Bio-inspired locomotion for a modular snake robot

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ABSTRACT

Inspired by the snake locomotion, modular snake robots have different locomotion capabilities by coordinating their internal degrees of freedom. They have the potential to access restricted spaces where humans cannot go. They can also traverse rough terrains while conventional wheeled and legged robots cannot. Modular robots have other features including versatility, robustness, low-cost, and fast-prototyping. We have built our first prototype that costs less than $200. In this paper, we describe the electronics architecture of our prototyped robot, and present a model for the locomotion of pitch-yaw snake robots that allows them to perform different gaits. Each mode of the robot is controlled by a sinusoidal oscillator with four parameters: amplitude, frequency, phase, and offset. We show the parameters that achieve snake-like locomotion.

Keywords: Modular robots, snake robots, locomotion control

1. INTRODUCTION

Qualitative research on snake locomotion was first given by Gray in 1946 [1]. Snake robot research began with Hirose's pioneering work in 1972 with the active chord mechanism which was designed to mimic the behavior of real snakes [2]. Research then continues in early 1990's with Chirikjian and Burdick's work on hyper-redundant mechanisms [3]. Modular snake robots, a class of hyper-redundant mechanisms, have different locomotion capabilities by coordinating their internal degrees of freedom. Because of locomotion capabilities, traversing through rough terrain becomes possible for modular snake robots, while it is difficult for conventional wheeled robots and legged robots. Features of modular snake robots include that they are versatile, and their motion is not limited to crawling, climbing [7], [10], but also swimming [9]. Robustness is another advantage of modular snake robots. They are robust to uncertainties due to modular and hyper-redundant mechanisms. Besides, low-cost and fast-prototyping are also important features. Those features empower modular snake robots to have great potential in military, civil, and commercial applications.

Our modular snake robot consists of eight one –degree-of-freedom modules. Eight modules are connected in a pitch-yaw way that allows the modular snake robot to locomote in all three dimensions and achieves complicated gaits and behaviors. Each joint of the robot is controlled by a sinusoidal oscillator with four parameters: amplitude, frequency, phase, and offset. We describe our prototyped snake robot in the paper, and focuses on the locomotion capability. We present the locomotion model, and describe the parameters that achieve snake-like locomotion.

The reminder of this paper is organized as follows. In Section 2, some relevant projects are described. In Section 3, we describe our prototyped robot, including hardware and electronics architecture. In Section 4, we present a model for the locomotion of pitch-yaw snake robots, and show locomotion capabilities. In Section 5, we introduce simulation platform for locomotion control. Finally, conclusions are mentioned in Section 6.

2. RELATED WORK

A variety of hyper-redundant snake-like robots can be lumped into two main categories. Some researchers, such as Yim [4], Miller [5], and Howie Choset [6], [7], have extended Hirose's work on snake robot

Bio-Inspired/Biomimetic Sensor Technologies and Applications,
edited by Nicholas F. Fell Jr., Venkataraman S. Swaminathan, Proc. of SPIE Vol. 7321,
73210E · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.820257

locomotion with undulatory mechanisms. All of these robots are undulatory in the sense that the mechanism uses its internal degrees of freedom to propel itself forward. Yim presented a class of three-dimensional snake-like robot- PolyBots [11], which are versatile modular robotic systems that feature one degree of freedom joints. One novelty of PolyBot (G2) is that the modules have the ability to automatically attach and detach from each other, making the system self-reconfigurable like a transformer. PolyBots have an excellent performance in self-reconfigurable. The interchangeable modules allow the robot to support a number of configurations which include snake, spider, and rolling modes. Gonzalez-Gomez et al. [21] presented a modular worm-like robot, named Cube in 2004. This is the simplest kind of modular robot, composed of 8 equal linked modules (1-modular robot). The locomotion is achieved by the propagation of waves that travel through the robot, from tail to the head. The entirely locomotion controller is embedded into an FPGA. Our modular snake robot also achieved locomotion by coordinating their internal degrees of freedom. Each module of the snake robot has a similar design as PolyBot (G1). We focus on robustness and reliable locomotion capabilities. Several gaits have been achieved: forward, backward, lateral shifting, rolling, rotating and gap crossing. Locomotion capabilities show that modular snake robots can be applied to tasks in complex environments.

