Locomotion Capabilities of a Modular Robot with Eight Pitch-Yaw-Connecting Modules

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Abstract— **In this paper, a general classification of the modular robots is proposed, based on their topology and the type of connection between the modules. The locomotion capabilities of the sub-group of pitch-yaw connecting robots are analyzed. Five different gaits have been implemented and tested on a real robot composed of eight modules. One of them, rotating, has not been previously achieved. All gaits are implemented using a simple and elegant central pattern generator (CPG) approach that simplify the algorithms of the controlling system.**

I. Introduction

The last few years have witnessed an increasing interest in modular reconfigurable robotic technologies. The applications include industrial inspection[1], urban search and rescue[2], space applications[3] and military reconnaissance.

Modular robots are very interesting for research purposes. New configurations can be built very fast and easily, for the exploration, testing and analysis of new ideas. Therefore, fast robot prototyping is another important characteristic of modular robotics, in addition to versatility, robustness and low cost[4].

A general classification of the different configurations of modular robots is essential for the study of their properties. This is not easy because of the infinite number of prototypes that can be built. It is even worst due to the exponential growths of the number of configurations with the modules. As much modules are used, much more configurations are possible. Therefore, a classification is needed to group the configurations and to analyze the properties of the sub-groups.

Such classification is proposed in this paper, based on the topology of the robots and the type of connection between the modules. It is further developed in section II.

The sub-group of pitch-yaw connecting robots are very interesting because they feature snake's structure. Some researchers have studied the locomotion properties of these robots. A deeply analysis was performed by Dowling[5]. He focused on learning techniques to move the snake robots. He simulated different gaits: side-winding and rolling among others. Very interesting conclusions are obtained, but the results are not easy to implement on a real robot.

Mori[6] achieved different kinds of lateral rolling gaits on ACM-R3 robot and Chen[7] studied it deeply and proposed to use it in pitch-yaw connecting robots to cross over obstacles. Stoy et al.[8] tested the side-winding gait in a pitch-yaw configuration composed of Conro Modules[9]. A very interesting simulation of the side-winding gait generated by means of genetic programing was achieved by Tanev[10].

For the control algorithm, the CPG approach has been successfully implemented on some modular robots, like Amphibot II[11], Yamor[12], M-TRAN[13] and also on non-modular robots like Aramies[14].

In this paper we focused on finding the locomotion capabilities of the pith-yaw configurations in general, using a sinusoidal CPG approach that can be implemented easily in an eight-bit microcontroller. A pitch-yaw connecting modular robot with eight modules have been built for testing. Five different gaits have been achieved on the real robot. One of them, the rotating gait, is a new one that has not been previously performed in other similar robots, from the best of our knowledge.

In previous work we have studied the pitch-connecting configurations[15] and the locomotion capabilities of 1D and 2D minimal configurations[16].

II. A general classification of the modular robots

A new classification of modular robots is proposed, based on their topology and the connection between adjacent modules. The diagram is shown in Fig.1. Some previous ideas of other researchers are included.

Mark Yim and other researchers at Palo Alto Research Center (PARC) established a first classification of modular robots in two groups: lattice and chain robots. The former arranges modules to conform a grid, just like atoms conforming complex 3D molecules or solids. Examples of this robots are:[17][18][19]. One of the promise of this kind of robots is building solid objects, like a cup or a chair, and then rearranging the atoms to form another solid. The latter structures are composed of chains of modules. For example, the structure of a four legged robot can be thought as five chains. A chain act as the main body (or the cord) and another four chains conform the legs. Chain robots are suitable for locomotion and manipulation since the modular chains are like legs or arms.

A new sub-classification of chain robots according to its topology is proposed. Three new sub-groups appear: 1D, 2D or 3D chain robots (Fig. 2) . If the robot consist of a series chain of linked modules, the topology is a 1D chain. Two or more chains can be connected forming 2D topologies like triangles, squares, stars and so on. All these configurations can be fitted into a plane (when they are in its home state). Finally, the chains

