The 4th International Conference on Control and Robotics Engineering

An Artificial Hormone System for Adaptable Locomotion in a Sea Turtle-Inspired Robot

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Abstract—**There are various challenges to operate autonomous robots for a long time in outdoor real-world environments. One of the most challenging tasks is to reduce the cost of transport when locomoting over hard ground or uneven complex terrain. This paper proposes using an artificial hormone system as a mechanism which responds to external environmental changes and alters robot behaviours to move with energy efficiency. Specifically, hormone systems are used to help the robot deals with terrain variations. The emergence of adaptive locomotion focuses especially on the cost of transport usage. The proposed system is tested in real sea turtle-inspired robot and environment. The results have shown that the robot can adapt its gait and demonstrate robust locomotion which associates with reducing the cost of transport while traveling in complex environments.**

Keywords-component; cost of transport; artificial hormone system; adaptive locomotion; sea turtle-inspired robot;

I. INTRODUCTION AND BACKGROUND

The locomotion of loggerhead sea turtle hatchlings illustrates various movement abilities including energy efficiency and adaptability to deal with environmental changes. One of the most robust locomotion is to move with stability over a wide range of complex terrestrial ground like stone, rubble, and especially granular substrates that yield upon the foot or body interaction [1]. The study in [2] developed and tested a sea turtle-inspired physical model, FBot, to improve understanding the principles of flipper-based locomotion on granular media. The research has shown that robot modeling with a free wrist at the end of the flipper holds a significant advantage over a fixed wrist because the robot which was fitted with a free wrist would allow the flipper to remain locked in place within a solid region of sand and thus disturb less material during the forward thrust. Furthermore, the researchers also investigated the different depths to which the flipper penetrated the poppy seeds, while also measuring the body lift, flipper thrust, the drag of the robot's base and the amount of ground being disturbed. The results showed that the relationship between each of these aspects was not trivial, but could, nevertheless, be understood using relatively simple models. These inspire us to develop the locomotion of sea turtle-inspired robot in order to achieve the ability to adapt its gait in changing environments for energy efficient movement.

The cost of transport (COT) quantifies the energy efficiency to transport the robot from one place to another. It is calculated from energy consumption of the motors by integrating their power over operating time, and then computing the ratio of energy consumption to weight times distances (COT = E/mgd).

To date, there have been approaches to reduce COT by improving the mechanical system, known as *mechanical energy capacitors* [3], that is able to store kinetic or elastic potential energy and recover without significant loss. One of the main methods in this concept is passive dynamics.

In term of passive dynamics, many researchers have investigated walking robot, and achieved energy efficiency [4]. For instance, The Cornell Ranger was successfully designed and it controlled a simple planar robot which could walk around 65 kilometers without charging and having human intervention. Consequently, its COT is the lowest when compared with other legged robots nowadays. However, this mentioned robot is challenged with the restriction of a particular velocity on flat terrain and a human-like walking movement.

Because these mechanical systems tend to be tuned for specific terrain and only a narrow range of speeds, implementing adaptive locomotion systems on the robot is considered.

Many researchers have studied biological organisms and found a phenomenon which helps creatures to adapt their body to maintain a stable internal state when the environment changes [5]. This biological phenomenon is known as *homeostasis* that is mostly influenced by the endocrine system [6].

The endocrine system is able to model as an element of both hormone gland and receptor. Glands normally generate and secrete hormones to destination cells which only have a receptor in the same type of hormone. As soon as the destination target cells receive the hormones, they respond by performing reasonably [7]. Following Artificial Endocrine Systems (AES), the utilization provides system adaptability, especially for autonomous robots. In [8], the study proposes a system called *neuro-endocrine*. AES was used to interact with the main robot controller which employed an Artificial Neural Networks (ANN). AES is a mechanism which responds to external environments and then releases hormones in order to update input weights of the ANN. This system can help the robot to adjust its

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behavior in various environments. As a result, the robot could approach the wall very closely in open space, but while in a tighter area, the robot could approach the wall with less proximity. The study in [9] proposes using an Artificial Hormone Network (AHN) as a mechanism which helps a mobile autonomous robot to deal with the situations when the robot moves on uneven terrain and faces some faults in the pitch sensory information in accordance with hormone network receiving environmental cues from both internal and external environmental changes. The result illustrated that the robot was capable of improving its performance by allowing the artificial hormone network to adjust the robot behaviors.

