DESIGN OF MATHEMATICAL MODEL FOR LOCOMOTION CONTROL OF SNAKE-LIKE ROBOT

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DECLARATION

I hereby declared that I have conducted and completed the work research and had written the dissertation entitled "**Design of Mathematical Model for Locomotion Control of a Snake-like Robot**". I also declared that it never been submitted before for the award of any degree or diploma or other similar title of this for any other examining body or University.

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NOMENCLATURE

N-Number of S shape of a snake-like robot

ABBREVIATIONS

MATLAB Matrix Laboratory (program)

ABSTRAK

Robot seperti ular telah meluas berkembang di dalam industri kerana ia boleh bergerak dalam laluan yang berbeza dan sukar. Tujuan kertas ini adalah untuk merealisasikan pergerakan tidak simetri dalam persekitaran berstruktur. Hal ini bertujuan untuk meniru pergerakan ular semula jadi di mana ia lebih mudah bagi mereka untuk menyesuaikan diri dengan bermacam-macam persekitaran dan tempat. Sistem kawalan penjana corak pusat (CPG) dengan ciri-ciri parameter penghantaran digunakan untuk mengawal pergerakan tidak simetri. Model matematik telah direka dalam perisian Matlab untuk mensimulasikan pergerakan itu. Bagi merealisasikan pergerakan ular tidak simetri, gerakan perubahan dan gerakan pusingan dikaji berdasarkan pergerakan ular semula jadi. Simulasi itu dilakukan dengan menggunakan perisian Matlab untuk mengawal pergerakan robot ular. Beberapa jurnal penyelidikan yang berkaitan untuk membangunkan dan memodelkan pergerakan alunan sisi "serpentine" telah digunakan sebagai rujukan. Dalam projek ini, parameter CPG telah diubah dengan memberikan bias kepada memandu input (driving input) atau pemalar masa untuk memperolehi pergerakan tidak simetri yang dikehendaki dalam robot seperti ular. Kaedah mengubah parameter CPG dalam robot seperti ular amat berguna untuk robot dalam menyesuaikan diri dengan persekitaran yang tidak berstruktur. Simulasi robot seperti ular telah diambil untuk menganalisis kawalan pergerakan. Corak pergerakan yang diinginkan dapat dicapai dengan menyesuaikan parameter CPG yang bersamaan dengan hasilnya.

ABSTRACT

The snake-like robot has been widely developed in industries because it can move in the different and difficult path. The purpose of this thesis is to realize an asymmetrical locomotion in an unstructured environment. This is to imitate the natural snake locomotion where it is easier for them to adapt to any environment and place. The central pattern generator (CPG) control system with parameter transmitting characteristics is developed to control the asymmetric locomotion. The mathematical model has been designed in Matlab software to simulate the locomotion. In order to realize the snake asymmetric locomotion, the turning motion and round motion is studied based on the natural snake locomotion. The simulation is done by using Matlab software to control the snake robot locomotion. Some journal of researches which developed and modeling serpentine locomotion has been used as references. In this project, the CPG parameter is altered by giving bias to driving input or time constant as to obtain the desired asymmetric locomotion of the snake-like robot. The method of altering the CPG parameter of the snake-like robot is very useful for the robot to adapt to an unstructured environment. Simulation of the snake-like robot have been taken for the analysis of the locomotion control. Desired locomotion patterns can be achieved by adjusting the CPG parameters corresponding from the results.

1 CHAPTER 1: INTRODUCTION

1.1 Introduction

Biological snakes have a variety of motion patterns and they can hunt on land or in the water and even could climb branches by vertical lateral undulation. Snakes exhibit a unique ability by curving its long cord-shaped body and realize extremely high environmental adaptability. Due to the small cross-sectional area, they can crawl into very narrow spaces. Besides that, by distributing their weight along with their long body, they can move on soft or fragile materials. They can move in almost all natural environments. Gait diversity and adaptability of natural's snakes in complex environments have arisen great interest of both biologists and engineer.

Inspired by biological snake locomotion, snake robots carry the potential of meeting the growing need for robotic mobility unknown and challenging environments. Snakes like robots offer potentials in assisting in some areas such as earthquake, rescue missions, firefighting, and maintenance. This is due to their high maneuverability and ability to move through tight space. This robot can bend and adapt to the form of the terrain on which they move. Aiming at realizing robots with such high adaptability, many snake-like robots have been developed. These robots can be classified into two categories which are crawler-based robots and meandering robots.

In this project, we will focus on an asymmetric locomotion of snake-like robot. As a typical biometric robot, the snake-like robot has a unique motion pattern without any leg [1]. With an elongated and limbless body, snake performs many kinds of nimbler motion adapting to different kinds of environments. However, mimicking the motion patterns of limbless animals such as snake and worm into mobile robot's control are different from the wheeled and legged robots. It is known that from biological snakes because its skeletal structure and scales are the vital parts that contribute to the efficient locomotion. This features of a snake can be realized into a snake-like robot by swinging the body joints from side to side to generate effective forward locomotion. By using these advantageous characteristics of the natural snakes, the snake-like robot is expected to be applied to perform searching and rescuing tasks in an unstructured environment, where traditional mobile mechanisms cannot access well. The original works of Hirose [2] have given out the mechanism for imitating snake-like locomotion. During the process of progressing, due to the particular scales and ribs of the snake-like animals, the friction coefficient of the snake in the normal direction with respect to the main axis of the segment is significantly greater than the tangential one.

