Design and Control of Biologically Inspired Wheel-less Snake-like Robot*

Zeki Y. Bayraktaroglu, Atilla Kılıçarslan, and Ahmet Kuzucu
Istanbul Technical University
Faculty of Mechanical Engineering
Inonu Cad. No:87, Beyoglu 34437 Istanbul, Turkey
zeki.bayraktaroglu@itu.edu.tr

Vincent Hugel and Pierre Blazevic
University of Versailles Saint Quentin-en-Yvelines
Versailles Robotics Laboratory
10 Avenue de l'Europe, 78140, Vélizy, France
hugel@lrv.uvsq.fr

***Abstract* - This paper describes our research project on snake-like locomotion of robotic platforms and the results of the experiments conducted with a wheel-less snake-like robot prototype. Biological inspiration has been at the hardcore of the mechanical design and the control method applied to the robot. With closed-loop control applied to the present wheel-less prototype, it has succeeded in progressing through lateral undulation, the most common limbless locomotion type observed in natural snakes. Main results consist of the robustness of the locomotion with respect to the variations in initial conditions and external perturbations.**

Index Terms* - *Limbless locomotion. Lateral undulation. Snake-like robot. Biologically inspired methods.

I. Introduction

Limbless locomotion has recently motivated the construction of a number of mobile machines taking advantage of the physical phenomena observed particularly with snakes and inchworms. Original works of Hirose [1-3] has inspired many of the following research on snake-like locomotion throughout the world [4-11]. Most of these locomotors consist of mobile platforms equipped with active or passive wheels. Despite their snake-like mechanical structures, locomotion of machines using active wheels is based on the principles of classical wheeled functioning. Most structures with passive wheels have been designed to exert biologically inspired snake-like locomotion [1-11]. However wheeled snake robots are intended to operate over perfectly smooth substrata, i.e. in artificially structured environments.

In addition wheeled motion does not appear in natural world. Among various limbless locomotion types, lateral undulation is the most frequently exerted progression by nearly all snake species [12-14]. Fig. 1(a) illustrates the tracks of a snake progressing through lateral undulation. Fig. 1(b) shows the discrete lateral reaction forces that propel the whole body.

Snake locomotion through lateral undulation is based on a continuous interaction of the animal's entire body with its environment. The animal curves its own body so that it could push against the environment's irregularities. Reaction forces from the so-called push-points constitute together the total propulsive force required for progression in a given direction [12-17]. Locally, sections of the mobile body slide along the push-points and the resulting global force/torque happens to propel the snake.

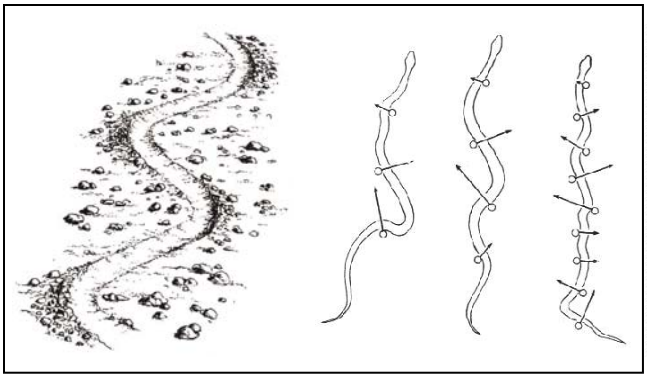

Fig. 1 (a) Tracks of a snake moving through lateral undulation. (b) Three different cases with various number of simultaneous lateral contacts.

The minimal number of simultaneous lateral contacts required between the mobile body and its environment is determined to be 3 in case of lateral undulation [13,16]. Highly articulated snake backbone ensures a kind of adaptation to a variety of substrata. Therefore snake-like locomotion is rather suitable for outdoor applications in uneven environments where wheeled and/or legged platforms could not operate properly.

