Adaptive impedance control based on CoM for hexapod robot walking on the bottom of ocean

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Abstract

This paper presents a proposed adaptive impedance control that derived based on Center of Mass (CoM) of the hexapod robot 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 need to be positive in order to ensure robot locomotion is not affected by buoyancy factor. As for this force control solution, impedance control has been derived based on the total of force of foot placement to consider CoM of the robot during walking period. This derived impedance control is design for the real-time based 4 degree of freedom (DoF) leg configuration of hexapod robot model. The scope of analysis is focus on walking on the varied stiffness of undersea bottom soil with tripod walking pattern. The verification is done on the vertical foot motion of the leg and the body mass coordination movement during walking period. The results shows that proposed impedance control able to control the force restoration factor by making vertical force on each foot bigger enough (sufficient foot placement) if compare to the buoyancy force of the ocean, thus performing stable tripod walking on the seabed with uncertain stiffness.

Keywords: Restoration force; CoM-based impedance control; Underwater seabed locomotion

1. Introduction

Underwater legged robot system became one of the interest area in underwater vehicle technology field. This biological inspired mobile robot technology has been implemented for underwater applications majorly for bottom or seabed operation. Previously most of the underwater vehicle for bottom operation are designed with wheel type such as reported in [1, 2]. After the legged robot technology has been introduced for land operation since 1970s, some of the researchers are attempted to design and developed an underwater vehicle for bottom operation with multi-legged configuration 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 main key points that multi-legged robot or adaptive suspension vehicle (ASV) is better than wheel type for underwater bottom operation same as land operation. The different between underwater and land is on the stability control whereby underwater consists of the unexpected peripheral disturbances, hydrodynamic and hydrostatic forces on the body and legs of the system, as well as the route of tidal current changes four time a day; which causes the system more vulnerable[8]. Several studies on existed multi-legged underwater robot, majority are emphasized on locomotion issues such as Whegs™ II [3] and C200 [9, 10] but less considering on the force control on facing hydrodynamic and hydrostatic factor that consist 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 both the water, robot's body and the system internal as well as external forces adding to the total forces on the system[11]. Therefore force control becoming crucial part for the multi-legged robot to crawl 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 able to modulate mechanical impedance of the multi-link joint. This force control approach also divided into two strategies and sometime integrated as a hybrid control; force-based impedance control and position-based impedance control or admittance control[12].

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 i.e. low stiffness and low damping even with ideal zero delay. These position based impedance control is suitable for lower robot mass as its stable state widens since the mass decreases. 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 the mass increases as its stable region increases[13]. However this perception has been break by several approach of adaptive technique whereby any impedance control can be comply for any size of the legged robot with adaptive elements as reported in [14, 15].

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For the seabed cases one of the elements that need to be considered for the underwater robot is buoyancy factor. Therefore in this paper will present the proposed adaptive impedance control that considered the center of mass (CoM) of the robot via total force on foot. The force input of the impedance of the controller will be the restoration force that considering force on foot placed on soil during walking period. This adaptive impedance control is verified in 4 degree of freedom (DoF) of hexapod robot with tripod walking pattern. The analysis of the results will be focused on foot motion and body mass coordination (BMC) including the total force on foot compares to the buoyance force of ocean.

2. Environment model considering the tidal hydrodynamics

As mentioned in section I, buoyancy factor via buoyance forces will affected multi-legged robot locomotion other than seabed gravity. The difference between gravitational and buoyancy forces are called restoring forces and this force is comparable to the spring forces in a mass-spring damper system [16]. With reference to the Archimedes' principle the buoyant force on the submerged rigid body will be an upward force equal to the weight of the fluid displaced by the object that resists the weight of an immersed object. The buoyant force is activated through the center of gravity of the objects which try to pull the object out of the surface. Fig. 1. shows the definition of buoyant force principle for a multi-legged robot system.

