Obstacle Avoidance of Snake Robot Moving with A Novel Gait Using Two-Level PID Controller

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***Abstract*— In this paper, we introduce a novel locomotion mode (gait) for 2D snake robots. The idea behind this new gait is to control orientation of snake robot by head link and use other links as a means of driving the robot. When snake robot moves using this gait, head link always looks at direction of motion and can therefore receive much better information of target and obstacles in the direction of motion. This will significantly improve the ease of robot control which is critical in the case of search and rescue operations. Finding the proposed gait parameters is an optimization problem that we solve it using genetic algorithm (GA). We then propose a two-level PID controller to guide snake robot to target while avoiding obstacles. The lower level PID controller controls actuators input torque while the higher level PID controller controls orientation of the head link. Simulation results confirm the effectiveness of the proposed method.**

***Keywords*— snake robot, gait, control, genetic algorithm.**

I. INTRODUCTION

Despite having challenges in the area of control and inefficiency in locomotion due to high friction, snake-like robots have attracted the attention of researchers for applications not suitable for wheeled and legged robots. Applications such as ruins of collapsed buildings or narrow passages in search and rescue (SAR) operations are good examples where snake robot may be used.

Snake robots have advantages over wheeled vehicles for terrainability, traction, universal penetration capabilities, high adaptability and task shapability due to kinematic redundancies. They also offer increasing reliability when made modular. On the other hand, the two main challenges of snake robots over wheeled mechanisms are difficulty in analyzing and synthesizing snakelike locomotion mechanisms as well as its control. This paper hopes to contribute to these challenges by using two-level PID controllers and introducing a novel gait.

Locomotion control of snake robot has been addressed by many researchers. Two broad classes of control methods have been used with snake robots. The first class can be described as trajectory-tracking control. It uses predefined gait patterns, usually computed as sine waves that are tracked with a feedback controller [1]. Typically, the control is open-loop: the set points of the joints are calculated and sent to the motor controllers without any form of feedback (the only feedback present in the system is the one used by the PID controller).

The other class can be described as online gait generation control. In this case, gaits (motion mode of snake robot) are not predefined in advance, but generated online during locomotion. These approaches can, therefore, better deal with perturbations and irregular terrains. Most of these approaches are model-based, i.e. they rely on a kinematic [2] or dynamic [3, 4] model of the robot's locomotion in order to design control laws for the gait generation.

Another new control method is using central pattern generators (CPGs). In this method locomotion in vertebrates is controlled by CPGs, which are networks of neurons that can produce coordinated oscillatory signals without oscillatory inputs [6, 7].

In this paper, after introducing a novel gait, we propose a structure for locomotion control of snake robot based on a two level PID controller to reach the target (for example in a search and rescue operation target is victim position) while avoiding obstacles (ruins of collapsed building in a SAR operation).

The most commonly used gait in reaching the target is the serpentine gait. In this gait, all links including the head link moves in a sinusoidally manner. Sensory devices, such as camera, are usually attached to the head link and therefore will also move in a sinusoidal manner. This will make the analysis of the sensory information complex and increases the difficulty of control.

In this paper we introduce a novel gait FHS (Forward Head Serpentine). When snake robot moves using this gait, the direction of the head link remains approximately constant in the direction of motion and can therefore receive much better information of target and obstacles.

The rest of the paper is organized as follows. Section II describes dynamic consideration of the snake robot and friction model. Section III introduces the FHS gait and its features. Section IV describes how to find parameters of the FHS gait. Section V discusses features of the FHS gait and compares it with serpentine gait. In section VI, proposed control architecture is described and results of simulations are presented and discussed. Finally, section VII concludes the paper and summarizes the future work.

II. HYPER REDUNDANT SNAKE ROBOT MODEL

In this paper we consider a planar 5-link snake robot without wheels with dynamically identical links. The robot model is composed of serially connected links. Between every two links, a one-dimensional joint rotating on vertical (yaw) axis is located. In the same way as living snakes, friction force between the robot body and the environment is supposed to be large in normal direction and small in tangential direction. Commonly this is realized using passive wheels in real robots.