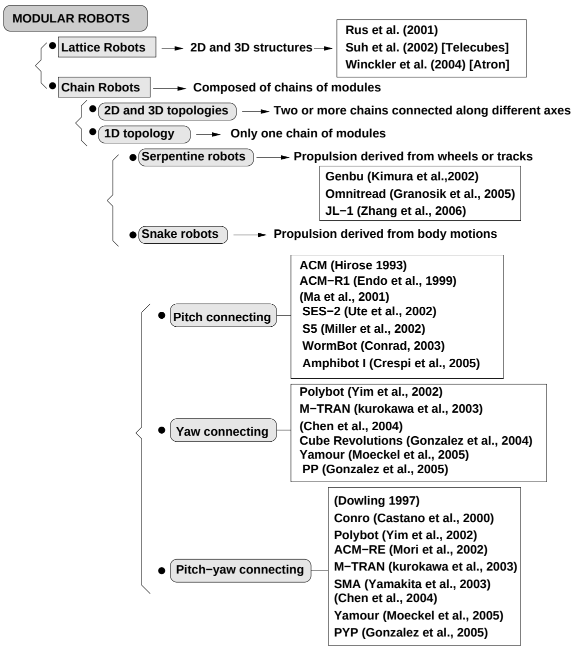

Fig. 1. General classification of modular robots

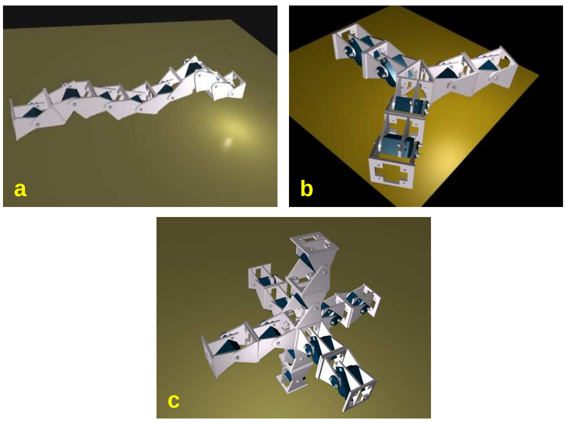

Fig. 2. Examples of the three sub-types of chain robots: a) 1D topology. A structure with only one chain of modules. b) 2D topology: a star structure, composed of three chain of two modules. c) 3D topology. A robot composed of six chains of two modules.

can be connected so that they do not fit into a plane, forming a 3D topology like a cube, pyramid, 3D star and furthermore.

1D chain robots are like snake, worms, legs, arms or cords. They can blend their bodies to adopt different shapes. They are suitable for going though tubes, grasping objects and moving in rough terrain. If the length is enough, they can form a loop and move like a wheel. 2D and 3D chain robots can move by body motions or using legs. In general, they are more stables, because they can have more points contacting with the ground.

The family of 1D chain robots can be divided into two groups. Granosik et al.[1] propose to call them serpentine and snake robots. The former have wheels or tracks for propulsion and the latter are propelled by body motions (this group also include the robots that

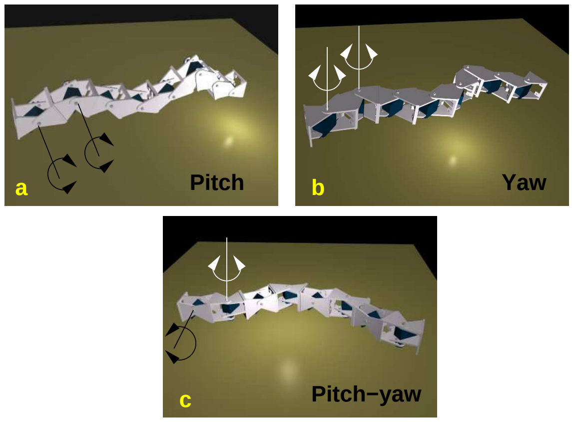

Fig. 3. Different connections for a snake robot. a) Pitch connecting. All the modules rotate around the pitch axis. b) Yaw connecting. The modules rotate around the yaw axis. c) Pitch-yaw connecting modules. Some modules rotate around the pitch axis, and others around the yaw.

have passive wheels to contact with the ground). Examples of serpentine robots are Omnitread[1], JL-I[20] and Genbu[22]. Serpentine robots can also have active joints which enable them to propel themselves using body motions, even if the primary propulsion system is a special driving wheels. The principles of the locomotion of snakes robots can be applied to them too. For example, the JL-I robot can perform a lateral shift and rotating gait which are developed for a snake robot.

Snake robots can also be divided in three sub-groups according to the connection axis between two adjacent modules: pitch connecting, yaw connecting and pitch-yaw connecting (Fig. 3).

The yaw-connecting snake robots move like the real snakes. All the joints rotate around the yaw axis, propelling the robot like a real snake. In order to get propelled, these robots creep along a given curve path, but the body should slip in the tangential direction without any sliding in the direction normal to the body axis. These conditions are met with passive wheels, but another type of special skin can be used. There have been an active research on these robots. Yaw-connecting robots were first studied by Hirose[23]. He developed the Active Cord Mechanism (ACM). A new version, ACM-R1 was developed in [24].

