Online Gait Adaptation of a Hexapod Robot Using an Improved Artificial Hormone Mechanism

Potiwat Ngamkajornwiwat[1], Pitiwut Teerakittikul[1] and Poramate Manoonpong[2,3]

[1] Institute of FIeld roBOtics,
King Mongkut's University of Technology Thonburi, Bangkok, Thailand
potiwat.n@gmail.com, pitiwut@fibo.kmutt.ac.th
[2] Institute of Bio-inspired Structure and Surface Engineering,
Nanjing University of Aeronautics and Astronautics,Nanjing, China
poma@nuaa.edu.cn
[3] Embodied AI and Neurorobotics Lab, Central for BioRobotics,
The Maersk Mc-Kinney Moeller Institute,
University of Southern Denmark Odense M, Denmark
poma@mmmi.sdu.dk

Abstract. Walking animals show a high level of proficiency in locomotion performance. This inspires the development of legged robots to approach these living creatures in emulating their abilities to cope with uncertainty and to quickly react to changing environments in artificial systems. Central pattern generators (CPGs) and a hormone mechanism are promising methods that many researchers have applied to aid autonomous robots to perform effective adjustable locomotion. Based on these two mechanisms, we present here a bio-inspired walking robot which is controlled by a combination of multiple CPGs and an artificial hormone mechanism with multiple receptor stages to achieve online gait adaptation. The presented control technique aims to provide more dynamics for the artificial hormone mechanism with an inclusion of hormone-receptor binding effect. The testing scenarios on a simulated hexapod robot include walking performance efficiency and adaptability to unexpected damages. It is clearly seen that varying of hormone-receptor binding effect at each time step results in a better locomotion performance in terms of faster adaptation, more balanced locomotion, and self-organized gait generation. The result of our new control technique also supports online gait adaptability to deal with unexpected morphological changes.

Keywords: Artificial hormone mechanism, Gait adaptation, Autonomous robot, Adaptive behaviours, Gait generation

1 Introduction

Walking animals show various movement abilities including versatility, energy-efficiency, and adaptable locomotion to cope with uncertainty and to react quickly enough to changing environments. These inspire us to develop the many-legged robots to imitate natural properties of locomotion control of these walking creatures.

Different approaches, including machine learning algorithms, traditional engineering control techniques, have been utilized, aiming to achieve such a sophisticated locomotion. Furthermore, when there are unexpected situations such as hardware failures, it is crucial for the autonomous robots to recover their operations quickly and complete their task [1]. Currently, it remains a challenge to develop legged-robots that have effective adaptability without a complex control system [2].

The use of central pattern generators (CPGs) has been widely applied to the development of legged robots [3]. A single CPG was applied in some works [2, 4, 5]. Although implementing a CPG on a legged robot can yield sophisticated gait patterns, such a single CPG controller still faces a challenge to deal with leg malfunctions. Instead of using a single CPG, Ren et al. [6] and Barikhan et al. [7] developed multiple CPGs to enhance traversability and flexibility of a legged robot. Another promising method is the use of artificial hormone mechanisms [8,9]. In [10], an artificial hormone network was introduced in helping an autonomous wheel robot to perform effective locomotion on unknown terrains as well as when faults occur in robot sensors.

Timmis et al. [11] proposed a combination of an artificial neural network and an artificial endocrine system (AES) to generate behaviour in artificial organisms. Here, what we improve is the AES to achieve online gait adaptation for a hexapod robot. According to this, the robot will be controlled by multiple decoupled CPGs with receptors and a hormone system. The improvement of the AES is achieved by an inclusion of receptor binding effect and resulted in not only self-organized locomotion generation but also online adaptation to unexpected malfunctions or leg damages.

The remainder of this paper is structured as follows: Section 2 presents the overall control mechanism where an improved artificial hormone mechanism (iAHM) and a multiple CPG model are introduced, Section 3 elucidates the experiment scenarios and parameters setting of the proposed model on a simulated hexapod robot, Section 4 demonstrates the experimental setup and discusses the results obtained from the experiments and the last section concludes the work and presents the recommendations for future work.

