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CENTER OF MASS-BASED ADMITTANCE CONTROL FOR MULTI-LEGGED ROBOT WALKING ON THE BOTTOM OF OCEAN

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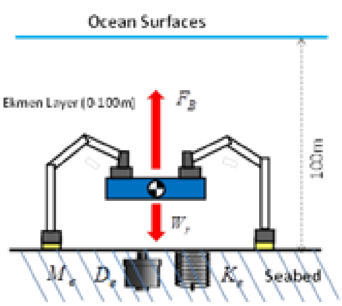
Graphical abstract



Abstract

This paper presents a proposed adaptive admittance control that is derived based on Center of Mass (CoM) of the hexapod robot designed for walking on the bottom of water or seabed. The study has been carried out by modeling the buoyancy force following the restoration force to achieve the drowning level according to the Archimedes' principle. The restoration force needs to be positive in order to ensure robot locomotion is not affected by buoyancy factor. As a solution to regulate this force, admittance control has been derived based on the total force of foot placement to determine CoM of the robot while walking. This admittance control is designed according to a model of a real-time based 4-degree of freedom (DoF) leg configuration of a hexapod robot that able to perform hexapod-to-quadruped transformation. The analysis focuses on the robot walking in both configuration modes; hexapod and quadruped; with both tripod and traverse-trot walking pattern respectively. The verification is done on the vertical foot motion of the leg and the body mass coordination movement for each walking simulation. The results show that the proposed admittance control is able to regulate the force restoration factor by making vertical force on each foot sufficiently large (sufficient foot placement) compared to the buoyancy force of the ocean, thus performing stable locomotion for both hexapod and quadruped mode.

Keywords: Buoyance factor, force restoration, center of mass, admittance control; seabed locomotion

Abstract

Kertas kerja ini membentangkan cadangan kawalan penyesuaian lepasan yang dibuat berdasarkan pusat jisim robot enam kaki yang direka untuk berjalan dibawah air atau dasar laut. Kajian ini telah dijalankan dengan memodelkan daya keapungan mengikut daya pemulihan untuk mencapai tahap lemas berdasarkan kepada prinsip Archimedes. Daya pemulihan perlu positif untuk memastikan perjalanan robot tidak terjejas dengan faktor apungan. Sebagai penyelesaian untuk mengatur daya ini, kawalan lepasan telah dibuat berdasarkan jumlah daya perletakan tapak kaki untuk menentukan pusat jisim robot semasa bergerak. Kawalan ini direka berdasarkan model masa nyata 4 darjah kebebasan (DoF) konfigurasi kaki robot enam kaki yang boleh menjalankan transformasi 6 kaki ke 4 kaki. Analisis ini berfokus kepada perjalanan robot dalam kedua-dua konfigurasi 6 kaki dan 4 kaki, dengan cara berjalan tripod dan traverse-trot. Pengesahan ini dilakukan berdasarkan perjalanan vertikal tapak kaki dan koordinasi pergeakan jisim badan untuk setiap simulasi perjalanan. Hasil menunjukkan bahawa kawalan lepasan boleh mengatur faktor daya pemulihan dengan membuat daya vertikal pada kaki cukup besar (perletakan kaki yang cukup) berbanding dengan daya apungan laut, menyebabkan perjalanan stabil kedua-dua mod 6 kaki dan 4 kaki.

Kata kunci: Faktor apungan, daya pemulihan, pusat jisim, kawalan lepasan, perjalanan dasar laut

1.0 INTRODUCTION

Underwater legged robot system has become one of the interest areas in the field of underwater vehicle technology. This biological inspired robot technology has been implemented for underwater applications for bottom or seabed operation such as conducted by Korea Research Institute of Ship and Ocean Engineering (KRISO) as reported in [1]. Commonly, bottom operation vehicles are designed with wheel-type such as reported in [2]. After the introduction of legged robot technology for land operation in 1970s, some researchers have attempted to design and develop underwater vehicles for bottom operation with multi-legged configuration, inspired by the arthropods creatures such as amphibian configuration [3, 4] and insect configuration [5-7]. Robust with high degree of inclination terrains and strong on horizontally stable control are becoming the main key points that the multi-legged robot or adaptive suspension vehicle (ASV) is better than the wheel-type robot for seabed operation. The difference between underwater and land robots is on the stability control. An underwater robot needs to overcome the unexpected peripheral disturbances, hydrodynamic and hydrostatic forces acting on the body and legs of the system, as well as the four daily changes in the route of tidal current that causes the system to be more vulnerable to the forces [1]. The majority of existing studies on multi-legged underwater robot are focused on locomotion issues, such as Whegs™ II [3] and C200 [8, 9], but little consideration is given on how to control the hydrodynamic and hydrostatic forces present in the water or ocean.