In order to provide adaptable locomotion for a sea turtle-inspired robot for the most effective use of the cost of transport while navigating through uneven terrain, this paper proposes using an Artificial Hormone System (AHS) as a mechanism which responds to external environmental cues and modifies robot behaviours to deal with environmental changes. The proposed hormone dynamics have led to a reduction in the cost of transport.

The research proceeded as follows. Section II describes a sea turtle-inspired robot which is the robot used in this research and provides background information of AHS based on the previous work in the area. Section III describes the detailed structures, mechanisms, and connectivity of the proposed AHS on the main robot controller. Then Section IV introduces the main experimental setup: a diverse set of challenging terrains, and the cost of transport calculation. Experiments and results of the proposed AHS assisting the sea turtle-inspired robot to deal with external environmental changes for the cost of transport reduction are described in Section V. Finally, Section VI will discuss the conclusions and further work.

II. SYSTEM ARCHITECTURE

To arrive at a practical design of artificial hormone in a sea turtle-inspired robot, an understanding of the basic principles of both systems, the mechanic of a hatchling sea turtle-inspired robot and artificial hormone mechanisms, is a critically required step.

A. Sea Turtle-Inspired Robot

In [2], the authors studied insights into the mechanics responsible for locomotion of the hatchling sea turtles and discovered the turtles propelled themselves forward with influence of their two front limbs. FBot is implemented in order to detail locomotion research of a sea turtle-inspired robot that used flippers to locomote on granular terrain.

In this research, FBot was used with slight modification and re-named FinBot, see Figure 1. FinBot has two limbs which are symmetric at the median line of the body and attach around the anterior at a position similar to the pectoral flippers of a sea turtle. Each limb is connected to the body by two servo motors (RDS3135 35 kg) as a shoulder-elbow linkage formed. A 2 degree of freedom front limb consists of an up-down motor, fore-aft motor, and an 11 cm × 1.7 cm flat aluminum bar with a distal flipper.

- The up-down motor is attached to the base. Its rotation axis paralleled to the anteroposterior line and angular position is ψ; it is defined to be zero when a limb was horizontal. A positive angle of ψ moves the limb downward, and for the negative angle, the limb moves towards the opposite direction.

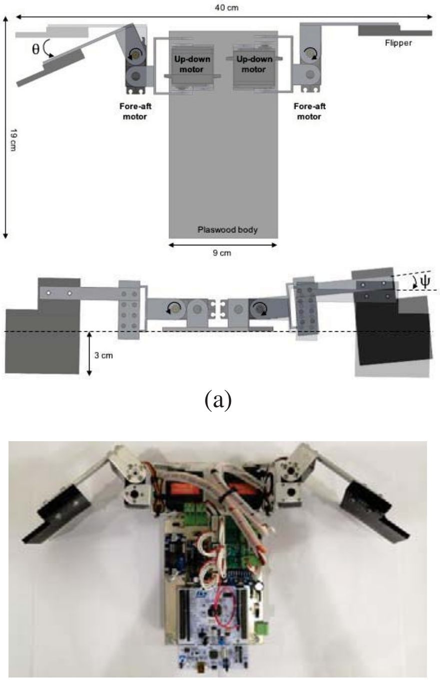


Figure 1. (a) drawings of FinBot depicting stroke angle θ and flipper insertion angle ψ. (b) illustrates the locations of flippers, servo-motors and the equipment on FinBot.