2 Hormone Mechanism

Hormones are regulatory substances released from endocrine glands into the blood vessel. When binding to specific receptors of their target cells, they trigger numerous cellular processes. The hormone mechanism is illustrated in Fig. 1A.

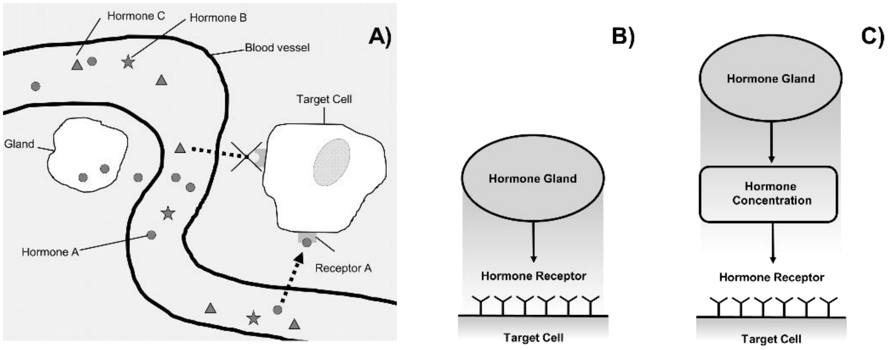

Fig. 1. A) Hormone mechanism. B) Standard artificial hormone mechanism. C) Improved artificial hormone mechanism.

2.1 Artificial Hormone Mechanism (AHM)

Timmis et al. [11] proposed a bio-inspired mechanism called an Artificial Endocrine System (AES) for locomotion control.

The main components of AES are hormone glands and hormone receptors as illustrated in Fig.1B. In this model, hormone concentration at a particular time is calculated according to Equation 1.:

$$H_C(t) = \beta \cdot H_C(t-1) + \alpha \cdot H_G(t) \tag{1}$$

where $H_C(t)$ is hormone concentration at the current time step, $H_G(t)$ is a stimulation value at a current time step, α is stimulation rate and β is decay rate of hormone. From the equation 1, it can be seen that the changes of hormone concentration at each time step are dependent on the stimulation of hormones at current time step and the decay quantity of the hormone at the previous time step, (t-1). The decay rate is equivalent to the metabolic clearance rate [10] which depicts the rate at which hormone is removed from the blood. The metabolic clearance rate is affected by many mechanisms [12], including metabolic destruction, binding of hormones to their receptors, excretion of hormones by the liver and excretion of hormones by the kidneys. In Timmis et al. study, these four mechanisms are presented conceptually as $\beta \cdot H_C(t-1)$ as shown in Equation 1.

2.2 Improve Artificial Hormone System (iAHM)

As mentioned above, all four factors that influenced the metabolic clearance rate are presented as β in Timmis et al. [11]. In this paper, a new model is proposed, aiming to provide more dynamics for artificial hormones mechanism. The overview of the proposed system is shown in Fig. 1C, the metabolic clearance rate is expressed as the metabolic destruction and hormone-receptor binding effects indicated previously, while the excretion of hormones by the liver and kidneys are still not considered. The hormone concentration at each time step of the improved mechanism is calculated as shown in Equation 2.:

$$\mathrm{H_C(t)} = \beta \cdot \mathrm{H_C(t-1)} + \alpha \cdot \mathrm{H_G(t)} - \mathrm{H_R(t)} \tag{2}$$

where $H_R(t)$ is a hormone-receptor binding effect. Additionally, the effect can be calculated as indicated in Equation 3.:

$$H_R(t) = \sum_{i=0}^{N} \left(\gamma_i \cdot Receptor_i(t)\right) \tag{3}$$

where γ_i is a binding effect rate for receptor i. $H_R(t)$ is the summation of a binding effect of each active receptor of cells influenced by the same hormone. However, $Receptor_i(t)$ is defined as a number of receptors in cell i at time t. There are two distinctive points where the improved artificial hormone mechanism can offer comparing to the system proposed in [10]. Firstly, the binding effects can influence hormone concentration. Secondly, each hormone receptor can be set to operate either at the same time or at the different time.