In the ocean environments, ocean waves have varying wave periods and height determined by winds and the distance traversed. According to D'Allemberts paradox, in a steady flow there is no force on a body under non-viscous fluid. For tidal current in an unsteady situation with added mass, drag forces, buoyancy and currents, especially in the existence of free surface waves, it is required to consider time-dependent motions of the water, robot's body and the system internal as well as external forces adding to the total force acting on the system [10]. Therefore, force control has become a crucial part of the multi-legged robot that crawls on the seabed soil. Common robotics force control for articulated configuration arm and legged system has been practiced in two strategies: force-based and position-based force control. On the other hand, impedance control is part of the force control methodology that is able to modulate mechanical impedance of the multi-link joint is divided into three strategies and sometime integrated as a hybrid control: force-based impedance control, position-based impedance control or admittance control [11].

In perspective of legged system, impedance control is developed in diverse forms and methods to comply with the leg pattern, walking model trajectory and body attitude of the robot. It is not possible for position-based control to get lower impedance (low stiffness and low damping, even with ideal zero delay) than force-based control. Thus, position-based impedance control is suitable for lower robot mass as its stable state widens as its mass decreases. On the other hand force-based impedance control can provide the full range of impedances with zero delay and this type of control strategy is suitable for medium to large sized legged robots as its stable region increases with increasing mass [12]. However, this perception has been broken by several approaches of adaptive technique, in which any impedance/admittance control can comply with legged robot of any size with adaptive elements, as reported in [13, 14].

For the case of the seabed, one of the elements that need to be considered in designing an underwater robot is buoyancy factor. This paper presents a proposed adaptive admittance control that considers the center of mass (CoM) of the robot via total force on foot. The force input of the controller will be the restoration forces that take into account the force that the foot placed on the soil during locomotion. This adaptive admittance control is verified using a hexapod robot having 4-degree of freedom (DoF) with tripod walking pattern and traverse-trot walking pattern after hexa-quad transformation [15]. The analysis of the results will be focused on the robot's foot motion, including the total force on foot compared to the buoyance force of ocean, and body mass coordination (BMC) for omnidirectional path flows.

2.0 ENVIRONMENT MODEL CONSIDERING THE BUOYANT FORCES

As mentioned in Section I, other than seabed gravity, buoyancy factor via buoyance forces will affect multi-legged robot's locomotion. The difference between gravitational and buoyancy forces is called restoring force, and this force is comparable to the spring forces in a mass-spring damper system [16]. With reference to Archimedes' principle, the buoyant force on a submerged rigid body will be an upward force equal to the weight of the fluid displaced by the body that resists the weight of an immersed object. The buoyant force is activated through the center of gravity of the objects that tend to pull up the object out of the surface of the water. Figure 1 shows the definition of buoyant force principle for a multi-legged robot system. In this study, Ekmen layer of the seabed is considered, in which the layer consists of a force balance between pressure gradient force, Coriolis force and turbulent drag; the temperature of the ocean is 20^0 C.

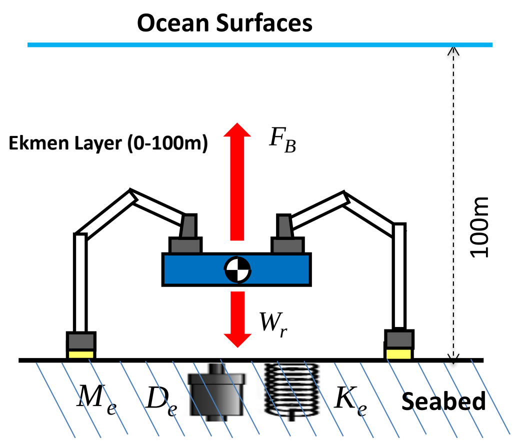


Figure 1 Buoyant force acting on multi-legged robot in underwater

The buoyant force (F_B) is equal to the mass of water displaced by the submerged robot (W_s), where W_s can be calculated as in Equation 1. Assume the ratio of the whole robot's body to water density as follows;