Dynamic analysis of such a mechanism, moving on a plane with friction has already been worked out by several researchers [5] and [11]. We implement the dynamics using MATLAB SimMechanics software package in our computer simulations, for which a snapshot is given in Fig. 1.

In our simulations, we consider a simple viscous friction model. Friction force is modeled by the following equations

$$f_{t,i} = -C_t m_i v_{t,i} \quad (1)$$

$$f_{n,i} = -C_n m_i v_{n,i} \quad (2)$$

Where Ct and Cn are normal and tangential viscous friction coefficients. Suffix i indicates corresponding i-th link, $f_{t,i}$ and $f_{n,i}$ are friction forces in tangential and normal direction respectively, m_i is mass of i-th link, $v_{t,i}$ and $v_{n,i}$ are velocities of center of mass of the i-th link in tangential and normal direction.

III. INTRODUCTION OF A NOVEL GAIT

An important feature of snake robot is its capability to move with different gaits. Some of these gaits are biomimetic such as serpentine and rectilinear (for a brief introduction of snake gaits refer to [8].) and others do not exist in nature. For example, gait introduced in [9] which is reminiscent of the back stroke used by human swimmers.

In this section, we first introduce serpentine gait because of its similarity to our proposed FHS gait. Next we will compare its advantages and disadvantages relative to serpentine gait.

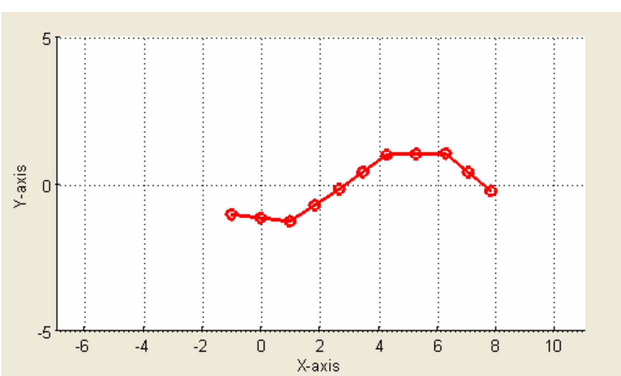

Figure 1. A snapshot from the Simmechanics software visualization of a 5-link planar serpentine structure. Links are similar with mass of 1 Kg, length of 2 m and inertia of 0.33 Kg.m^2.

A. Serpentine Gait

The most straightforward way to generate traveling wave in a serial chain of n link is by having the joint angles vary sinusoidally with a common frequency and a constant phase lag between consecutive joints. The undulatory motion of a snake can be imitated by changing the relative angles of the snake robot in the following manner:

$$\theta_i = \alpha \sin(\omega t + (1-i)\beta) + \gamma \quad (3)$$

Where $i=1$ to $n-1$ is the number of link, α is the maximum angular deflection for each joint. β is the phase difference of any two adjacent relative angles. ω is frequency of locomotion which specifies how fast the serpentine wave propagates along the body. γ is the angular offset that provides a means for steering the mechanism and is set to zero for locomotion in straight line. If γ is non-zero the mechanism moves along a curved path, clockwise or counter clockwise, depending on the sign of offset γ. Depending on the type of interaction with the locomotion environment, the generated body wave will propel the mechanism either in the direction of propagation of body wave (polyacheate-like) or in opposite direction (eel-like). The wave propagation direction depends on the sign of β, and is from link n to link 1 for positive β; if this wave propagation direction results in forward motion, then reversing this sign results in backward motion. The condition of $\beta=\pm 2\pi/n$ yields one wavelength of the propulsive wave across the undulation body, with beneficial effects on the speed of the robot. Varying the joint angle amplitude α affects the wavelength and propagation velocity of the body wave.

B. Novel Gait - Forward Head Serpentine

In general, when snake is moving, it is preferable for its head to remain in a fixed orientation directed towards the target. This will facilitates the processing of the information received from sensors that are usually attached to the head link.