Snake robots have many applications, but they are hard to control. People cannot simply operate each joint of a snake individually because there are too many. These robots required a motion planning algorithm. Motion planning algorithm for snake-like robots is difficult due to the robots have many internal degrees of freedom that has to be coordinated to achieve purposeful motion. In motion planning jargon, the snake-like robots exist in large dimensional configuration spaces. The robot will be able to optimize its own path based on a range of cost function from power consumption to safety or even stealth. [3]

Snake have redundant designs that rely on the same kind of joint and structure that is repeated many times. It means that, if one joint fails, the snake can continue the locomotion. The simplicity of the design means that the snake does not have any fragile appendages that can easily break. The snake's locomotions form relies on a large amount of contact between the ground and the posterior. The large surface area gives the snake good traction characteristics in various environment. Snakes are very versatile and can act as both locomotor and manipulators, as they can use their body to wrap around objects to grasp them. It can be seen in the climbing action across tree branches, or when a constrictor is clenching its prey. [4]

Besides that, the snake-like robot also has many disadvantages to snake locomotion as well. The disadvantage of the snake-like robot is that it is often slower than another form of locomotion. The fastest snake has a maximum speed of 3 m/s (Black Mamba) and others snake mostly travel much slower. Other wheeled devices and organisms with legs that have similar size have the ability to travel much faster. For example, the Prairie Racerunner, a species of lizard, has been clocked at speeds up to 8 m/s. mobile robots often carry a suite of sensors and actuators as well as power consumption. Typically, for a wheeled or legged robot, the majority of the body provides a place to carry a payload, and the legs or wheels require a comparatively small amount of the volume. [4]

To create a robot, modeling and simulation are closely related and influence its performance. Simulation is the imitation of the operation of a real-world process or system over time. In order to do the simulation, a model needs to be developed first. This model representing the key characteristics or behaviours/functions of the selected physical or abstract system or process. The model represents the system itself, while, the simulation represent the operation of the system over time. [5]

1.2 Problem statement

The ability to move efficiency in a complex environment is a key property of animals. Many biomimetic robots are expected to operate in the unpredictable complex environment whereas it is difficult for a human to access directly [6] [7]. Therefore, it is important to imitate the animals' locomotion. Snake has a unique motion pattern without any leg. It can perform many kinds of nimbler motion adapting to different kinds of environments.

However, most of the previous studies are limited to a symmetrical locomotion with fixed amplitude and phase difference among joints' angles. This kind of locomotion is limited to the certain environment only. If we were only concerned with producing a regular creeping motion of the snake-like robot in a flat or uniform environment, it would be convenient to introduce symmetrical locomotion. But, with this kind of symmetrical locomotion, it is difficult for the robot to steer to the desired direction of movement or adapt to a complex environment with a suitable gliding curve. When natural snake creeps over an unstructured terrain, it may change its body curve with an asymmetric locomotion to pass around branches, rocks, and other obstacles to move forward more efficiently.

1.3 Objective

The objectives of this research are as stated below:

- Using an existing mathematical model to imitate the natural snake locomotion into snake-like robot locomotion
- To realize an asymmetric locomotion of the snake-like robot by altering the CPG parameter.

- To study the influences of each parameter in the CPG module on the CPG output.

1.4 Project Scope

In this project, a control system for an asymmetric locomotion of a snake-like robot is designed by using the CPG-based model. The locomotion of the snake-like robot is controlled by altering the CPG parameter to produce turn motion and round motion by altering the driving input and time constant. How to realize these adaptive motions with the CPG-based model is investigated. Furthermore, the asymmetric locomotion of the snake-like robot is verified through simulation. The simulation was done by using Matlab/Simulink software.

1.5 Thesis Outline

This thesis consists of five chapters. The first chapter is the introduction of the project. In this chapter, the problem encountered is explained at section 1.2 and the way to solve is proposed in objectives, section 1.3. While the project scope is listed in section 1.4.

In the second chapter, the term that related to this project such as types of snake locomotion, types of mathematical model and software used is explained in the literature review. In section 2.5, the discussion about the existing project that related to this project that has been done by other researchers and students.

Chapter three is about the methodology to complete the project. In this chapter, the way of designing the mathematical model is discussed. Besides that, in this chapter, the proposed CPG network is introduced with its mathematical model. The explanation about the CPG network chose and the way to controlled is discussed in detail in this chapter.

Chapter four consists of the result and discussion. This chapter briefly describes about the data was obtained from the simulation. It also describes on how the CPG module work does and produces the data needed.

The last chapter is about the conclusion. In this chapter, it describes briefly about the title and objective and the successfulness of this project. The limitation for this project also mentioned in section 5.2.

2 CHAPTER 2: LITERATURE REVIEW

2.1 Overview

In this chapter, the term related to this project will be explained below. Section 2.2 will introduce the common types of snake locomotion, section 2.3 will be discussed about the control approach of the snake-like robot and section 2.4 will explain about the modeling software. While the existing work will be discussed in section 2.5.

2.2 Snake locomotion

In snake robot, there are various forms of movement that are applied to the implant to snake robots. Every form of movement is designed for different purposes which are depending on the type of situation, terrain, as well as the surrounding environment. This section focusses on the movement of snake robots in both two-dimensional (2D) and three-dimensional (3D) plane. It discusses various locomotion such as lateral undulation or serpentine motion, linear progression, concertina locomotion, and sidewinding locomotion.