$$\frac{d_r}{d_w} = \frac{W_r}{W_s} \quad (1)$$

Thus,

$$W_s = F_B = \frac{W_r}{d_r} d_w \quad (2)$$

where $d_r = M_r V_r$ is the density of the robot, M_r and V_r are weight and volume of the robot, respectively. $W_r = M_r g$ is the robot's mass. Thus

$$W_s = F_B = \frac{1024.8103}{V_r} \quad (3)$$

Where d_w = 1024.8103 kgm^{-3} for ocean's *Ekmen layer* at 20°C with reference to the International Association for the Properties of Water and Steam (IAPWS). In order to indicate whether or not the robot is floating or drowning on the bottom of water or seabed, restoring force (F_R) is calculated by the difference of robot's mass and buoyant force as follows:

$$F_R = W_r - F_B \quad (4)$$

where F_R must be sufficiently positive to ensure the robot stand on the bottom of water or seabed. In the case of multi-legged robot, the above calculation is only for the static or standing position. For locomotion cases, total force on each stepped foot needs to be considered, where the force on each foot can be calculated with reference to Figure1 as follows;

$$F_{f_n} = -F_{e_n} = M_{e_n}\ddot{z(t)} + D_{e_n}\dot{z(t)} + K_{e_n}z(t) \quad (5)$$

where n is the number of legs on a robot, D_{en} and K_{en} is respectively the damper and stiffness of the soil/ground encountered by the leg. D_{en} is determined, based on the vibration theory for spring-mass dampers, by rearranging Equation (6) using Newton's law:

$$\ddot{z} = \left(\frac{D_{e_n}}{M_{e_n}}\right)\dot{z} + \left(\frac{K_{e_n}}{M_{e_n}}\right)z = 0 \quad (6)$$

Thus, the natural frequency and damping ratio for the impedance model can be written as follows:

$$\omega_0 = \sqrt{\frac{K_{e_n}}{M_{e_n}}}, \qquad \zeta = \frac{D_{e_n}}{2\sqrt{M_{e_n}K_{e_n}}} \quad (7)$$

In order to control the oscillation in the input, critical damping (free vibration with damping) is chosen, where $\zeta = 1$. Thus, D_{en} can be expressed as follows:

$$D_{e_n} \cong 2\sqrt{K_{e_n}} \quad (8)$$

where the weight of the soil (M_e) is assumed to be unknown and $z(t)$ is the changes of vertical axis motion of the leg in real-time t. Thus, the restoration force during locomotion can be calculated as in Equation (9) with different phases: walking phase with l number of legs on the ground/soil and transient phase with n number of legs.

$$F_R = \begin{cases} -\sum_{k=1}^{l} F_{e_k} - F_B \;\; walking\ phase \\ -\sum_{k=1}^{l} F_{e_n} - F_B \;\; transient\ phase \end{cases} \quad (9)$$

3.0 CoM-BASED ADMITTANCE CONTROL FOR TRANSFORMED HEXA-QUAD ROBOT

According to the buoyance factor as discussed in Section II, the total F_f need to be sufficiently positive to ensure $F_R>0$. Most of the terrain at the bottom of an ocean consisted of soft soil; hence the need for the robot's legs to have adaptable stiffness. In order to achieve this purpose and to ensure that robot locomotion is on the bottom surface of the sea, impedance equilibrium is derived by considering the F_R as expressed in Equation (10):

$$-F_R(t) = M_r \ddot{h(t)} + D_r \dot{h(t)} + K_r h(t) \tag{10}$$

where D_b is the total damping coefficient, similarly determined as D_{en}, discussed in Section 2, with weight of the robot assumed as follows:

$$D_b = 2\sqrt{K_b M_b} \tag{11}$$

K_b is the total stiffness of the body from the shoulder to the ground (total stiffness of supported legs) as shown in Figure 2; this is a positive tuning parameter. F_R is the total vertical force acting on the legs touching the ground by considering the F_B as buoyancy factor. Hence, the total force now includes the center of mass (CoM) of the robot during transient and walking phases. As mentioned earlier, 4-DoF leg configuration of hexapod robot model with tripod walking pattern, as shown in Figure 4, is used in this study. The stabled CoM for staffic stability configuration robot [17] such as hexapod robot need to have at least near to the actual total weight of the robot itself.

