Snake-Robot Control Strategy for Navigation in an Unknown Environment

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Abstract: - This paper presents a nature-inspired model of a hyper-redundant robot and its feasibility for autonomous and intelligent navigation. Based on local sensor information and imitating animal instincts of orientation, "Snake-Robot" is able to reach a target in an unknown environment. In the following paper, physical attributes, obstacle avoidance criteria, path planning and control strategy are all described in the following paper. A simplified version of this robot was designed and tested so that it could move about on the ground.

Key-Words: - Snake, Robot, Redundant, Path, Control, Navigation.

1 Introduction

Earth's natural habitats are irregular, unmarked and random in shape; yet, living creatures accomplish their survival needs without any coordinate system of reference. Animals trust in their instincts and sensor information to perform a motion, overcome obstacles, and reach targets. Targets such as sound, heat, light, vibration, etc. are information that animals obtain locally and continuously in order to adapt a particular behavior towards motion direction, which may not be necessarily optimal, but highly effective and robust. The planets or unstructured and hazardous ocean environment presents many challenging problems for robots [1]. Therefore, the new generations of robots are needed for unstructured environment, which requires high degrees of kinematic redundancy [2, 3, 4].

The present work shows the study of a "Snake Like" robot as an autonomous mobile system with some of the physical attributes and behavior resembling the snake found in nature. This study is organized in sections that cover:

- Description of the system (physical attributes and capabilities)
- Basic kinematics formulation
- Artificial Intelligence criteria
- Path planning
- Control strategy

2 Description of the Proposed System

The system is known as a multi-section body having (n) quasi-independent rigid sections connected to each other by (n-1) flexible links. These links are spring elements that can only pull the sections (Fig. 1).

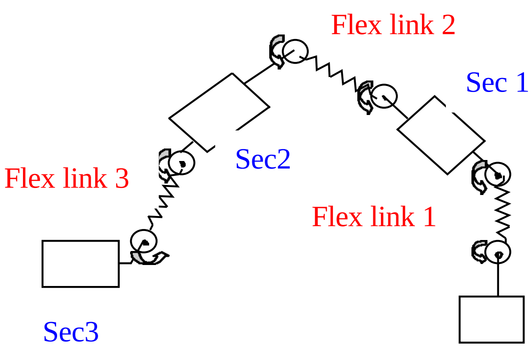

Figure 1: Example of a 4-Section Snake Robot Model.

Each rigid section is carried on four wheels, and the front wheels are able to rotate around their vertical axes. One section named the “head” leads the rest of the robot and decides the path to be followed as shown in Fig. 2. Every section has restricted independent controllable motion. This means that any of the sections has a motor that enables it to move slower or faster, no matter what the status of the other sections are. Consequently, an appropriate section-control sequence was developed to rule the overall motion.

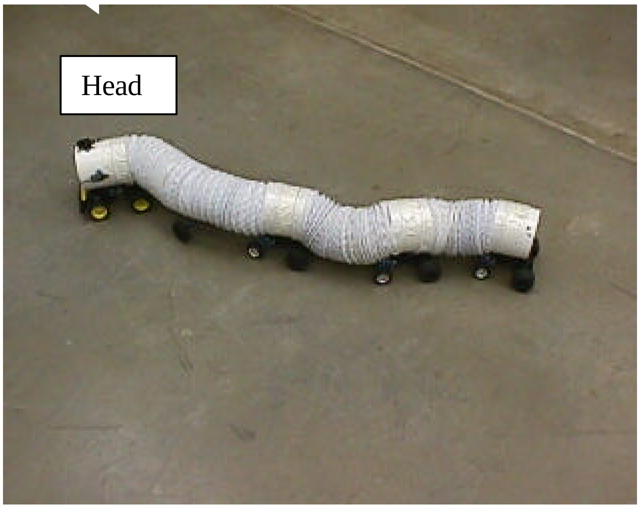

Figure 2: The prototype snake-robot.