In order to examine the effect of the improved mechanism on a legged robot, a series of experiments is performed and illustrated in the next section.

3 Test Scenario

3.1 Mechanism for Implementation

In order to examine robot walking performance in the new proposed model, the simulation toolkit LPZROBOTS [13] based on the open dynamics engine was employed in a testing environment to represent the tested hexapod robot as shown in Fig.2A. These six legs are identical, and each leg consists of three joints emulated from a basic structure of a cockroach leg [14] without tarsus. Each robot leg consists of a thoraco-coxal joint (TC), a coxa-trochanteral joint (CTr), a femur-tibia joint (Fti), and a foot contact sensor (Fig 2B).

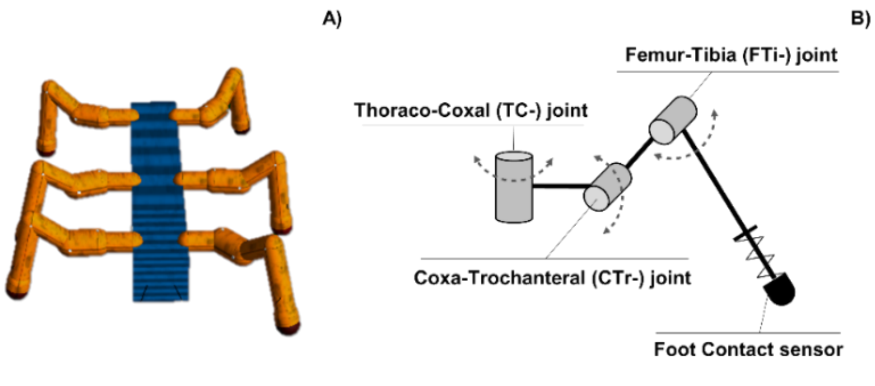

Fig. 2. A) hexapod robot in LPZROBOTS. B) Example of the simulated robot components and motor joints location.

3.2 Configuration and Parameters Setting

Both AHM and iAHM diagrams possess the same structure as illustrated in Fig. 3 except the iAHM has $H_R(t)$ in Equation 2. For both AHM and iAHM, the hormone gland is stimulated from the correlation between six-foot contact signals (R1-R3 and L1-L3) and six motor commands (CR1-CR3 and CL1-CL3). After having been stimulated, the hormone is secreted and, subsequently, the hormone concentration rate will be changed. The hormone concentration will be increased when there is more orchestration of foot contact signals and motor commands.

In iAHM, when $H_R(t)$ is introduced into the Equation 2, the hormone concentration can be varied according to $H_R(t)$ in a particular time step. Thus, the receptor on each leg can be set as either active or inactive at each time step, consequently, each leg can move adjustably in the online gait adaptation.

