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Adaptive Control Mechanism for Snake with Intelligent Distributed Controller (SiD)

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Abstract*—The ability to comprehend and decide the trajectory defines the intelligence and the adaptability of the snake robot. The proper selection and distribution of the controllers helps every segment of the snake body to execute manifold gait and easy obstacle avoidance. Differential drive for DC motor connected at each wheel is generated by a DSP processor to control the segment following the path. This paper holds a thorough discussion on generation of differential drive signal with both, PWM and continuous pulse train control for right and left wheel and intelligent decision of trajectory by the SiD with the help of obstacle sensor and control pattern generator placed at the rear head of the designed adaptive snake robot. Phase differences between each segment of snake body and stability analysis of the controller part are also shown. Finally the compensation technique for designing the controller is justified for a given set of robot parameters in TMS320C6713 DSP platform.

***Index Terms*— ACM, Biologically Inspired Robots, Differential Drive, Snake-like Motion.**

I. INTRODUCTION

Adaptability and capability of snake-like locomotive mechanism for moving over complicated and unknown terrain using manifold gaits is the key reason for its booming research study. Research has been carried out toward applying this form of locomotion to rescue robots designed to rove through disaster debris with the help of designed differential drive snake robot. The motion type to be deployed by the respective SiD depends on its traversing environment. There are four main types of biological snake locomotion shown in Fig 1: (a) Lateral undulation, (b) Concertina, (c) Side winding motion, (d) Rectilinear motion. The paper focuses on the achievement of lateral undulation type of motion using differential drive system whereas side-winding and rectilinear type of motion can be easily obtained in the same design using omni-directional wheel and the later by producing zero joint angles. The proposed designed Snake robot with intelligent distributed controller over its augmented architecture and presence of a signal generator and an obstacle sensor at its head module helps to wish its trajectory, which further justifies its adaptability in diversified terrains. This control pattern generation can be classified in two types (a) Synchronous Control (b) Asynchronous Control. This paper focuses on asynchronous type of control pattern generation of pulses which further produces a differential drive in the wheeled SiD. Asynchronous approach is preferred to that of synchronous or central pattern generation approach because wheeled robots are usually thought to require a continuous control of the wheels while CPG circuits produce rhythmic motion. In 1972, the first snake robot namely ACM-Ill was built under Active Cord Mechanism (ACM) concept developed by S. Hirose. This ACM concept is further used in addition with differential drive system with both PWM and continuous pulse train signal control methods to obtain lateral undulation and easy obstacle avoidance. The need of fast transient response along with low steady state response is achieved by using lag-lead compensators. The lag-lead compensators are designed using three approaches: graphical domain approach, PID method, frequency response approach, each method having its own pros and cons. Since then after Hirose's invention in 1972 a variety of different snake robots have been designed [2], [3], [4], [5], and [6], some of which are currently used for the inspection of pipes [7], for example and some swimming snake robots, the eel robot REEL II [8], the lamprey robot built at Northeastern University [8] and the spirochete-like HELIX-I [10]. Some more swimming and crawling robots AmphiBot II, presented in [11], AmphiBot I [12], [13] with onboard central pattern generator (CPG) running on a microcontroller, have been previously designed. In present design analysis we aim at MIMO system with DSP platform where the signal is processed at each segment in contrast to CPGs or any other signal generation method in each segment. The proposed Serially Linked Robot (SLR) needs only one operator whereas some snake robot like Omni Tread [14] requires minimum of 3 operators. Controller design, segmentation along with differential drive wheeled-based approach palliates the problem that still persists in other robots referred in other like stability, obstacle avoidance in[3], interchangeability, increased fault tolerance, pay load etc. Thus, we discuss how differential drive is generated using PWM signal and continuous pulse train signal. And further how the controlling of these signals in both left and right wheels control the gait of the snake robot.