- The fore-aft motor is fixed to the up-down motor by a bracket. The rotation axis of the fore-aft motor is perpendicular to the rotation axis of the up-down motor, and its angular position is θ. It is defined to be zero when a limb is perpendicular to the anteroposterior line. A positive angle of θ moves the limb end effector towards the posterior.
- Flipper is connected to the flat bar by a fixed wrist. The 7 cm × 4 cm × 0.3 cm flipper extends 3 cm below the base when the flat bar is parallel with the plane of the body ($\psi = 0°$).

FinBot is equipped with electronic components including a four cell lipo batteries, four power monitoring (PM) sensors, an inertial measurement unit (IMU) sensor (MPU9250), and a nucleo-f411re microcontroller. Moreover, FinBot is a sea turtle-inspired locomotor with a 40 cm limb span. Its plastron-inspired base is a 19 cm × 9 cm plaswood plate and FinBot's weight is 0.878 kg.

The main robot controller basically contains the limb kinematics for normal gait. The gait is symmetric, and a stroke consists of four stages which are modeled by a state machine as shown in Figure 2. At the initial stage, the limbs are orthogonal to the anteroposterior line ($\theta = 0°$) at an angle of $\psi = -45°$.

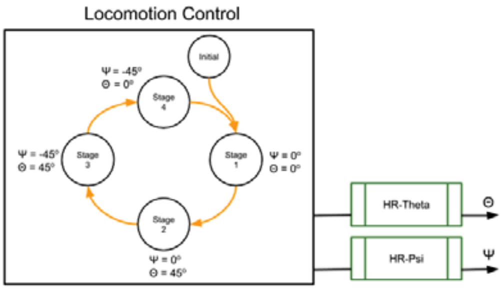


Figure 2. A state machine diagrams of FinBot gait.

- Stage 1: the up-down motors rotate the limbs downward from a rotation angle of $\psi = -45°$ to $\psi = 0°$.
- Stage 2: the fore-aft motors rotate the limbs toward the posterior from a rotation angle of $\theta = 0°$ to $\theta = 45°$
- Stage 3: the up-down motors rotate the limbs upward from a rotation angle of $\psi = 0°$ to $\psi = -45°$.
- Stage 4: the fore-aft motors rotate the limbs toward the anterior from a rotation angle of $\theta = 45°$ to $\theta = 0°$.

A visual depiction of the robot's stroke can be viewed in this video: https://youtu.be/S05yQSGM9zw

B. *Artificial Hormone System*

Based on the paper proposed in [9], the artificial hormones mechanism was designed into two subsystems, one of which is Hormone Gland (HG), and another is Hormone Receptor (HR).

A Hormone Gland is a mechanism which responds to the environmental information in term of quantity and existence in order to produce and secrete a hormone. Fig. 3 shows insight into the hormone gland mechanisms. It consists of two input types: Signal inputs (S_i) and Control inputs (C_i), and there are three main processor units inside.

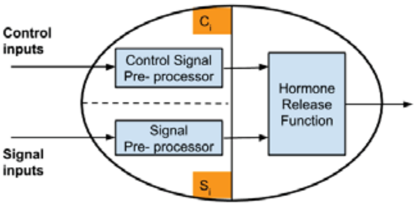


Figure 3. Hormone gland mechanisms.

Firstly, a Signal Pre-processor unit receives a set of signaling (e.g. environmental cues) via the Signal inputs connecting to HG, and it provides a way for the gland to respond to different aspects of environmental information. Input is used directly for the calculation of hormone stimulation in each gland.

Secondly, a Control Feature unit receives the inputs (e.g. hormone signals from another gland) via the Control inputs which also connect to HG, and this provides a way for the gland to interact with one another in order to implement hormone networks. Then the input is processed to define the effect of Signal Input on the hormone stimulation.