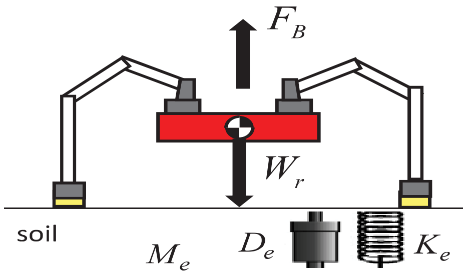

Fig. 1. Buoyant force acting on multi-legged robot in underwater

The buoyant force (F_B) is equal to the mass of water displaced by the submerged robot (W_s) whereby W_s can be calculated as Eq.1. Let's considered the ratio of the whole robot's body to water density as follows;

$$\frac{d_r}{d_w} = \frac{W_r}{W_s} \tag{1}$$

Thus,

$$W_s = F_B = \frac{W_r}{d_r} d_w \tag{2}$$

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 makes

$$F_B = W_s = \frac{1027}{V_r} \tag{3}$$

whereby $d_w \cong 1027 kgm^{-3}$ for ocean. In order to indicate whether the robot floating or drowning on the bottom of water or seabed, restoring force (F_R) is calculated by difference of robot's mass and buoyant force as follows;

$$F_R = W_r - F_B \tag{4}$$

whereby F_R must be positive enough to ensure the stand on the bottom of water or seabed. In the case of multi-legged the previous calculation is only for the static or standing position. For locomotion cases, total force on each stepped foot need to be considered whereby the force on each foot can be calculated with reference to Fig.1 as follows;

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

whereby n is the number of leg for a robot, D_{e_n} and K_{e_n} is damper and stiffness of the soil/ground respectively that feet by the leg where D_{e_n} is determined based on the vibration theory for spring-mass dampers by rearranging Eq. 5 using Newton's law, as follows:

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

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

$$\omega_0 = \sqrt{\frac{K_{e_n}}{M_{e_n}}}, \zeta = \frac{D_{e_n}}{2\sqrt{M_{e_n} K_{e_n}}} \tag{7}$$

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

$$D_{e_n} \cong 2\sqrt{K_{e_n}} \tag{8}$$

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

$$F_R = \begin{cases} -\sum_{k=1}^{l} F_{e_k} - F_B & walking\_phase \\ -\sum_{k=1}^{n} F_{e_n} - F_B & transient\_phase \end{cases} \tag{9}$$

3. Admittance control for horizontal leg positioning in seabed environment

According to the buoyance factor as discussed in Section II, the total of F_f need to be positive enough to ensure $F_R > 0$. In the bottom of ocean environment the terrain majority is contained with soft soil and leg with the adapted stiffness is needed. Therefore to achieve this purpose and to ensure robot locomotion is on the bottom surface of the sea, impedance equilibrium is derived by considering the F_R as expressed in Eq.10 as follows:

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

where D_b is the total damping coefficient that determined same as D_{en} discussed in Section 2 with weight of the robot is considered 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 Fig. 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. This total of forces brings the center of mass (CoM) information for the robot during transient and walking phases. As mentioned earlier, 4-DoF leg configuration of hexapod robot model with tripod walking pattern is used in this study as shown in Fig.4. The stabled CoM for static stability configuration robot[17] such as hexapod robot need have at least near to the actual total weight of the robot itself.

Thus the calculation of F_e based on tripod walking pattern is shown in Table 1 with reference to the notification in Fig. 3. Furthermore, the virtual vertical position of the robot body height (h) from Eq. 12 is divided equally (based on the hexapod robot configurations and force delivery on the foot for each leg[2]) to each one of the robot's legs at support phase period (t_q)[15], as follows:

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

Thus, 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 buoyancies factor and environment trailed trajectory (ETT)[18] is described by the diagram of Fig.4.

[2] *The force delivery on the foot of Leg 2 and 5 (center legs) is two times higher than that on the other legs during walking via heuristic analysis of the robot.*

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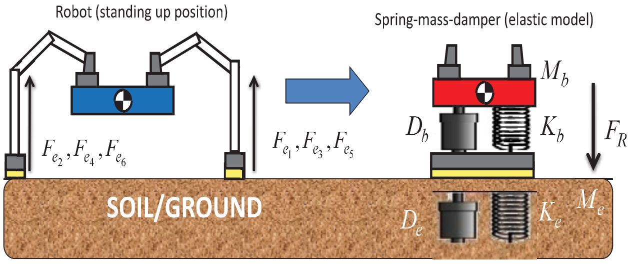

Fig. 2. Equivalent elastic model of the robot's body

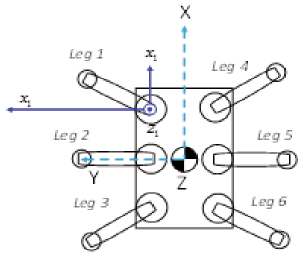

Fig: 3. Coordinate system and leg's notification for hexapod robot model

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

Status	Supported Leg	FT
Walk	1,3,5	$F_{e_1}+F_{e_3}+F_{e_5}$
Walk	2,4,6	$F_{e_2}+F_{e_4}+F_{e_6}$
Transient	All (For hexapod robot)	$\sum_{n=1}^{6} F_{e_n}$