When snake robot moves with serpentine gait, orientation of its head link changes sinusoidally and therefore sensory information about front condition is constantly changing during motion. This makes the control more difficult especially in more autonomous snake robots that have to be equipped with different sensors.

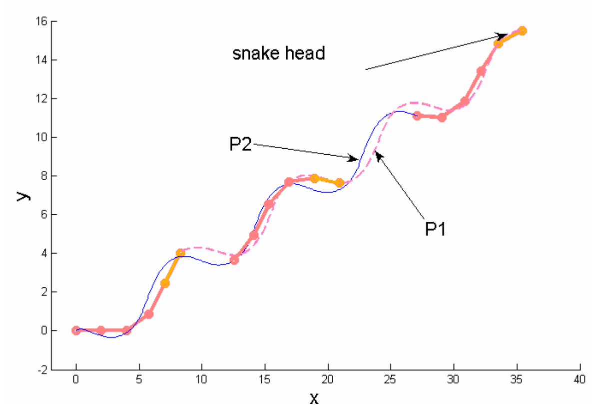

Figure 2. Serpentine gait of snake robot. P1 is path followed by head. P2 is path followed by tail.

In order to solve this problem we propose FHS gait that minimizes the orientation changes of the first link while the remaining links continue to follow a serpentine motion. Therefore, we call this gait, forward head serpentine (FHS) gait because first links moves in a forward direction while all other links move similar to serpentine gait (compare Fig. 2 and Fig. 3.)

Relative angle of adjacent links for driving an *n*-link snake robot to the forward direction in FHS gait is:

$$\theta_i = \alpha \sin(\omega t + (1-i)\beta) \qquad (i = 1,\ldots,n-2) \quad (4)$$

$$\theta_h = \alpha_h \sin(\omega t + \beta_h) + \gamma_h \quad (5)$$

Where θ_h is head link relative angle and n is the number of links. α_h and β_h are maximum angular deflection and phase shift of the head link, respectively. These two parameters have to be found for a given α and β to insure the snake robot head remains approximately parallel to the target direction.

Comparing (3) with (4) and (5) one can find out that locomotion in FHS gait is decoupled into two separate tasks each generated by a separate parts of the snake robot body. Task one uses head link to set the direction of motion by means of steering parameter γ_h(5). Task two uses the remaining links to generate a traveling wave (4) through the body of snake in order to propel the robot to the forward direction.

IV. Finding FHS Gait Parameters

Problem of finding parameters of FHS gait is an optimization problem that can be solve with different methods. In this paper we use genetic algorithm (GA) to solve the problem. GA has widely been used in literature for optimization of complicated dynamics system [10].

GA is an optimization method imitating biological evolution. The target of optimization (FHS gait parameters α_h and β_h) are coded as chromosome and called genotype. Phenotype is the result of decoding of genotype (resultant robot locomotion, in this study) and is evaluated by the use of computer simulations. Genotypes with lower evaluation in gene pool will be deleted from the pool and remaining superior genotypes will succeed to next generation after being processed by genetic operators, i.e. mutation and crossover. By repeating this process, finally chromosomes with high quality can be derived. GA process steps are listed as follows:

Coding - As genotype, we code chromosomes by serially connecting parameters discretized into 16-bit integers within given ranges. The resultant length of chromosomes become 32-bit (α_h and β_h). At the first stage of GA, new chromosomes are created by randomly setting parameters within ranges given to each parameter.

Constraints - Because of mechanical limit of motor rotation angle, parameter α_h is constrained to a maximum value of $\alpha_h \leq \pi/2$. Chromosomes not satisfying these values will be deleted and new random chromosome will be created.

Fitness Evaluating - Fitness function in our study is a function of FHS parameters and is calculated by measuring orientation of the head link during the fixed time of locomotion simulation. The difference between minimum and maximum values of the measured head orientation is defined as fitness value that has to be minimized. In addition to FHS parameters, fitness function depends on environmental conditions as well as α and β. Therefore, for a given (α, β) and environmental conditions (Ct and Cn) we will find FHS parameters (α_h, β_h) that minimizes fitness function.

Selection - Chromosomes are selected using roulette rule based on fitness value. We apply elite preservation method for fast convergence.

