	1.020	2.530
5	0.890	1.180
6	0.630	0.450
7	0.310	0.780
8	0.080	2.530

Table I shows the comparison of joint torques obtained from simulation of both gaits used in this study for each joint. For simulation purpose, all parameters values used are the same as in the prototype developed. The number of joint used is eight (*i*=8) connecting nine segments (n=9). The prototype design is discussed in section V.

From Table I, for standardizing the actuators size, the maximum torque of 2.53 kgf.cm is selected and thus, actuator chosen should be equal or larger than this value. However, if a different size of actuators needs to be considered, larger values of torque for each joint should be selected. This value in other words is minimum requirement to select actuator and to ensure actuator could provide enough torque to execute both gaits under consideration.

IV. GAIT SWITCHING ALGORITHM

Once kinematic models of the gaits have been obtained, the control algorithm could be developed. The main purpose of the gait switching algorithm is to ensure that the snake robot could switch its gaits efficiently from one to another and consequently maintain the desired shape of the gait. As previously stated, the mechanism involved is shown in Fig. 6.

Fig. 7 illustrates a simple gait switching algorithm used in this study. A new gait starts when all the data has been compared and the robot is in new gait initial position. The simplest form of gait transition is to change all current joint angles values with new initial position of the upcoming gait before a full gait sequence could be executed. Through this approach, gait kinematic structure is guaranteed. The process is executed sequentially from the head down to the tail of the snake robot. Joint position only will change if the value between two gaits is different or else it will remain the same.

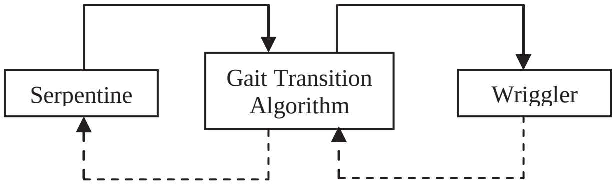

Fig. 6: Gait switching mechanism

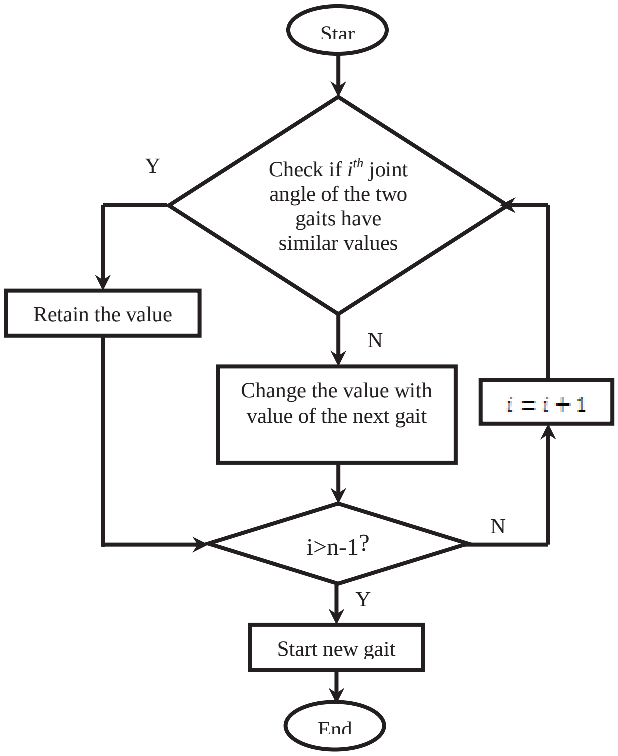

Fig. 7: Gait transition algorithm

V. STRUCTURE OF SNAKE ROBOT

Designing a prototype requires analysis of kinematics constraints and dynamical constraints of the snake robot to synchronize gaits under consideration or else the prototype fails to work properly. The design of the snake robot body should satisfy both geometrical shapes requirement of the two gaits. Thus, a complete prototype design to satisfy these constraints is shown in Fig. 8 where the shape of the robot body is designed to adapt the two geometrical structures.

In term of friction generated elements, serpentine gait require backward direction frictional force higher compares to the forward direction. At the same time it is capable of avoiding side slippage by providing higher frictional force in tangential direction of motion as compared to the normal direction. On the other hand, for wriggler gait to work effectively, friction force is considered infinite and zero for backward and forward respectively. Thus frictional elements were designed to satisfy these frictional requirements. The frictional element used to be attached at the belly of the snake robot are shown in Fig. 9.

VI. EXPERIMENTAL RESULTS

A series of experiments has been conducted to test the viability of the proposed locomotion strategy. Table II summarized the forward speed achieved by the prototype under two different surfaces i.e. carpet with higher friction and tile floor with lower friction. These results demonstrate that the serpentine gait has higher speed compare to wriggler gait for both surfaces.