Finally, a Hormone Release Function is a mechanism which identifies the hormone concentration in each iteration and provides the HG to secrete the amount concentration appropriately. Mathematically, the hormone concentration at each time step ($C_g(t)$) is a summation of two main terms given by (1).

$$C_g(t) = (\,\alpha_g * f(S_i)\,) + (\,\beta_g * C_g(t-1)\,) \qquad (1)$$

The first term pre-processes the S_i inputs and then the inputs are multiplied by a stimulation rate (α_g). The second term depends on the hormone concentration at a previous time step ($C_g(t-1)$) which is multiplied by a decay rate (β_g). Moreover, the hormone concentration is rescaled by hyperbolic tangent function ($\tanh(C_g)$), and the value of α_g and β_g are restricted between 0 and 1.

A Hormone Receptor is subjected to interact between the hormone system and the main controller of the robot. The HR allows associated hormones to affect the base controller depending on the amount of hormone concentration received by each HR, its location on the main controller, and its function.

Fig. 4 shows the Artificial Hormone System (AHS) designed to cope with external environmental changes. HRs are represented by a rectangle, and HGs are elliptical. There are two types of data in the connectivity: sensory information and a hormone. A sensory data is transmitted through a solid line, while a hormone data is sent via dot line.

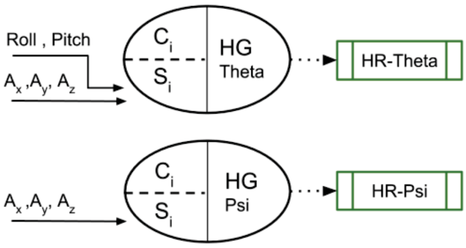


Figure 4. Artificial Hormone System.

III. HORMONE DESIGN

In order to help FinBot to reduce the cost of transport while travelling in changing environments, this paper proposes hormone architecture using two HGs as the AHS shown in Fig. 4. Hormone Gland Theta (HG-Theta) and Hormone Gland Psi (HG-Psi) similarly generate a Terrain-Excitation hormone. Although HG-Theta and HG-Psi secrete the same hormone, they are stimulated from different environmental information. HG-Theta responds to changes of terrain roughness. On the other hand, HG-Psi releases the hormone concentration depending on changes of terrain hardness. In general, a rougher or harder terrain motivate a higher concentration of the hormone.

When considering the sensory information acquired from IMU which influences the responsibility of each HG, there are two types of environmental information acceleration and rotation angle of the robot presented at each HG in every stroke.

For the acceleration ($\vec{A}$), it is a three-dimensional vector with components in the x, y and z directions defined as A_x, A_y and A_z respectively. The HG which receives this vector firstly processes in Signal Pre-processor unit at each time step by (2).

$$\vec{A}(t) = \sqrt{A_x(t)^2 + A_y(t)^2 + A_z(t)^2} \tag{2}$$

For the rotation angle ($\vec{R}$), it is a two-dimensional vector with components in Roll and Pitch, and the HG initially processes this rotation vector at each time step by (3).

$$\vec{R}(t) = \sqrt{Roll(t)^2 + Pitch(t)^2} \tag{3}$$

Following the locomotion of FinBot which consisted of four stages per stroke, secreting of the Terrain-Excitation hormone occurred only at the end of stage 4. HG-Theta responds to the average of $\vec{A}$ at stage 2 ($\vec{A}^{S2}$) and $\vec{R}$ at stage 4 ($\vec{R}^{S4}$): $Avg(\vec{A}^{S2}\colon \vec{R}^{S4})$. Alternatively, HG-Psi responded to the average of $\vec{A}$ at stage 2 and 3: $Avg(\vec{A}^{S2}\colon \vec{A}^{S3})$. Note that both averages were processed by the second pre-processing in Signal Pre-processor unit of each HG.

Additionally, in our preliminary experiments of the locomotion of FinBot that interacts with the ground, we have analyzed the sensory information and discovered that the higher value of $Avg(\vec{A}^{S2}\colon \vec{R}^{S4})$ got, the rougher the terrain was. While $Avg(\vec{A}^{S2}\colon \vec{A}^{S3})$ represented terrain hardness, the harder ground motivated a higher value of $Avg(\vec{A}^{S2}\colon \vec{A}^{S3})$.

