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Research Paper

Optimizing central pattern generators (CPG) controller for one legged hopping robot by using genetic algorithm (GA)

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Abstract

This paper presents the optimization process of Central Pattern Generator (CPG) controller for one legged hopping robot by using Genetic Algorithm (GA). To control the one legged hopping robot, a CPG controller is designed and integrated with a conventional Proportional-Integral (PI) controller. Conventionally, the CPG parameters are tuned manually. But by using this method, the parameters produced are not exactly the optimum parameters for the CPG. Therefore, a computational stochastic optimization method; GA is designed to optimize the CPG controller parameters. The GA is designed based on minimizing the error produced towards achieving the reference height. The re-sponse of the one legged hopping robot is compared and the results of the error towards reference height are analyzed.

Keywords: *One Legged; Hopping; CPG; PI; Genetic Algorithm*

1. Introduction

In robotics research and development field, computational tools are nowadays commonly used and embedded in the control system of robotics. Artificial neural network is one of the computational tools. Artificial neural networks can increase the possibilities and power of all kinds of system such as in object classification, learning, voice recognition or movement generation [1].

In designing of an artificial neural network, there are a lot of different approaches which are depending on specific tasks had been developed. These approaches can be categorized into two main techniques, which are classical technical way and biological inspired approach [1]. The technical way evolved out the computer science and the neurons are organized in layers and connected each other. Meanwhile, the biological inspired approach depends on the findings in neural networks and uses differential equations for simulating the behavior of biological neurons.

One of artificial neural network concepts is Central Pattern Generator (CPG). There are two types of CPG structure model which are Amari-Hopfield and Matsuoka structure model. Amari-Hopfield structure commonly use in the electronic hardware implementation field to minimize power consumption and raise the speed calculation [2]. While, the Matsuoka's CPG model is one of popular neural network concepts among researchers in robotics control system. In [3] explained his fundamental knowledge concepts of artificial neural oscillators in 1985. In 1987, a mathematical model and analyzed the mathematical conditions for mutual inhabitation networks was proposed by [4].

In [5-6] designed a principle of adaptive control of locomotion that involves nervous, musculo-skeletal and sensory system to adapt on unpredictable environments. CPG has been implemented in the control system for walking, running, crawling, hopping and swimming. Inada implemented CPG into a biped walk to control the target joint angle of the biped walk [7]. In [8] used CPG to create a traveling wave through the robot in order to model the undulatory-like swimming pattern of the lamprey. CPG also had been used for moving control of multi-legged hopping robot [9].

Previously, the effectiveness of standalone CPG result in [10] and integration Proportional-Integral (PI) controller with CPG result for one legged hopping robot have been presented in [11] containing the set of CPG parameters by using manual tuning. Due to the fundamental of simulated CPG model fact, there are few parameters need to be set and it is a very complex process in order to get an optimized CPG behavior by using manual tuning method. Hence, this research focuses on determining the optimum CPG parameter. Therefore, in this paper a Genetic Algorithm (GA) is applied to optimize the set of CPG parameters. The basic GA is designed to optimize the CPG parameters based on minimizing the error of output to reference and the output of the CPG network represent the hopping height of the one legged hopping robot is discussed and analyzed towards reference height given. The simulation model and control system of one legged hopping robot are constructed with MATLAB/Simulink.

2. One legged hopping robot

This section focuses on hopping robot modeling. The hopping robot consists of two parts of modeling which are electrical and mechanical parts. The electrical modeling includes the Direct Current (DC) motor modeling, while the mechanical modeling of the hopping robot structure covers the crank and mass-spring-damper system.

2.1. Electrical modeling

A DC motor is the main electrical part in producing hopping mechanism. Refer to Figure 1, the motor applies a torque, τ which the maximum torque is 0.098 Nm at 12 Volt to the platform.
The hopping height of the robot is controlled by regulating the voltage supply to the motor. Different speed of the motor produced different hopping height of the robot. The voltage to speed transfer function of the motor

$$\frac{\omega(s)}{V_a(s)} = \frac{(K_m / L_a J)}{(s + c/J)(s + R_a / L_a) + (K_e K_m / L_a J)}$$

$$\frac{\omega(s)}{V_a(s)} = \frac{265731.3}{(s + 3.57)(s + 83.3) + (6.5e - 05)} \tag{1}$$

Where the output of the motor speed within range of 0% and 100% depend on the voltage input as follows:

Clockwise:

$$\omega = \begin{cases} \omega_{max} & \text{if} \quad V = 12V \\ 0 < \omega < \omega_{max} & \text{if } 0 < V < 12V \\ 0 & \text{if} \quad V = 0V \end{cases}$$

2.2. Mechanical design and modeling

The mechanical structure and component of the one legged hopping robot is designed as shown in Fig. **1Error! Reference source not found.** A stand is attached to the one legged hopping robot to ensure the vertical hopping dynamic produced.