In this study, the hexapod model is used and the proposed admittance control is implemented with the proposed hexa-quad transformation [15] in order to verify hexapod and quadruped configuration. Two types of gait patterns has been configured for the proposed admittance controller: tripod and traverse-trot gait [18]. Thus, the calculation of F_e based on tripod and traverse-trot gait patterns are shown in Table 1, with reference to the notification in Figure 3. The scope of this study proposed the center-leg-disable (CLD) [15] situation is used, where Leg 2 and Leg 5 are disabled to transform hexapod robot into quadruped mode as shown in Figure 4.

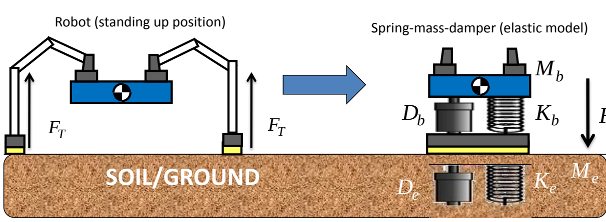


Figure 2 Equivalent elastic model of the robot's body

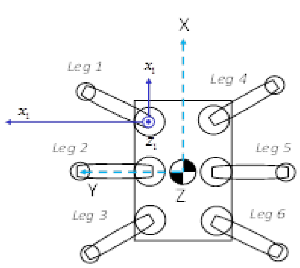
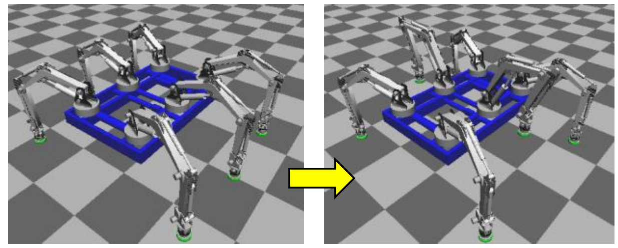


Figure 3 Coordinate system and leg's notification for hexapod robot model



(a) (b)

Figure 4 CLD transformation in proposed hexa-quad transformation: (a) hexapod mode, and (b) quadruped mode

Furthermore, the virtual vertical position of the height of the robot's body (h) from Equation (12) is divided equally (based on robot shape and coordination as in Figure 3 to each one of the robot's legs at support phase period (t_q) as follows:

$$h_n(t_q) = \begin{cases} \dfrac{h(t)}{3}; n = 1,3,4,6 \\ \dfrac{2h(t)}{3}; n = 2,5 \end{cases} \tag{12}$$

The new z-axis position reference for each leg at t_q can be written as follows:

$$Z_{I_n}(t_q) = Z_{r_n}(t_q) + h_n(t_q) \tag{13}$$

The proposed CoM-based impedance control, with consideration of buoyancy factor and environment, trailed trajectory (ETT) [19] is described by the diagram shown in Figure 4.

Table 1 Calculation of the total vertical force based on the tripod walking pattern

Status		Supported Leg	F_T
Tripod gait	Walk	1,3,5	$F_{e_1} + F_{e_3} + F_{e_5}$
	Walk	2,4,6	$F_{e_2} + F_{e_4} + F_{e_6}$
Traverse-trot	Walk	3,4,6	$F_{e_3} + F_{e_4} + F_{e_6}$
	Walk	1,3,4	$F_{e_1} + F_{e_3} + F_{e_4}$
	Walk	3,4	$F_{e_3} + F_{e_4}$
Transient	Stop	All	$\sum_{n=1}^{6} F_{e_n}$