The other category of snake robots includes those using some sort of surface mounted wheels or tracks to move the body, such as Active Cord Mechanism (ACM) [8], which was developed by Hirose. Hirose's group has developed the snake-like robot since 1972. Recently, they presented ACM-R3 [18], which is a new version of the ACM with three-dimensional mobility. This ACM-R3 is equipped with large passive wheels that wrap its body overall, and has frictional characteristics similar to snake-like skin. It is also equipped with radio control servomotors with gears added to them, held tightly by shell frames, so that it can move steadily and with high power. The various locomotion methods realized by 3- dimensional ACM-R3 are divided into three types. The first type gaits are generated by a shift control system, including serpentine, sinus-lifting, pedal wave, and side-winding. The second type gaits are generated by the rolling control system, including lateral rolling and lateral walking. The third type gaits are generated by those compositions, including lean serpentine, lean sinus-lifting and lift rolling.

Other snake-like robots achieve locomotion by tread [12], [19], toroidal skin drive mechanism [13]-[16], or internal shape changes [17]. McKenna's group introduces an alternative approach to snake robot locomotion, a toroidal skin drive (TSD), in which the entire surface of the robot provides continuous propulsive force to significantly improve speed and mobility in different environments. The TSD system consists of an elongated toroidal skin that covers the entire length of the robot, and a driving unit that propels the skin. The outer (tubular) layer of the skin slides axially from the head to the tail of the snake robot, and wraps inside itself over a captured ring at the tail. The skin then recirculates from the tail to the head (through the center of the outer tubular layer), and changes direction again (over a second captured ring at the head) to again become the outside layer. In this configuration, the skin forms a continuous toroidal loop. The driving unit produces the sliding action of the skin through rolling contact with the inner (recirculating) layer of the toroidal skin via friction. A number of qualitative experiments were conducted to test and demonstrate the system capabilities, such as gap crossing, brush navigation, stair climbing, hole entry, and vertical pipe climbing.

3. SNAKE ROBOT PROTOTYPE

We design a modular snake robot with eight rigid links connected by one –degree-of-freedom modules. Eight modules are connected in pitch-yaw way that each module's axis of rotation rotates ninety degrees from the previous module. Based on this design, the modular snake robot can locomote in all three dimensions and implements gaits, including forward and backward, lateral shifting, rolling, rotating, and gap crossing. The primary mechanical component of the snake robot is the module. Each module functions as a single rotational joint with one degree of freedom. Considering the module of the robot, we partition modules into horizontal group and vertical group. Each joint is actuated by a servo. According to the desired gait, each servo is given a series of control parameters, including amplitude, frequency, phase and offset. We discuss the control parameters to achieve various locomotion types in the next section. Fig. 1

shows our first prototype of the robot.

3.1 Servos

The main component of the module is the servo. The servo is used to control one degree of freedom in each module. We select Futaba S3003 Standard Servo as the servo. Servos utilize an electric motor, a gear train, and electronics to control the motor according to outside commands. The output shaft protrudes from the servo and has a range of motion between negative 90 and positive 90 degrees relative to center in .16 sec / 60 degrees speed. The module is a joint in which the servo creates half of the structure and provides the torque to move and maintain angles while resisting forces from the environment. High quality servo will be adopted when snake robots need high torque to achieve some complicated gaits. The parameter of torque will play an important role in achieving combined gaits. The other vital parameter is speed. Because the speed alters as the voltage goes down which will cause the snake robot fails to achieve the desired gaits. This phenomenon should be avoided through keeping the voltage constant.

3.2 Modules

Our modular snake robot consists of eight modules. Each module has a similar design as PolyBot (G1) [20]. Fig. 2 shows the module. It has just one degree of freedom, actuated by a Futaba S3003 RC servo. The dimensions of each module, in its center position, are 65 x 65 x 83mm, and the weight is 70gr. They are made out of PVC. The rotations range is between negative 90 and positive 90 degrees. The robot is 622 mm in length and 530gr in weight. The electronic and power supply are located off-board. In this first version, there is an infrared sensor embedded on the front module for detecting obstacles. Sensors can make the robot adaptive and intelligent. In this paper, we focused on the study of locomotion capabilities.