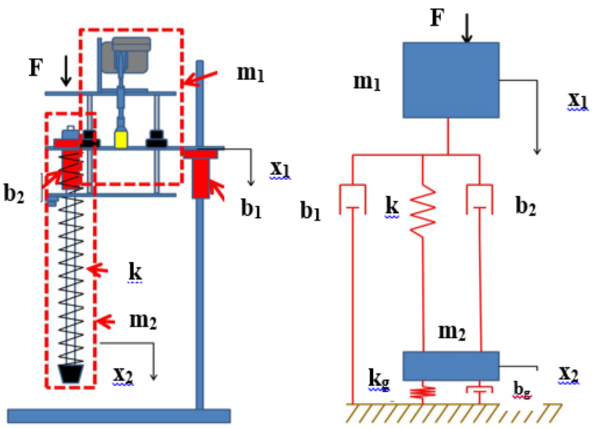

Fig. 1: Internal Structure of the One Legged Hopping Robot.

The one legged hopping robot in Fig. **2** is developed based on passive dynamic' of the mass-spring-damper model. Table 1 describes the parameter of the one legged hopping robot structure.

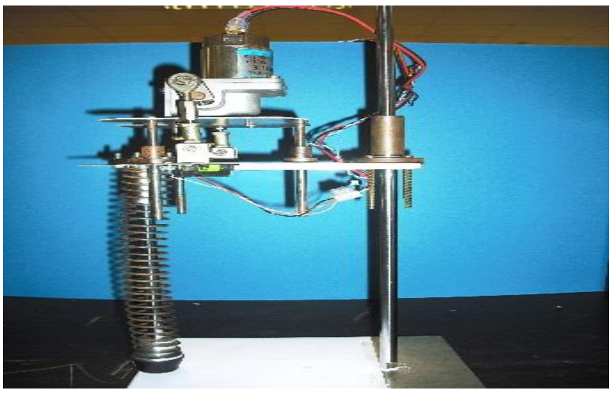

Fig. 2: One Legged Hopping Robot Developed.

The force reacts on the spring is produced by a crank attached to the motor, which inspired from piston mechanism. The rotation angle of the motor is modeled in (2).

$$\theta = \sin^{-1}\left(\frac{\dot{p} + l\dot{\phi}\sin\phi}{-r\Omega}\right) \tag{2}$$

The distance from the motor to the platform is increased continuously until the angle of the motor reaches 180° and ease to the initial distance at 360° as follows:

$$p(t) = \begin{cases} l_O < l \le l_{max}\,; \text{if} \quad 0 < \theta < 180^o \\ l_{max} > l \ge l_O\,; \text{if } 180^o < \theta < 360^o \end{cases}$$

$$\dot{p} = -r\Omega\sin\theta - l\dot{\phi}\sin\phi \tag{3}$$

Table 1: Parameter of One Legged Hopping Robot Structure

Parameter	Description	Value	Unit
m1	Upper mass	0.996	kg
m2	Lower mass	0.240	kg
k	Spring stiffness	490	Nm-1
kG	Foot to ground stiffness	300	Nm-1
b1	Viscous damping coefficient	2.75	Nsm-1
b2	Viscous damping coefficient	2.75	Nsm-1
bG	Viscous damping coefficient	8	Nsm-1
x1	Distance upper mass to ground	0.25	m
x2	Distance lower mass to ground	0	m
J	Motor inertia	2.8x10-6	kgm2
c	Motor viscous friction coefficient	1.0x10-5	Nms
τ	Motor torque	0.098	Nm
Ra	Armature resistance	2.8	Ω
La	Armature inductance	0.0336	H
Km	Motor torque constant	0.025	Nm/Amp
Ke	Electromotive force constant	0.0026	V/rpm
θ	Motor angle		rad
F	Force exerted to mass		N
ϕ	Rod end bearing angle		rad
p	Distance motor to platform	0.09	m
r	Crank length	0.026	m
l	Rod end bearing length	0.09	m

2.3. Hopping mechanism

The hopping mechanism of the one legged hopping robot is illustrated in Fig. **3**. The motion of the mechanism consists of four states as follows:
Touch down: The moment of the base makes contact to the ground.
Stance: The cranks attached at the motor operate the same mechanism to convert the motor torque as the conservation energy into the spring.
Lift-off: The moment when the base losses contact with the ground. This phase occurs caused by the conservation energy of the depressed spring and ground repulsive force that boost the robot to hop.
Flight: The moment that the robot has peak altitude and vertical position/motion changes from downward to upward or otherwise.