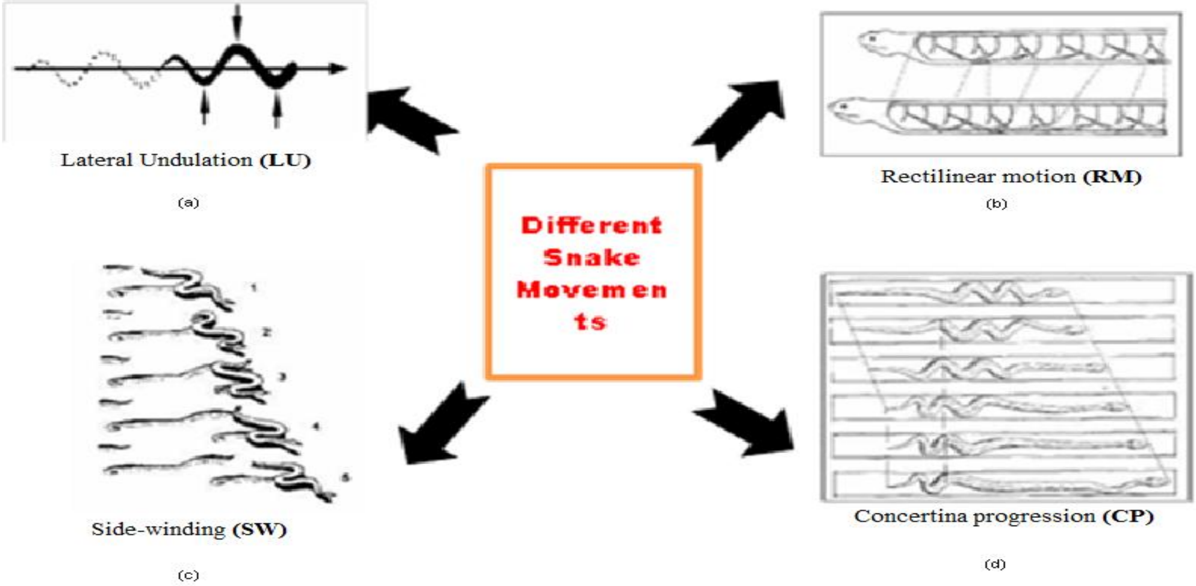


Fig. 1. (a)Lateral Undulation Motion [15], (b) Concertina Motion [15], (c) Side Winding Motion [15], (d) Rectilinear Motion

This paper is organized as follows. Section II presents the mathematical models of the snake robot along with the parametric comparison of different types of motion achieved by the proposed design. The motor parameters and controller design with different approaches and their respective stability analysis are given in Section III. Section IV provides the mathematics and simulation results for differential drive generation and concluding remarks are found in Section V.

II. MATHEMATICAL MODELLING OF SID ALONG WITH ITS CONTROL PATTERN GENERATION

Undulation is the basic movement exerted by the snake by continuous side to side movement of the body sections perpendicular to the direction of forward motion. Active cord mechanism providing a slender chain like grouping of joints and links that make active and flexible winding motions under the control of actuators attached along its body results in undulatory motion of the SLR. Thus, to achieve serpentine movement in the multi-segment serpentine robot using ACM every segment is provided with a phase difference to each other by appending a phase shifter in segment. For further control of the designed serially linked model asynchronous pattern generation is chosen over synchronous pattern control.

A. Mathematical model of Force Exerting on Snake Body

Using ACM snake's integrated body is modeled by some jointed connectors with length δs. In the connection of J_i joints, when the actuator positioned at an arbitrary joint J_i gives rise to joint torque T_i, a force defined as

$$f_i = \frac{T_i}{\delta s} \tag{1}$$

is produced at joint J_i and joints J_{i-1}, J_{i+1} or either side of it.