Modules cost less and are very easy to be assembled. We have built our first prototype that costs less than $200. For fast-prototyping, the simple way to build prototype of a worm-like robot is that two adjacent modules have the same orientation. Therefore modular snake robots have these two attractive features, low-cost and fast-prototyping. Furthermore, we can see two other features of modular snake robots, versatility and robustness. In pitch connection, all the articulations of the worm-like robot are in the same plane, perpendicular to the ground so that it can move along a line, forward or backward. Eight modules of our snake robot are connected in pitch-yaw that enables the modular snake robot to move in all three dimensions. Also, our modular snake robot can still achieve some gaits in condition of the failure of one module.

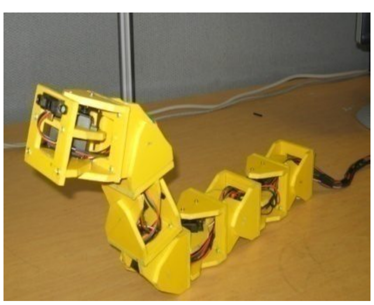

Fig. 1. Our modular snake robot

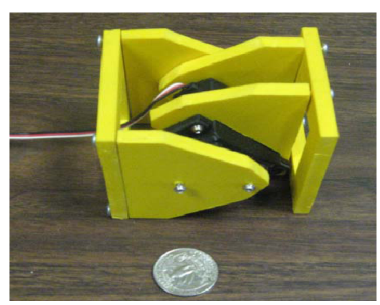

Fig. 2. A snake robot modul

3.3 Electronics architecture

The robot is controlled by two Microchip microprocessors. One processor controls all the servos to implement different gaits and the other processor deals with sensors. These two microprocessors can work independently or dependently. A personal computer coordinates the distributed system made up of the modules in the snake. Two microprocessors communicate with PC via Inter-Integrated Circuit (I2C) bus.

I2C performs chip-to-chip communications using only two wires in a serial interface, allowing ICs to communicate with fewer pins. The two wires in the I2C Bus carry addressing, selection, control, and data, one bit at a time. The Data (SDA) wire carries the data, while the Clock (SCL) wire synchronizes the sender and receiver during the transfer. A schematic diagram of the control system is shown in Figure 3. The master microprocessor can determine when to send or receive data from the slave microprocessor. Meanwhile, the master microprocessor may exchange data with the PC and transfer command from the PC to the slave microprocessor.

In our first prototype, only one sensor, an infrared distance detector, is embedded on the front of the modular snake robot. It is capable of measuring the distance between itself and an object that is within a distance range of 10cm to 80cm .We use the infrared distance sensors to achieve obstacle avoidance. When the distance between the robot and obstacle is within 30cm (safe distance), the master microprocessor will send an interrupt message to the slave microprocessor to suspend the robot and then trigger another detection which gets information from the left and the right directions. After comparison, the robot will shift laterally to the direction without obstacles and then move forward again.

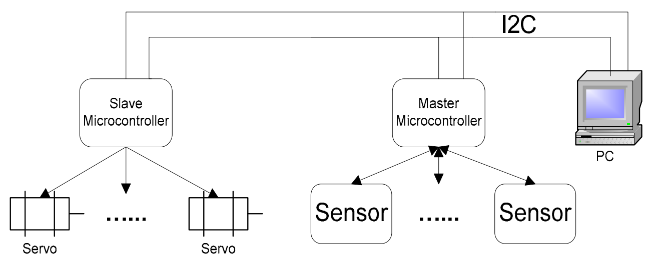

Fig. 3.Block diagram of control system

4. SNAKE ROBOT LOCOMOTION

Real snakes could use several unique modes of terrestrial locomotion. The type of locomotion a snake uses depends on environments. It can choose proper locomotion gait that is adaptable to the surface on which it is crawling, and the speed to travel. We were inspired by the biological gaits of the typical locomotion modes of snakes, namely lateral undulation, sidewinding, concertina, rectilinear, and slide-pushing, when designing our robotic gaits. The locomotion mode of our snake robot is simple undulation, which is characterized by waves of lateral bending being propagated along the body from head to tail. The bends push laterally against surface objects, but do not deform locally around them, and usually slip out of contact quickly. Based on simple undulation, our modular snake robot successfully achieved several locomotion gaits.