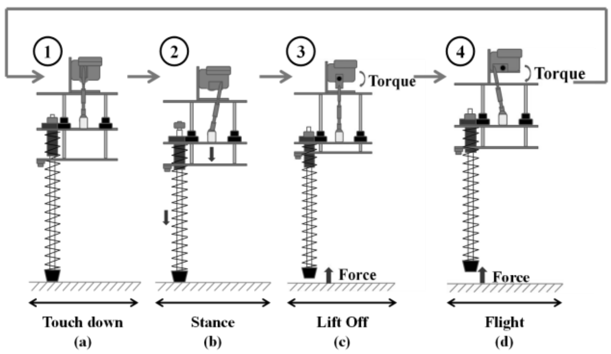

Fig. 3: Principle of Hopping Mechanism.

3. Parameter optimization

3.1. Central pattern generator (CPG)

Central Pattern Generator is a neural network that can generate output in rhythmic pattern and underlies the production of most rhythmic motor patterns [12].
The CPG plays an important role in generating various types of periodic motion of vertebrate animal. The CPG can be expressed by the neural oscillator model as shown in Fig. **4**. Based on psychology, a neural oscillator can be represented by two neurons which are excitatory and inhibitory neuron that interconnecting to each other. The CPG neuron model is regarded as one unit of the nerve oscillator, which is acted as the command center for a musculoskeletal system to generate the periodic motion pattern.

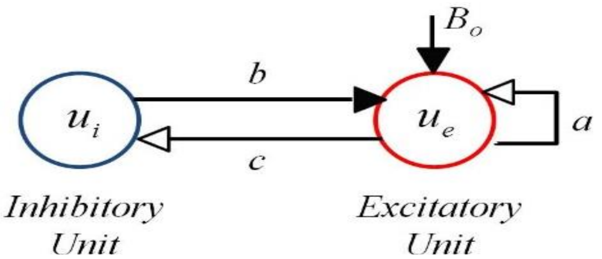

Fig. 4: CPG Neuron Model.

u_e and u_i parameters are donated to the internal states of the excitatory unit and inhibitory unit respectively. b and c are represent the intrinsic excitatory and inhibitory coupling parameters respectively. Meanwhile, a is the excitatory coupling factor and Bo is the constant bias input. The output of inhibitory unit, ui in the model equivalent to the hopping height of the one legged robot infrared output signal and feedback through a nonlinear function $\tan^{-1}(u_i)$ and gain b to the excitatory unit, u_e as formulated in

$$t_e \frac{du_e}{dt} = -ue + a\tan^{-1}(u_e) - b\tan^{-1}(u_i) - B_o \tag{4}$$

$$u_i = f(K_a c \tan^{-1}(u_e) - d) \tag{5}$$

Where f ( ) represent the mechanical dynamic of one legged hopping robot. While, K_a and d represent the gain constant of DC amplifier and external disturbance respectively.

3.2. Optimization technique-genetic algorithm (GA)

Genetic Algorithm (GA) is one of computational methods which are direct, parallel, stochastic method for global search and optimization process. GA is part of Evolutionary Algorithms (EA) that applied three main principles of natural evolution [13]. The principles are reproduction, natural selection and diversity of the species. There are a few stages or process in GA as shown in Fig. 5 which are:

- Generate initial population: The first generation is randomly generated by selecting the genes of the chromosome
- Selection: Between all individuals in the current population are chose will continue for crossover and mutation to produce offspring population.
- Crossover: Recombine the individuals chosen by selection with each other and create new individuals
- Mutation: Random change of some genes to reach the extremum even if none of the individuals contain the necessary gene value for the extremum.
- New generation: The elite individuals chosen from the selection are combined with those individuals passed the crossover and mutation to form the next generation.