Genetic operations - Between remaining chromosomes, crossover and mutation operation is applied. The way of cross over is one-point crossover and mutation is done by randomly reversing bits with a given probability P_m.

V. Results and Discussion

Based on the above-mentioned settings, we optimize FHS gait parameters. GA Conditions are as follow: Population $N=10$, Crossover probability $P_c= 0.5$, Mutation probability $P_m=.01$, Number of generations $G= 100$.

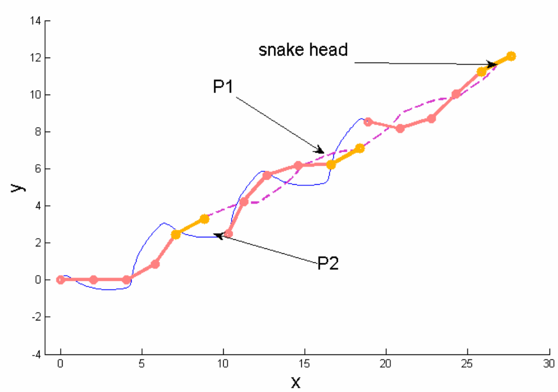

Figure 3. Forward head serpentine gait of snake robot. P1 is path followed by head. P2 is path followed by tail of snake robot.

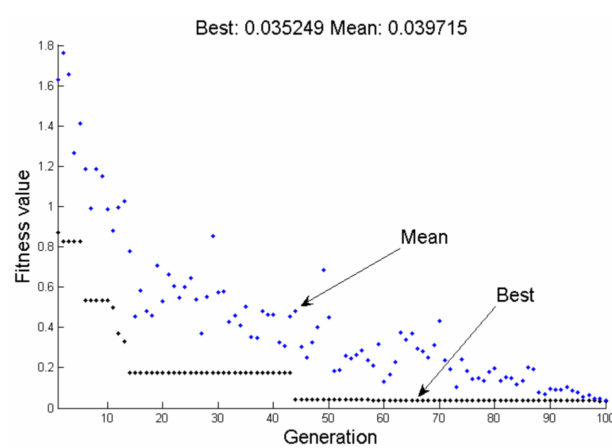

Figure 4. Development of the best and mean value of fitness for every generation.

Development of fitness value for one of the optimizations performed in this study is shown in Fig. 4. In this example we find FHS parameters for a given serpentine gait parameters $\alpha=\pi/6$ rad, $\beta=\pi/3$ rad and $\omega=1$ rad/s. Environmental conditions defined in (1) and (2) are $C_t/C_n = 0.01$. In Fig. 4. "best" and "mean" are the best fitness and mean value of the population, respectively. As it is shown in Fig. 4, after 100 generations best fitness value converges to 0.035 that corresponds to α_h=0.471 rad, β_h=-1.704 rad. Using these FHS parameters, maximum value of orientation change of the head link is only 0.035 radians.

A. Comparing with Serpentine Gait

Two main characteristics of snake robot locomotion are speed of motion and input power. These two characteristics are compared for serpentine and FHS gaits. To find the FHS gait parameters, we must first choose a serpentine gait. Serpentine gait is selected by choosing a desired (α, β). FHS gait will use the given (α, β) for all links except the head link and find the optimum (α_h, β_h) for the head link. Next, a simulation is performed where both gaits are ran with a same amount of time. Robot speed and input power for both gaits are calculated. Environment conditions (Ct, Cn) are also equal for two simulations.

Average velocity is calculated by determining displacement of center of mass (CM) of snake robot during the simulation time. Input power of any actuator, at any time, can be obtained by multiplying input torque by angular velocity of the actuator. We use mean value of these signals as a measure of average of input power for the snake robot.

Results of three sets of simulations are listed in Table I and Table II. Table I shows the FHS parameters calculated by GA and Table II compares input power and speed of snake robot moving with serpentine and FHS gait.