As we stated in Section 3, each module is controlled by a sine wave signal. Modules are partitioned into horizontal group and vertical group. Base on locomotion principles presented by Gonzalez-Gomez et al. [22], a general equation for depicting snake locomotion can be written as:

$$\begin{cases} \theta_{vi} = A_{ver}\sin(\omega_{ver}t + (i-1)\delta_{ver}) + O_{ver} \\ \theta_{hi} = A_{hor}\sin(\omega_{hor}t + (i-1)\delta_{hor} + \delta_0) + O_{hor} \end{cases} \tag{1}$$

where the subscript vi denotes the ith actuated joint of the vertical group, the subscript hi denotes the ith actuated joint of the horizontal group, and ver, hor represent the vertical and horizontal directions, respectively. The parameters θ_{vi} and θ_{hi} are the rotation angle about the vertical and horizontal axis of ith actuated joint, respectively. The parameter A is the amplitude, ω is the angular frequency, δ is the phase difference between modules, O is the phase offset, and δ_0 is a phase difference between the vertical and the horizontal wave.

The amplitude, A , describes the amplitude of each module. In most gaits, the amplitude and speed of the robot are directly correlated and both increase. However, larger amplitude waves cause the robot's center of gravity to rise which reduces the stability of the robot. The frequency of the sine wave is determined by ω . The same as the amplitude, the frequency is directly proportional to the speed of the snake robot. In order to get a high moving speed, we could properly increase the frequency of the sine wave signals. But, exceeding frequency may damage the servo. The offset parameter, O , is generally used to implement turning gait. We usually set the offset to zero when the robot fulfills other gaits. δ is simply the phase offset to control the timing between the motions of the two orthogonal waves. δ_0 is the phase difference between the vertical and the horizontal wave. It is a very important parameter for the gaits which need to coordinate vertical and horizontal groups, such as lateral shifting, rolling, and rotating. The modular snake robot shows locomotion capabilities through adjusting these control parameters. Many different gaits are obtained by modifying these parameters.

4.1 Forward and backward

Forward and backward are inspired form the rectilinear locomotion, which is a mode of locomotion most often associated with snakes. Rectilinear locomotion is a movement in a straight line. In rectilinear locomotion, the snake's belly scales are alternately lifted slightly from the ground and pulled forward, and then pulled downward and backward. In order to achieve forward and backward gaits, vertical joints have identical waves with $\delta = 120^0$. The amplitude of the horizontal joints is set to zero so that only the modules of the vertical axis execute a sine wave. Modules move sequentially from the rear of the robot to the front. Each vertical module alternately lifts slightly from the ground and pulls forward, and then pulls downward and backward. Fig. 4 shows experiments on forward and backward gaits. The parameters A and ω determine the speed of the robot. Although larger amplitudes and frequencies generate faster locomotion, we prefer to select proper sine waves for stability purposes. For instance, on the slippery ground, we may increase amplitude and decrease frequency. On the contrary, if the snake robot moves on the sticky ground, we may decrease amplitude and increase frequency.

4.2 Lateral Shifting

Sidewinding is another biological gait that has inspired our robot gaits-lateral shifting. Lateral shifting enables the robot to move in perpendicular direction (Fig. 5.). With $\delta_{ver} = 120^0, \delta_{hor} = 120^0$, vertical and horizontal sine waves interact to locomote the snake sideways, orthogonal to its length. Through modifying the value of δ, we can control the angle at which the snake robot moves sideways. The snake robot could travel diagonally.

4.3 Rotating

Rotating is a kind of lateral shifting. Identical vertical and lateral waves, with $\delta_{ver} = 120^0, \delta_{hor} = -120^0$, are used to perform rotating gait. In this case, the front and back halves of the snake robot move in opposite directions so that the robot rotates parallel to the ground clock-wise or counter-clockwise, as seen in Fig. 6. This gait is utilized to implement changing direction or turning.

