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Development of a Snake-like Robot

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This paper presents the development of a robot that mimics the movement of a live snake. A prototype robot comprising six links was constructed. Torque actuators between the links modify the robot's shape. Anisotropic friction between the links and the ground generates the force that propels the robot. A control variable that determines actuator angles is used to achieve a wave-like body motion. The corresponding signal is transmitted over a radio link. Measurements of average velocity and trajectory of the robot were performed with different control parameters. Basic properties of the robot's movement are presented.

Keywords: snake-like robots, control, serpentine windings, friction forces

0 INTRODUCTION

In relation to the development of modern endoscopes, there is increasing interest in snake-like robots achieving motion in a desired direction by undulation of the body as shown in Fig. 1. Such robots make feasible new solutions to complex problems, such as the non-destructive testing of mechanical parts in technical devices, flexible machining of geometrically complicated cavities and various surgical operations in medicine [1].

0.1 Characteristics of Snake-like Robots

A limited number of degrees of freedom in existing endoscopes lead to restrictions in their application where movement in a geometrically complex space is required. Consequently, the development of a robot mechanism with many of degrees of freedom has been initiated recently in order to enable movement in diverse environments. Imitation of biological organisms with flexible bodies, such as highly developed snakes, is a possible course in the development of such robot mechanisms.

Snakes can be found in diverse natural habitats [2]: they live in deserts, tropical forests; they are capable of swimming in rivers and oceans. During evolution snakes have lost their limbs and developed an extended spine in order to facilitate movement in constrained environments, such as narrow underground tunnels, or grass and bush terrain. These characteristics lead us to imitate snakes in the development of a robot designed for performance that requires high flexibility.

The body of a snake consists of a spinal column, muscles and a sensory-neural network. The spinal column is a passive element that transmits forces and determines the dimensions of the body. The same property is achieved by the mechanical structure of a snake-like robot that includes links and that permits variation of the robot shape. Muscles can be replaced by controllable torque actuators causing undulation of the robot. The actuators should be positioned at the joints in order to change the angles between adjacent links. Adaptation of a body to complex forms in the environment and creeping locomotion is controlled in snakes by a complicated sensory-neural network. In our development of this snake-like robot, this task is performed by the controller of the torque actuators.

Our goal was to develop an appropriate control strategy by which desired robot propulsion could be achieved. The structure of a snake-like robot is presented in Figure 2.

0.2 Propulsion Principle

Different types of snake locomotion for various purposes exist [2]. For example, one type of locomotion is suitable for soft terrain, while another works on hard terrain. Locomotion in narrow channels is also possible. Well-known locomotion types are serpentine, rectilinear, lateral rolling, concertina, etc. [3] and [4]. Our research is focused on serpentine locomotion, because it appears to be the simplest. Its main characteristic is the wave-like undulation of the snake body. To generate propulsion with this kind of movement, adequate friction between the body and

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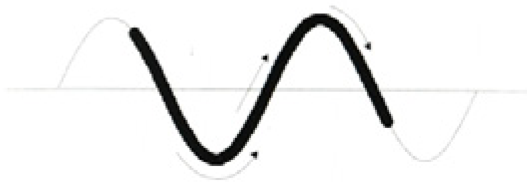

Fig. 1. *Undulating movement*

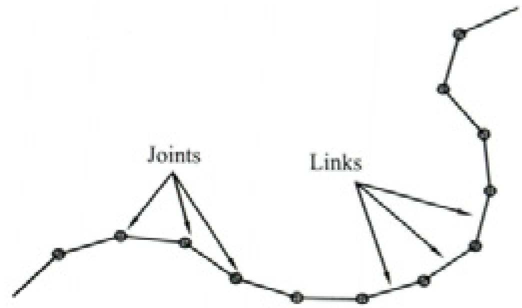

Fig. 2. *Scheme of a snake-like robot structure*

the ground must exist. The friction should be anisotropic with regard to the direction of velocity and orientation of a particular link [1]. This means that the transverse frictional force on a particular link should be much greater than in the direction of the link. The basic problem is then to find the undulation of the body that would result in the movement of the robot along a prescribed path.