This force has two components tangential and normal which when integrated over the full body length L of the snake robot assuming θ_i (i.e. the angle between the connectors) to be very small and defined as

$$\rho_i \approx \frac{\theta_i}{\delta s} \tag{2}$$

we get,

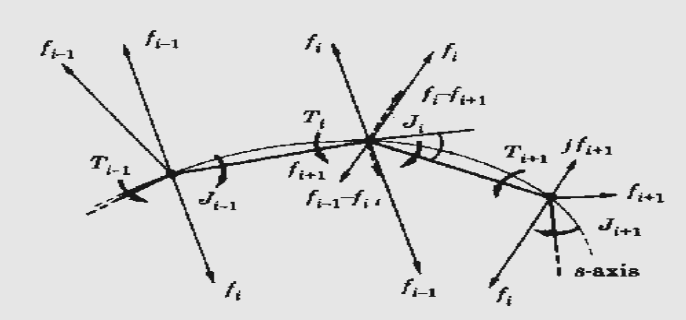


Fig. 2. Modeling snake's continuous body [1]

$$F_t = \int_0^L \frac{dT(s)}{ds}\rho(s)ds \qquad (3)$$

$$F_n = \int_0^L \left|\frac{dT(s)}{ds}\right| ds \qquad (4)$$

Where, F_t is the net tangential force (propulsive force) and F_n is the net normal force which results in side slipping. Due to limitation to the power which the actuators positioned on the ACM's body can generate there are many cases when its posture and speed of movements are restricted, the power can be formulated for a moving body with speed 'v' along body axis's'.

$$P_i = T_i \frac{d\theta_i}{dt} \qquad (5)$$

Or, $$\mathrm{P(s)} = T(s)\frac{d\rho(s)}{ds}v \qquad (6)$$

Where,

$$\rho(s) = \frac{2K_n\pi\alpha}{L}\sin\left(\frac{2K_n\pi\alpha}{L}s\right) \qquad (7)$$

where, L is the whole length of snake body, K_n is the number of the wave shape, α is the initial winding angle of the curve, and s is the body length along the body curve, as shown in Figure 3.

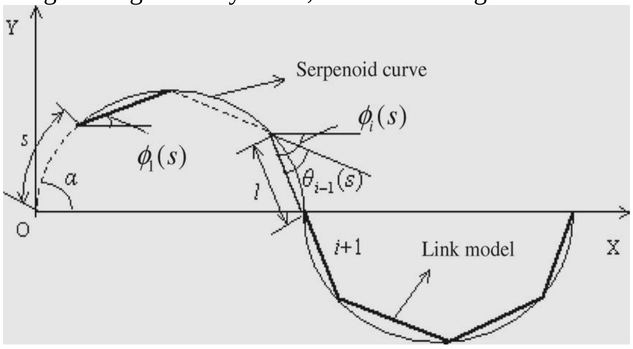


Fig.3 Scheme for fitting the serpenoid curve. [16]

Thus, equation (6) expresses the torque distribution and curvature distribution by the continuous functions T(s), $\rho(s)$ and the power density function denoted by P(s). And this curvature distribution function given by equation (7) characterizes the sinusoidal variation in curvature along the length of the multi-segment snake robot. This sine like curve is termed as serpenoid curve developed by Hirose which the snake would trace as it slithers forward. This serpenoid movement is thus achieved in the multi-segment snake robot by continuous oscillatory rotation produced in the joints of the segments. The dynamics of the positioning of joints which process the effect of continuous constringency and extension are given by the standard form of Fresnel's integrals given below:[25]

$$x(s) = s\,J_o(\alpha\alpha + \frac{4l}{\pi}\sum_{m-1}^{\infty} J_{2m}(\alpha)\left(\sin\frac{m\pi\pi}{l}\right) \quad (8)$$