This particular organization allows the overall system to have the following attributes:

- The body (overall system) can adapt to the shape of the terrain on which it lies. This allows the robot to overcome irregular and uneven terrain.
- It can easily modify its total length at any instant, therefore, adapting to congested spaces.
- It is able to perform multiple motion behaviors based on the combination of the following three basic motions: concertina, linear, serpentine.
- Due to its high redundancy, overall motion can be performed even if an individual section fails.
- As a unit, the system can be fully active, partially active or fully passive with regards to motion. Being fully passive means the head will lead and the other sections will exhibit a tractrix displacement [5].
- It is able to perform cooperative motion tasks when needed.
- The energy needed for the starting motion can be distributed over the sections so that a smooth and efficient energy management system can be achieved during transient time. Because the robot is mobile, the trajectory planning of [6] cannot be used.

3 Notation

l_i	link length
L_i	section length
ω	angular velocity (steering)
R	wheel radius
T_1	time constant
T_2	time constant
v	front wheel
V_1	input voltage
V_2	input voltage
ω_r	wheel angular velocity
è	angle between sec. axis and x axis
ϕ	angle between sec. axis and x axis
γ_i	angle between sec. axis and z axis
β_i	angle between sec. axis and x axis

4 Kinematics

Ignoring the head of the robot, the overall system is composed of (n-1) modules in a cascade. Each module contains one revolute and one prismatic link. A particular position of the overall structure will be totally described by $L_{I,}$ l_i, $\hat{a}_i$ and $\tilde{a}_i$ parameters. Therefore, the position of each section at any given time is in 3-D is given by:

$$x_i = x_0 + \sum_{k=1}^{k=i-1}(L_k.\sin\gamma_k \cos\beta_k + \ell_k.\sin\gamma'_k \cos\beta'_k) + L_i.\sin\gamma_i \cos\beta_i$$

$$y_i = y_0 + \sum_{k=1}^{k=i-1}(L_k.\sin\gamma_k \sin\beta_k + \ell_k.\sin\gamma'_k \sin\beta'_k) + L_i.\sin\gamma_i \sin\beta_i$$

$$z_i = z_0 + \sum_{k=1}^{k=i-1}(L_k \cos\gamma_k + \ell_k \cos\gamma'_k) + L_i \cos\gamma_i \tag{1}$$

Figure 3 shows the projection of the robot sections in 2-D space.

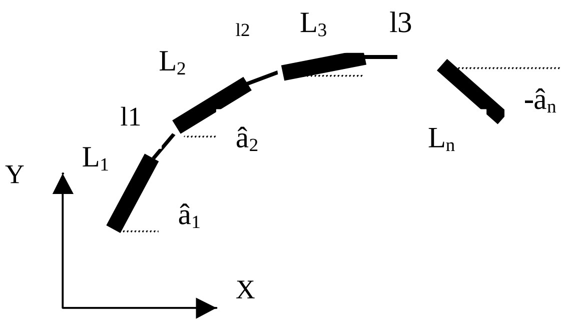

Figure 3: Simplified Representation of Snake Robot for the Kinematics Formulation

It should be mentioned that because of the specific construction of robot, speed cannot be obtained from the direct derivative of displacement. It is because each section moves independently.

5 Motion Strategy

The configuration of the system at any time can be expressed in terms of the position vector of each joint. Then at time "k", following the head trajectory Γ, the system has the following configuration:

$$P_{(k)} = [\, S_0 \; S_1 \; \dots \; S_i \; \dots \; Sn]\, \Gamma \qquad (2)$$

where S_i is the position vector of joint i.

For the motion strategy that follows, the information needed is the initial position of the system, and the current up-to-date information of the direction of the objective. The fundamental idea to perform the proposing motion is to have each subsection of the system to "follow" its corresponding heading subsection, with the exception of the extreme head which will move towards the desired trajectory "Γ" towards the objective. The term "follow" used here does not necessarily indicate that a section has the same path of its leading section. However, it means that the new position of a section will be in the line between its past position and the current position of the leading section. All displacements considered in this model are linear, and the overall motion is piece wise linear. The overall motion is achieved through several linear displacements. Figure 4 shows a full sequence of motion for each section to make one "cycle" in this paper.