1 CONSTRUCTION OF THE SNAKE-LIKE ROBOT

The aforementioned propulsion principle is applicable to achieve robotic movement in two or three dimensions. In our research we have considered just two-dimensional cases on a flat plane. Hence the joints axes between the links are parallel to each other and normal to the plane. The robot was composed of six links connected by hinges (Fig. 3). Between the links there are five torque actuators.

For our research it is not necessary for the robot to withstand high mechanical loads and the path following tolerance is not very strict. Therefore, the robot needs not to be built of highly accurate and rigid parts with tight tolerances. Consequently, we have assembled the robot from simple flexible plastic elements [5]. These elements also enabled the simple changing and improvement of the structure. The final version of the robot is presented in Figures 4 and 5.

As torque actuators we used DC electric servo motors, of the type usually used in remote control model aircraft. These motors are convenient for developing robot prototypes because they have a built-in feedback loop that simplifies control of their position angles. Furthermore, these motors are designed to work with radio control and receiving units permitting remote control. The servo motors are positioned on the turning axis of the joints between adjacent links. The motors do not need any additional gears, since they generate enough torque for the change of the angles between links. The motors receive control signals from the radio receiver unit placed on the head of the robot.

To assure anisotropic friction, we need suitable contact of the robot with the ground. Different materials have already been tested for this purpose by other researchers [2]. Passive wheels have been found to be the most appropriate, since they have a very high coefficient of friction in the transverse direction and almost no friction in the direction of rolling. Consequently, we have also utilized passive wheels. Initially, we used plastic wheels, but these

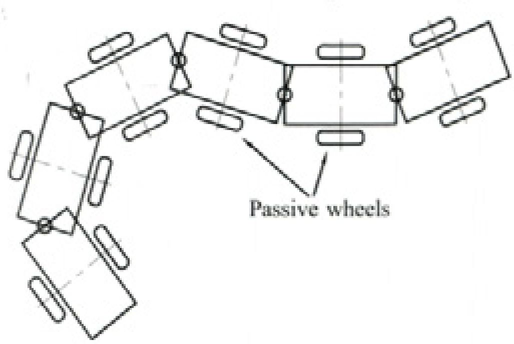

Fig. 3. *Snake-like robot made up of six links connected by hinges*

Fig. 4. *Final version of a snake-like robot*

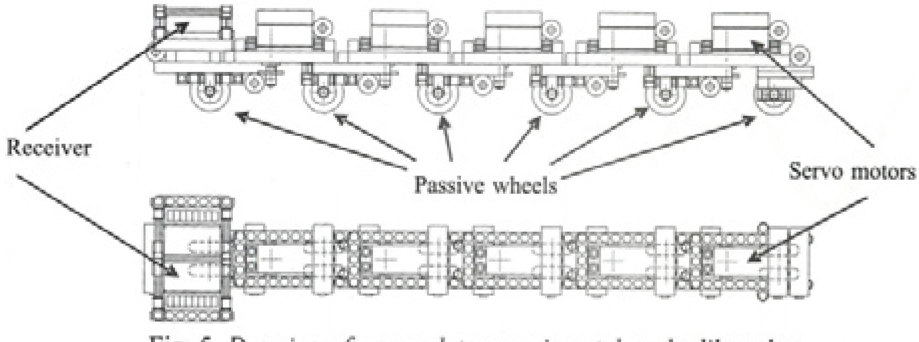

Fig. 5. *Drawing of a complete experimental snake-like robot*

lacked sufficient transverse friction for good propulsion. To increase friction, we replaced the plastic wheels with rubber wheels.

As a power supply for the radio receiver and servo motors we utilized rechargeable electrical accumulators. It is important to achieve uniform and sufficient friction along the robot. For this reason a pair of accumulators is placed on each link as extra weight.