TABLE I. FINDING FHS GAIT PARAMETERS

NO.	α (rad)	β (rad)	α_h (rad)	β_h (rad)
1	$\pi/2$	$2\pi/5$	1.132	-1.268
2	$\pi/4$	$\pi/4$	0.768	-2.076
3	$3\pi/8$	$\pi/8$	1.528	-2.728

TABLE II. COMPARING SERPENTINE WITH FHS GAIT

NO.	Gait	Power (W)	Speed (cm/s)
1	FHS	84.92	60.61
	Serpentine	72.83	68.80
2	FHS	54.87	115.42
	Serpentine	42.50	160.68
3	FHS	216.16	119.16
	Serpentine	239.20	94.68

For all these analysis, simulation time is 50 seconds and friction coefficients ratio is 0.002.

As shown in Table II, in case 1 and 2 velocity of serpentine gait is higher than FHS gait and input power of serpentine gait is less than of FHS gait. Therefore, serpentine gait is likely to be more efficient than FHS. However, this is reversed in case 3 which shows faster speed and lower input power for the FHS gait.

From these results, we cannot derive a general statement regarding velocity and power efficiency advantages of one gait over another. However, generally speaking, we can conclude that there is not a significant difference between these two characteristics for snake robot locomotion.

B. Sensitivity to Environment Conditions

In real world application of snake robot, environment condition is not constant therefore snake robot should be adaptive to different environments. Or at least if it is designed for a specific environment, it should be less sensitive to environmental conditions.

In our case, as was mentioned before we calculate FHS parameters for a specific ratio of friction coefficients. Therefore, we should investigate effectiveness of the designed FHS gait in environments with different friction coefficients.

This is performed by first calculating FHS parameters for a hypothetical environment condition of Ct/Cn=0.01. Next, simulation is ran while C_t/C_n values varies from 0.001 to 0.1. The maximum rotation angle of the head link is calculated. The simulation is repeated for two different FHS parameters. Results are shown in Fig. 5.

As illustrated in Fig. 5, Maximum rotation angle of the head link slightly increases when C_t/C_n increases. In the worst case ($C_t/C_n = 0.1$) maximum rotation angle is approximately 0.14 radians (8 degrees). This means that in the worst case, when snake robot is moving with FHS gait, the head link rotates by a maximum of 8 degrees (±4). Fig. 5 also shows that slope of the two curves P1 and P2 are the same. These results imply that we can extend our conclusion for different serpentine and FHS gait parameters.

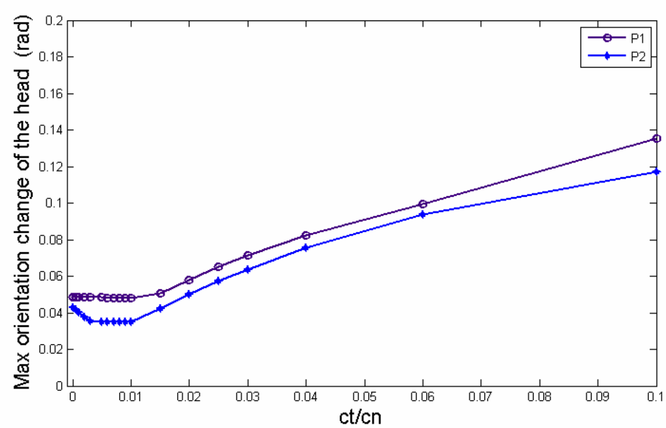

Figure 5. Sensitivity of designed FHS gait parameters to environment condition. P1 (αh=0.471 rad, βh=-1.704 rad, $\alpha=\pi/6$ rad , $\beta=\pi/3$ rad, ω=1 rad/s).P2 (αh=0.768 rad, βh=-2.076 rad, $\alpha=\pi/4$ rad , $\beta=\pi/4$ rad, ω=1 rad/s).

Therefore, we can conclude that FHS gait parameters designed for a specific environment condition can continue to perform well in different environmental conditions.

VI. CONTROL STRUCTURE

In section V, we demonstrated that by using FHS gait, head link is along the direction of robot motion. This feature of FHS gait can help us to construct a simple locomotion control structure that can be easily applied in real world applications. Objective of the proposed control structure is to guide snake robot to target while avoiding obstacles.