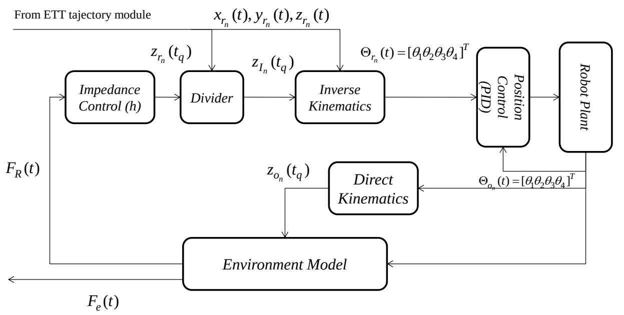


Figure 5 Implementation of the proposed CoM–based admittance control on the 4-DoF leg configuration hexapod robot model

4.0 SIMULATION AND RESULTS

Several simulations were conducted using the 4-DoF leg configuration of hexapod robot based on the identification model of COMET-IV [20]; the simulations can be classified as follows;

- Sim 1 – Tripod walking with CoM-based but without CoM-based admittance control.
- Sim 2 – Traverse-trot walking with CoM-based but without CoM-based admittance control.
- Sim 3 – Omnidirectional walking with transformation for both tripod and traverse-trot walking with CoM-based admittance control.

In this simulation, M_r is tuned to achieve hexapod robot statically drowning into the sea and stand on the bottom of the sea to ensure $F_R>0$. For simulation as a whole, several tuning have been done to the controller parameters and to the model to ensure the time response of walking cycle is stabled as tabulated in Table 2.

Table 2 Model and controller parameters set based on the drowning on seabed condition, leg motion time response and cycle time

Parameter	Value
K_r	80 knm^{-1}
K_e	22 knm$_{-1}$
M_r	300 kg
V_r	0.03255 m^3

The simulations were done with robot side-walking from left to right mode for Sim 1 and 2. With reference to Sim 1 and Sim 2 as shown in Figure 6, on stand-up position both robots with CoM-based admittance control (With Admt) and without admittance control (No Admt) perform the same vertical foot motion until the first step of walking phase is taken at about 34 seconds. After the first Swing-phase robot locomotion with CoM-based admittance control, both Hexa-CA and Quad-CA show an extra push down to the soil compared to the locomotion of the robot without the proposed CoM-based with admittance control. This means that extra forces are applied to each robot leg and, as noted in Figure 7, $F_e>F_B$ for Hexa-CA and Quad-CA. Thus, the situation is in compliance with the condition for hexapod robot to walk on the bottom of the sea with minimal buoyancy.

As shown in Figure 6 and Figure 7, Quad-CA locomotion performs 'extra push' compared to the Hexa-CA locomotion since the number of foot placement for the quadruped locomotion is less than that of the hexapod. In this situation the proposed CoM-based admittance control and ETT systems have compensated with the foot motion circle time and force threshold. The simulation is extended with Hexa-CA and Quad-CA walking in omnidirectional mode [20], while applying Hexa-Quad transformation, in order to analyze the performance of body mass coordination (BMC) [21]. Figure 8 and 9 show Sim 3 results which is omnidirectional walking. As shown in Figure 10, with reference to the center of mass, the robot body bounced for Hexa-CA and Quad-CA locomotion compared to the robot walking without CA. However, as shown in Figure 11, the moving curve of omnidirectional mode is not disturbed and the bouncing can be considered as a minor disturbance in robot vertical stability.

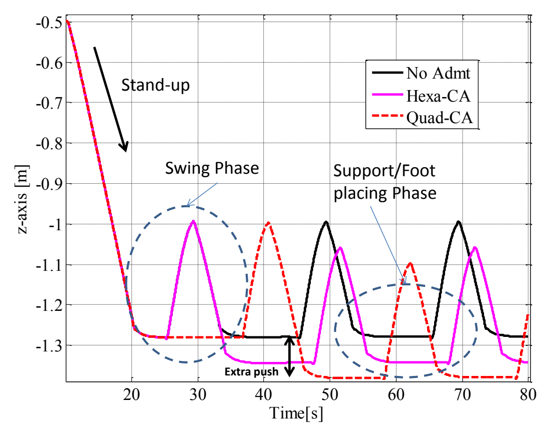


Figure 6 Sample of foot point motion on the z-axis output for both Sim 1 and 2 (sample: Leg 3)