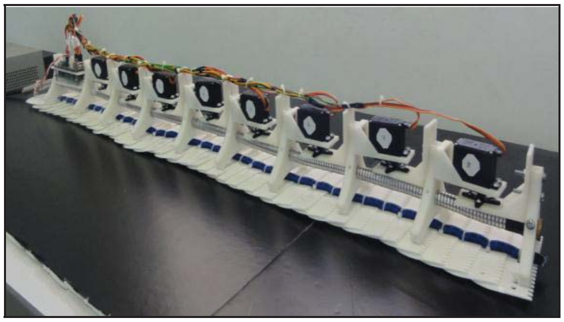

Fig. 8: Snake robot prototype

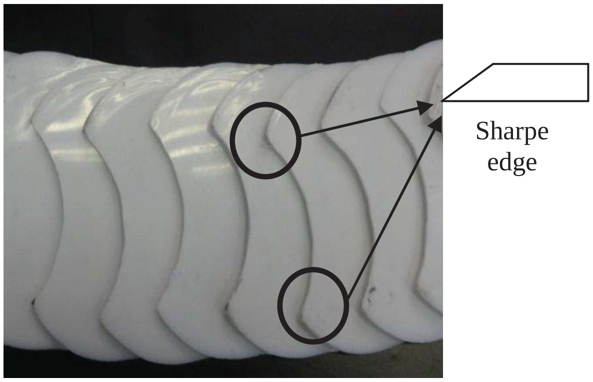

Fig. 9: Scales with sharp edge (in circle)

Moreover, both gaits achieved higher speed on the carpet (high friction) compare to tile floor (low friction). It also shows that, the scales used in this study work better on a rough terrain than a smooth surface.

TABLE II. EXPERIMENTAL RESULT OF FORWARD SPEED

Testing Environment	Speed (cm/s)					
	Serpentine Gait			Wriggler Gait		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Carpet	3.45	3.68	3.50	1.23	1.39	1.26
Tile floor	2.12	2.40	2.18	1.03	1.17	1.21

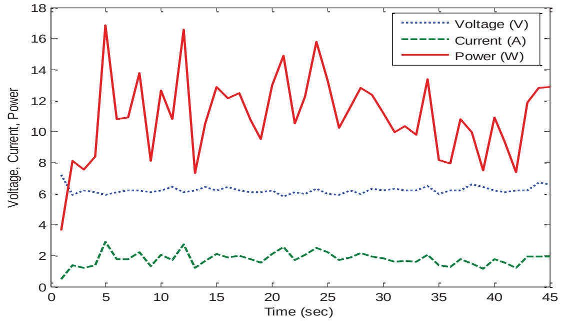

Fig. 10: Power consumption for serpentine gait

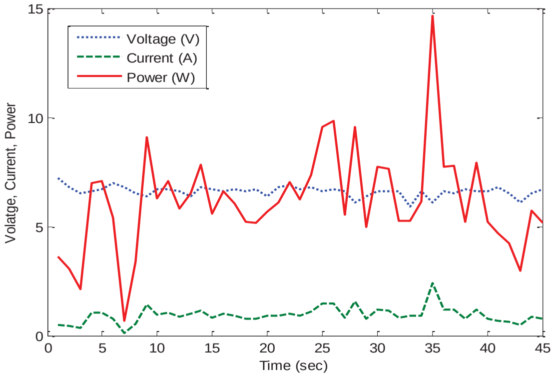

Fig. 11: Power consumption for wriggler gait

In term of power consumption, serpentine gait consumes more power (about 50%) compared to the wriggler gait as could be seen from Fig. 10 and Fig. 11 which is determined while testing the robot on the carpet. These power described the energy required by snake robot to overcome frictional force applied by surface to allow the snake robot to move forward.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, a snake robot design using mixed gaits is described. Important considerations for design are also highlighted. The kinematics for serpentine and wriggler gait is described and related geometrical constraints for respective gaits are also pointed out. Prototype developed for mixed mode gait successfully executed the two gaits in two different workspaces and effectively switched its gaits using the proposed gait switching algorithm. In the future 3D motion will be considered with turning capability for higher motion flexibility.

REFERENCES

[1] S. Hirose and Y. Umetani,. “Kinematic control of active cord mechanism with tactile sensors,” in Proc. 2nd RoMAnSy Symp, Warsaw, 1976, pp. 241-252.

[2] J. Gray, “The mechanism of locomotion in snakes,” Journal of Experimental Biology, 23(2), 1946, pp. 101-120.

[3] S. Hirose and Y. Umetani, “Kinematic control of active cord mechanism with tactile sensors,” in Proc. 2nd RoMAnSy Symp, Warsaw, 1976, pp. 241-252.

[4] K. H. Chang and Y. Y. Chen, “Efficiency on snake robot locomotion with constant and variable bending angles,” in IEEE International Conference on Advanced Robotics and its Social Impacts Taipei, Taiwan, Aug. 23-25, 2008.