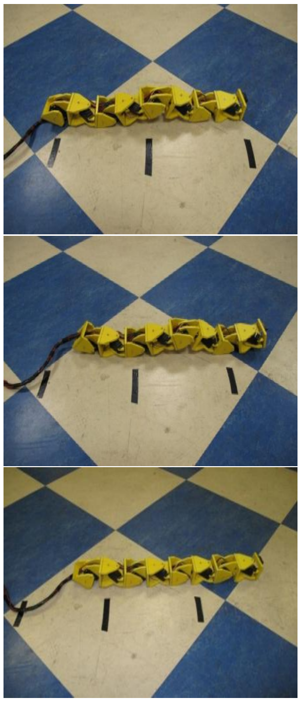

Fig. 4. Forward gait

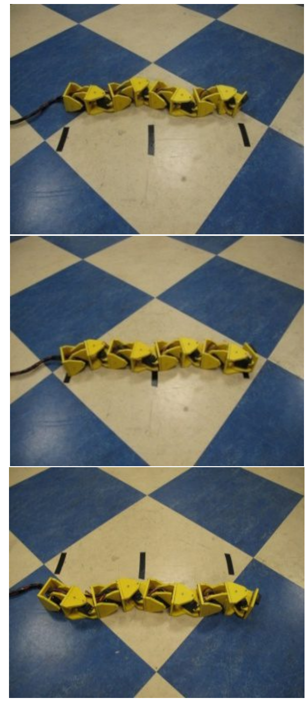

Fig. 5. Experiments on lateral shift gait

4.4 Rolling

Rolling gait is not inspired by biological snakes. It is a particular gait which could reinforce stability of the system. When the robot moves in a rough terrain and turns over accidently, it can go back to stabilize itself by using this gait. To achieve this gait, δ_{ver} and δ_{hor} are set to zero so that each axis always keeps to an arc. δ_0 is the phase difference between the vertical and the horizontal waves. When $\delta_0 = 90^0$, a full offset is set between the waves of two axes. As shown in Figure 7, the snake robot rolls side over side across the ground. As δ_0 decreases, the lateral moving speed of the snake robot decays. The snake robot rolls around its body axis but almost has no displacement at $\delta_0 = 30^0$.

4.5 Gap Crossing

Gap crossing is a very useful locomotion gait. It makes the snake robot more adaptable to complicated environments. Forward gait is used to drive the robot over the edge of the gap. The modules that are overhanging the gap are bent downwards into the gap. Once enough modules are down in the gap, the snake robot will not stop moving forward until these extended modules make contact with the ground on the other side of the gap, so that the robot has successfully crossed the gap. After several tries, we found that large amplitude is helpful to achieve gap crossing gait successfully. Fig. 8 shows the processes of gap crossing gait. Based on the dimensions of the module, this gap crossing gait is effective for any gap shorter than 300mm (approximate half length of the robot).

The control parameters for each gait discussed above are summarized in Table 1.

Gait	A	ω	δ	δ_0	O
Forward	$A_{ver}=60^0$ $A_{hor}=0$	$\omega_{ver}=\frac{5}{6}\pi/s$ $\omega_{hor}=0$	$\delta_{ver}=\frac{2}{3}\pi$ $\delta_{hor}=0$	$\delta_0=0$	$O_{ver}=0$ $O_{hor}=0$
Backward	$A_{ver}=60^0$ $A_{hor}=0$	$\omega_{ver}=\frac{5}{6}\pi/s$ $\omega_{hor}=0$	$\delta_{ver}=-\frac{2}{3}\pi$ $\delta_{hor}=0$	$\delta_0=0$	$O_{ver}=0$ $O_{hor}=0$
Lateral Shifting	$A_{ver}=30^0$ $A_{hor}=30^0$	$\omega_{ver}=\frac{5}{6}\pi/s$ $\omega_{hor}=\frac{5}{6}\pi/s$	$\delta_{ver}=\frac{2}{3}\pi$ $\delta_{hor}=\frac{2}{3}\pi$	$\delta_0=0$	$O_{ver}=0$ $O_{hor}=0$
Rolling	$A_{ver}=60^0$ $A_{hor}=60^0$	$\omega_{ver}=\frac{5}{6}\pi/s$ $\omega_{hor}=\frac{5}{6}\pi/s$	$\delta_{ver}=0$ $\delta_{hor}=0$	$\delta_0=30^0$	$O_{ver}=0$ $O_{hor}=0$
Rotating	$A_{ver}=45^0$ $A_{hor}=45^0$	$\omega_{ver}=\frac{5}{6}\pi/s$ $\omega_{hor}=\frac{5}{6}\pi/s$	$\delta_{ver}=\frac{2}{3}\pi$ $\delta_{hor}=-\frac{2}{3}\pi$	$\delta_0=0$	$O_{ver}=0$ $O_{hor}=0$