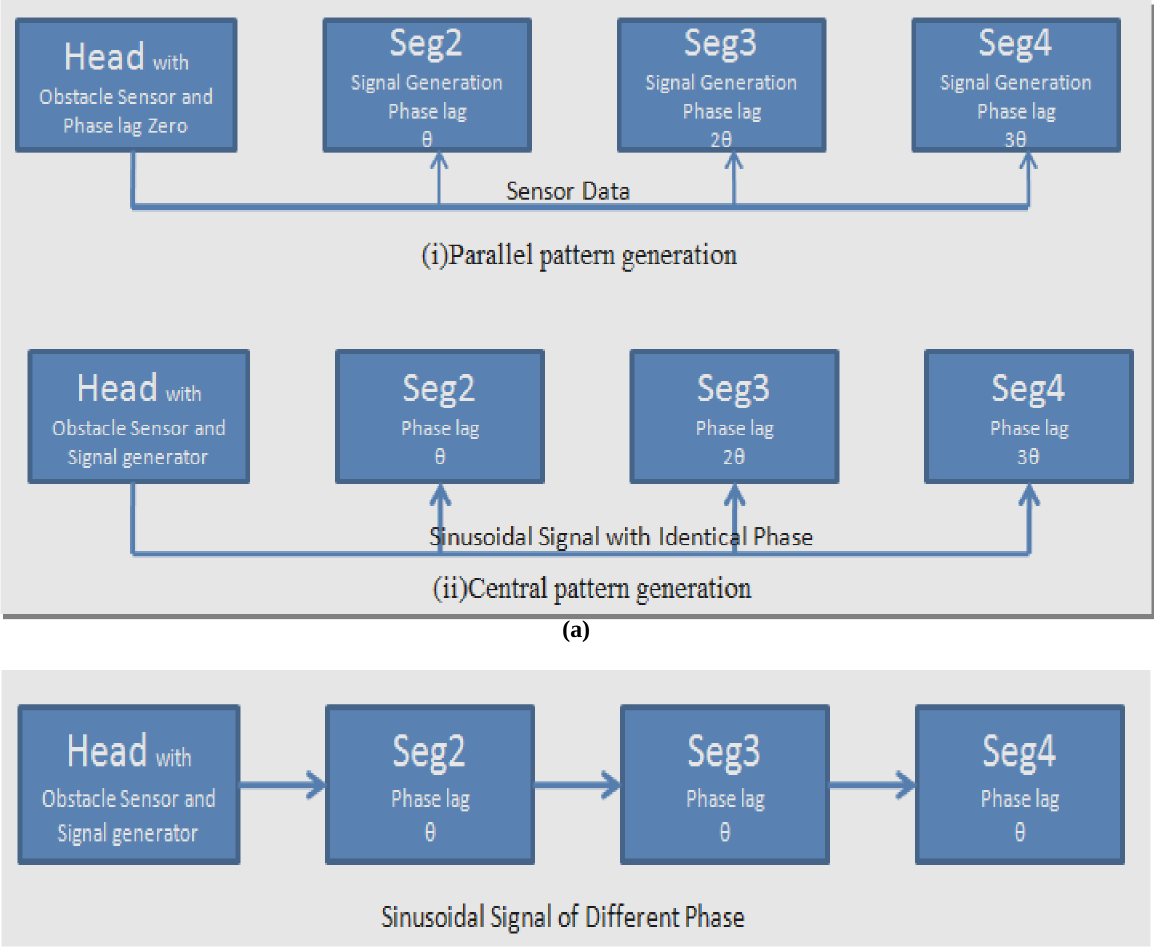
$$y(s) = \frac{4l}{\pi}\sum_{m-1}^{\infty}\frac{(-1)^{m-1}J_{2m}(\alpha)}{2m-1}\left(\sin\frac{(2m-1)\pi s}{l}\right) \quad (9)$$

Where, $J_n(\alpha)$ is the Bessel function and is expressed as,

$$J_n(\alpha) = \left(\frac{\alpha}{2}\right)^n \sum_{m-1}^{\infty}\left(\frac{-1^m}{m!\,\Gamma(n+m+1)}\right)\left(\left(\frac{\alpha}{2}\right)^{2m}\right) \quad (10)$$

B. Control Pattern Generation

This control pattern generation can be classified in two types as shown in Fig. 4. (a) Synchronous Control (b) Asynchronous Control. This paper focuses on asynchronous type of control pattern generation of pulses which further produces a differential drive in the wheeled SiD. Asynchronous approach is preferred to that of synchronous or central pattern generation approach because wheeled robots are usually thought to require a continuous control of the wheels while CPG circuits produce rhythmic motion.