Ma et al. also developed his own yaw-connecting robot and studied the creeping motion on a plane[25] and on a slope[26]. Another prototypes are SES-2 [27], S5 [28], WormBot[29] and Amphibot I[11], which has been designed for swimming.

The pitch-connecting robots only can move in 1D, forward or backward. Its movement can be generated by means of waves that travel the body of the robot from the tail to the head. The robots move in different ways according to the wave parameters (amplitude, frequency, wavelength...). Although the pitch-connecting structure is one of the simplest configuration, it can perform a simple self-reconfiguration, for example forming

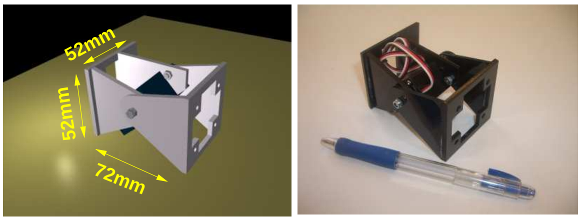

Fig. 4. The Y1 module. A very cheap and easy to build module.

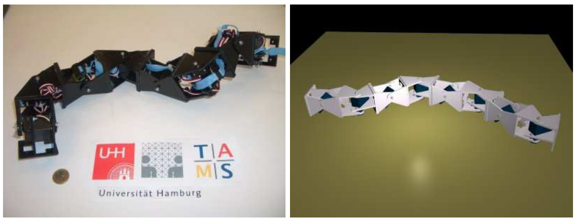

Fig. 5. The pitch-yaw-connecting modular robot built to test its locomotion capabilities (Image on the left). It is composed of 8 linked modules (image on the right).

a loop and moving like a wheel. In previous work, we have studied deeply this type of structures[15]. Other modular robots can be connected in this way like Polybot[4], M-TRAN [13], Yamour [12], and the robot developed in the Robotics Laboratory of Shenyang Institute of Automation [7].

The pitch-yaw-connecting modular robots have some modules that rotates around the pitch axis and others around the yaw axis. These robots have new locomotion capabilities, like side-winding, rotating and rolling. Some pitch-yaw-connecting robots has modules with two DOF, like the Conro modules[9]. Others have one DOF and can only be connected in a pitch-yaw way, like ACM-R3 [6], SMA[30]. Some modules can be connected both in pitch-pitch and pitch-yaw configurations: Polybot[4], M-TRAN [13], Yamour [12], and [7]. This characteristic makes the modules more versatile.

III. An overview of the new pitch-yaw connecting modular robot

A. Mechanics

A pitch-yaw connecting modular robot has been developed for locomotion testings. The prototype is based on the Y1 module (Fig 4), which has been also used for building a worm-like robot[15] and some minimal configurations[16] in previous work. It is a very cheap and easy to build module. It only have one degree of freedom, actuated by an RC servo. There are two connection surfaces for attaching another modules. The rotation range is 180 degrees.

The robot consists of eight modules connected in a chain (Fig. 5). Four of them rotate around the pitch axes and the other four around the yaw axes respectively (The basic connection is shown in Fig. 6). Two adjacent modules are connected rotating 90 degrees so that one moves around the pitch axis and the other around the yaw axis.

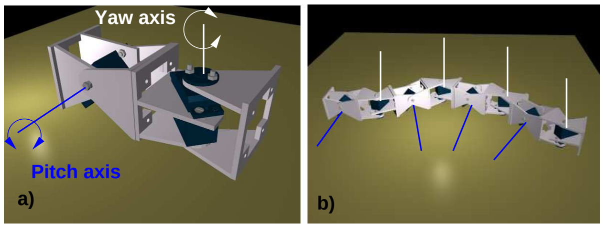

Fig. 6. a) Two Y1 modules in a 90 degrees connection. The modules rotates around the pitch and yaw axes respectively. b) The robot is made of four of this basic unions between the modules.

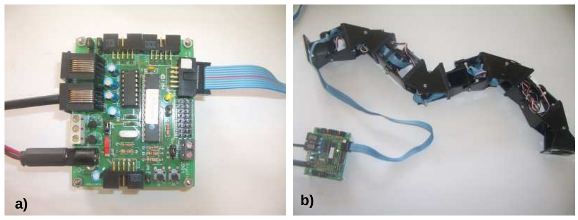

Fig. 7. a) the PIC16F876 based controller used . b) The electronic is connected to the robot by a cable.

B. Control hardware

The electronic and power supply are located off-board. Y1 modules have been designed for fast prototyping and for the study of the locomotion capabilities of the modular robots. All the locomotion algorithms are executed on a PC that communicates with the electronics by RS-232 connection.