2.2.1 Lateral undulation or serpentine locomotion

Lateral undulation is the fastest and the most common form of snake locomotion. This type of locomotion is also called serpentine locomotion. The serpentine curve gives the mathematical description of lateral locomotion [8]. It is a continuous movement of the entire body of the snake relative to the ground. Movement is acquired by propagating waves from the front to the rear of the snake robot while using roughness in the environment. Thus this form of locomotion is not suitable on smooth surfaces. All the part of the body passes the same part of the ground ideally leaving a single sine curved track, while there is never any fixed contact between the ground and any point along the body [9]. The weight distribution of a snake during this motion is not uniform, but rater distributed so that the peaks of the body wave curve are slightly lifted from the ground. The efficiency of lateral undulation is mainly based on two factors: (1) the contour of the ground, the more contour the ground the more efficient is the locomotion; (2) the ratio between the length of the snake and its circumference [10]. Figure 2.1 show the movement of the lateral undulation/serpentine locomotion.

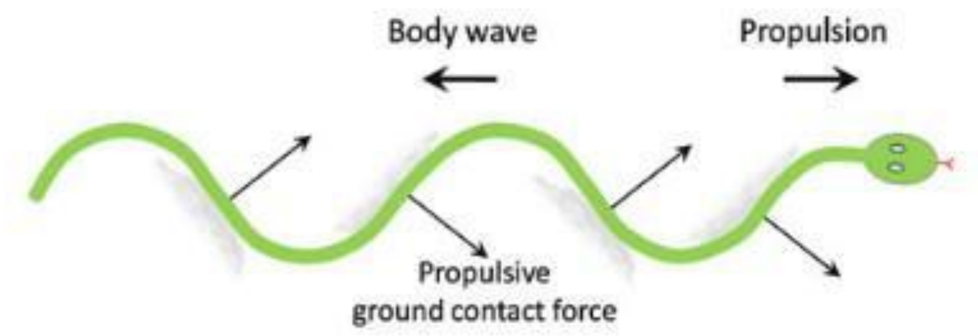


Figure 2:1 Lateral Undulation Locomotion

2.2.2 Rectilinear locomotion

From Figure 2.2, the snake grapples its body at a specific point that appears continuously move tail wards. Sine waves are directed through the length of the snake robot, driving it either in forward or reverse direction. This sine wave is sent through the vertical modules, which repetitively picks up modules, advances them through the air and places them slightly forward of their initial position on the ground. The horizontal modules are utilized only to steer and adjust the robot [11] [8].

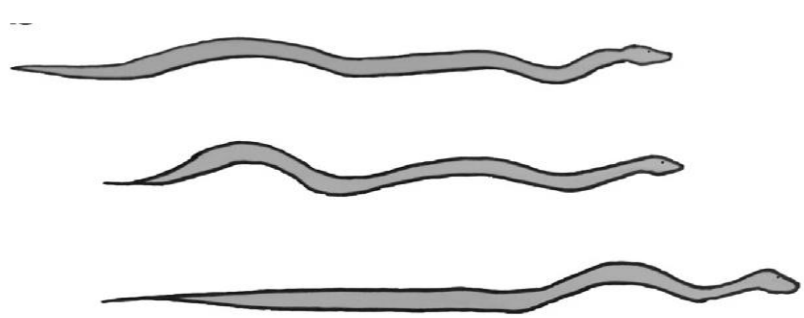


Figure 2:2 Rectilinear Locomotion

2.2.3 Concertina locomotion

Concertina locomotion is a type of motion where parts of the body contract, expand or do not change their shape [12]. To obtain concertina locomotion, the snake body was divided into three different modules; head module, tail module and main body module which connects from the head to the tail module as shown in Figure 2.3. Each module forms a specific curve which can be modeled using the proposed dynamic function. At each moment during snake locomotion, the kinematics of different links can be derived by fitting robots links to the body curve. To model the concertina locomotion, first, the head module is stretched followed by the body module and last the tail module. According to the number of modules types, the stages of stretching can be divided into three stages. The first stage is the stretching of the head module, the second stage is the stretching of the body modules, and the third stage is the stretching of the tail module.

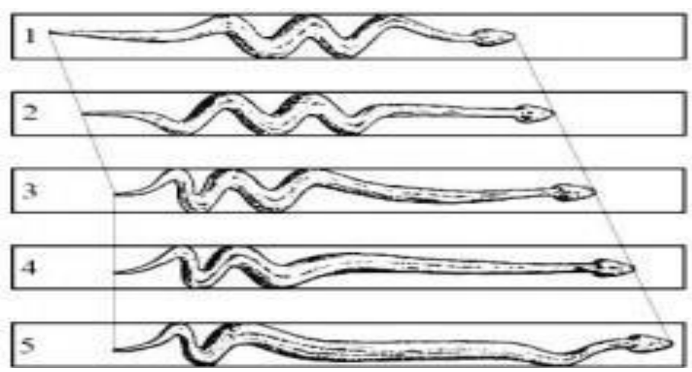


Figure 2:3 Concertina Locomotion

2.2.4 Sidewinding locomotion

This type of locomotion is typically utilized on surfaces with low shear, for example, sand, desert, and loose gravel. It is currently one of the fastest ways for these snakes' robots to travel through the rugged or uneven terrain. Unlike lateral undulation, there is a brief static contact between the body of the snake and the ground. At any given instant, at least two portions of the snake are in static contact with the ground. The rest of the snake body is lifted and moved forward. To rotate the robot at the same place the front half of the snake to the right, and the back half of the snake to the left has the effect of spinning the snake robot in place [12]. In control point of view one vertical and one horizontal sine wave interact to make the snake robot move sideways. Figure 2.4 show the movement of the sidewinding locomotion.