(a)

(b)

Fig.4 Schematic block diagram for control pattern generation (a) Synchronous Control (b) Asynchronous Control

III. CONTROLLER DESIGN USING DIFFERENT APPROACHES

Ccontroller attempts to correct the error between a measured process variable and a desired set point by calculating and then outputting a corrective action that can adjust the process accordingly. Here we design lag-lead compensators with cascaded phase shifter to control the positioning of each segment. Lead compensation basically speeds up the response and increases stability of the system whereas lag compensation improves the steady-state accuracy of the system, but reduces the speed of response. So, to achieve both fast response and minimized steady state error lag-lead compensators are used. And phase shifter is cascaded along with each controller to provide multi segment robot a movement following serpenoid curve.In this work 1.2 watt DC motor from MAXON Motor which is smaller in size and suitable for our desired SLR has been used to drive the wheels resulting a differential drive system.

Fig. 5. 4.5 Watt, Maxon DC Motor: Model Number- 215999

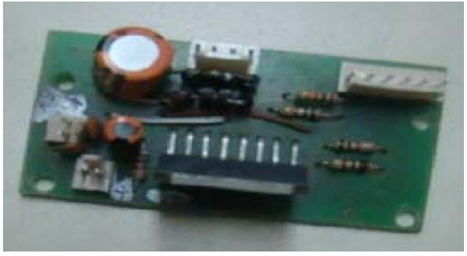


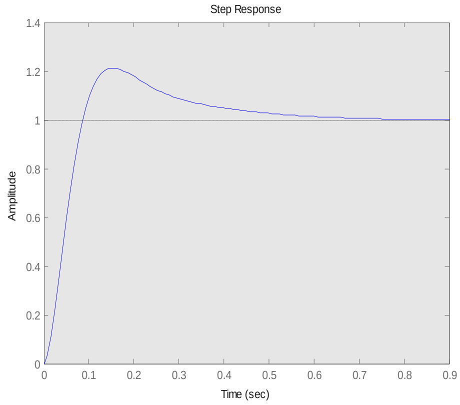
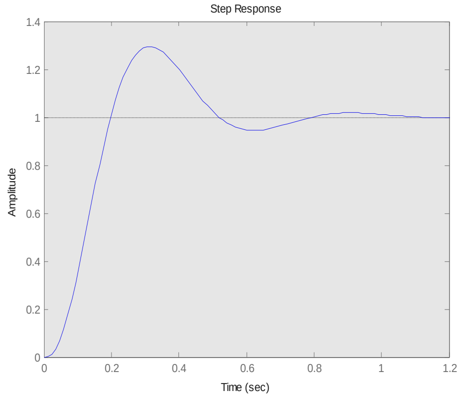
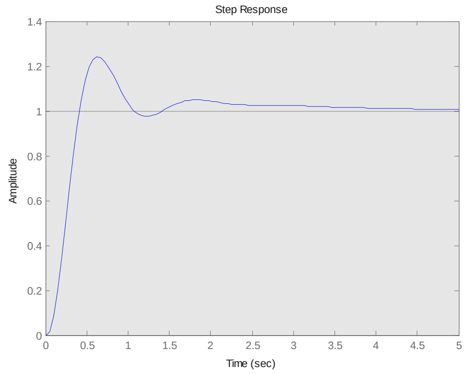
Fig.6. Driver Card for Snake Wheel Control

Table 1. DC motor Parameters from MAXON Motor

Symbol	Parameter	Value
La	Armature Inductance	0.223mH
Ra	Armature Resistance	11Ohm
J_m	Rotor Inertia	0.306gcm2
K_i	Torque Constant	5.08mNm/A
v_{nl}	No load Speed	11100rpm
I_{nl}	No load Current	10.4 m A
G	Speed/Torque Gradient	4050rpm/mNm