In this work we propose a wheel-less snake-like mobile mechanism, capable of exerting biologically inspired locomotion. The mechanical design and the control approach presented in this work have been motivated by our previous works on the subject [18-20].

The second part describes the mechanical structures of the mobile mechanism and its artificial environment. In the third part, the control algorithm and its implementation are presented. The results of experiments are given in the forth part. In the fifth and last part, a discussion on the actual results as well as the ongoing work is presented.

II. Experimental Setup

A. *Wheel-less Snake-like Mechanism*

The experimental environment shown in Fig. 2 consists of a horizontal plane with vertical cylindrical profiles representing the available push-points to be contacted during the locomotion. Disposition of the push-points over the horizontal plane is pre-defined. The mobile mechanism consists of ten identical modules (Fig. 3) interconnected with one DOF joint, i.e. the rotation around the vertical axis to the motion plane. Modules are connected through servo-motors which control the relative angular positions between module orientations.

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The dimensions of one module are given by 40x40x65, the height, the width and the length in millimeters respectively. One module's weight is 90g and the total module's weight and length are 900g and 650mm respectively. The dimensions of the horizontal plate are 700x1100 millimeters.

The initial conditions for the motion are defined by the geometric configuration of the mechanism with respect to the given push-point disposition. We assume that there exist at least three push-points in the reachable zone of the mechanism's modules. The propulsion of the mechanism is inspired by the one of natural snakes exerting the lateral undulation. The mechanism maintains a continuous lateral interaction with simultaneous push-points, which is only due to the internal action provided by joint actuators. Since the actual configuration is known, one can compute a required "following" internal configuration which would make the mechanism's modules simultaneously push against and rotate around the push-points. Inputs of the joint actuators are therefore determined with regard to required instantaneous configurations. Sliding of the mechanism along the push-points can be observed during the progression. Details of the motion control algorithm are given in the following section.

B. *Hardware Implementation*

The supervision unit for the control application consists of a PC running MS Windows® operating system. Matlab® v13 is used to accomplish required computational tasks. Desired joint positions as the robot's input are determined and sent directly to the RS232 serial port *via* the serial port interface commands. 8N1 formatted data flow is used over 2400 baud rate asynchronous communication.

Each module consists of one Hitec® HS475HB type servomotor providing 5,5kgcm of maximal torque and one 16F84A type microcontroller (4MHz). Microcontrollers are driven by an appropriate oscillator circuit.

As it will be described in the next section, the applied control algorithm is based on the position control of the mechanism's joints. On the other hand, the system is supposed to undergo exterior forcing due to geometric constraints and friction operating between the robot and its environment. Although these geometric constraints and frictional effects happen to be highly unpredictable in such an application, torque provided by the above mentioned servomotors proved to be sufficient experimentally for a number of different trajectories.

III. Motion Control

A. *Biologically Inspired Approach*

The closed-loop control algorithm used for locomotion control has been based on natural undulatory motion observed in snakes. Experiments conducted with snakes exerting lateral undulation ([1], [13-16]) provide the following significant result: During the progressive motion, each section of the snake body faithfully follows the path taken by the head of the animal and the whole snake body is observed as a moving wave from the head to the tail. In other words, the animal controls the angular positions between its successive vertebrae along the backbone. Given any set of simultaneously contacted push-points, the animal translates its mass center and maintains its overall geometric configuration with respect to the push-points. Hence the progressive motion continues over the available push-points. We know by far that snakes control the relative angular positions between their successive vertebrae through contractions of their musculature system.

This biological control mechanism observed in snakes can be translated in a position control problem of the orientations of mechanical modules along our artificial mechanism. Let us call $\vec{\theta}$ the vector of module orientations with respect to a fixed reference frame and θ_{i_j} the orientation of the i^{th} module at $t = t_j$. Table I shows the desired evolution of the module orientations for a snake-like mechanism with n modules.

On the other hand, we do not have a direct access to the module orientations. The global configuration of the mechanism must be controlled through the joint positions.