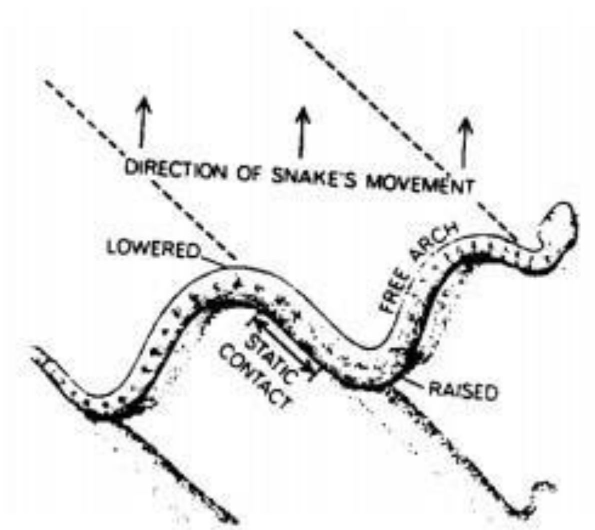


Figure 2:4 Sidewinding Locomotion

2.2.5 Slide-pushing Locomotion

Slide-pushing involves vigorous undulations of the body that slide widely over the surface. According to [13], escape responses on smooth surfaces usually result in slide-pushing, a relatively irregular type of undulation used when the body slips over the substrate. This mode resembles a combination of sidewinding and lateral undulation but is a distinct locomotors mode [14]. Slide-pushing locomotion usually will be used when a snake on a smooth surface is a starlet and tries to escape quickly, but slips over the surface. For this type of locomotion, irregular bends of the body and tail press vertically on the surface at a different point, even though the body slips on the surfaces, it pushes down enough force to move the center of mass in a quasi-regular, often step-like pattern. Therefore the snake progresses irregularly by slipping along the ground. In slide-pushing, sliding friction is the most important although there may be occasional moments of static contact. Figure 2.5 show the movement of the slide-pushing locomotion.

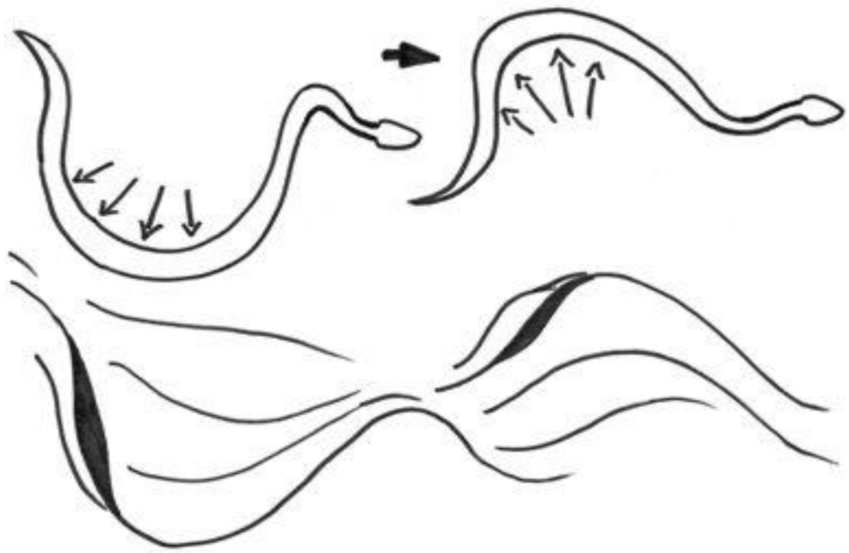


Figure 2:5 Slide-pushing Locomotion

2.3 Control of snake-like robot

This section discussed control of a snake-like robot and the way distributed control is implemented through it. Control of snake robot can be performed using various theories and methods which have been discussed before regarding the Central Pattern Generators (CPG) and sine-based model.

2.3.1 Central Pattern Generator (CPG)

This controller is a new method of control that has been developed specifically for snake robotics. This method of control is based around trying to solve the problem of the large amount of computing time which required it to control a system with such a large amount of degree of freedom (DOF) robot [15]. As explained in [15], this method allows the individual segments of the robot to control segment orientation so that better motion of the snake can be achieved, and each segment can adjust locally for different scenarios, such as applying more contact force to the ground. By using this method, Wu, et al. [16] able to propose a simplified control method on how to make its current position to the next segment in line, when it receives a new position from the control unit. This control approach also can be easily integrated with sensory feedback signals in differential equations, and show interesting properties such as entrainment by the mechanical body.

However, one difficulty with CPG- based approached is how to design the CPG to produce a particular pattern. Many CPG models do not have explicit parameters defining quantities such as frequency, amplitude, and wavelength (for instance, a van der Pol oscillator does not have explicit frequency and amplitude parameters). The CPG model that has been used for the snake robot was based on amplitude controlled phase oscillator. Furthermore, our CPG model is computationally very light which makes it well suited to be programmed on a simple microcontroller on the board of the robot.

2.3.2 Sine-based model

The sine-based controller is easy to implement and can mimic lots of rhythmic motion patterns [17]. Sine based approaches use simple sine based function for generating traveling waves. The advantages of such an approach are its simplicity and the fact that important quantities such as frequency, amplitude, and wavelength are explicitly defined. A disadvantage is that online modifications of the parameters of the sine function such as the amplitude and frequency will lead to discontinuous jumps of set points, which will generate jerky movements with risks of damaging the motors and gearbox. This problem can to some extents be overcome by filtering the parameters and the output but the approach them loses its simplicity. Another disadvantage is that sine-based functions do not offer simple ways of integrating sensory feedback signals.