Here, the controllers are designed using three approaches, (1) PID using Ziegler-Nichols Tuning Rule based on critical gain and critical period, (2) Graphical Domain Approach, (3) Frequency Response Approach. Graphical domain approach provides with easy, less and fast approach but with assumption of a zero to find its relative pole. Whereas, frequency domain approach requires no such assumptions as it persists a direct relationship with steady state response. The output of a controller when subjected to a third order system given by the motor transfer function G(s) with the given preferences of maximum peak of 25%, rise time to be 0.3 seconds and no. of joints given to be 3 using three different approaches are characterized in Table 2.

Table 2. Simulation Results of Designed Controllers Using Three Different Approches

S. no.	**Approach**	**Simulation results**	**Step Response**
1.	PID	G. M : Inf Freq : Inf Stable loop P. M : 108 deg Freq : 22.2 rad/sec Peak time : 0.152 s Maximum peak: 1.21	
2.	Graphical Domain Approach	G. M : 12.7 db Freq : 25.2 rad/sec Stable loop P. M : 54.1 deg Freq : 13.6 rad/sec Peak time : 0.312 s Maximum peak: 1.29	
3.	Frequency Response Approach	G. M : 17.8 db Freq : 15.9 rad/sec Stable loop P. M : 64.3 deg Freq : 6.44 rad/sec Peak time : 0.636 s Maximum peak: 1.24	

IV. DIFFERENTIAL DRIVE GENERATION USING PWM AND CONTINUOUS PULSE TRAIN

A. PWM signal generation for differential drive

In PWM type of control signal generation the pulse width varies in accordance to signal amplitude treating positive maxima of the sinusoidal input as the maximum amplitude and the minima (i.e. negative maxima) as the minimum amplitude for left channel signal generation and vice versa for right channel. The equations below describes the PWM signal generation.

PWM Signal for left channel Control:

$$L(n,t) = \sum_{n=-\infty}^{\infty} u(t-(2*n)) - u(t-((2*n+1)+|m[n]|)) \qquad (11)$$