Therefore one has to reconstruct Table I, where the vector of module orientations $\vec{\theta}$ will be replaced by the vector of joint positions $\vec{q}$, with $q_i = \theta_i - \theta_{i+1}$. The evolution of joint variables described in Table I happens to be case observed with natural snakes.

There are two types of independent variables to be determined. The vector $\vec{\theta}$ at $t = t_0$ represents the initial configuration of the mechanism. The second class of unknowns consist of θ_{1_j}, orientation of the head module during the progression. The determination of these variables within the control algorithm will be presented in the next parts.

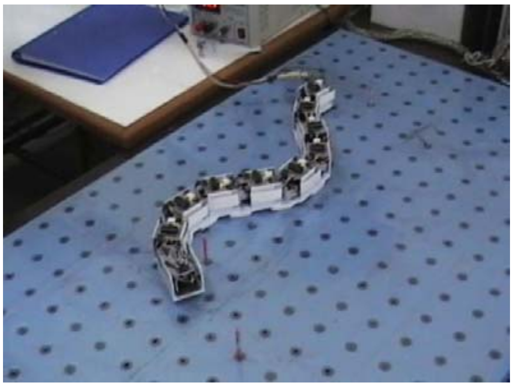

Fig. 2 The experimental environment.

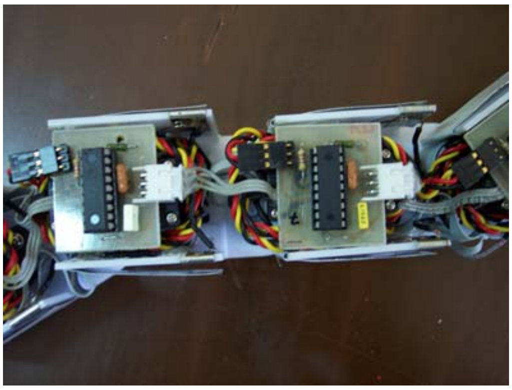

Fig. 3 Two successive modules.

TABLE I
DESIRED EVOLUTION OF THE MODULE ORIENTATIONS

t	t_0	t_1	t_2	t_3
θ_1	θ_{1_0}	θ_{1_1}	θ_{1_2}	θ_{1_3}
θ_2	θ_{2_0}	θ_{1_0}	θ_{1_1}	θ_{1_2}
θ_3	θ_{3_0}	θ_{2_0}	θ_{1_0}	θ_{1_1}
θ_4	θ_{4_0}	θ_{3_0}	θ_{2_0}	θ_{1_0}
$\vdots$	$\vdots$	$\ddots$	$\ddots$	$\ddots$
θ_{n-1}	θ_{n-1_0}	θ_{n-2_0}	θ_{n-2_1}	θ_{n-2_2}
θ_n	θ_{n_0}	θ_{n-1_0}	θ_{n-2_0}	θ_{n-2_1}

B. *Assumptions*

The snake-like locomotor presented in Fig. 2 happens to be a scaled imitation of a snake backbone. Hundreds of articulations between successive vertebrae have been approximated by only nine joints and distributed push-surfaces in natural substrata by discrete push-points. Many complex properties of natural snake skin have been omitted in favor of simplicity since we consider contact between artificial materials.

Simplifications brought to the snake-like structure do not prevent the feasibility of lateral undulation. In fact, a ten-module mechanism is a minimalistic one since we need at least three simultaneous lateral contacts to exert lateral undulation.

Apart from these properties concerning the modeling of the mechanical structure, assumptions to be made for a proper functioning of the considered locomotion method are as follows:

1) Initial conditions: We assume that initially at $t = t_0$, the mechanism is in a certain proximity of at least three push-points. By this way, it can reconfigure itself for an initial configuration to begin immediately the locomotion. One can consider that this assumption is in accordance with observations of natural snakes since the animal can begin to move through lateral undulation in any initial configuration.