The hardware comprises a small board based on the 8-bit PIC16F876 microcontroller (Fig. 7). It is in charge of generating the pulse width modulation (PWM) signals that position the servos. Software in the PC send the desired position of the servos to the control board where the PWM signals are generated. The control is in open loop. There is no feedback from the servos.

IV. Control approach

The control of the robot is based on CPGs to produce rhythmic motion. One CPG per module is used

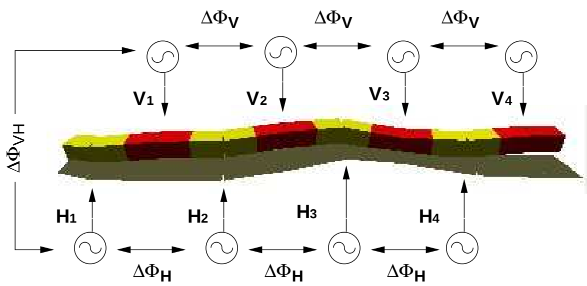

Fig. 8. A graphical representation of the control approach. Eight sinusoidal CPGs are used to control the rotation angle of each module. They are divided into two groups: horizontal(H_i) and vertical(V_i)

to control the variation of the rotation angle.

In our previous work with minimal configuration[16], sinusoidal signals were used for controlling each joint. This simplified CPG produce very smooth movements and has the advantage of making the controller much simpler. Our model of CPG is described by the following equation:

$$p_i = A_i \sin\left(\frac{2\Pi}{T_i}t + \Phi_i\right) + O_i, \;\; i \in \{1, 2, ..8\} \qquad (1)$$

Where p_i is the position angle of the articulation i. For each CPG there are four parameters: the amplitude A_i, the period T_i, the phase Φ_i and the offset O_i. As there are eight CPGs, the total number of parameters is 32. In order simplify the study of the locomotion principles, a number of assumptions are applied:

- All the modules move with the same period: $T_i = T$
- The modules are divided in two groups: vertical and horizontal modules. There are four joints per group (V_i, H_j with $i, j \in \{1, 2, 3, 4\}$).
- All the vertical and horizontal modules have the same amplitude A_V,A_H respectively.
- All the vertical and horizontal modules have the same offset O_V,O_H respectively
- All the vertical and horizontal modules have the same phase difference between two adjacent modules $\triangle\Phi_V$, $\triangle\Phi_V$ respectively
- Between the vertical and horizontal modules the phase difference is $\triangle\Phi_{HV}$

All these assumptions mean that there are two groups of CPGs, one for controlling the pitching modules and the other for the yawing modules, as shown in Fig. 8. Therefore, there are only 8 essential parameters for specifying the gaits: A_V,A_H,$\triangle\Phi_V$, $\triangle\Phi_H$,$\triangle\Phi_{HV}$,O_V,O_H and T. The equations for these two groups are now:

$$V_i \;\; = \;\; A_V \sin\left(\frac{2\Pi}{T}t + (i-1)\Delta\Phi_V\right) + O_V \qquad (2)$$

$$H_j = A_H \sin\left(\frac{2\Pi}{T}t + (j-1)\Delta\Phi_H + \Delta\Phi_{VH}\right) + O_H \qquad (3)$$

V. Locomotion capabilities

The simulation has been programmed using the Open Dynamics Engine[31] (ODE) physical engine, in C language. Five different locomotion gaits have been achieved using the sinus-CPG model described in section IV. The values, ranges and restriction of the eight essential parameters that characterize the different gaits are given.

The values of the Amplitudes A_V, A_H, if not specified, can vary from 0 to 90 degrees. The period (T) has been set to 20 units for all the gaits.

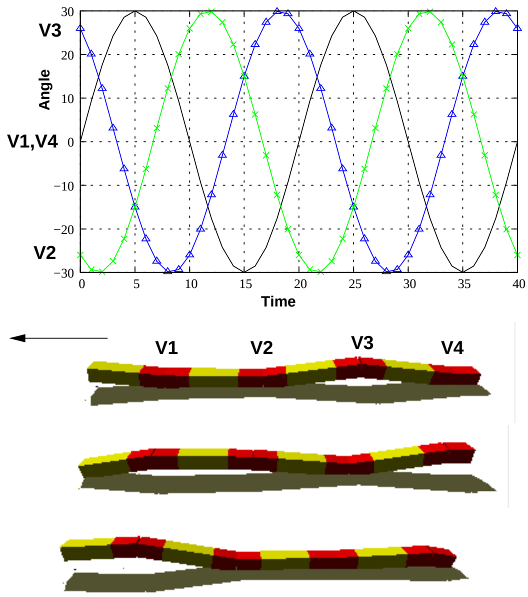

Fig. 9. 1D sinusoidal gait. The angles of the articulations V_1,V_2,V_3 and V_4 are changed according to the function depicted