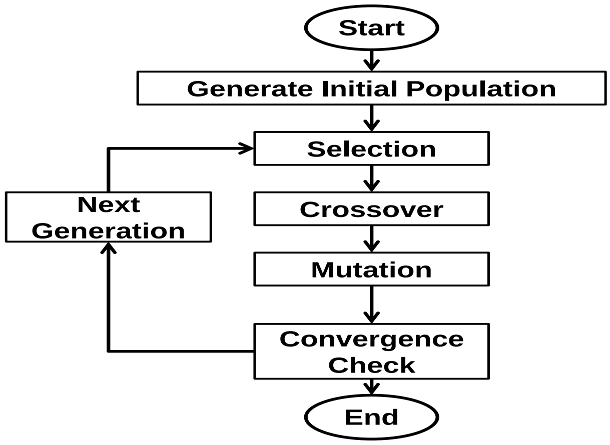

Fig. 5: General Scheme of Genetic Algorithm.

In control system engineering, in [14] used the GA for PID tuning of bus suspension system. In [15] applied the GA to assist in designing PI controller by using near–optimal locate approach. Based on previous research [16], the rhythm-generation of the CPG was optimized by using an EA. Then, in [1] employed the EA to optimize the human movement generating by CPG and Electromyography (EMG) data.

4. Results and discussion

This section presents the simulation result of optimizing the CPG parameters for one legged hopping robot hopping height control.

4.1. PI-CPG integration

Based on theory, CPG generates output in rhythmic pattern which can be represented the hopping mechanism produced by one legged robot. In order to control the hopping height of the one legged robot, PI controller is integrated with CPG as shown in Fig. **6**. The integration of PI controller purposed to compensate the error of the one legged hopping height. The PI controller is expressed as

$$u(s) = K_p + K_i\left(\frac{1}{s}\right) \tag{6}$$

Where Kp is proportional gain and Ki is integral gain. The gain Ki is set equal to zero, while Kp is tuned until the output reach the reference. Then, the gain Ki is tuned until the steady state error converged to zero. Table2 shows the gain of PI controller.

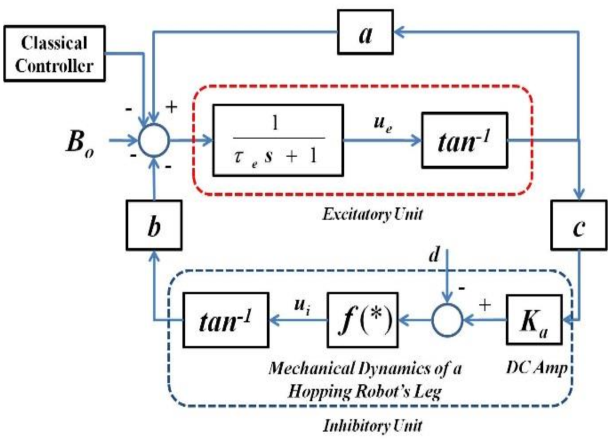

Fig. 6: CPG Model with PI Controller Integration.

Table 2: Gain of PI Controller

Controller	Parameter	
	Kp	Ki
PI Controller	0.1	0.4

4.2. Parameter optimization with genetic algorithm

A Genetic Algorithm is a computational optimization method that can work in large-dimensional, nonlinear and large unknown parameter spaces. Therefore, a genetic algorithm is used to efficiently search the optimum value for CPG parameters of one legged hopping robot. Optimization based reference height approach is designed to control the generated hopping height. The parameters of CPG for the optimization process are set as below.
CPG parameter, a within [0, 5.0];
CPG parameter, b within [0, 0.2];
CPG parameter, c within [0, 2.0].
There are three different reference height are set for each optimization run. Each optimization process is run with GA for 15 generations. Table3 shows the GA parameter setting which consists of mutation rate, selection, population size and number of iterations. The fitness functions for the optimization process which is minimized by the GA can be formulated as:

$$fitness = \frac{\sum_{i=2001}^{j} abs\left(h_{ref} - h_{out,i}\right)}{j-i} \qquad (7)$$

where h_{ref} is the reference height, hout is the hopping height of the one legged hopping robot. While, i is the number of data to be started process and j is the number of data. Simulation of the hopping robot is run for 5 seconds but only the last 3 seconds data are considered to be processed.

Table 3: GA Parameter Setting

GA Setting	Value
Mutation rate	0.15
Selection	0.5
Number of iterations	15
Population size	20

Fig. **7** shows the optimized CPG parameter a, b and c trajectory. The maximum generation which is 15 generations is selected with 20 populations in every single computation to generate the CPG parameter a, b and c. The maximum generation is selected based on computational time process consideration. From the figure, three values are optimized for each CPG parameter; a, b and c based on three different reference height as shown in Table4.