2) Push-point disposition: We assume that on the path to be followed by the robot, there always exists an available push-point in a reasonable proximity of the head module. This is a fundamental condition without which the exercise of lateral undulation would not be feasible.

3) Instantaneous configurations: Distribution of lateral contacts is an important aspect of locomotion by lateral undulation. The geometry of this distribution has consequences on the energy consumption, attainable maximal velocities, etc [21]. Decrease in the length of the mobile mechanism exerting the lateral undulation brings geometric constraints on the possible configurations where the mechanism can progress in a given direction. Since we consider a minimal mechanical structure, without loss of generality, we assume that three simultaneously contacted push-points by the mobile mechanism are distributed around itself such that one of them will be placed on the opposite side than the others with respect to the curve determined by the mobile mechanism and dividing the motion surface into two parts.

C. *Control Algorithm*

The algorithm is decomposed into 5 steps as depicted in Fig. 4. Thanks to switch sensors located sideways of each module the motion control of the snake can be achieved in closed loop (steps 3 to 5).

1) Steps 1 and 2. Preparation procedure: The algorithm starts with a preparation that enables to set the robot into an initial configuration with 3 push-points in contact. There are two ways of implementing the preparation procedure. The first way assumes that the 3 contact points are known in advance, which enables to set the shape of the snake quickly by moving the actuators in a predefined way. In the second way the robot will move its body to form a sine shape in order to get into contact with some push-points. The curve fitting procedure in step 2 permits to smooth the shape of the robot so that it fits a spline curve. This ensures a 2^{nd} order of continuity of the curve at the push-point contacts. To deal with the curve fitting procedure the position of each contact point with respect to others has to be known. This can be done without knowing the relative positions of the initial 3 push-points thanks to the sideways switch sensors.

2) Step 3. Propulsion: Then the snake robot begins to move itself by pushing on the push-points. To achieve this motion, each module follows the path of its predecessor. This means that the head module shows the way at instant t_x with a position and direction, and that all modules will consecutively pass through this position with the same direction. The angle between the head module and the second module will be reproduced by the actuator joining the second and third modules after a certain time period ΔT, and so on. During propulsion the snake robot tries to simultaneously maintain its 3 contact points.

3) Step 4. Head module exploration: Once the robot loses its last push-point located at the back, it moves its head module to the left or to the right according to the sideways position of the first front push-point. If the first front push-point is situated on the right of the snake's body, the head starts to move to the left and vice-versa. The on/off switch sensors located sideways of the head module permit to detect the contact with a new push-point of the environment.

4) Step 5. Curve fitting: After the head module establishes contact with a push-point, the control program runs a procedure of curve fitting for the body shape between the first two contact points. Since the system knows which modules are in contact with a push-point, it can approximate the position of a push-point with respect to others and calculate the Spline curve to be used for the shape of the robot. To determine the Spline curve we need 2 contact points that pass trough the curve and 2 control points. The contact points are the push-points in contact with the modules. The control points are used to set the tangents at the contact points. The tangents are set to make an angle of 45° with respect to the direction of motion, this is to ensure that the direction of the pushing force contributes to the propulsion in the direction of motion. The direction of motion is determined thanks to the three current push-points, but this can be easily extended to more than 3 push-points. For three push-points the direction of motion is calculated as the regression line. For more than 3 push-points, the direction of motion can result from the interpolation of the points.

Fig. 5 shows the direction of motion for 3 push-points and the tangent defined at the last two contact points. Then the algorithm loops back to step 3 to keep on propelling the snake robot.

D. Biologically inspired generation of propulsive forces

Let us now consider a 5-link mechanism in simultaneous contact with three push-points **PP1**, **PP2** and **PP3** as shown in Fig. 6. At this stage, we have to determine an appropriate vector of motor inputs $\Delta\vec{q}_i$ which would make the mechanism mimic the natural snake motion. We know by far that every module has to follow its predecessor, as illustrated in Table I.