HG-Theta and HG-Psi connected with HR-Theta and HR-Psi respectively via the hormone channel. The location of both HRs was at the outputs of Locomotion Control on the main controller as shown in Figure 2. Consequently, the Terrain-Excitation hormone had an effect on the robot behaviour by altering the joint angle of the servo motor in each stage depending on its concentration. The receptor functions of both glands HR-Psi and HR-Theta were mathematically defined by (4) and (5) respectively.

$$\gamma_1(t) = -25 * C_g^{Psi}(t) + 17.5 \tag{4}$$

$$\gamma_2(t) = 75 * C_g^{Theta}(t) \tag{5}$$

Where:

- $C_g^{Psi}(t)$ is the hormone concentration of HG-Psi.
- $C_g^{Theta}(t)$ is the hormone concentration of HG-Theta.

Moreover, an angle of ψ was modified by γ_1 in stage 1 and stage 2, on the other hand, an angle of θ was adjusted by γ_2 in stage 2 and stage 3.

IV. EXPERIMENT SETUP

In this research, the robot was built based on [1] and tested in the real environment. An Inertial Measurement Unit (IMU) sensor was used to consider external environmental cues that changed terrain roughness and hardness, and the Power Monitoring (PM) sensors were used to measure the power consumption of each servo motor directly to find the cost of transport.

There are several different terrain types to study system performances when dealing with changing environments. The arena was defined to two main types of terrains as follow:

1) Single-type terrain: Only one terrain was in the rectangular-arena of 60 cm by 60 cm such as flat only, gravel only and pebble only. Examples of the terrain are shown separately in Fig. 5.

Figure 5. Example of Single-type terrain. Left to right: flat, gravel and pebble.

2) Mixed terrain: Consisting of two arenas, all of them included a wide range of terrain with varying levels of roughness and hardness. We structured an arena into three different terrains on our concept similar to terrain variations of real-world environments. For instance, Figure 6 began with the flat first, the second region is gravel and the last area is foam because foam surface has the mixed property of terrain between flat and gravel like smooth and soft ground.

- A terrain with the different features is in a sequence of flat (0.6 m), gravel (0.6 m) and foam (0.9 m), this is called "Flat-Gravel terrain." Figure 6 shows the terrain used in the experiments, and the robot started from left to right.

Figure 6. Example of Flat-Gravel terrain.

- The terrain consists of a sequence of gravel (0.6 m), pebble (0.6 m) and mixed of both (0.9 m). This is called "Gravel-Pebble terrain," as shown in Figure 7.

Figure 7. Example of Gravel-Pebble terrain.

To calculate the cost of transport, COT was defined as (6). The energy consumption required for locomotion E is given by PM sensors which measured the power usages of all servo motors (four servo motors used on the FinBot) then the power usages would be integrated over time before being summed up.

$$COT = \frac{E}{mg\Delta d} \tag{6}$$

where:

- m is the mass of the robot.
- g is the gravity.
- Δd is the locomotion displacement.

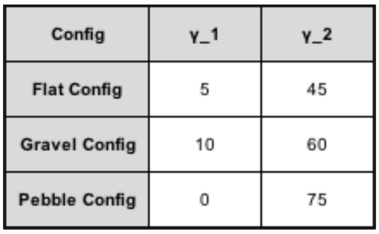
V. EXPERIMENT AND RESULTS

First of all, it is important to investigate every possible joint angle of the robot limbs during locomotion in order to find the gait which consumes the lowest cost of transport on the Single-type terrain.

In the preliminary experiment, FinBot moved separately on three different types of terrain consisting of flat, gravel and pebble. Every round test without the AHS or both angles γ_1 and γ_2 were fixed and would change in the next round by the chosen angles. The COT was measured as the combinations of gait parameters γ_1 and γ_2 and the terrain types.