Fig. **8** shows the behavior of fitness values for each optimization based on different reference height; 26cm, 27cm and 28cm. All three fitness function values show a sudden decrease in the early generation stages of the optimization process and present the constant value after 10th generation.

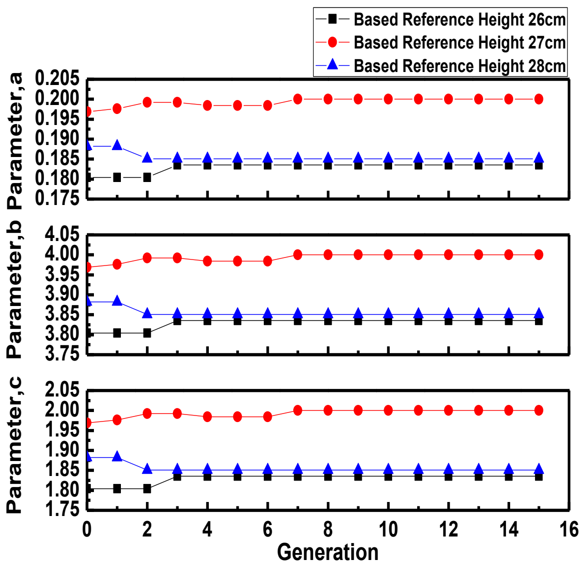

Fig. 7: Optimized CPG Parameter Trajectory.

Table 4: Optimized CPG Parameter

Reference Height (cm)	CPG Parameter		
	a	b	c
26cm	0.184	3.835	1.835
27cm	0.200	4.000	2.000
28cm	0.185	3.851	1.851

The optimized CPG parameter; a, b and c values as stated in Table4 are applied to the one legged hopping robot control system. Table5 shows the result of hopping height produced for each optimized CPG parameter; a, b and c values applied to the system.

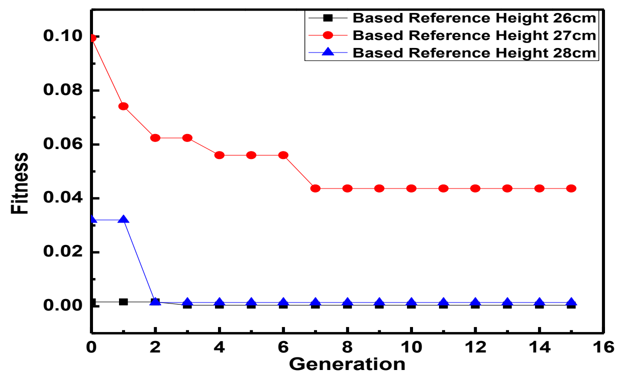

Fig. 8: Behavior of Fitness Value for Each Optimization

From the obtained simulation result in Table, the hopping height produced by using the optimized CPG parameter based reference height 26cm shows 1.50%, 19.35% and 43.30% error in achieving reference height given at 26cm, 27cm and 28cm respectively. The 9.70%, 10.50% and 1.63% error of hopping height produced by using the optimized CPG parameter based reference height 27cm. Meanwhile, the optimized CPG parameter based reference height 28cm presents 5.60%, 16.15% and 1.87% error of hopping height.

Table 5: Average Hopping Height and Error

Height (cm)	Average Hopping Height (cm)	|Error|
	Optimized CPG Parameter Based Reference Height 26cm	
26	26.015	0.015
27	26.613	0.387
28	26.700	1.300
	Optimized CPG Parameter Based Reference Height 27cm	
26	26.097	0.097
27	26.790	0.210
28	28.049	0.049
	Optimized CPG Parameter Based Reference Height 28cm	
26	26.056	0.056
27	26.667	0.323
28	27.944	0.056

Based the error percentage of the hopping height produced in achieving the reference height at 26cm, 27cm and 28cm, the optimized CPG parameter values of a = 0.2, b = 4.0 and c = 2.0 which based reference height 27cm led the other of optimized CPG parameter in producing low hopping height error. The optimized CPG parameter based reference height 27cm presents the lowest hopping height error at height 27cm and 28cm compared to the hopping height error produced by optimized CPG parameter based reference height 26cm and 28cm.

5. Conclusion

In this paper, the optimized CPG parameter a, b and c values based reference height 27cm produced the lowest error of hopping height even though the fitness shows the highest among the others. Therefore, the optimized CPG parameter based reference height 27cm produced better hopping performance and precise hopping height in achieving the reference height.

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