2 CONTROL OF THE SNAKE-LIKE ROBOT

The propulsion of the robot results from friction of the wheels due to undulation of the body on the surface. This undulation is achieved by controlling the angles between links by servo motors [4]. A control variable $\phi_s(t)$ determines the values of the angles between the links. To control the movement of the robot along a prescribed planar path this control variable was determined by a sum of two control signals. The first component causes undulation of the robot body, while the second one causes an average bending that corresponds to the curvature of the prescribed path. The corresponding control variable $\phi_s(t)$ is described by the following function:

$$\phi_s(t) = R \cdot \sin\left(2\pi v \cdot t - (s-1)\varphi\right) + R_{tr} \quad (1).$$

Here R, v, φ and R_{tr} are settable parameters. R is the relative amplitude of oscillation of the servo motors with regard to the maximum possible amplitude, v is the frequency of oscillation of the servo motors and φ is the phase delay between servo motors. R_{tr} is the parameter that determines the average bending of the robot body and leads to steering along the prescribed path as shown in Figure 6. Index s denotes the index of the link and tr denotes path curvature.

In our testing, two control strategies were examined: in the first the relative amplitude of oscillation was kept constant (1), while in the second it was modulated with the position of the link [1]:

$$\phi_s(t) = R\xi^2 \cdot \sin\left(2\pi v \cdot t - (s-1)\varphi\right) + R_{tr} \quad (2).$$

Here $\xi = s/S$ is the normalized index of a link, where S is the number of links, and additional parameter ξ^2 describes the modulation of the undulation amplitude that increases along the body from the head towards the tail of the robot.

The robot is controlled by a personal computer. In our case the control signal is transmitted from the computer to the servo motors over a radio unit designed for remote control of model aircraft [6]. Since the robot has no direct mechanical connection to the controller, the only restriction regarding its movement is the range of the radio signal. The range greatly depends on the ambient obstacles (walls and cabinets in the laboratory), but in open space it should be at least 80 m.

The structure of this control system is presented in the diagram in Fig. 7. This is an open-loop, real-time control. The user enters control parameters either through a keyboard or joystick to the control algorithm that runs on a personal computer, which generates the required control signal in real-time.

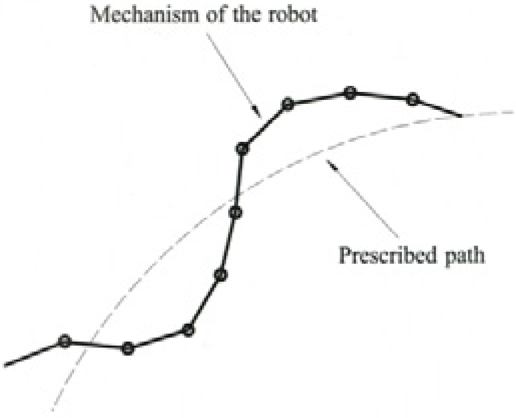

Fig. 6. *Scheme of a snake-like robot tracing a prescribed path*

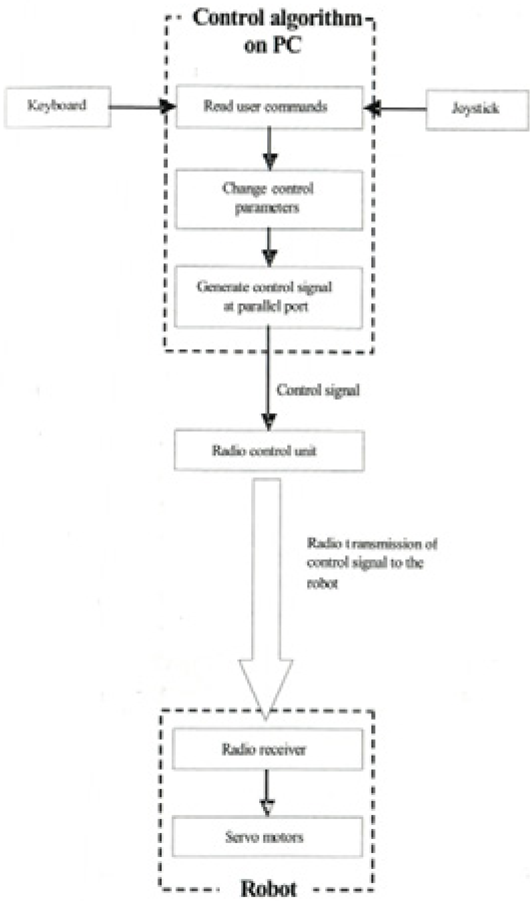

Fig. 7. *Flow diagram of control system*

The computer is connected to the radio control unit through the parallel port [7]. The radio unit transmits the signal using modulation of high frequency radio waves. The radio receiver on the robot extracts the control signal from the received radio wave and transforms it to match the characteristics of the servo motors. Then it routes the correct signals to particular motors. A weakness of this type of control is that it does not provide for a feedback connection by which the controller could receive information about the state of the robot. We assume that using a feedback would lead to increased robot movement accuracy.