[5] M. Dehghani and M. J. Mahjoob, “A modified serpenoid equation for snake robots,” in Proc. of the IEEE International Conference on Robotics and Biomimetics, , Bangkok, Thailand, February 21 - 26, 2009, pp. 1647-1652.

[6] G. Poi, C. Scarabeo, and B. Allotta, “Traveling wave locomotion hyper-redundant mobile robot,” in Proc. of the IEEE International Conference on Robotics and Automation, Leuven, Belgium, May, 1998, pp. 418-425

[7] W. Burdick, J. Radford and G. S. Chirikjian, “A “sidewinding” locomotion gait for hyper-redundant robots,” Vol. 9, No. 3, 1995. pp. 195 – 216.

[8] I. Tanev, “Automated evolutionary design, robustness, and adaptation of sidewinding locomotion of a simulated snake-like robot,” in IEEE Transactions on Robotics, Vol. 21, No. 4, August, 2005, pp. 632-645.

[9] R. L. Hatton and H. Choset, “Sidewinding on slopes,” in: IEEE International Conference on Robotics and Automation Anchorage Convention District, Anchorage, Alaska, USA, May 3-8, 2010, pp. 691-696.

[10] M. Tanaka, and F. Matsuno, “Modeling and control of a snake robot with switching constraints,” in SICE Annual Conference, The University Electro-Communications, Japan, August 20-22, 2008, pp. 3076-3079.

[11] C. Y. Liu and W. H. Liao, “A snake robot using shape memory alloys,” in Proc. of the IEEE International Conference on Robotics and Biomimetics, Shenyang, China, August 22 - 26, pp. 601-605.

[12] B. W. Spranklin, “Design, analysis, and fabrication of a snake- inspired robot with a rectilinear gait,” Master Thesis, University of Maryland, 2004.

[13] A. Gmiterko, and I. Virgala, “Simplified model of the snake rectilinear motion,” in 9th IEEE International Symposium on Applied Machine Intelligence and Informatics, Smolenice, Slovakia, January 27-29, 2011, pp. 307-310.

[14] F. Barazandeh, B. Bahr, and A. Moradi, “Investigation of self-locking in concertina movement,” in Mediterranean Conference on Control and Automation, Athens-Greece July 27-29, 2007.

[15] A. Akbarzadeh, J. Safehian, and H. Kalani, “Generating snake robot concertina locomotion using a new dynamic curve,” International Journal of Modeling and Optimization, Vol. 1, No 2, 2011, pp. 134-140.

[16] S. Hasanzadeh and A. A. Tootoonchi, “Obstacle avoidance of snake robot moving with a novel gait using two-level PID controller,” in RAM, 2008, pp. 427-432.

[17] S. Hasanzadeh and A. K. Tootoonchi, (2010). Ground adaptive and optimized locomotion of snake robot moving with a novel gait. Autonomous Robot, 28, pp. 457–470.

[18] S. Yu, S. Ma, B. Li and Y. Wang, “Analysis of helical gait of a snake-like robot,” in Proc. of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics, 2008, pp. 1183-1188.

[19] H. Shin, K. M. Jeong and J. J. Kwon, “Development of a snake robot moving in a small diameter pipe,” in International Conference on Control, Automation and Systems, Gyeonggi-do, Korea Oct. 27-30, 2010, pp. 1826-1829.

[20] T. Baba, Y. Kameyama, T. Kamegawa and A. Gofuku, “A snake robot propelling inside of a pipe with helical rolling motion,” in SICE Annual Conference, Taipei, Taiwan, August 18-21, 2010, pp. 2319-2325.

[21] H. Yamada and S. Hirose, “ Steering of pedal wave of a snake- like robot by superposition of curvatures,” in IEEE/RSJ International Conference on Intelligent Robots and Systems, 2010, pp. 419-424.

[22] W. M. Shen, M. Krivokon, H. Chiu, E. Jacob, R. Michael and J. Venkatesh, (2006) Multimode locomotion via superbot robots. In: Proc. 2006 IEEE International Conference on Robotics and Automation Orlando, Florida. Pp. 2252 – 2257.

[23] A. Crespi and A. J. Ijspeert, “Online optimization of swimming and crawling in an amphibious snake robot,” in IEEE Transactions on Robotics, Vol. 24, No. 1, February, 2008.

[24] K. Wang and S. Ma, “Kinematic Analysis of snake-like robot using sliding joints,” in Proceedings of the IEEE International Conference on Robotics and Biomimetics, Tianjin, China December 14-18, 2010, pp. 1484-1489.

[25] M. Saito, M. Fukaya and T. Iwasaki, “Serpentine locomotion with serpentine snake,” Control Systems Magazine, 2002, pp. 64-81.

[26] R. Khan, M. Watanabe and A.A. Shafie, “Kinematics model of snake robot considering snake scale,” American Journal of Applied Sciences, Vol. 7, No. 5, 2010, pp. 669-674.