A. *Orientation Control Structure*

The proposed orientation control structure consists of two control level. The low level controller is a PID controller that controls input actuator torques of all joints. Its input is difference between desired and actual relative angle of adjacent joints. Every joint has its own PID controller, however, the values for all gains are assumed identical for all controllers. This structure is similar to PID controller commonly used in industrial serial robots. Gains of the PID controller are simply tuned by trial and error

The high level controller controls steering parameter γ and its input is deference between desired and actual head link orientation. Because steering parameter of all joints except head link joint are zero, the high level controller is only applied to the head link joint. Another word, motion direction of the whole snake robot is controlled by head link orientation.

Fig. 6 shows schematic view of the orientation control structure of the head link. The goal of this control structure is to guide the snake robot head to the desired orientation. In Fig. 6, ξ_d is desired orientation of the head link, u is the input torque to the head link joint and θ is relative angle of the head and its adjacent link. The block named T in Fig. 6 generates the command motion variable $\theta_{d,}$ through the time-varying transformation of (5).

Simulation results for a 5-link snake robot are shown in Fig. 7. As illustrated in this figure, robot reaches the desired orientation (ζd=π/2) after about 20 seconds.

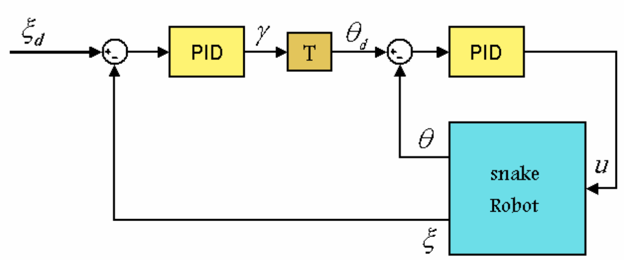

Figure 6. Head link two-level orientation control structure.

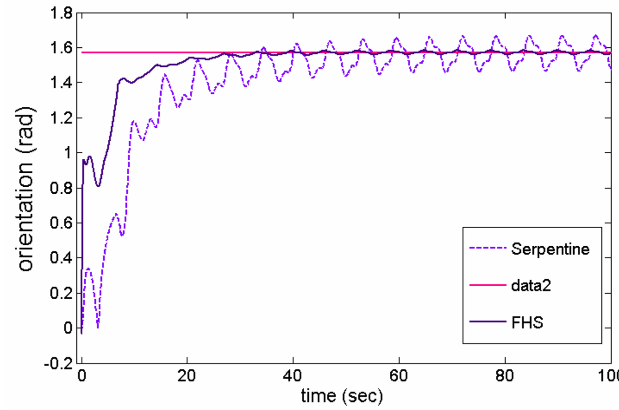

Figure 7. Result of simulation for snake robot moving with serpentine and FHS gait. Desired orientation is π/2.

Fig. 7 also compares results of the snake robot moving by FHS gait as well as serpentine gait while control structure and other parameters are kept equal. As shown, the FHS gait is advantageous over serpentine gait because of its smaller radius of rotation. Another word, by using FHS gait, snake robot can reach its desired orientation quicker than serpentine gait. This is because in FHS gait the steering parameter, γ, is only added to the head link joint.

The proposed control structure can be used to guide snake robot from any initial position to its goal by measuring $\Delta\zeta$ and z variables shown in Fig. 8. Where z is distance between center of mass of the mid (third) link and the goal and $\Delta\zeta$ is relative angle between actual and the goal orientations. In real snake robots, for example in a search and rescue, this information can be obtained by means of sensors that measure location of the victim through using environment temperature.

B. *Adding Obstacle Avoidance Capability*

We divide the basic control goal into two classical behaviors of “target reaching” and “obstacle avoidance”.

"Target reaching" behavior is activated by default and its aim is to guide snake robot to the target. It uses two-level orientation control structure shown in Fig. 6 for orientation control of the head which was explained earlier in the previous section.

"Obstacle avoidance" behavior is activated when an obstacle is sensed by sensor or in our simulation when an obstacle reaches to critical distance of the snake robot ($r \le R_c$).