3 EXPERIMENTAL RESULTS

Measurements of average velocity and head trajectory were made on the robot creeping on various surfaces.

3.1 Movement on Various Surfaces

Properties of the ground surface directly affect the movement of the robot. They are described by the coefficient of friction k and the roughness R_a. The higher the coefficient of friction between the surface and the passive wheels, the more effective is the creeping of the robot. The best conditions are met when there is no slip of the wheels in the transverse direction.

To analyze the influence of surface on the effectiveness of creeping we conducted a set of experiments on surfaces of linoleum ($R_a \approx 0.5$ µm), spongy plastic ($R_a \approx 10$ µm) and smooth plastic ($R_a \approx 0.1$ µm). We found that propulsion of the robot is most effective on the spongy plastic material, which has the highest roughness R_a. The results on linoleum were also satisfactory, while creeping on smooth plastic was rather ineffective.

3.2 Measurements of Average Velocity

Measurements of the average velocity of the robot were made on the linoleum surface. We adapted the non-modulated control variable (1), where four control parameters R, v, φ and R_{tr} are present. For velocity measurements we only used creeping in a straight line. In this case $R_{tr} = 0$ and the control variable is:

$$\phi_s(t) = R \cdot \sin\left(2\pi v \cdot t - (s-1)\varphi\right) \qquad (3).$$

We measured the average velocity at seven different combinations of the remaining three parameters R, v and φ (Table 1). The highest velocity of approximately 0.26 m/s was observed at the following combination of parameter values: R = 100%, v = 0.8 Hz and φ = 1 rad. Based on the combinations of parameters used, we can roughly estimate the influence of control parameters on movement. Results of the measurements, given in Table 2, indicate that in the tested range of parameters velocity increases with increasing amplitude and increasing frequency. The velocity also increases with the phase delay increasing from φ = 1 rad (Fig. 8) to φ = 1.5 rad (Fig. 9).

3.3 Measurements of Head Trajectory

Measurements of the head trajectory of the robot were also made on the linoleum surface. The trajectories were recorded from the vertical

Table 1. *Combinations of control parameters used in average velocity measurements*

Parameter set no.	R [%]	ν [Hz]	φ [rad]
1	100	0.4	1.5
2	100	0.6	1.5
3	100	0.8	1.5
4	100	0.6	1
5	60	0.6	1
6	60	0.6	1.5
7	100	0.8	1

Table 2. *Results of velocity measurements*

Rank	v [m/s]	Parameter set no.
1.	0.258	7
2.	0.202	4
3.	0.197	5
4.	0.176	3
5.	0.126	2
6.	0.099	6
7.	0.088	1