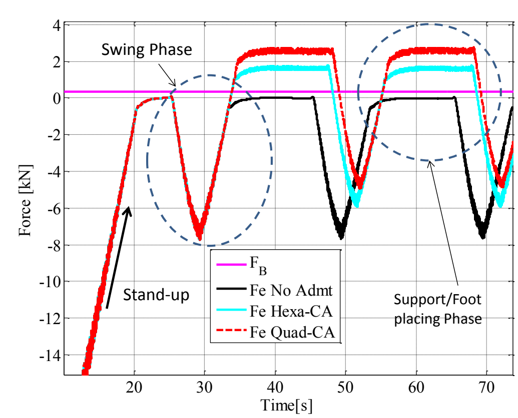


Figure 7 Sample of vertical force on foot for both Sim 1 and 2 (sample: Leg 3)

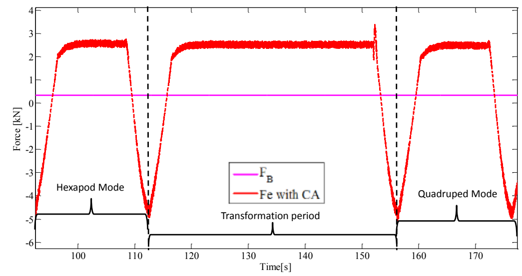


Figure 8 Sample of vertical force on foot in Sim 3 (sample: Leg 1)

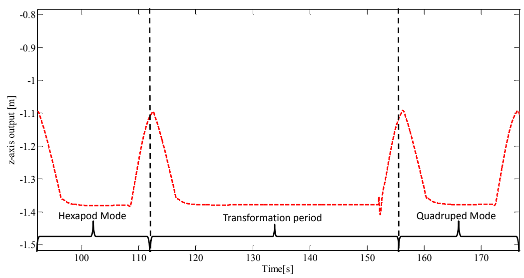


Figure 9 Sample of foot point motion on the z-axis output for Sim 3 (sample: Leg 1)

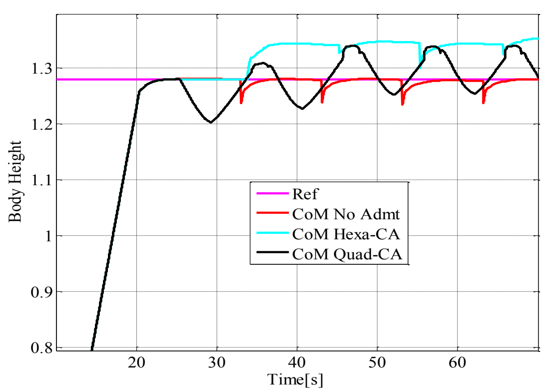


Figure 10 Sample of CoM signal representing robot height performance

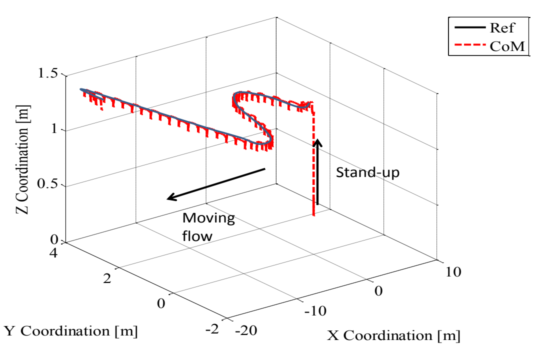


Figure 11 Sample of BMC for omnidirectional walking mode

5.0 CONCLUSIONS

The simulation results show that the proposed adaptive admittance based on CoM, or CoM-based admittance control, has successfully compensated with the resultant force restoration that acts vertically on hexapod robot during walking on the bottom of the sea. The admittance for each leg is able to tune-up using one admittance model that is derived based on the CoM with force restoration as the controller input. The sufficient drowning condition into the bottom of the sea can be achieved during walking session with tuned CoM-based admittance control on each foot placement. This proposed position-based admittance control is also verified in omnidirectional mode walking, and the result shows stable omnidirectional movement although having a small vertical bounce. In the real situation of undersea environment, horizontal tidal current acting on the robot is very crucial than the buoyance factor itself. Therefore, to further improve the control of underwater multi-legged robot, this issue should be taken into account in future study.

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