2.4 Existing work

2.4.1 Serpentine locomotion of a snake-like robot controlled by cyclic inhibitory CPG model [18].

This paper using cyclic inhibitory CPG theory to control the snake-like robot locomotion. This method is used to construct a neuron network model of the snake-like robot based on the structure of both biological snakes and snake-like robot and their rhythm locomotion. The relation between the CPG parameters and the serpentine locomotion of the snake-like robot is defined by using this method. The validity of the serpentine locomotion controlled by the CPG model is verified through a snake-like robot model. The modulating methods of the CPG parameters are brought forward and stimulated to realize the required turn motion and the reconfiguration.

To control the locomotion, a mathematical model of an individual neuron and mathematical model of cyclic inhibitory CPG is used. The comparison between the cyclic inhibitory CPG model and mutual inhibitory model is determined. The mechanism of the rhythm generation in the cyclic inhibitory CPG model is completely different from which in the mutual inhibitory one. In this paper, to realize the turn motion of a snake-like robot, the author changes the curvature by though modulating CPG's self-excitatory weight to change the phase shift of the adjoining joints. As a result, the snake-like robot can perform serpentine locomotion using control signal from the proposed neuron network based on the theory of cyclic inhibitory CPG, and realize the required turn motion and reconfiguration by parameter modulation.

2.4.2 A simplified CPGs network with phase oscillator model for locomotion control of a snake-like robot [19].

In this journal, the author used CPGs network with phase oscillator to control the snake-like robot locomotion. The phase oscillator model possesses attractive characteristics such as limit cycle and robust. The author proposed to use the unidirectional coupling oscillator in this journal. This is because the unidirectional coupling oscillator provides simple coupling with each CPG oscillators, less mathematical computation, fast convergence speed and less complexity.

The author used phase different to control the serpentine locomotion using the phase oscillator as the CPG mathematical model. Each of the snake-like robot joints drives the motor according to the CPG output. To achieve higher locomotion efficiency, each joint of the motor have to start simultaneously. By changing the phase differently, the author controls the number of S-shape of the snake-like robot, and forward and backward movement.

2.4.3 Locomotion mechanism of the snake-like robot [20].

Snake move by pushing their body against the environment. In order to achieve the real snake's locomotion, the snake robot must generate a lateral undulation, where lateral undulation is a sequence of left-right wave movements. Besides that, the important issues in designing the locomotion for the snake robot are the co-coordinate between the adjacent segments and the robot performance in case there are any failure segments of the snake robot.

Snake robot is driven in a closed circuit, which means the processor in the snake robot will receive any feedback signals from the sensors and respond to the feedback by making a new decision for the snake robot. Figure 2.6 show the control configuration of the snake-like robot:

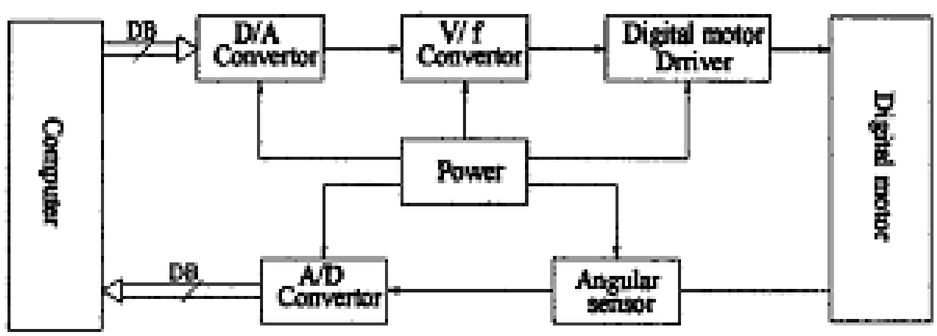


Figure 2:6 The control configuration of the snake-like robot

The locomotion mechanism of the snake robot can be analyzed in moving forward, backward and steering. For moving forward and backward, a mathematical model can be used to analyze the locomotion mechanism:-

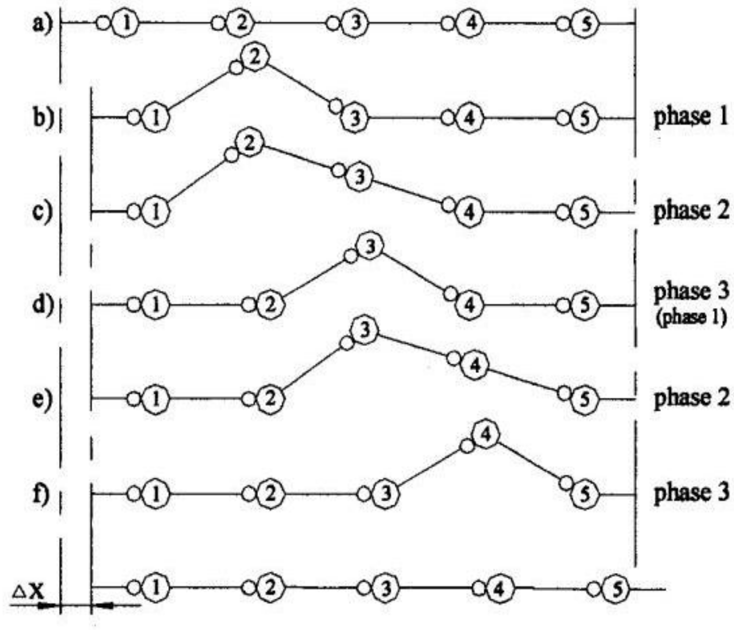


Figure 2:7 The locomotion mechanism of moving forward and backward

From the Figure 2.7, the small circles represent the motor and the big circles represent the big gear, where the straight lines represent the segments for snake robot. The wave is produced at first phase by moving the gear 1 and 2, at the same time, the end of the snake robot had been move forward with the distance equals to Δx. The wave will then continue to propagate to the gear 3 and 4 and last to the gear 5 which will push the head of the snake robot forward with the same distance Δx. The locomotion mechanism of moving forward and backward can be used as the reference in design the snake-like robot, but the direction of the gears can be changed from moving upward and downward to left and right to produce the lateral undulation, where the motors and big gears in Figure 2.6 can be replaced by the servo motor, and the left-right locomotion concept can be achieved by programming the servo motor.