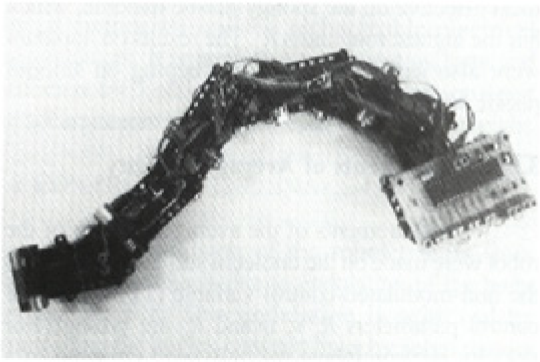

Fig. 8. *Shape of a snake-like robot at phase delay $\varphi = 1$ rad*

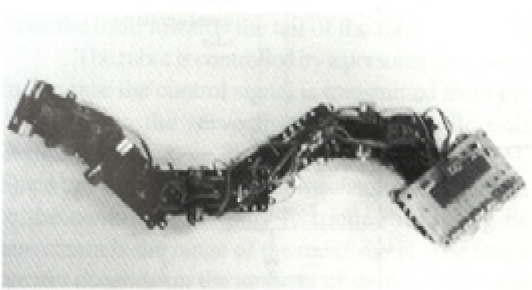

Fig. 9. *Shape of a snake-like robot at phase delay $\varphi = 1.5$ rad*

perspective by a digital camera. During experiments we applied the same non-modulated control variable (3) as for the velocity measurements and the same seven combinations of control parameters.

Figure 10 shows the head trajectory for three different combinations of control parameters, including the parameters at which the highest velocity was achieved. The trajectories are rather smooth and resemble a sine curve determined by the control of the body undulation. Since there are no peaks in the curves we conclude that there is no abrupt slipping of the body. Beside this, we observed rather good tracing of a straight line. Similar observations have been found with following a curved prescribed path, when the radius of curvature is much larger than the length of a single link.

4 CONCLUSIONS

We have developed a snake-like robot capable of creeping along a prescribed planar path on various surfaces. The robot is controlled by a personal computer, where a user enters control parameters by keyboard or joystick. Application of a joystick offers convenient and continuous manual control of the robot's movement.

In our experiments, velocity and head trajectory of the robot were measured. We tested seven different sets of control parameters and roughly estimated the influence of the control parameters on the movement. The highest achieved velocity of the robot was approximately 0.26 m/s. A surface with a high coefficient of friction has proven to be the most suitable for effective propulsion.

At this stage we have only used open-loop control. The next research step is to upgrade the open-loop into a closed-loop control, where the controller constantly receives feedback information from the robot. The feedback information can contain position coordinates, indication of obstacles, etc. By applying the closed-loop control of the robot, increased tracking accuracy and reliability of the robot can be expected.

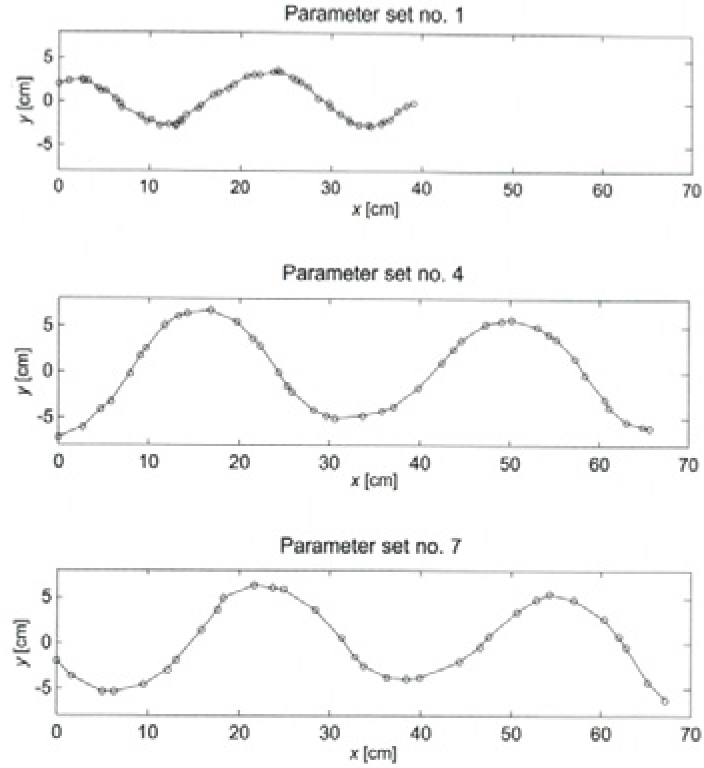

Fig. 10. *Head trajectories measured at different combinations of control parameters. At parameter combination 7, the robot achieved the highest velocity.*

Some work has already been done on a development of a control system with a feedback loop that includes an infrared optical tracking sensor, where we achieved some promising preliminary results. Our long term goals are to fully implement closed-loop control and to utilize an artificial neural network for autonomous optimization of the robot movement.

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