A. 1D sinusoidal gait

For the locomotion in 1D, forward and backward movements are achieved by means of variations only in vertical joints ($A_V \neq 0$), with an offset equal to zero ($O_V = 0$). The horizontal modules are kept in their home position all the time ($A_H = 0$, $O_H = 0$). The phase difference between the vertical CPGs is $\triangle\Phi_V = 120$. As studied in previous works[16], the phase difference is the parameter that determine the coordination between the joints. The value of 120 is the best. The rhythm pattern and the simulation state at three instants are shown in Fig.9.

B. Turning gait

The robot can move along an arc, turning left or right. The values of the parameters are as same as that in the 1D sinusoidal gait (Fig. 10), but now an offset in the horizontal joints is applied ($O_H \neq 0$). Therefore, the horizontal joints are at fixed position all the time. The robot has the shape of an arc. By changing O_H, the radix of curvature of the trajectory can be modified.

C. Rolling gait

The robot can roll around its body axis. The same sinusoidal signal is applied to all the vertical joints and a ninety degrees out of phase sinusoidal signal is applied to horizontal joints (Fig. 11). The amplitudes should be bigger than 60 ($A_V > 60$, $A_H > 60$). The results are the same obtained with the pitch-yaw-pitch minimal configuration studied in [16].

D. Rotating gait

The robot can also rotate parallel to the ground clockwise or anti-clockwise. This is a new gait not previously

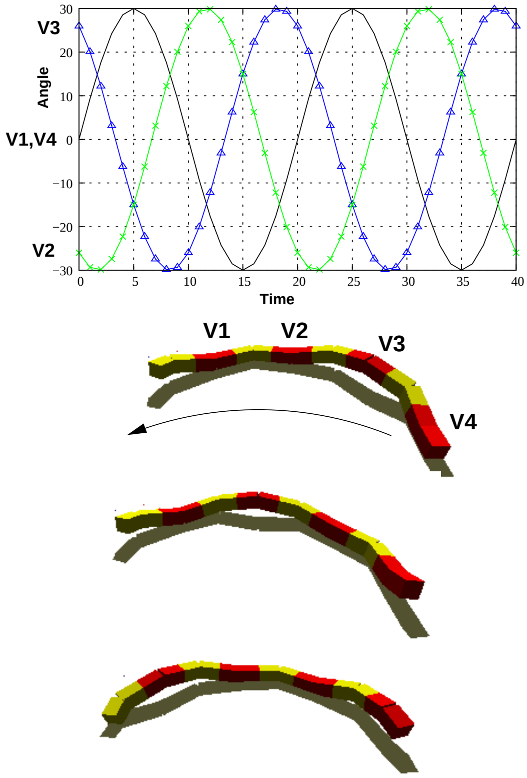

Fig. 10. Turning gait. The same coordination is applied than in the 1D sinusoidal gait. The offset of the horizontal joints determines the arc.

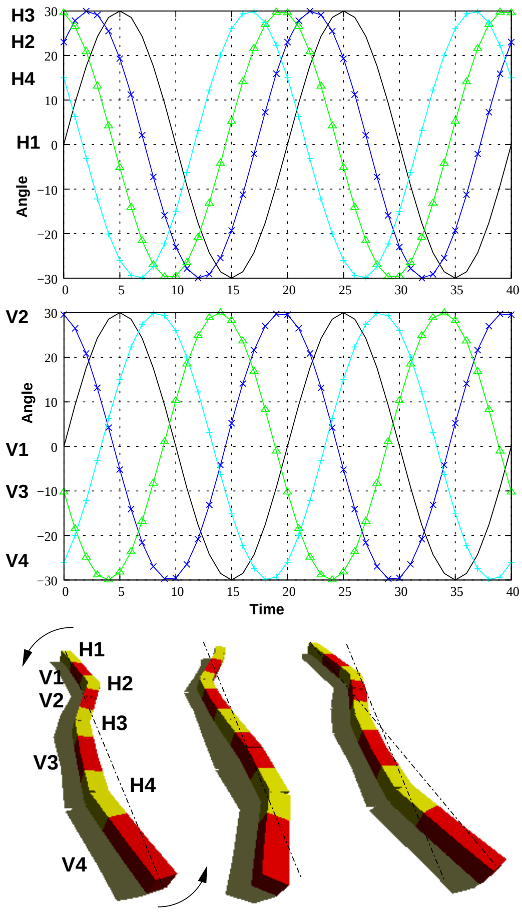

Fig. 12. Rotating gait. Eight different sinusoidal CPGs are used. A phase difference of 50 degrees is applied to the horizontal joints and 120 for the vertical