The results showed the lowest cost of transport on each terrain. Firstly, only 178.813 J/kg*m was consumed on flat terrain when the robot moved with the gait parameters $\gamma_1 = 5^\circ$ and $\gamma_2 = 45^\circ$. Secondly, on the gravel terrain, the robot used 257.755 J/kg*m for gait configurations $\gamma_1 = 10^\circ$ and $\gamma_2 = 60^\circ$. Finally, $\gamma_1 = 0^\circ$ and $\gamma_2 = 75^\circ$, this gait used 245.751 J/kg*m on pebble terrain. Overall, this preliminary experiment provided the gaits that consumed the lowest cost of transport in each terrain and consequently defined them as gait configurations in Table I. These three gait configurations would be used as a baseline to perform the comparison in the experiment.

TABLE I. THE GAIT CONFIGURATIONS WHICH CONSUMED THE LOWEST COT ON EACH TERRAIN



Config	γ_1	γ_2
Flat Config	5	45
Gravel Config	10	60
Pebble Config	0	75

Experiment : AHS in dealing with the environmental changes

This experiment investigated the robot's cost of transport while traversing on mixed terrain by comparing between with and without AHS implemented on the robot. Usually, the robot which has AHS implementation would have its first gait configuration defined. Alternatively, robot gait is always the same as it is configured from the main controller when AHS is switched off. In addition, the robot is allowed to walk 25 strokes in each episode.

There were six robot locomotion behaviors for testing on both arenas, Flat-Gravel and Gravel-Pebble terrains, as follow:

- *AH-FlatConfig*: AHS implemented on the robot which starts moving with flat configuration first.
- *AH-GravelConfig*: AHS implemented on the robot which starts moving with gravel configuration first.
- *AH-PebbleConfig*: AHS implemented on the robot which starts moving with pebble configuration first.
- *No AH-FlatConfig*: the robot moves with flat configuration without the AHS.
- *No AH-GravelConfig*: the robot moves with gravel configuration without the AHS.
- *No AH-PebbleConfig*: the robot moves with pebble configuration without the AHS.

In Flat-Gravel terrain, there were four different kinds of robot gait behaviours for testing, in this case, consisting of AH-FlatConfig, AH-GravelConfig, No AH-FlatConfig, and No AH-GravelConfig as shown in Figure 8. The chart compared all of the gait behaviors in term of the cost of transport. For robot which has AHS implementation, AH-FlatConfig and AH-GravelConfig consumed average cost around 227 and 229 J/kg*m respectively. The amount of both COTs was quite close even though they started with different first gait configurations because of AHS help to adjust the robot locomotion based on the changing environments. On the other hand, No AH-FlatConfig and No AH-GravelConfig used average cost above 237 J/kg*m. The results illustrated an improvement in the cost of transport for this arena; there is a reduction of COT of about 4.2% when the AHS was implemented on the robot.

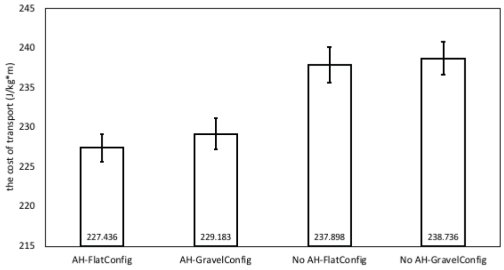
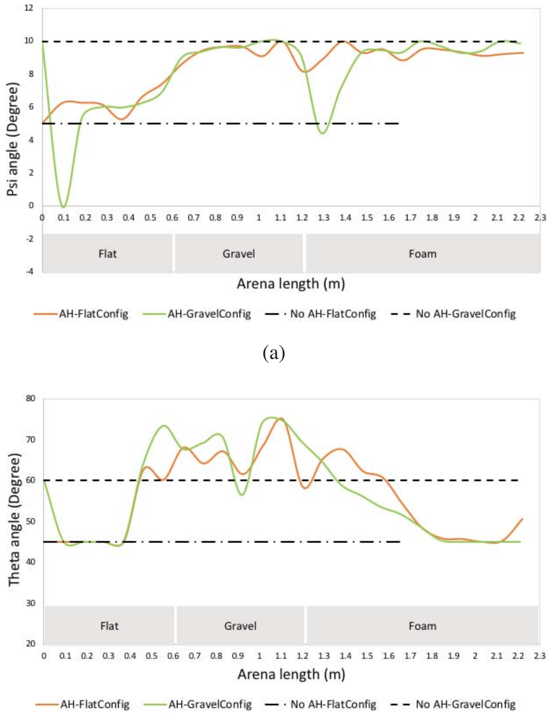