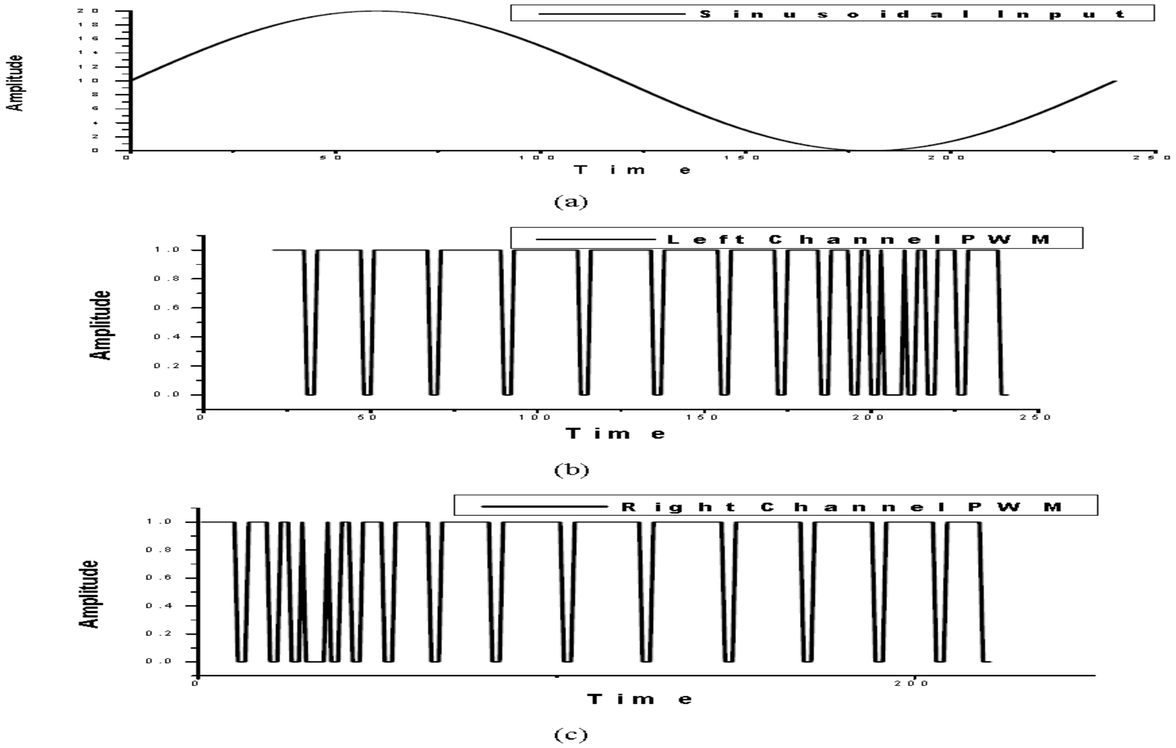
Where,

$$m[n] = A\ (\sin(\frac{2\pi f n}{f_s}))| \qquad (12)$$

PWM Signal for Right channel Control:

$$R(n,t) = \sum_{n=-\infty}^{\infty} u(t-(2*n)) - u(t-((2*n+1)-|m[n]|)) \qquad (13)$$

In this method the SLR turns left at the instance when left channel output is low and turns right when the right channel output is low. This technique can be further used to obtain rectilinear type of motion in addition to lateral undulation by making the duty ratio the output control signal to be 100%.



(a)

(b)

(c)

Fig.7. PWM control signal generated to achieve differential drive with (a) Sinusoidal input signal (b) Left channel output (c) Right channel output

B. Continuous Pulse Train

In continuous pulse train generation method pulse are generated at maxima and minima of the input sinusoidal signal. In this method the output control signal for right channel is a unit pulse at the maximas of the input otherwise zero whereas for left channel control output is a pulse at input minima's and otherwise zero. The signal generated is used for directional control of the SLR. The equations and the Fig. 8 shown below describe the following mechanism. Here, for the message signal given in (12), Control signal for both the Channels:

$$C(n,t)=\sum_{n=-\infty}^{\infty}[u(t-\tau)-u(t-(\tau+\Delta\tau))] \qquad (14)$$