3 CHAPTER 3: METHODOLOGY

3.1 Overview

In this chapter, the methodology of the research is presented including modeling of the mathematical model and simulation of the snake-like robot using Matlab/Simulink. The method that had been used for this project will be discussed in detail in this section. The project flow chart is used on the methodology to ensure this project run smoothly and organized from the literature review until the discussion of the result and conclusion.

3.2 Project flow

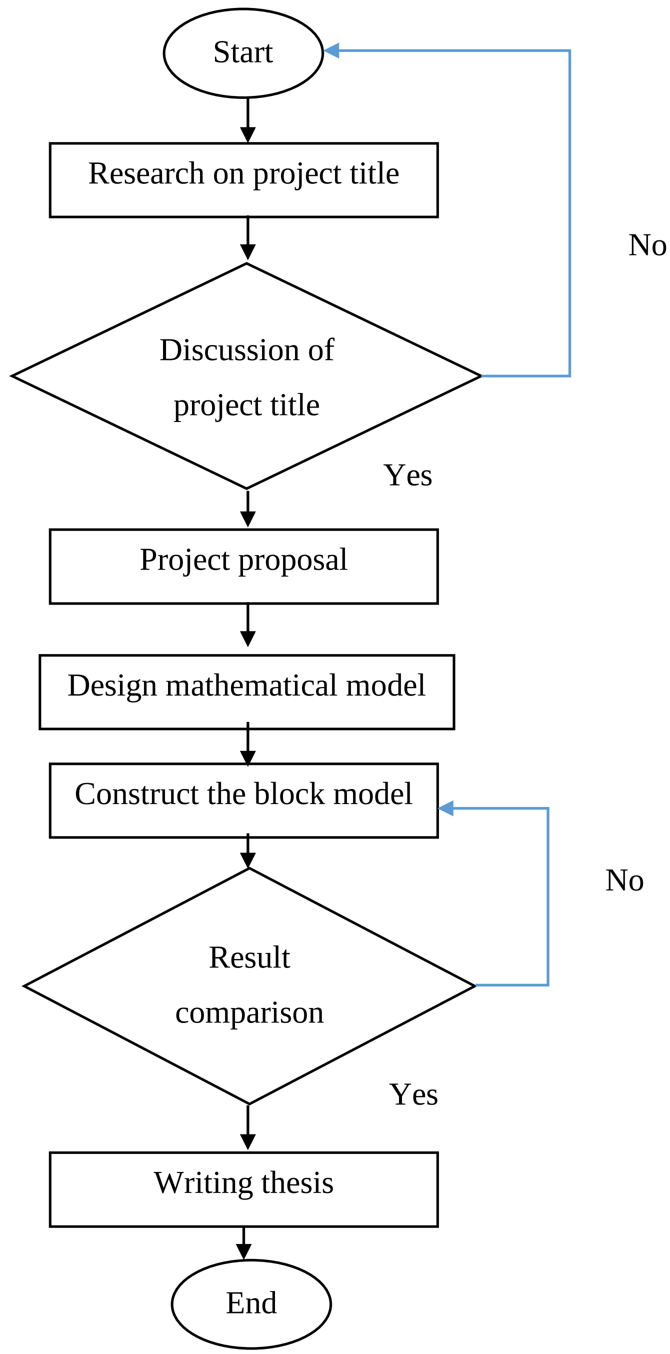


Figure 3:1 Flow Chart of the Project

3.3 Central Pattern Generator (CPGs) Mathematical Model

Network architecture using CPG for locomotion control of mobile robot had been widely used. Central pattern generator (CPGs) are biological neural networks that can produce rhythmically patterned such as walking, flying, breathing and swimming without sensory feedback. A CPG could be crudely analogized to the pendulum of a clock, generating a repeating signal at a constant frequency in order to coordinate rhythmic motions.

The CPG-based model has been developed together with Auke Ijspeert. It is based on a system of amplitude-controlled phase oscillators. The design of the CPG is loosely inspired from the neural circuit controlling swimming in the lamprey. It spontaneously produces travelling waves with constant phase lags between neighboring segments along the body, and it is made of multiple oscillators center in the lamprey, such as sub-network of several thousand of neurons located in one segment of the spinal cord that is capable of producing oscillations independently of other centers.

One of an interesting about a natural snake is its body can change according to the environment surrounding and its space travels. Thus, for this project, the focus is to mimic the body shape transition feature into a snake-like robot to make it capable to traveling in different types of space and environment.

One of the biggest challenges in developing versatile mobile robot is their control design. A simple control is penetrated which promises a light computational cost, simple, and understandable by a human operator who may be not familiar with the robot's control system. This project will focus on locomotion control of multi-units of the mobile robot to achieve high maneuverability for obstacle avoidance.

3.4 CPG Mathematical Model and Network

Based on the previous research, a various model of CPG neuron have been proposed, such Ekeberg model and Matsuoka model. According to [21], the CPG proposed by Ekeberg is structurally difficult to analyze numerically and complicated. While for Matsuoka model [22], the CPG model has the feature of continuous-variable and continuous-time in its simple structure and can be easily implemented into a mobile robot. Besides that, Matsuoka model also has been proved that it's mathematical can generate rhythmic output. Thus, this neuron model is adopted into this snake robot.