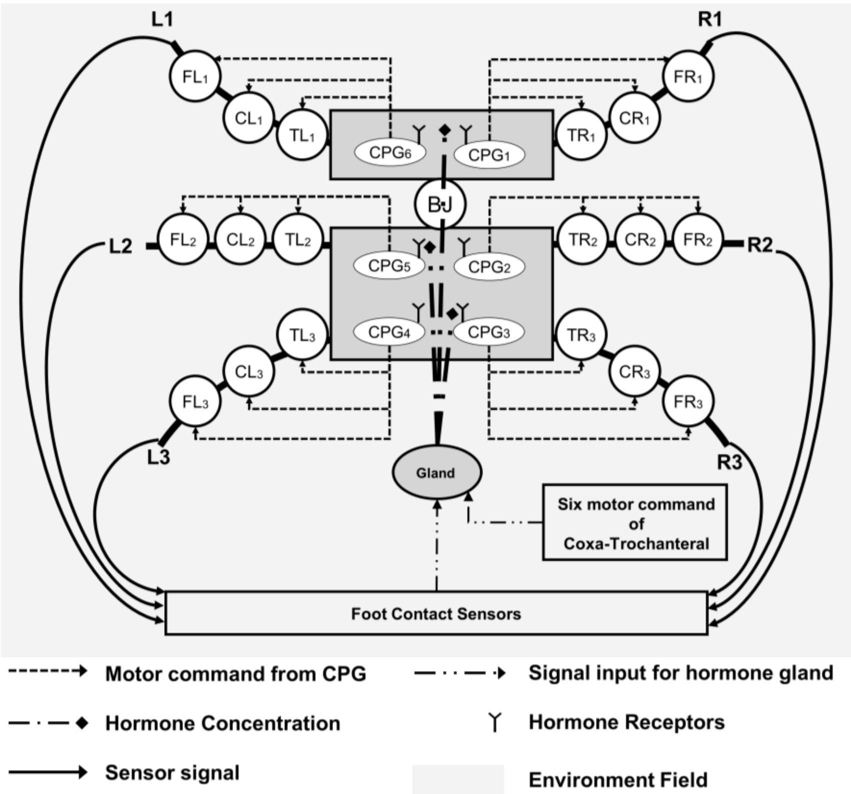

Fig. 3. The diagram of both AHM and iAHM with multiple CPGs of a hexapod robot. Each leg possesses a modulated CPG. The CPG has one receptor which binds the hormone and triggers the reactions of the target cell and subsequently change parameters for frequency control in the CPGs. Abbreviations are: TL, CL and FL = TC, CTr and FTi joints of the left leg while TR, CR and FR = TC, CTr and FTi joints of the right leg and 1,2 and 3 = the front, middle and hind legs respectively and finally BJ=backbone joint.

A CPG- based control system proposed by Manoonpong et al. [5] was adopted here to use in our experiment to generate basic rhythmic movement. The frequency control inputs that vary according to the hormone concentration operate the Module I through IV of the CPG (Fig 4A). When the frequency control input increases, the angular velocity of the three joints will also increase. As a consequence, a CPG-controlled leg moves faster.

The relationship of the frequency control input and the hormone concentration is illustrated in Equation 4.:

$$Frequency\ control\ input = \left(0.17 * H_C(t)\right) + 0.02 \tag{4}$$

In our experiment, the frequency control input is set in a range of 0.02-0.19. The movement frequency of each leg is shown in Fig. 4B.

In all testing scenarios, the parameters for the stimulation rate, the decay rate, and the binding effect rate are 0.219, 0.2185, and 0.0005, respectively. Each receptor is set to be active at intervals of 20 steps starting from the receptor of L1, L2, L3, R1, R2 and R3 subsequently.

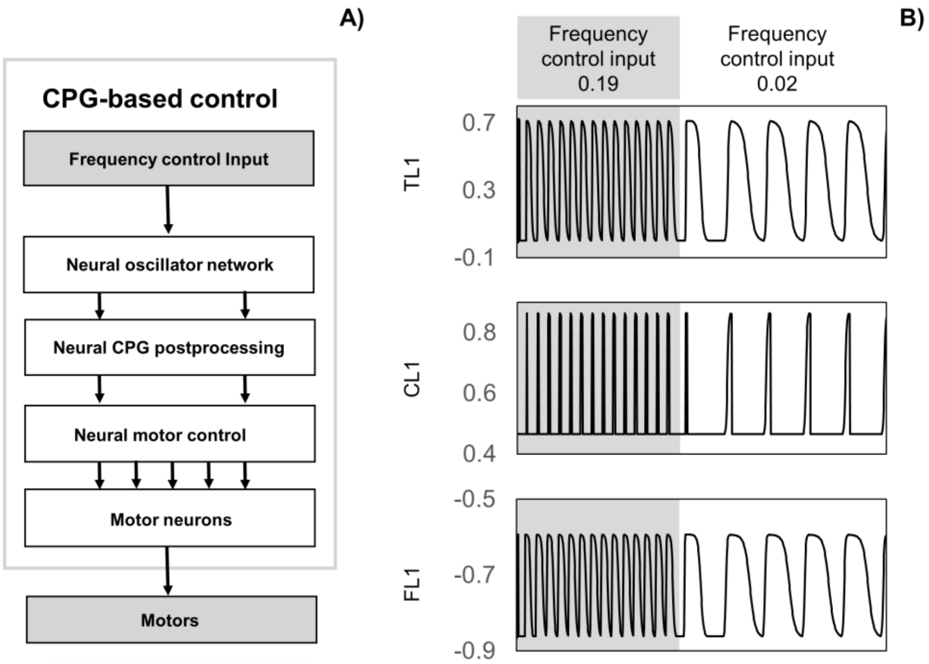

Fig. 4. A) The diagram of a CPG-based control system on each leg of the robot. B) The movement frequency of the joints on each leg when the frequency control inputs are 0.19 and 0.02. Notice that when the frequency control input is 0.19, each joint move faster than the frequency control inputs is 0.02, thus the leg also moves faster.