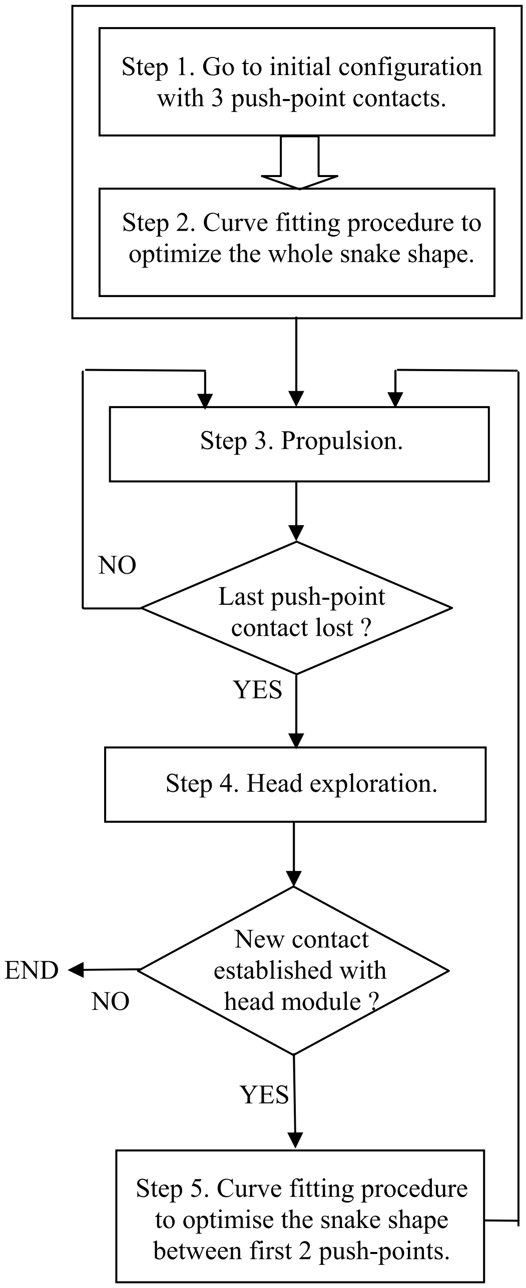

Fig. 4 Control algorithm for the snake robot.

At this end, the first joint is actuated to make the head module push against the corresponding push-point. The following joints are actuated so that each module orientation evolves toward its desired value. Instantaneously required control inputs are illustrated in Fig. 6.

Finally, the orientation of the sum of the reaction forces $\vec{R}_i$ along the mechanism gives the global progression direction, in accordance with the lateral undulation observed in natural snakes. Results of the experiments with the above mentioned control are discussed in the next sections.

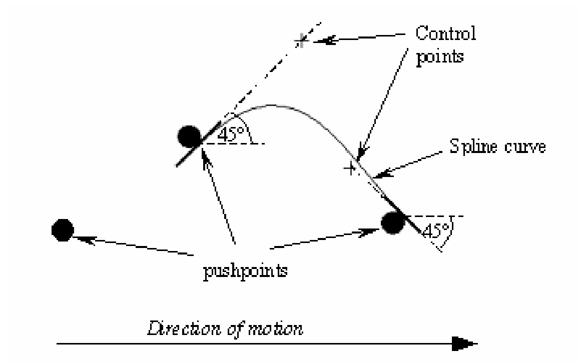

Fig. 5 Curve fitting with 3 simultaneous contact points.