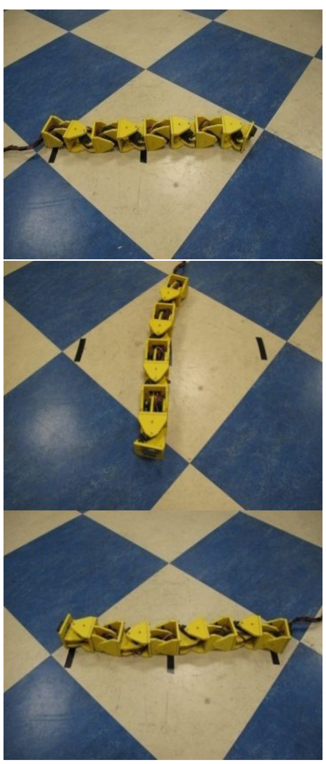

Fig.6. Experiments of rotating gait

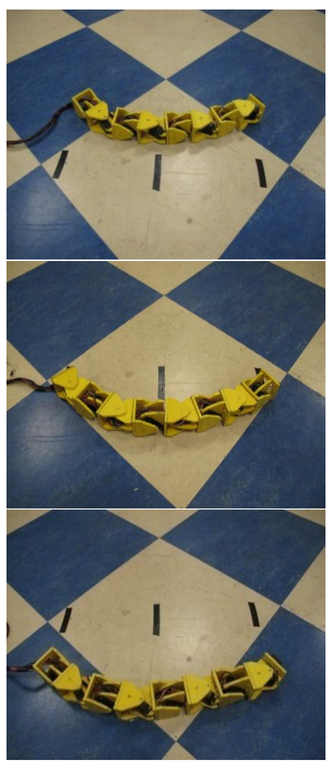

Fig. 7. Rolling gait

Fig. 8. The modular snake robot is crossing a gap

5. SIMULATION PLATFORM FOR LOCOMOTION CONTROL

We use Webots as a simulation platform to study locomotion control. Webots is a professional mobile robot simulation software package. It offers a rapid prototyping environment, which allows the user to create 3D virtual worlds with physics properties such as mass, joints, friction coefficients, etc. A software application has been developed to both simulate the modular robots and control of the real prototypes. Webots relies on ODE, the Open Dynamics Engine, for physics simulation. Also, Webots can use any GUI (graphical user interfaces) library for creating user interfaces for controllers (including GTK+, wxWindows, MFC, etc.).All the data generated during the simulations can be dumped into a Matlab/Octave file for processing and drawing.

We test control parameters on the prototype which we build in Webots. Through observing performance, we select control parameters. So far, we use trial and error to get a good performance for each gait. Recently, some researchers use central pattern generators (CPGs) for locomotion control of animal-like robots [28]-[30]. CPGs are neural networks capable of producing coordinated patterns of rhythmic activity without any rhythmic inputs from sensory feedback or from higher control centers. Ijspeert presented swimming and walking locomotion of salamander [23]. Kimura realized quadruped walking robot adaptable to outdoor environment using a controller with a CPG and reflex arcs [24]. Also, some groups study the control of locomotion of snake-like robots with CPGs [25]-[27]. In the future, we will find a better gait generation approach suitable to our prototype. Not only can the control method generate optima control parameters for a desired gait, but also it can guide us to discover new gaits.

6. CONCLUSIONS

In this paper, we describe the electronics architecture of our prototyped robot and its locomotion capabilities. The modular snake robot is implemented by coordinating their internal degrees of freedom. Several gaits have been achieved: forward, backward, lateral shifting, rolling, rotating and gap crossing. We have implemented the gaits mentioned above and presented the relationship between different phases and the locomotion types. Locomotion capabilities demonstrated that modular snake robots using biologically inspired gaits can access constrained space in complicated environments. The successful performance of our first prototype robot confirms the locomotion capabilities of pitch-yaw-connecting modular snake robots.

ACKNOWLEDGMENT

The work was supported in part by US Army contract W15QKN-05-D-0011.

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