In one Matsuoka's CPG model usually has several neurons. The neuron in the CPG will be affected by each other. By the interaction of neurons, it will produce a group of rhythmic outputs. The structure of the individual neuron can be expressed as

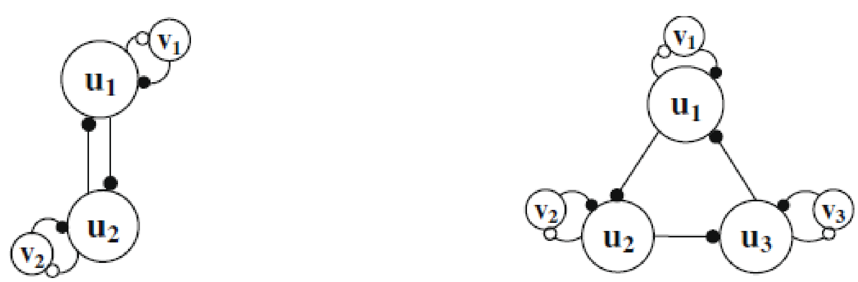
$$\tau_1 \dot{u} + u = u_0 - \beta v - \sum_{j=1}^{m} w y_j$$

$$\tau_2 \dot{v} + v = y \tag{1}$$

$$y = g(u) = \max(0, u)$$

where u is the membrane potentials of the neuron; v is the variable that represents the degree of adaptation; y is the output of the CPG neuron, and its value always positive; u_0 is the tonic driving input; τ_1 and τ_2 are the parameter that specify the time constant for membrane potential and adaptation degree, respectively; wy_j represent the input from other neurons; m is the number of all the neurons in one CPG model.

There is a several ways to construct a CPG model by connecting a different number of neurons. For example, a dual neuron model and tri-neuron model are shown in Figure 3.2: (a) and (b), respectively. The CPG model with four and more neurons not widely used in practical application due to the numerous computational and complicated structure.



(a) Dual-neuron Model (b) Tri-neuron Model

Figure 3:2 CPGs Model of Neural Oscillator

According to the previous research, a mutual inhibition model was successfully adopted for a snake-like robot to realize meandering locomotion [23]. Besides that, a cyclic inhibitory CPG model with triple neurons has been approved that it is more suitable for a snake-like robot control [24]. By using cyclic inhibitory CPG model, it can produce two outputs which are to control yaw and pitch movement of the snake-like robot. In addition, cyclic inhibitory CPG model does not necessitate adaptation neuron, and its internal strong cyclic inhibition can perform rhythm generation. This model also can realize a three-dimensional locomotion with least computational cost in the neural control system [25].

The rhythm creeping motion of a natural snake is generated by the CPG mechanism. The CPG neural oscillators in the spinal cord stimulate the muscle extension and contraction to generate rhythmic swing of the body. By constructing an oscillation network mimicking the neural system of the animal, a series of successive rhythmic signals with the certain phase difference can be generated to realize the snake-like locomotion. Figure 3.1 shows a CPG network implemented to control a snake-like robot, where one CPG module corresponds to one joint motor. Each CPG works as a basic neural oscillator to generate a rhythmic signal for the angle of the robot joint. Each CPG will contain three neurons to control the turning and shape of the snake robot.

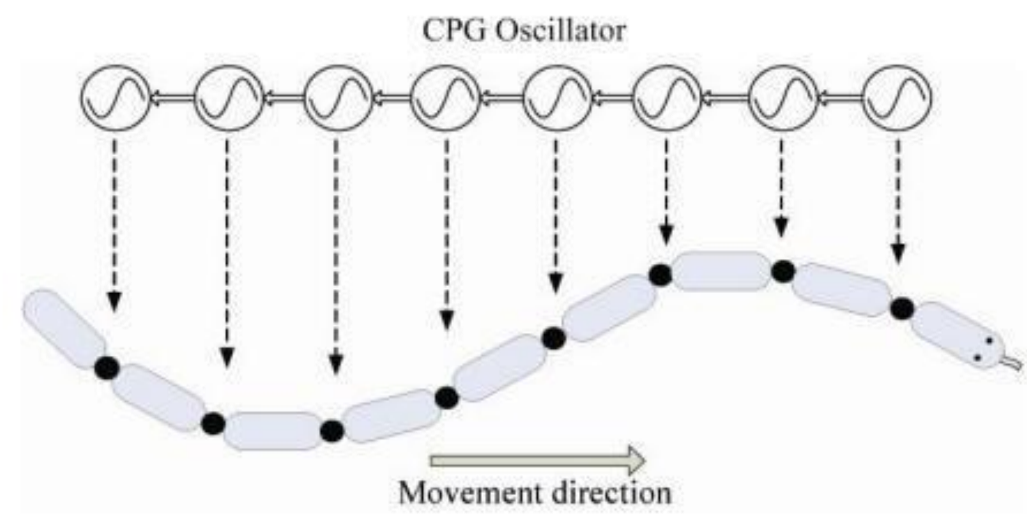


Figure 3:3 CPG network implemented to control a snake-like robot [24]