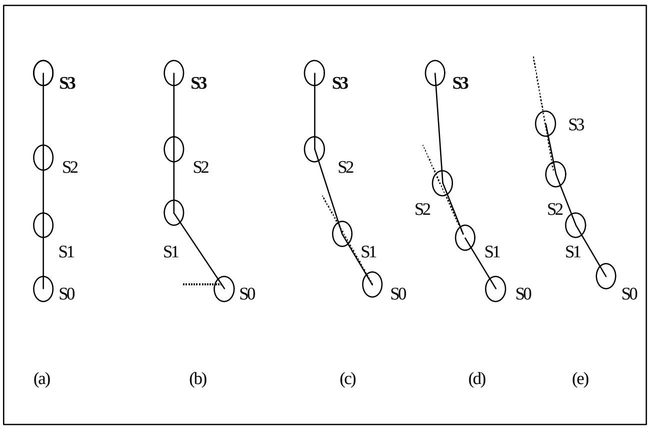

Figure 4: A Full Motion Cycle

The position of the head is given by:

$$S_o(k+1) = S_o(k) + \Gamma(k) \qquad (3)$$

and a generic subsection will have the following position:

$$S_i(k+1) = S_i(k) - \rho\,(S_i(k) - S_{i-1}(k+1)) \qquad (4)$$

Where:

i = 1 .. 3 for the three sections in this example.

$\rho = (\rho \in R,\ \rho \subset [0,1])$ is a constant.

$k = nT\ (n \in Z^{+})$.

T= motion period = 1 (for simplicity.)

Eqs. 3 and 4 are valid for a single cycle. Now, thought that the overall motion consists of several cycles, then a cycle descriptor must be introduced in the previous equation. Then Eq. 3 and 4 can be rewritten as:

$$S_o(c+k+1) = S_o(c+k) + \Gamma(c+k) \qquad (5)$$

$$S_i(c+k+1) = S_i(c+k) - \rho\,[S_i(c+k) - S_{i-1}(c+k+i+1)] \qquad (6)$$

The following algorithm was used to study, visualize, and compare the overall displacement of the system under predefined paths. The parameter

ρ, which determines how far a section will move towards the next section, has an important effect on the overall curve description of the sections. It can be noted that when $\rho \rightarrow 1$ the sections will tend to follow the real path of the head.

Figures 5 through 7 show results of the computer simulation that visually describes the displacements attributes of the proposed system for N=4 and different values of ρ. Each set of circles represent the path that a section describes during motion. The path is defined by Γ=A.atan(sin(x(k))/x(k)) where "A" is a constant number. The arrows indicate the starting and ending direction of the head.