4 Experimental Setup and Results

4.1 Walking Performance and Self Organized Gait Generation

The aim of the first experiment was to indicate that the impact from varying of receptor stages could aid a robot in delivering better walking performance. In the first testing scenario, we compared iAHM with AHM by setting all initial parameters as indicated previously. We let the robot walk in forward direction for five minutes on the horizontal surface from the same starting point and orientation. Note that all legs on each side of the robot were initiated to move at the same phase. In iAHM, the receptors' status is set to be active as mentioned above while the receptors of AHM remained active in all time steps. We measured the distance that the robot moved along the X-axis and the swing magnitudes in Z-axis from both mechanisms. Each experiment was repeated for 10 times in order to investigate the variability of the performance.

It turned out that in iAHM, the robot was able to achieve almost three times greater of average walking distance and less standard deviation of the body swing compared to those of AHM (Fig. 5).

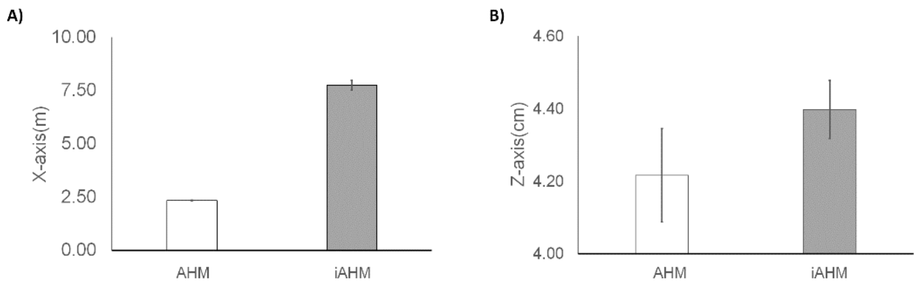

Fig. 5. A) Average walking distances measured along the X-axis in AHM and iAHM were 2.34 meters and 7.74 meters and standard deviation were 0.01 meter and 0.24 meter, respectively. B) Average of the center of mass height in the Z-axis measured when the robot walked in AHM and iAHM were 4.22 and 4.40 centimeters and standard deviation were 0.13 and 0.08 centimeters, respectively.

When the stance phase of the walking robot in both mechanisms was considered, it was found that all three legs of the same side were uplifted simultaneously in AHM since the legs of the same side possessed the same frequencies and phases (Fig.6A). The robot walked jerkily and lost its body balance. The robot "heaved and rolled" simultaneously on the ground. The ground clearance of the robot during its movement varied wisely resulting in higher SD of the distance on the Z axis (Fig.5B).

In contrast with the robot in the iAHM, all legs of the robot were self-organized to automatically adjust to the variations of the activation stage of the receptors to obtain stable gait patterns. Then they paced in slightly different frequencies and phases according to their adjustment (Fig 6B). The walking performance of the robot in iAHM is more adjustable than the robot in AHM due to the hormone-receptor binding effect (see Equation 2).