3.5 Mathematical model of CPG network

According to [26], a closed loop CPG network with feedback connection is adopted for the control of a snake-like robot. The tri-neuron cyclic inhibitory CPG model is used as the oscillator in the network. From the mathematical model of Matsuoka's single neuron [27], a CPG network includes n CPG modules which have m neurons can be described in a group of basic equations. For the *j*-th neuron of the *i*-th CPG module, its mathematical model can describe by:

$$\tau_{1,i}\dot{u}_{j,i} + u_{j,i} = u_{0,i} - \beta v_{j,i} - w y_{s,i} + \sum_{k=1}^{n} w_{ik}\, y_{j,k}$$

$$\tau_{2,i}\dot{v}_{j,i} + v_{j,i} = y_{j,i}$$

$$y_{j,i} = g\left(u_{j,i}\right) = \max\left(0, u_{j,i}\right)$$

$$y_{out,i} = y_{1,i} - y_{2,i} \tag{2}$$

$$i, k = 1,2, \dots n, i \neq k; j = 1,2, \dots m;$$

$$s = \quad m, if\ j = 1$$

$$j - 1, others$$

where *n* is the number of CPG modules in the network; *m* is the number of neurons in one CPG module; *s* is the serial number of neuron connected to the *j*-th neuron; $u_{j,i}$ is the membrane potentials of *j*-th neuron in the *i*-th CPG module; $y_{j,i}$ is the variable that represents the degree of adaptation; $u_{0,i}$ is the tonic driving input; $\tau_{1,i}$ and $\tau_{2,i}$ are the parameters that specify the time constants for membrane potential and adaptation degree, respectively; β is the adaptation coefficient; *w* is the weight between neurons; w_{ik} is the connection weight of the *i*-th module from the *k*-th module; $y_{j,i}$ is the output of *j*-th neuron in *i*-th CPG module; $y_{out,i}$ is the output of the *i*-th CPG module.

Table 3.1 Parameters of the CPG model

Driving input, u_0	2.5
Time constant, τ_1	2.0
Time constant, τ_2	6.0
Adaptation coefficient, β	2.5
Connection weight inner neurons, w	2.7
Connection weight among CPGs w_0	0.1

The CPG model proposed by Ekeberg is structurally complicated and difficult to analyze numerically. However, the model of CPG neuron proposed by Matsuoka has the features of continuous-time and continuous-variable in its simple structure, and can thus be easily implemented onto the control of the robot. Moreover, since the Matsuoka's model has been proven mathematically to generate rhythmic output, this neuron model is thus adopted into the control of our snake-like robot.

3.6 Asymmetric locomotion

Snakes in nature can perform many kinds of movement to adapt to the environment. The body of snake performs various curves to move across the uneven ground interspersed large and small rocks or plants. However, the traditional control of the snake-like robot with symmetrical body curve is difficult to achieve adaptive locomotion. For this reasons, an asymmetric locomotion needs to be investigated.

To realize the asymmetric locomotion, the following motion control system needs to be adapted. The control system of the snake-like robot is connected in serial network structure and each joint is treated as a correlative servo system. When there is a high signal command from the high central nerve system, the motion configuration of the head will be altered. After a certain time, the first joint of the modification will be shifted to the second joint and so on. By using this kind of motion control system, it is possible to transmit a wave all the way from the head to tail and realize an asymmetric locomotion of the snake-like robot. In addition, it allows smooth operation of actuators and also closely matches the body curves of a real snake. This is a close approximation of the motor-neural mechanism of a snake [28].

Due to the fact that trajectory of each body segment which can follow the previous one in this locomotion control method, it is necessary to plan the motion of the head module to obtain the desired locomotion. As to combine the information from the sensor into the control system, it is necessary to collect the feedbacks signals from the head module. Compared with the research in which numbers of sensors are installed on each segment to perform adaptive locomotion [29], this method will show its advantages on the simplicity of control with sensors.

3.7 CPG controlled motion

The modification in the first joint configuration in the snake-like robot needs to be transmitted one after another from the head to the rear segments with a fixed interval. Thus, a parameter transmitting principle is proposed to generate a series of the rhythmic signal with this characteristic. In order to perform an asymmetric locomotion for the snake-like robot with turning and round motion, the driving input,u_0 and time constant, τ_1 of CPG have been used to adjust the output amplitude and frequency due to their linear relation [26]. Since the value of ${}^{\tau_1}/_{\tau_2}$ is always constant, the only value of τ_1 is considered as the variables.

A transmission procedure of CPG parameters to realize asymmetric locomotion can be expressed by firstly, modify the parameters of the first CPG at the time, t_0 by giving the bias on the driving input of the CPG. The value of the first CPG would change into $u_{0,1} + \Delta u_0$. After a fixed time interval, Δt from the time, t_0 the parameter of second CPG will also alter their driving input followed same as the first one. At the same time, other CPGs will also change their driving input, $u_{0,1}$ to follow the previous CPG after time interval, Δt.

4 CHAPTER 4: RESULT AND DISCUSSION

4.1 Overview

This chapter focusing on the result and the discussion of result for the simulation that has been conducted. Simulation is valuable for testing conditions that might be difficult to reproduce with hardware prototype alone, especially in the early phase of the design process when hardware may not be available.

4.2 Simulation

During simulation, a variety of different scenarios were considered by controlling the number of S-shape by altering the specific parameter.

4.2.1 Number of S-shape

A snake-like robot will produce locomotion with one S-shape when the total phase difference is 2π. The number of S-shape will increase as increasing the phase difference of joint. The phase differences of CPG output are homogenously distributed in one period if the network is a closed-loop type. The total of phase difference of CPG outputs can be derived by using $(n-1)\emptyset$ where n is the numbers of CPGs. One S-shape locomotion can be obtained by a group of rhythmic signals with total 2π, number of the locomotion, N can be derive as below:

$$N = \frac{(n-1)\emptyset}{2\pi} = \frac{n-1}{r} \qquad (3)$$

Thus, the number of the locomotion S-shape can be derived by changing the connection of rth CPG module to the first CPG module. Since the total of CPG module that has been used are six, the largest number of S-shape is N=1.