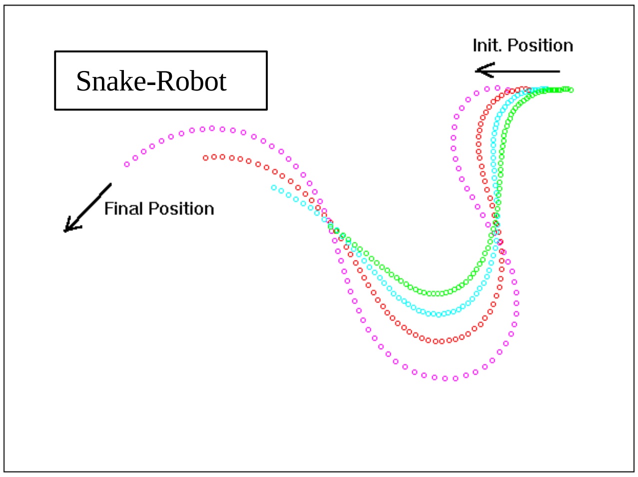

Figure 5: Composite path for ρ= 0.1 , N= 4

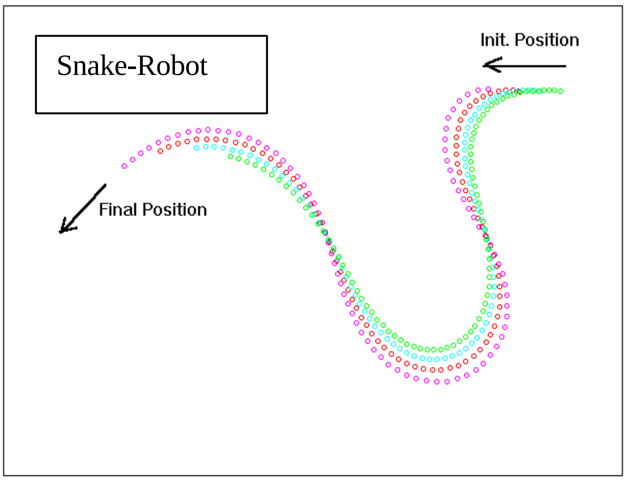

Figure 6: Composite path for ρ= 0.2 , N= 4

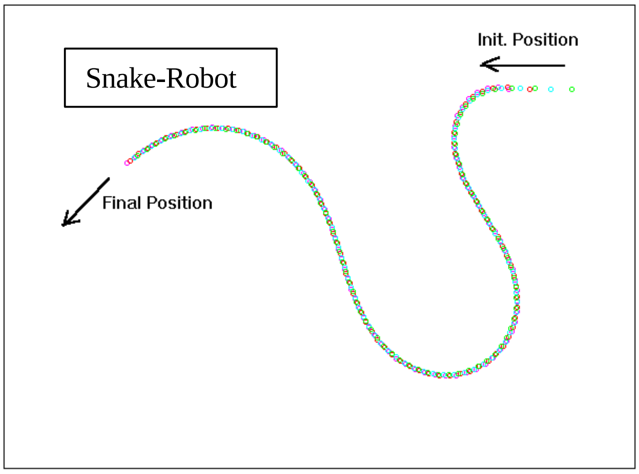

Figure 7: Composite path for ρ= 0.7 , N= 4

6 Obstacle Ovidance Strategy

The control strategy can be described as the following, provided that the existence of the target's information within the robot's world is guaranteed:

1. Set initial condition information.
2. At the initial step the robot will navigate randomly until information (heat, light, radio-frequency signals, etc.) of the target's direction is obtained by means of sensors. Moreover, the target's additional obstacle sensors will start being active.
3. Move in a straight line towards the target until it reaches the target and stops. However, if an obstacle is detected, the robot changes its path. Depending on the position of the obstacle the robot selects a random angle in either of these intervals [-30°, –90°] or [30°, 90°].
4. Move in a straight line in the new direction, until the distance to the obstacle is minimized.
5. If target is not reached, go back to step 3.

Under the described strategy the total trajectory of the system can be considered to be piece-wise linear as shown in Fig. 8. There exist many other methods to increase the maneuvering ability [7], and to avoid obstacle [8, 9].