Where, for right channel

$$\tau=(4*n+1)*f\_s/(4*f) \qquad (16)$$

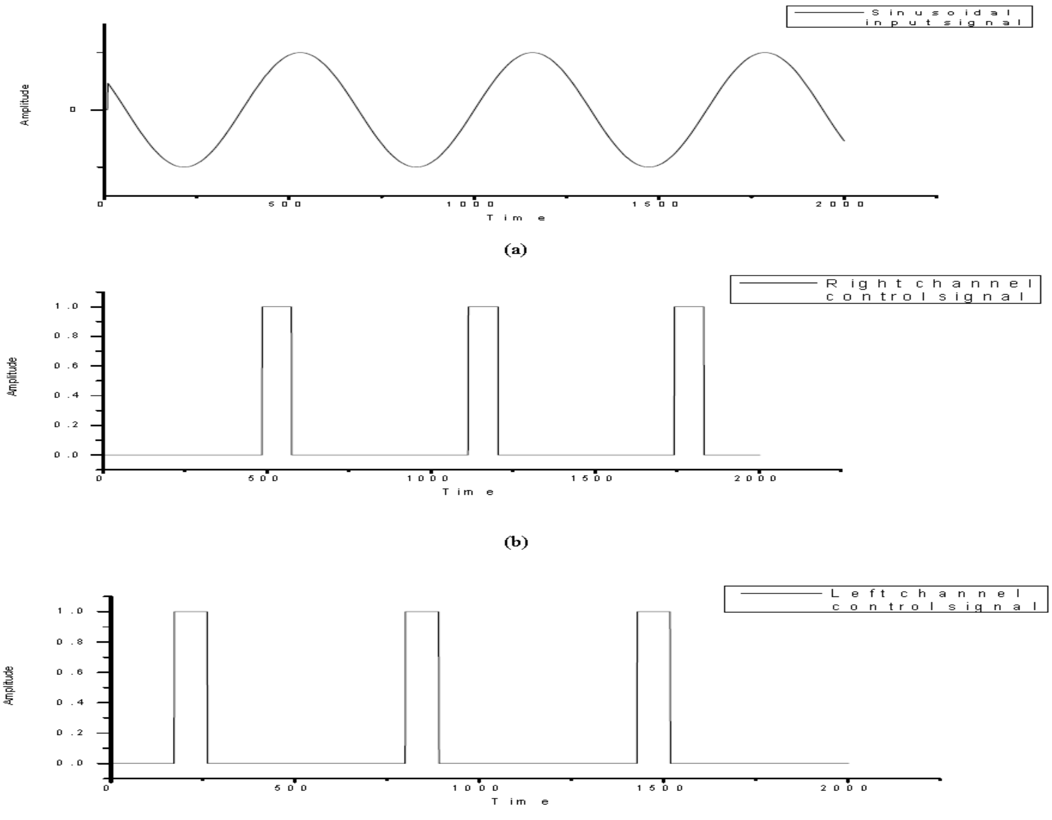
$\Delta\tau$ = pulse width

f =frequency of the sinusoidal input signal

Similarly, for Left Channel:

$$\tau=(4*n+3)*f\_s/(4*f) \qquad (17)$$

This method results the SLR to turn left at the instance when left channel control signal is high and vice versa.



(a)

(b)

(c)

Fig. 8. Continuous pulse train control signal generated to achieve differential drive with (a) Sinusoidal input signal (b) Left channel output (c) Right channel output

Thus, we obtain differential drive resulting to obtain lateral undulations using both methods PWM signal and continuous pulse train generation methods. Further we can also make the snake robot move round about by varying the duty cycle of the left and right channel output. Differential drive causes the easy turning of wheels thus resulting in easy and fast obstacle avoidance. The same design can also be used to obtain side-winding by the usage of omni-directional wheels instead of simple wheels.

C. Parametric Comparison

The designed SiD being able to adapt to different environment and accordingly execute required type of gait as it wishes with the control pattern generator. The trajectory wish is decided by the motion or obstacle sensor and control generator placed at the SiD head. The parameters like velocity, obstacle avoidance, etc decides the adaptability of the designed SiD. The Table 3 presents a parametric comparison of the wheeled SiD for different snake movements.

\Table 3. Parametric comparison of the wheeled SiD for different snake movements

Parameter	LU	RM	SW	CP
Velocity	B	C	A	D
Obstacle Avoidance	C	B	D	A
Path Planning	C	A	D	B
Pay Load	B	A	C	D
Controllability	C	A	D	B
Design Complexity	B	A	C	D
Adaptability to Surface Friction	D	B	C	A

V. CONCLUSION

Biologically inspired robots have become a very important area of robotics research for surviving in a hazardous environment which needs to be localized for mapping simultaneously with obstacle avoidance. While improving its smartness this type of robots incorporates complexity and calculation difficulty for the controlling processor in terms of computational load. Therefore, we need high end processor for specific application that makes the system, on the other hand, less cost-effective. Snake-like robots are generally comes under the category of serial linked robots i.e. mirroring the controller design procedure as the number of segments increases. Basically this type of robots holds another drawback such as, inability of carrying payloads so that SLAM and mimicking of snake-like motion are considered as the matter of research. Here in this paper lateral undulation of snake-like motion has been targeted with DSP processor to follow ACM curve. Additionally IR sensor and Camera are mounted at the front end of the model developed in the lab scale for testing purpose.

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