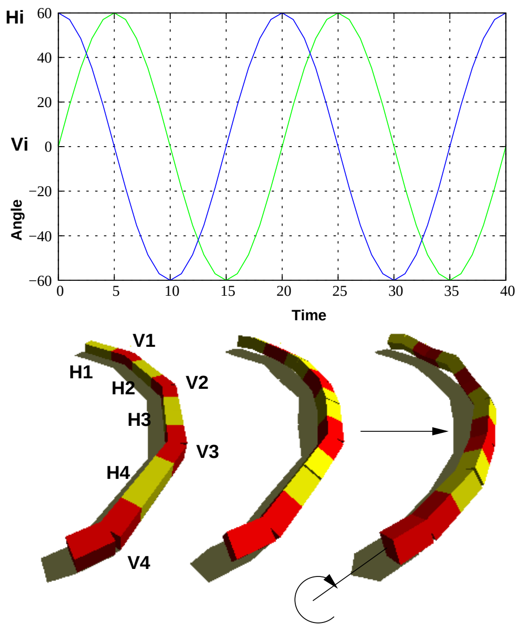

Fig. 11. The rolling gait. The same sinusoidal signal is applied to all the vertical joints and a ninety degrees out of phase sinusoidal signal is applied to horizontal joints

mentioned by other researchers. The robot can change its orientation in the plane. Eight different sinusoidal CPGs are used. A phase difference of 50 degrees is applied to the horizontal joints and 120 for the vertical (Fig. 12).

E. Lateral shift

Using this gait, the robot move parallel to its body axis. A phase difference of 100 degrees is applied both for the horizontal and vertical joints (Fig. 13). The orientation of the body axis does not change while the robot is moving.

F. Locomotion areas

The lateral shift and rotating gaits differ only in the value of the $\triangle\Phi_V$ and $\triangle\Phi_H$ parameters. Their values determine which gait is performed. A picture showing the relations between $\triangle\Phi_V$ and $\triangle\Phi_H$ is drawn in Fig.14. There are three regions. In the middle there are an area in which the robot perform a lateral shift to the right. There are two parallel sub-regions in which the robot rotates anti-clockwise. In the transitional areas, the movement is not well defined. It is a mixture between both gaits. In the rest of points, no locomotion is performed.

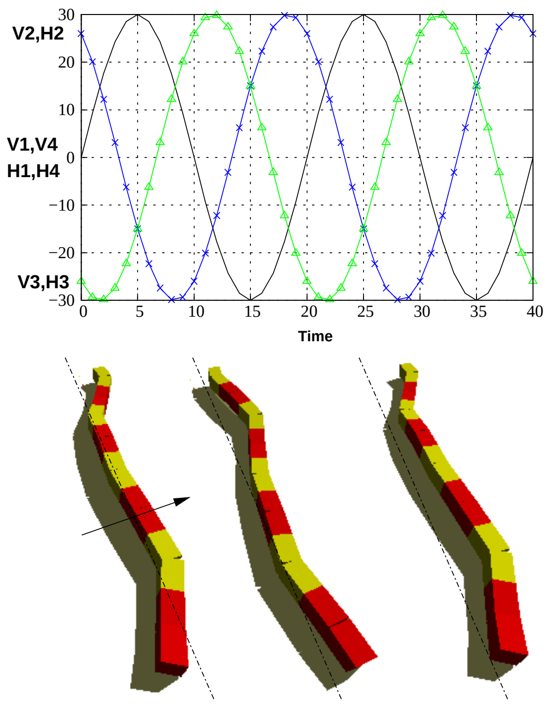

Fig. 13. Lateral shift gait. Eight different sinusoidal CPGs are used. A phase difference of 100 is used both for the horizontal and vertical joints

The further analysis of these regions and the determination of the best points in them is left as a future work.

VI. Experiments

All the locomotion capabilities have been successfully implemented and tested on a real robot. Using the 1D sinusoidal gait, the robot is capable of going through a narrow pipe (Fig. 15). Also, it can traverse a curved tube by means of the turning gait (Fig. 16).