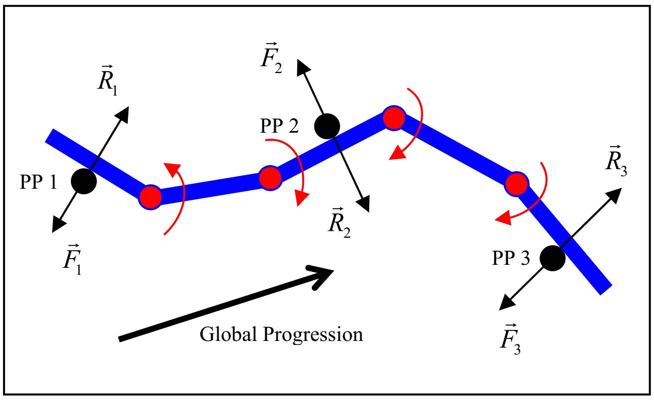

Fig. 6 Interaction forces along the snake-like mechanism in simultaneous contact with three push-points.

IV. Results

A. Trajectories

Fig. 7 shows eight instantaneous configurations captured during the locomotion over a desired trajectory. In spite of the constraining number of its DOF compared to natural snakes, the 10-link mechanism has succeeded in the exercise of lateral undulation along a number of trajectories with the developed control algorithm.

Correlations between module orientations as presented in Table I have been observed between joint positions during the experiments. Fig. 8 shows the evolution of successive joint position values.

We have also observed that the frequency of input application to the joint actuators determines the locomotion speed. A maximal speed of approximately 0,05 m/s along straight paths has been obtained in the experiment whose snapshots are presented in Fig. 7.

B. *Stability of Motion*

Another interesting result concerns the stability of motion. Motion stability resulted from the applied control method has been experimented with respect to variations in initial conditions and random perturbations provided by manually induced force/torque.

1) Initial conditions: For a given push-point disposition on the motion plane, the mobile mechanism has been given different initial configurations with respect to three push-points to be simultaneously contacted. Examples of two different initial conditions for a unique available push-point disposition are illustrated in Fig. 9. When subjected to a same control law established as mentioned in the previous section, we have observed that the mobile mechanism has terminated its progressive motion at a unique final configuration with respect to the push-point disposition around the pre-defined final state.

2) Random perturbations: During locomotion along given desired trajectories, random perturbations in terms of manually induced exterior force/torque have been applied to the mechanism in motion. We have observed that these random perturbations have not succeeded in deviating the mechanism from its desired trajectory. The stability of motion in presence of randomly applied exterior force/torque is a consequence of geometric constraints taking place for a given mechanism/push-point interaction. In fact these geometric constraints instantaneously reduce the number of DOF and possible progression directions.

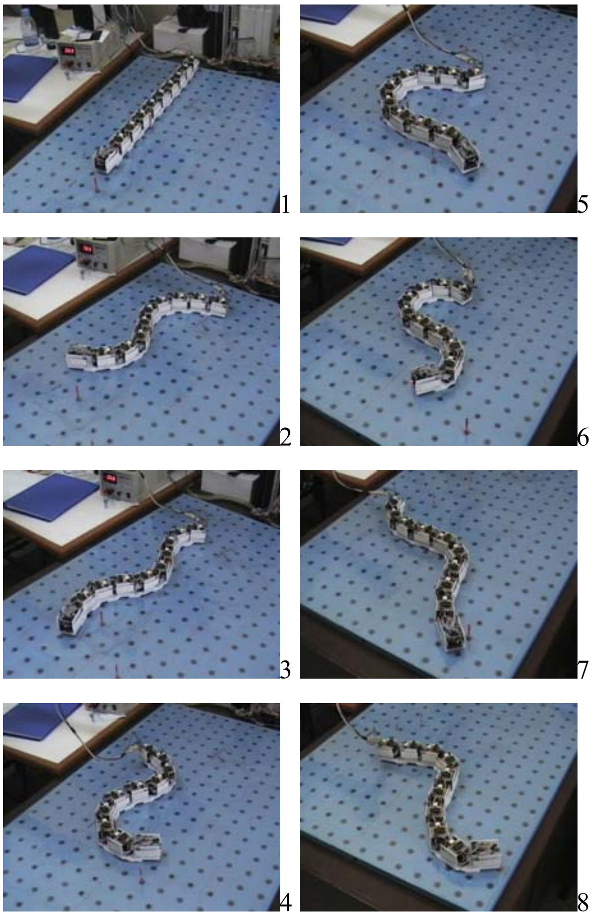

Fig. 7 Eight intermediary configurations with initial (1) and final (8) conditions of the mechanism for a given trajectory.