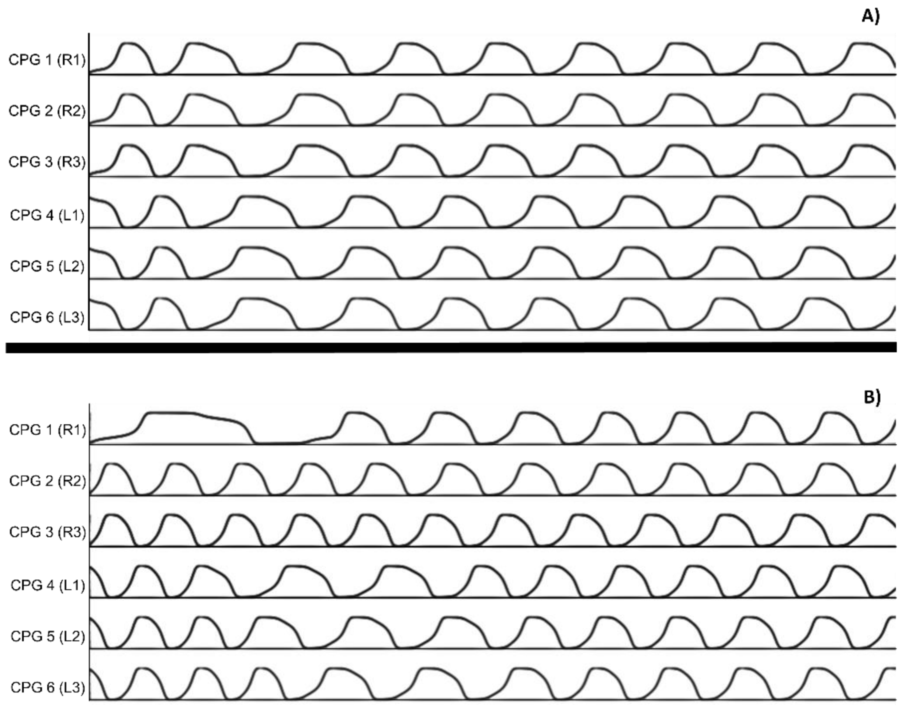

Fig. 6. A) The frequency patterns of each side legs of the AHM robot (A) and iAHM robot respectively (R1, R2, R3 represents each right leg and L1, L2, L3 represents each left leg.)

4.2 Adaptability to Morphological Change

In the second testing scenario, we focused on the adaptability to an unknown damage of the tested robot. We let the robot walk with complete six-legs for 1.5 minutes. Then we disabled R2 and L3 leg as indicated in Fig.7A and disabled R2, R3, and L3 legs as indicated in Fig.7D and we allowed the robot to walk for 3.5 more minutes. The testing of each mechanism was repeated for five times. The result shows that the robot with the AHM could not adjust its walking performance and direction along the X-axis. It walked circularly and failed to move forward (black line in Figs.7B and 7E for the two disabled legs and three disabled legs, respectively).

While the robot with the iAHM had an online learning capability to adapt its walking performance to walk towards the desired trajectory (gray line in Figs.7B and E). When the movement orientation was considered, the robot with the AHM walked in a curved path (black line in Figs.7C and 7F) while the robot with the iAHM tried to keep its orientation straight forward (gray line in Figs.7C and 7F).