The robot can move parallel to its body axis using the lateral shift gait (Fig. 17) and also can rotate to change its orientation in the plane (Fig. 18). Both gaits have a little error. When performing lateral shift, the body of the robot also experiment a small rotation. It is not moving perfectly parallel to its body axis. Also, when performing rotation, it has a small displacement. Both effects can be corrected by mixing these two gaits. If the robot has to move a long distance parallel to its body axis, after some time, a rotating gait can be perform to correct the error on the body orientation.

Finally, the experiments on the rolling gaits are shown in Fig.19. The robot moves very smoothly. If an amplitude of 90 is used ($A_V = 90$, $A_H = 90$) the robot has the shape of a square and no global displacement is achieve. The four sides roll inside or outside the square at the same time.

VII. Conclusion and future work

A classification for the modular robots has been proposed based on the topology and the type of connection between the modules. Pitch-yaw connecting robots are a sub-group of snake robots in which the modules rotate around the pitch and yaw axes. The locomotion capabilities of an eight pitch-yaw connecting robot has been implemented and studied on a real robot. Five different gaits have been achieved: 1D sinusoidal, turning, lateral shift, rotating and rolling. All of them have been implemented using a sinusoidal CPG approach. We have realized all gaits mentioned above and concluded the relationship of the different phases and the locomotion capabilities. The information is summarized in Fig. 20.

The successful experiments confirm the principles of CPGs and the locomotion capabilities of pitch-yaw-connecting modular robots. All the gaits can be described by means of seven parameters: amplitude for the vertical and horizontal joints (A_V,A_H), the offset (O_V, O_H), the phase difference between two adjacent vertical and horizontal joints ($\triangle\Phi_V$, $\triangle\Phi_H$) and the

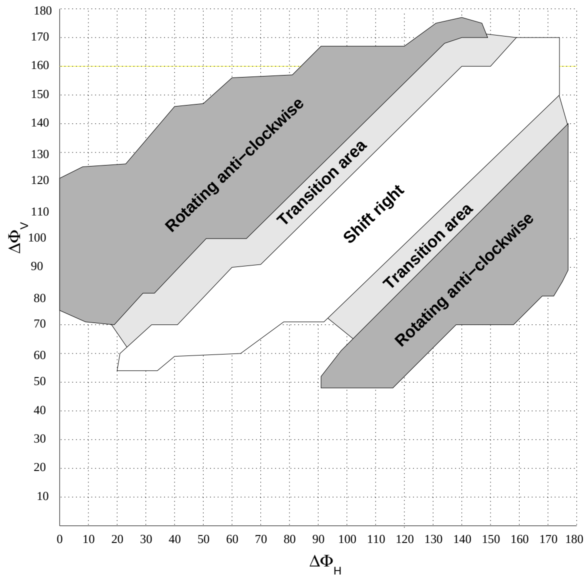

Fig. 14. Areas of locomotion for the different parameters $\triangle\Phi_V$, $\triangle\Phi_H$ when $\triangle\Phi_{HV} = 0$ is set.

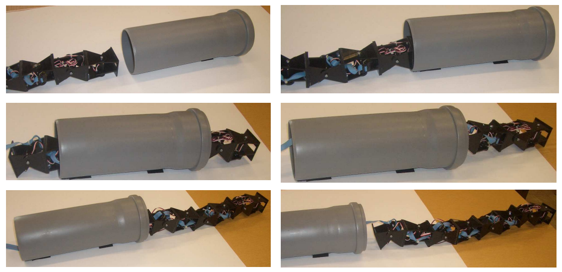

Fig. 15. An example of 1D Sinusoidal gait. The robot can go through a tube.

Fig. 16. An example of the turning gait. The robot is going through a curved tube

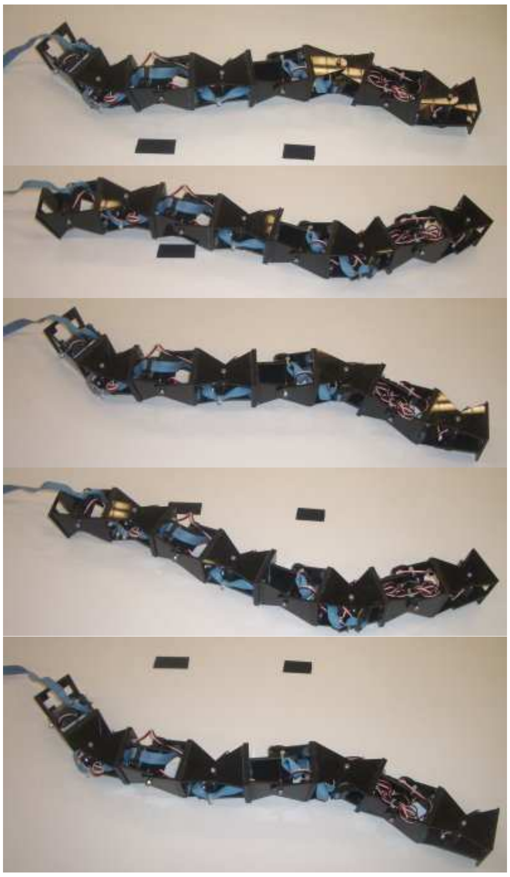

Fig. 17. Experiments on lateral shift gaits. The robot moves parallel to its body axis.

phase difference between horizontal and vertical modules ($\triangle\Phi_{HV}$).

