

# Active Cord Mechanism (ACM) Controller for Biologically Inspired Robots Designed with Frequency Response Approach

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*Abstract*— Multi-segmented robots earn some basic advantages of assembling and disassembling of their body parts and different types of movement in a single body structure. Snake robots can manifolds four types of motion in the surface level using different transfer function. The main task is to derive the transfer function of each segment that can control the snake body to navigate with Active Cord Mechanism. Lead compensators are subject to improve the speed of response of the snake body while lag compensators optimize its errors in deviation while obstacle avoidance. A composite of lag-lead compensator is discussed and examined for SUPRA Institutional Serpentine robot to be employed in a coal mine for disaster management. The side winding movement is taken into consideration and wireless control of snake robot is a matter of importance. This paper holds a discussion over the controller design procedure using frequency response approach and shows a comparison between the lead-lag and only lag compensators with their transient and impulse responses. Finally results are shown to support the stability analysis of the designed control system.

*Keywords:* - ACM, snake robot, frequency domain approach, lag-lead compensator.

## 1. Introduction

A “Snake robot” is a multi-segment mechanism that derives propulsion from undulations. Its design is biologically inspired from real snakes as snake being able to reside and locomote in more diversified terrains due to its architecture which helps to adopt manifold gaits. These characteristics of terrain ability, scalability, high stability, and ground adaptability the snake like robot can be used in many purposes such as pipe repairing, rescue, payload, medical purpose, space research etc. In 1972, the first snake robot namely ACM-III was built under Active Cord Mechanism (ACM) concept developed by S. Hirose[1]. Using this ACM concept in this paper we focus on how it along with differential friction helps in serpentine motion and then how to control the motion with the help of controller to avoid the obstacles. The application of lag-lead compensator designed using graphical domain approach is the key concept for designing the controller which thus helps is giving fast response along with small steady state error at same time. Thus, providing a good control over the segmented snake robot.

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Controller design, segmentation along with wheeled approach palliates the problem that still persists in other robots referred in other like stability, obstacle avoidance in[4], interchangeability, increased fault tolerance, pay load etc. One of first snake-like robot, named an active cord mechanism [1], has been constructed in 1972. Since then a variety of different snake robots have been designed [3], [4], [6], [7], and [8], some of which are currently used for the inspection of pipes [9], for example. A review of snake robots can be found in [11] and [12]. Most of these robots have been designed for locomotion on ground, and only a few working examples of swimming snake robots currently exist. The most interesting ones are the eel robot REEL II [13], the lamprey robot built at Northeastern University [14] and the spirochete-like HELIX-I [15]. Another work also carried away in [17], to build an amphibious snake-like robot that can both crawl and swim for outdoor robotics tasks, taking inspiration from snakes and elongate fishes such as lampreys, and to demonstrate the use of central pattern generators (CPGs) as a powerful method for online trajectory generation for crawling and swimming in a real robot. AmphiBot II, presented in [17], is the new

version of AmphiBot I [18], [19], with comparison to its predecessor, features a significant number of improvements, like: A better mechanical design, more powerful motors, wireless communication capabilities, onboard CPG running on a microcontroller, therefore removing the need of running the controller on an external computer.

Thus, to design the multi-segment snake robot we firstly study the 4 main types of biological snake locomotion

### 1.1 Lateral Undulation

Waves of muscular contraction and relaxation propagate from front to rear. The sections continuously move from side to side perpendicular to the direction of forward motion. This oscillation, as a directional vector has both a tangential and a normal component relative to the forward direction. In this the net result of the lateral oscillation cancels the normal force being opposite to each other whereas the tangential components for both sides are in the same direction, parallel to the direction of forward motion. The motion requires three points of contact. Two points for forward pressure and a third for balance.