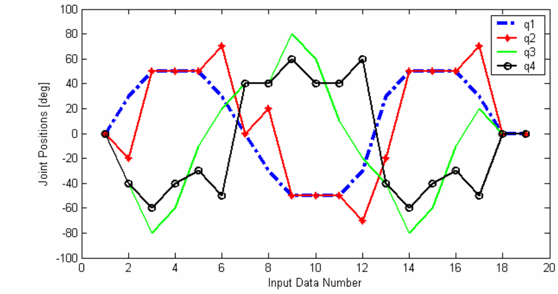

Fig. 8 Correlations between successive joint positions values.

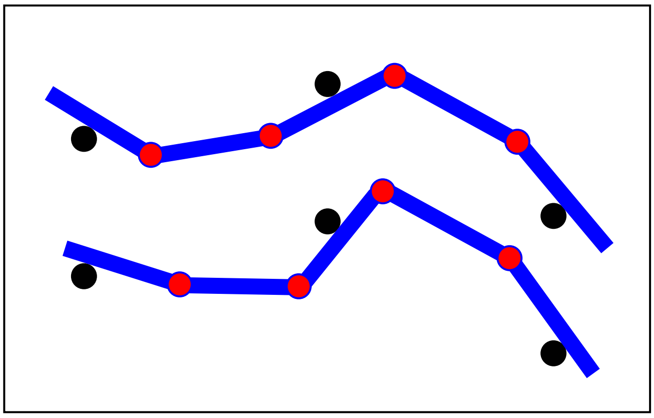

Fig. 9 Two different initial configurations of the mobile mechanism with respect to a same push-point disposition.

C. *Alternative types of locomotion*

Beside the above mentioned research on lateral undulation, we have also obtained two alternative types of undulatory motion with the same mechanism.

First, the transversal axis of the mechanism has been reoriented with respect to the motion plane. In this inchworm-like motion whose sequences are given in Fig. 10, the propulsion has been ensured through a so-called traveling wave created along the whole mechanism. Experiments have been conducted with traveling waves of constant amplitude and frequency. By this way, the robot has succeeded in progressing over a number of artificially created irregular grounds as the one in Fig. 10.

The second type of progressive motion has been experimented in a constrained environment, namely a U-profile arc as shown in Fig. 11. The mechanism has succeeded in moving in the arc through lateral undulation of fixed amplitude and frequency.

Investigation of performances of these secondary locomotion types is subject to the ongoing work.

V. Discussion

A. *Experiments*

Experiments have been carried out by closed-loop control of the snake-like locomotion through lateral undulation. The main result is that the physical phenomena observed with natural lateral undulation have been reproduced with a wheel-less snake-like mechanism with a relatively restricted number of DOF and a simple mechanical structure. The present approach has been based on biological inspiration, which guided the design and control aspects of the wheel-less snake-like mechanism. Stability of motion has also been experimentally investigated.

Control issues such as optimality have not been considered at this first stage of experiments. The second wheel-less prototype which is currently being designed will let us experiment various closed-loop control methods for the related developments.

B. Description of the second prototype

The second prototype, whose design is subject to the ongoing research will consist of 15 joints with embedded power supply. Communications between the robot and the control unit will be ensured through a wireless communication protocol *via* the computer's serial port.

The main development in favor of the robot's autonomy will be the novel joint design which will let the robot switch its transversal orientation with respect to the motion plane. By this way, the robot will be able to switch between the two types of locomotion presented above.

Fig. 10 Six intermediary configurations with initial (1) and final (6) conditions of the mechanism over an irregular ground.

Fig. 11 . A view from the robot exerting lateral undulation in an arc.

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