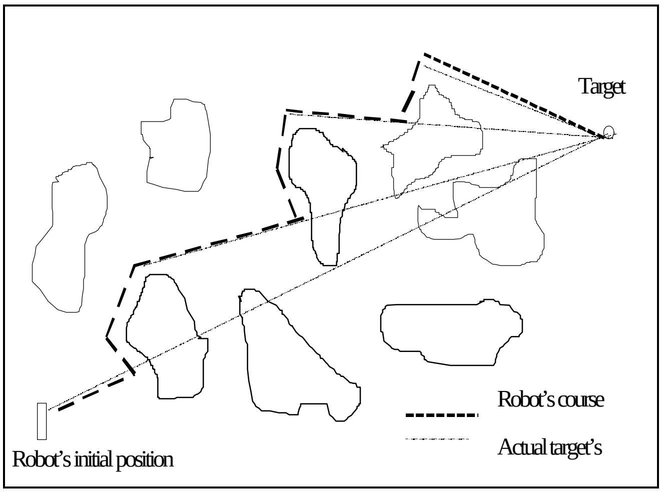

Figure 8: Target's Capture Strategy

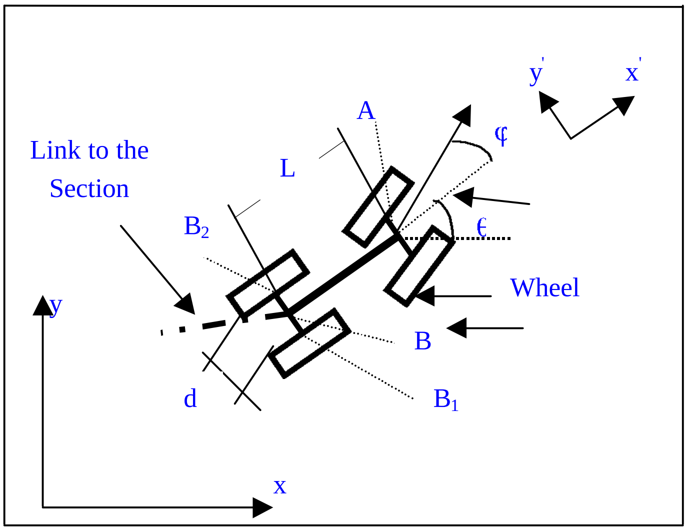

Figure 9: Front Drive and Steering Wheel Vehicle

7 Linear Motion Control

Consider the mobile unit in Fig. 9 as the head module of the system. This unit can be modeled as a front wheel drive and steering wheel vehicle, whose kinematics equations can be developed. Assuming ω_{r1} and ω_{r2} are the angular velocities of the front wheels, then the velocity of point "A", at the middle of front wheels axis, with respect to the x'- y' axes is:

$$\vec{V}_A = \frac{R}{2}(\omega_{r1} + \omega_{r2})(\cos\varphi * \hat{i} + \sin\varphi * \hat{j})$$

If φ is small, then $\omega_{r1} \approx \omega_{r2} = \omega_r$ and then:

$$\begin{aligned} v &= R.\omega_r \\ \vec{V}_B &= v * \cos\varphi.\hat{i} + (v * \sin\varphi - L * \theta').\hat{j} \end{aligned} \quad (7)$$

It should be mentioned that B could not have the j component of the velocity. If these formulas are written with respect to X-Y coordinate, they will be the same as those developed in [10].

For small values of θ and ϕ the Eq. 7 will have the following reduced form [11]:

$$\begin{aligned} x' &= v \\ y' &= K_a.\theta \\ \theta' &= k_b.\varphi \\ \varphi' &= \omega \end{aligned} \quad (8)$$

where: $K_a = v$ and $K_b = v/L$.

It can be noticed that the overall control system is composed of two control blocks that can be analyzed separately as shown in Fig. 10.

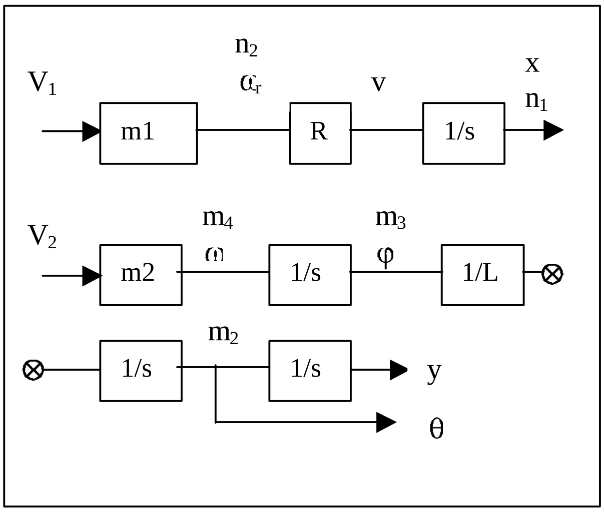

Figure 10: Block Diagram of the Controller.

The relationship between V_1 and v can be expressed as:

$$v=[R/(sT_1 +1)]V_1 \quad (9)$$

and for the second motor the relationship between ω and V_2 is as follow:

$$\omega = [1/(sT_2 +1)]V_2 \quad (10)$$

8 Conclusion

In this paper, the possibility for the conception of an autonomous hyper redundant mobile robot navigating in unknown terrain was shown. Also the passive and active modes were used to guide the robot. The control strategy based on linear and non-linear head displacements was established to pass the obstacles in front of the robot. To accomplish these goals, an experimental prototype was developed to satisfactorily test the basic capabilities and attributes of the system.

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