The lateral shift, rotating and rolling gaits only differ in terms of their phase difference. That means that the phase difference is the key parameter determining the characteristics of gaits.

All of the research results can be directly implemented in the self-reconfigurable robot which is our ultimate research object.

Currently, we are studying the climbing properties of the pitch-yaw-connecting configuration and the locomotion capabilities of 2D and 3D configurations. Also, a new generation of modules are being designed.

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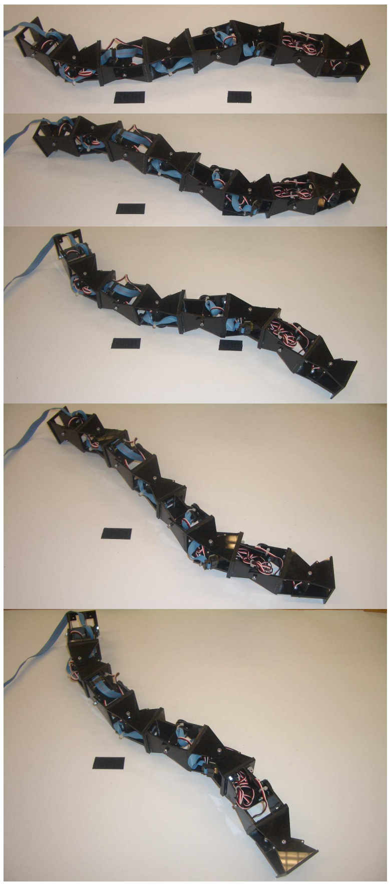

Fig. 18. Rotating gait. The robot can change its body orientation in the plane.

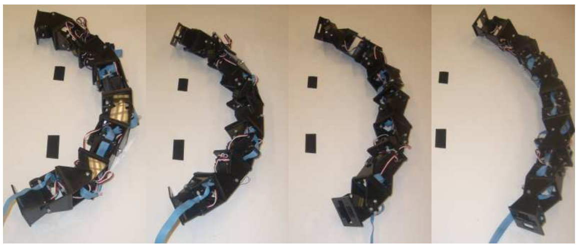

Fig. 19. Experiments of the rolling gait

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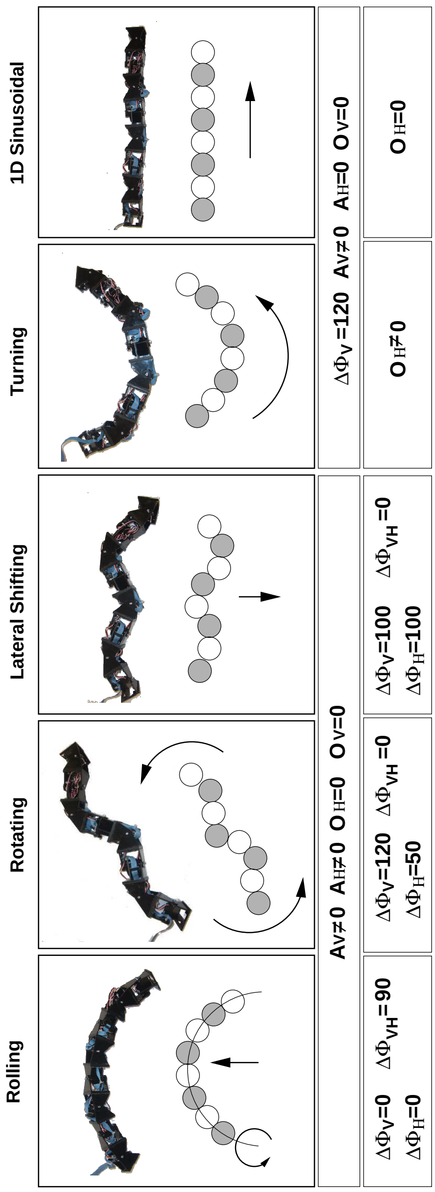

Fig. 20. The five different gaits the robot can perform and the CPGs parameters realization

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