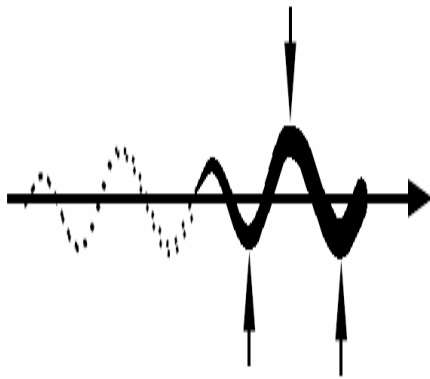


Fig. 1.1 Lateral Undulation Motion<sup>[24]</sup>

### 1.2 Concertina

Sequential folding and unfolding of the body using differences in static and dynamic friction along different parts of the body. When extending the front section i.e. during unfolding, the snake reaches forward a distance, while the back sections remain stationary providing a foundation for the moving section. Whereas during folding the front sections provide the

foundation to the moving back section. The pattern results in a series, alternating between pushing against a back foundation and pulling against a front foundation. Static friction is the key; thus, this gait is more useful on low friction surfaces

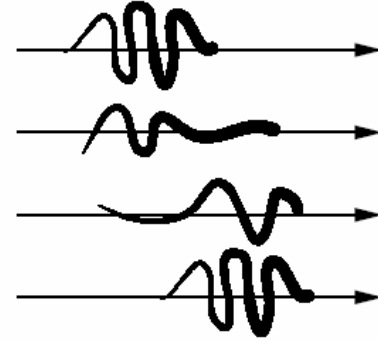


Fig. 1.2 Concertina Motion<sup>[24]</sup>

### 1.3 Side Winding

Continuous alternating waves of lateral bending while maintaining only two contact points to the ground. Thus, the body is shifted to the side. The segments not in contact with the surface are lifted and move to the side. They then become the new contact points. The previous contact point is then lifted and moved. Repeating this pattern, the snake moves in a direction to its side. Since sections must be lifted, the snake moves in both horizontal and vertical planes. Lateral undulation and concertina only necessitate horizontal mobility; thus, the side-winding gait requires more complex muscular and skeletal structures to facilitate the two degrees of freedom.



Fig. 1.3 Side Winding Motion<sup>[24]</sup>

### 1.4. Rectilinear motion

Muscles shift the skeleton with respect to the skin. Waves of muscular contraction along the body propels the whole body. Traction to the ground is enabled by belly scales.

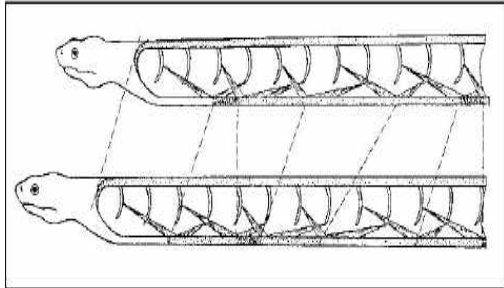


Fig. 1.4 Rectilinear Motion

## 2. Mathematical model of Force Exerting on Snake Body

In the proposed design of snake robot the side winding type of locomotion is achieved with the help of Active Cord Mechanism. Active Cord Mechanism is 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. Thus to achieve serpentine movement in the multi-segment serpentine robot using ACM every joints are provided with a phase difference to each other by appending a phase shifter in segment.

Using ACM snake's integrated body is modeled by some jointed connectors with length  $\delta s$ . 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.

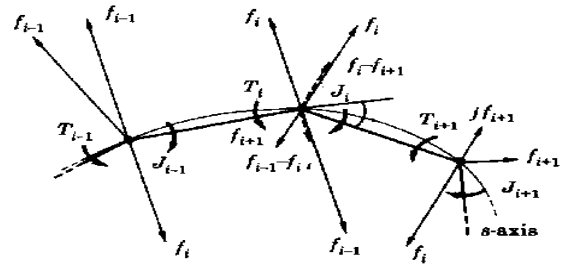


Fig.2.1 Modeling snake's continuous body<sup>[24]</sup>

This force has two components tangential and normal which when integrated over the full body length  $L$  of the snake robot assuming  $\theta_i$  (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,

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

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

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'.

$$P_i = T_i \frac{d\theta_i}{dt} \tag{5}$$

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

Where,

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

where,  $L$  is the whole length of snake body,  $K_n$  is the number of the wave shape,  $\alpha$  is the initial winding

angle of the curve, and  $s$  is the body length along the body curve, as shown in Fig. 2.2.