Figure 8. The COT used on Flat-Gravel terrain.

Fig. 9 illustrated the angles of Psi (ψ) and Theta (θ) with respect to changes in the hormone concentration of HG-Psi and HG-Theta respectively in accordance with environmental cues perceived by each HG. In the beginning, the robot started moving with the first gait configuration on the flat terrain. The angle of Psi and Theta was adjusted almost as same as a fixed gait in the flat terrain (No AH-FlatConfig). Even though in Fig. 9 (a), a Psi angle of AH-GravelConfig began dramatically a downward to around 0°, but it rebounded and gradually rose until it remained stable at 6°. As soon as the robot started to climb on gravel terrain, the Psi angle increased to around 9.5°, and the Theta angle also built up to about 67° by average. It had to be noted that hormone system should adjust Psi and Theta angle to converge nearly to the fixed gravel gait (No AH-GravelConfig). However, in Fig. 9 (b), the Theta angle was quite high and fluctuated because there was an effect of ground disturbance in gravel terrain by previous steps which consequently caused the amount of concentration of HG-Theta to be high and varied. Until around 1.2m, the robot was traversing on the foam ground which was an unknown terrain. The Psi angle changed slightly and stayed around the same level at 9°. It should be noted that it is possible to exponentially change the angle in the transition area of an arena. However, the Theta angle slowly declined to around 45° at 1.9m. To sum up, these dynamics adjusted the robot locomotion based on the changes of terrains and helped to reduce its cost of transport.



(a)

(b)

Figure 9. Example of the variation of both angles Psi and Theta based on the changes of Flat-Gravel terrain shown as (a) and (b) respectively.

In Gravel-Pebble terrain, Figure 10 also compared the gait behaviour in term of the cost of transport between with and without AHS implemented on the robot. It is clear that the robot performance when the AHS was implemented remained around 16% better than when compared to having no AHS on the robot. The COTs used between 254 and 257 J/kg*m in cases when the AHS was switched on. In contrast, No AH-PebbleConfig consumed considerably around 333 J/kg*m, and 273 J/kg*m for No AH-GravelConfig.

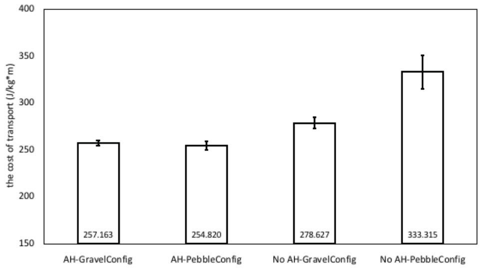


Figure 10. The COT used on Gravel-Pebble terrain.

VI. CONCLUSION AND FURTHER WORK

This paper proposed the implementation of an artificial hormone system on a sea turtle-inspired robot to improve its locomotion behaviours when traversing on uneven complex terrain or especially on unknown terrain, and hormone dynamics have brought about the concern for reducing the cost of transport. The results have shown that the robot could adapt its gait to reduce its cost of transport when facing external environmental changes by allowing the artificial hormone system to modify the flipper thrust and lift by following environmental cues perceived by the hormone system.

Further work will focus on making the use of the artificial hormone system more generic. That is to be able to assist other types of robots to improve moving efficiency and reduce the cost of transport. Moreover, the work will focus on using machine learning approaches to alter the hormone system parameters so that the robot can adapt itself online.

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