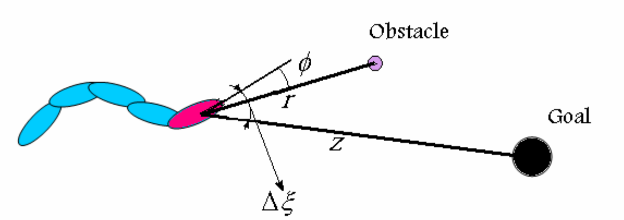

Figure 8. Schematic view of the information to be sensed by snake robot. (φ :relative angle of the obstacle compare to the head. $\Delta\xi$: relative angle of the goal compare to the head) .

When controller switches to "obstacle avoidance" behavior the steering angle for the head link is calculated as follows:

$$\gamma_{obs} = \frac{\gamma e^{cr} + \gamma_{\max} e^{-cr}}{e^{cr} + e^{-cr}} \tag{6}$$

Where r is distance between obstacle and the head, c is a constant that define how fast snake robot turns to avoid obstacle. γ is steering angle which is calculated by the PID controller. γ_{max} is maximum value of γ that corresponds to mechanical limit of the head link joint. When the sensed obstacle is in the left of head link γ_{max} is positive and negative when is on its right hand side.

Equation (6) implies that obstacle has no effect on snake robot motion when is too far from it and its effect gradually increases as snake reaches to obstacle. When obstacle avoidance behavior is activated, γ is substituted by γ_{obs} in control structure of Fig. 6.

In order to apply obstacle avoidance control to real snake robot, one needs to be able to measure parameters φ and r shown in Fig. 8. This can be done by equipping the head link of snake robot with appropriate IR sensors.

Fig. 9 shows the path followed by the robot's center of mass. This illustrates capability of the proposed control structure to guide the snake to reach its target while avoiding obstacle.

VII. CONCLUSION AND FUTURE WORK

In this paper, we introduced a novel gait, FHS gait, for snake robot and compare it with commonly used serpentine gait.

Using the proposed gait, the head of snake robot always remains in the general direction of motion. This allows easier sensing of obstacles in environment and therefore greatly enhances the ease of the information processing.

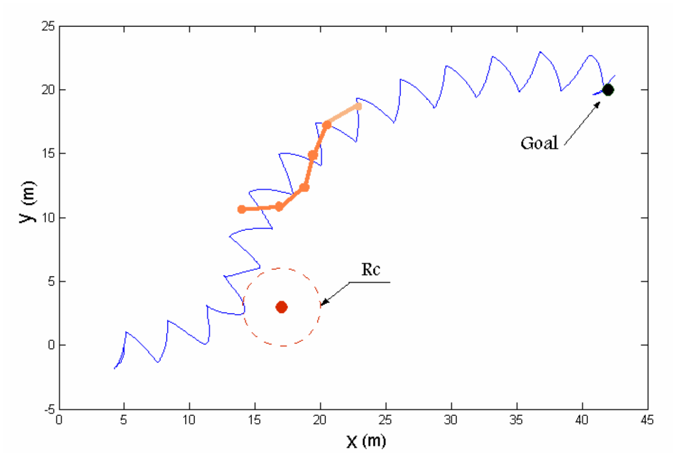

Figure 9. Result of simulation of the proposed control structure. Parameters for this simulation are as follows: c=1, γmax= π/2, Rc =2.5 m).

We next proposed a two-level PID controller to guide the snake robot moving using FHS gait to the target while avoiding obstacles. Simulation results verified the effectiveness of the proposed control structure.

We concluded that in spite of similarity and in some cases less efficiency of FHS gait compare to serpentine gait, in terms of power and velocity, FHS gait is advantageous over serpentine gait for its maneuverability and applicability.

This paper is a step toward construction of an autonomous biologically inspired snake robot with high intelligence that can be used for search and rescue operations.

Future research will focus on optimizing the proposed gait in terms of power and velocity, developing the autonomy and intelligence of the snake robot, and construction an experimental test bed to verify theoretical results.

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