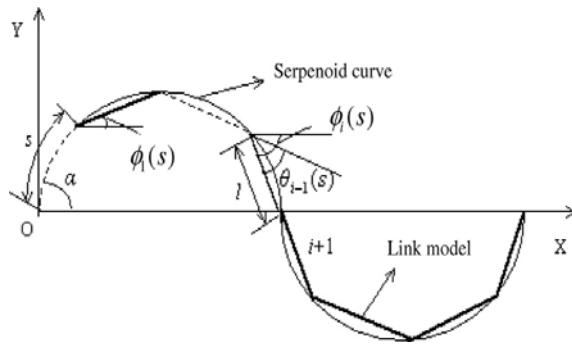


Fig. 2.2 Scheme for fitting the serpenoid curve<sup>[5]</sup>

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:[24]

$$x(s) = s J_0(\alpha) + \frac{4l}{\pi} \sum_{m=1}^{\infty} J_{2m}(\alpha) \left( \sin \frac{m\pi s}{l} \right) \quad (8)$$

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

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

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

### 3. Controller design with phase shifted signal

Controller 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 using frequency response approach with cascaded phase shifter to control the positioning of each segment.

#### 3.1 Lead compensator to enhance response time using frequency domain approach

Lead compensators are used to meet the transient response specifications for the system. It increases both phase margin and system bandwidth which implies the increasing the speed of response. The existing system's angle deficiencies are provided by it.

#### 3.2 Lag compensator to reduce steady state error using frequency domain approach

Lag compensators are used when the system exhibits unsatisfactory steady-state characteristics and maintains the low frequency gain. It basically provides the attenuation necessary to bring the magnitude curve down to 0dB at new gain crossover frequency.

#### 3.3 Phase shifter to achieve serpentine motion

In this wheeled snake robot each module should be at some phase difference to each other to produce serpentine movement. The amount of phase shift for  $n^{\text{th}}$  segment is  $n-1$  times that of angle where,

$$\text{angle} = \frac{360^\circ}{\text{total no. of segments}} \quad (11)$$

e.g. if  $A * \text{Sin}(2 * \pi * f * t + \text{phi})$  be the input to the first module

where,

A=Amplitude of input sinusoidal signal

f=Frequency of input sinusoidal signal

t=Time in seconds

phi=Initial phase of input signal

Then, the input to the  $n^{\text{th}}$  module will be equal to

$$A * \text{Sin}(2 * \pi * f * t + \text{phi} + (n * \text{angle}))$$

In case the serpentine robot meets an obstacle the snake is made to move in same direction with greater angular displacement. So, to attain greater angular displacement initial sinusoidal input is fed with a phase shift. Thus, the steps for designing the controller to meet the steady state and transient performance

specification along with the aid of obstacle avoidance are given by the flowchart below:

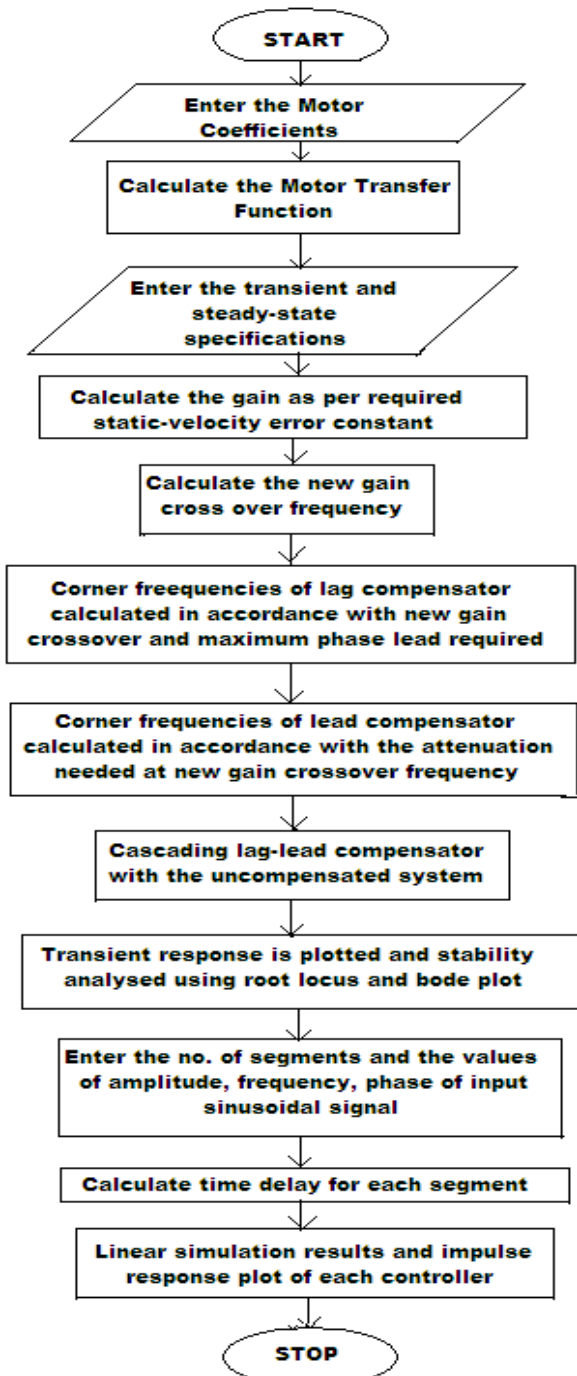


Fig.3.1 Flow chart of controller design procedure

#### 4. Simulation results of the designed controller:

Two different methods for controller design are discussed in [25]. Design of only lead compensator may satisfy the speed of response of the snake body which may affect the wireless control of the snake robot described in [26] and [27]. An optimized control of snake robot needs a lag-lead compensator to be designed for the following specification.

- The controlled output of the system (motor) with the given specification of maximum peak of 25%
- a rise time of 0.3 seconds
- no.of segments to be present in the multi-segment robot is 4.

We get a controlled output with phase shifted results for each controller to produce serpentine motion is shown in Fig. 8

In this work 1.2 watt DC motor from MAXON Motors has been used which is smaller in size and suitable for our desired SLR. Table-1 shows detailed specification of this motor.

Table-1 Technical Specification of Maxon RE- max DC motor (model No.-203889), 1.2 watt.

Parameter	Value
Armature Inductance( $L_a$ )	0.223 mH
Armature Resistance ( $R_a$ )	11 ohm
Rotor Inertia( $J_m$ )	0.306 gcm <sup>2</sup>
Torque Constant( $K_i$ )	5.08 mNm/A
No load Speed	11100 rpm
No load Current	10.4 mA
Speed/Torque Gradient	4050 rpm/mNm