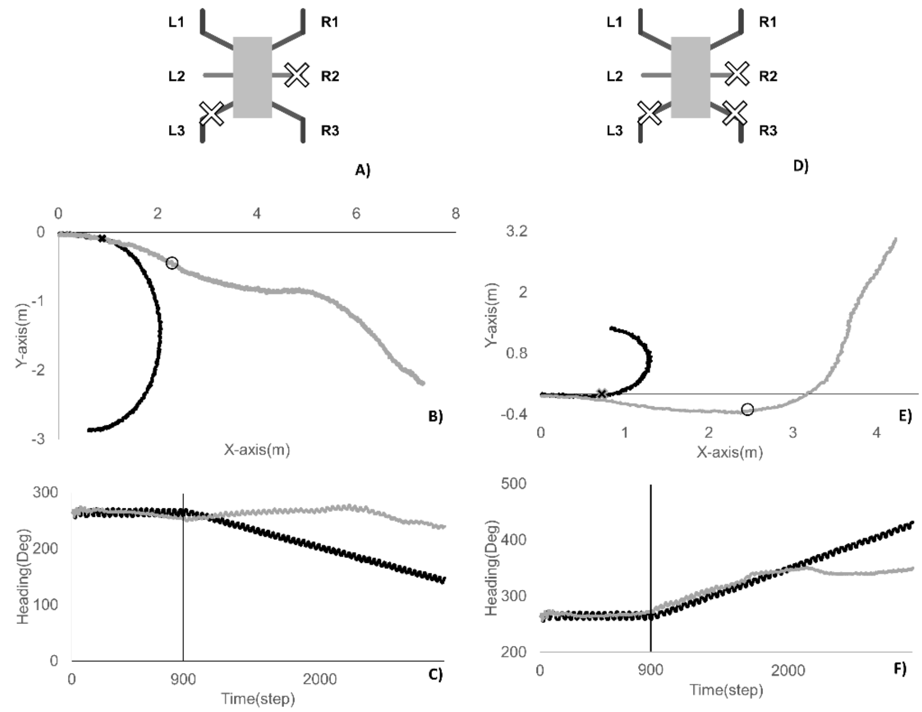

Fig. 7. Robot with disabled R2 and L3 legs (7 A) and robot with R2, R3 and L3 legs (7 D) failed to walk towards the desired trajectory (black line in Figs.7 B and E) and they also lost their orientation (black line in Figs.7 C and F) in AHM while they still kept their walking orientation in iAHM (gray line in Figs.7 B and E and 7 C and F, respectively).

The hormone concentration of the robot in iAHM was investigated. Firstly, the normal hexapod robot was allowed to walk for 1.5 minutes, and the hormone concentration was calculated from the Equation 2. The level of the hormone fluctuated highly for the first few seconds, then the hormone concentration fluctuated narrowly as shown in Fig.8A. After being disabled for three legs, the hormone concentration was dropping significantly (see Fig. 8B). However, the robot spent a minimum time to adapt its gait to deal with the situation. When the robot achieved appropriate gait, the hormone concentration would increase again (see Fig. 8C).

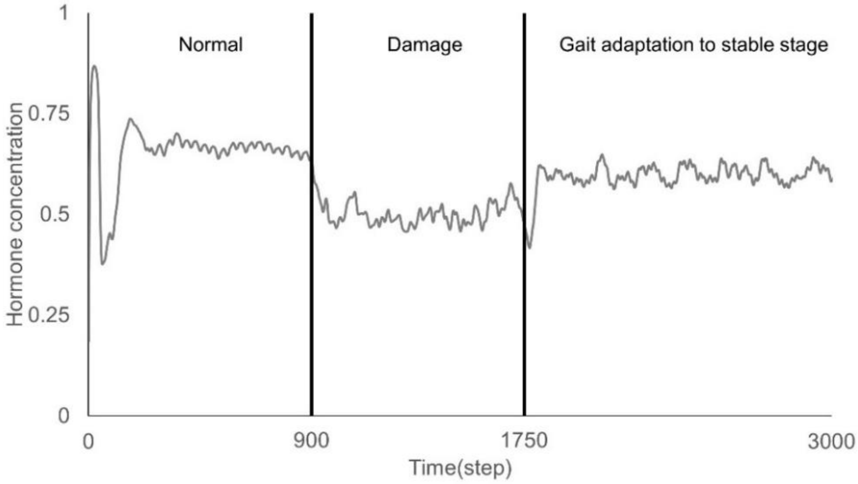

Fig. 8. The level of hormone concentration in each time step for the iAHM-driven robot

5 Conclusion and Future work

We presented here a bio-inspired walking robot which was controlled by a combination of multiple CPGs and an artificial hormone mechanism with multiple receptor stages. The results are promising to prove that, the hexapod robot with iAHM can achieve a better locomotion not only faster but also more balanced locomotion compared to the previous AHM robot performance. The receptor activation in various times causes different frequencies and phases for gait generation. This enables the robot to move autonomously and adapt its gait pattern to handle morphological changes or damage. Although the walking performance of the legged robot has been improved by the stimulation of the hormone receptors at different phases, there are some limitations of the robot in achieving the walking performance of an insect.

Our future work will focus on conducting these experiments in real legged robots moving on different types of terrain to verify and confirm that an artificial hormone mechanism proposed in this study could improve walking efficiency and reduce the cost of transportation.

6 Acknowledgements

Poramate Manoonpong acknowledges funding by the Thousand Talents program of China and the research grant RGP0002/2017 from the Human Frontier Science Program (HFSP).

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