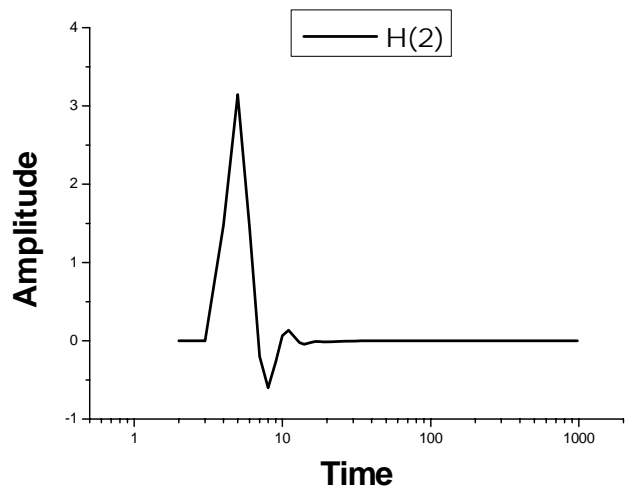
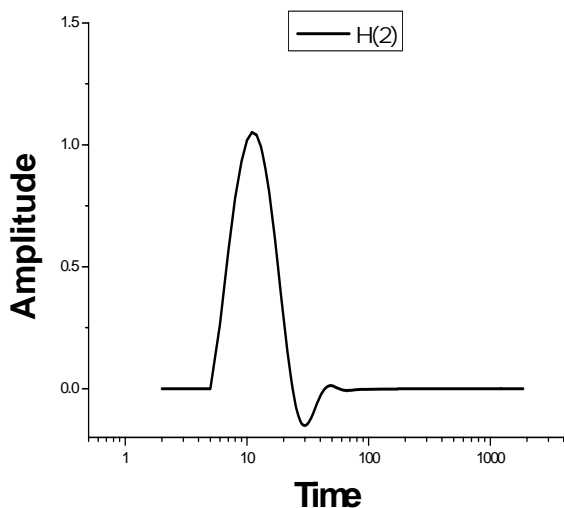
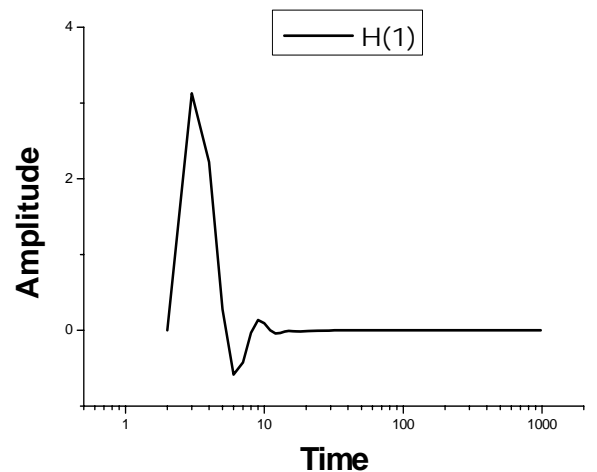
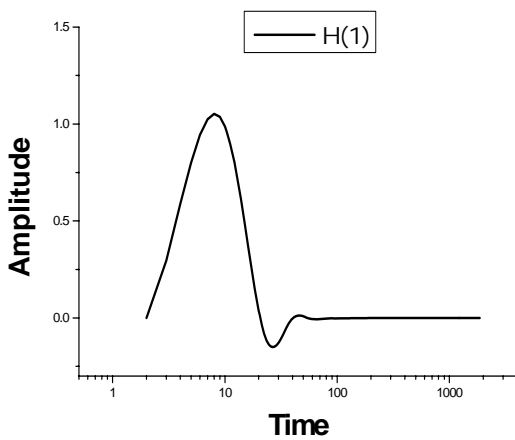
The motor transfer function obtained for the uncompensated systemis:

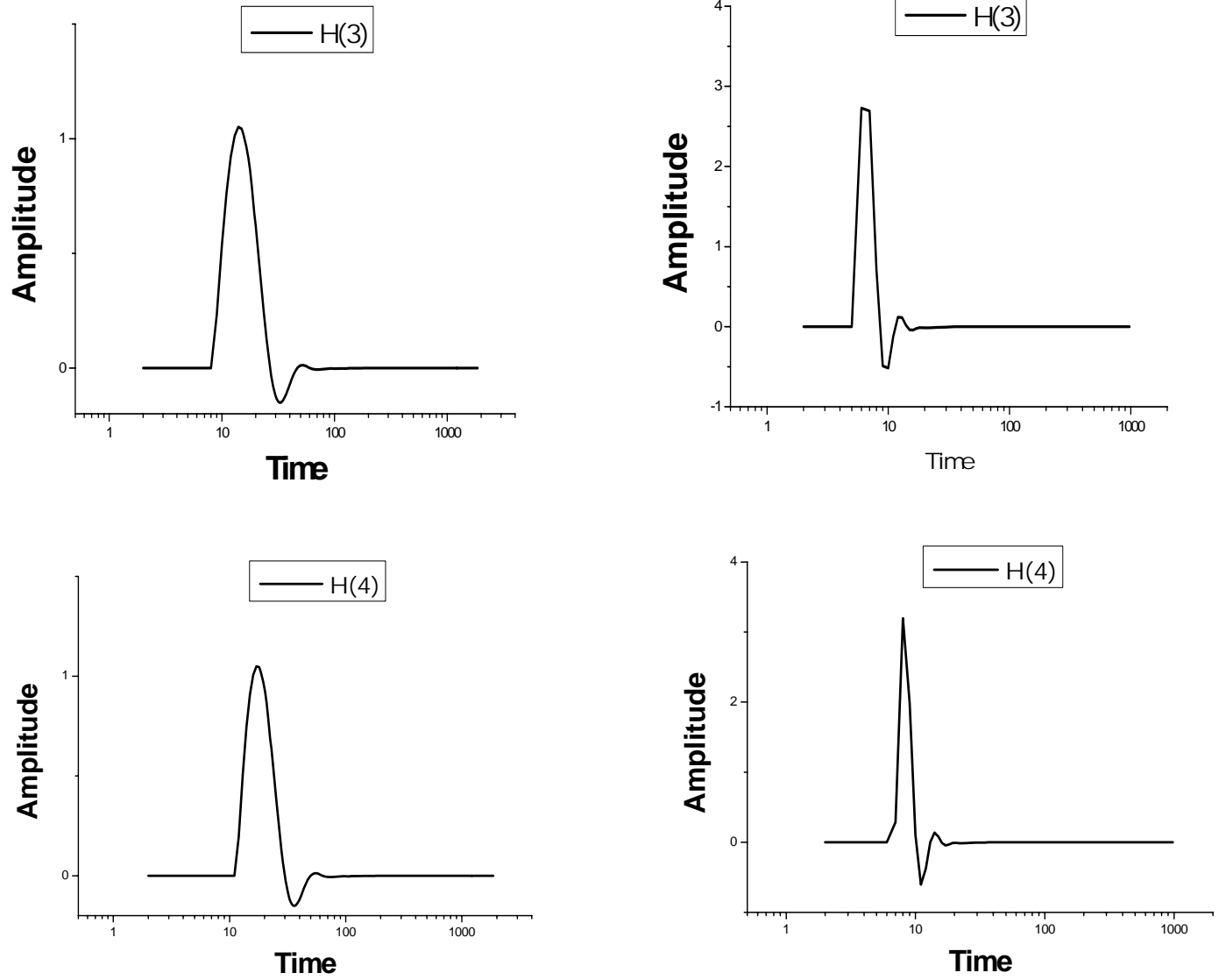
$$\frac{5.08}{0.06802 s^3 + 3.453 s^2 + 7.338 s}$$

This work bears the importance of designing and distinguishing lag and lead-lag compensators designed for each segment of a 4-segmented snake robot. Table-2 displays the transfer function for each part of the snake body. Impulse responses of individual segment are compared in fig.4.

**Table-2** A Comparison between the Transfer Functions of Each Segment designed for Lag and Lag-lead Compensation Technique

Segment	Lag Compensation	Lag-Lead Compensation
1	$\frac{12.36s + 1.743}{0.06802s^4 + 3.454s^3 + 7.396s^2 + 12.49s + 1.743}$	$\frac{104s^2 + 208.7s + 104.5}{0.06802s^5 + 3.818s^4 + 25.94s^3 + 146.9s^2 + 216.1s + 104.5}$
2	$e^{-0.333s} * \frac{12.36s + 1.743}{0.06802s^4 + 3.454s^3 + 7.396s^2 + 12.49s + 1.743}$	$e^{-0.333s} * \frac{104s^2 + 208.7s + 104.5}{0.06802s^5 + 3.818s^4 + 25.94s^3 + 146.9s^2 + 216.1s + 104.5}$
3	$e^{-0.667s} * \frac{12.36s + 1.743}{0.06802s^4 + 3.454s^3 + 7.396s^2 + 12.49s + 1.743}$	$e^{-0.667s} * \frac{104s^2 + 208.7s + 104.5}{0.06802s^5 + 3.818s^4 + 25.94s^3 + 146.9s^2 + 216.1s + 104.5}$
4	$e^{-1s} * \frac{12.36s + 1.743}{0.06802s^4 + 3.454s^3 + 7.396s^2 + 12.49s + 1.743}$	$e^{-1s} * \frac{104s^2 + 208.7s + 104.5}{0.06802s^5 + 3.818s^4 + 25.94s^3 + 146.9s^2 + 216.1s + 104.5}$





**Fig. 4** Comparison between the Impulse Responses of Individual Segment for a 4-Segmented Serpentine Robot Designed with Lag and Lag-Lead Compensation Technique