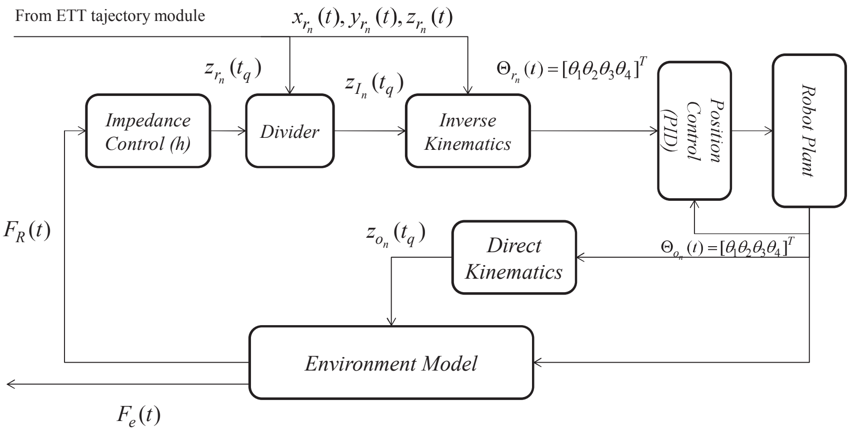

Fig. 4. Implementation of the proposed CoM–based impedance control on the 4-DoF leg configuration hexapod robot model

4. Simulation and results

Several simulations are done for both tripod walking with CoM-based impedance and without CoM-based impedance for 4-DoF leg configuration of hexapod robot. 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 has been done not only for controller parameters but also model itself to ensure the time response of walking cycle is stabled as tabulate 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

Moreover simulation has been done by running the tripod side walking from left to right. The analysis is done on the foot point motion on vertical position since the vertical force is a main issue. With reference to the Fig. 5 on stand-up position both robot's with CoM-based impedance control (With Imp) and without impedance control (No Imp) performing same vertical foot motion until the first step of walking at about 34 seconds. After the first Swing-phase robot with CoM-based impedance control shows extra push down to the soil if compare CoM-based with impedance control. It is mean extra force is applied on each leg for robot with CoM-based impedance control. It can be seen in Fig. 6 whereby $F_e > F_B$ for robot with CoM-based impedance control makes

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this condition complied for hexapod robot to walk on the bottom of the sea if compare to robot without CoM-based impedance control. The simulation in extended for walking in omnidirectional mode[19] in order to analyze the performance of body mass coordination (BMC)[20]. As shown in Fig. 7, the moving line for hexapod robot walking with CoM-based Impedance control is nearly smooth. The fluctuated foot placement does not disturbing the omnidirectional path unless small on vertical bouncing.

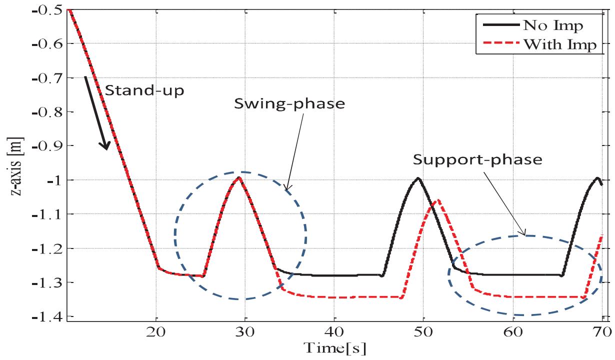

Fig.5. Sample of foot point motion on the z-axis view (Leg 3 sample)

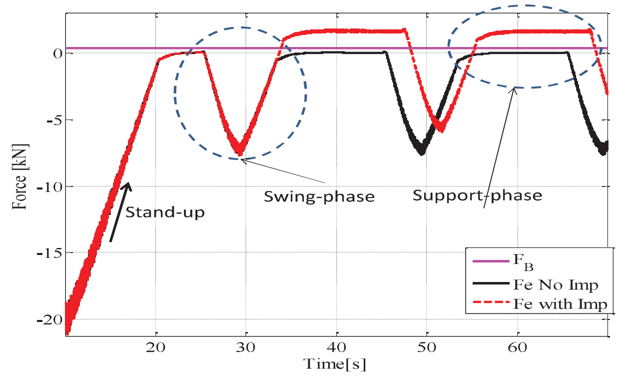

Fig.6. Sample of vertical force on foot (Leg 3 sample)

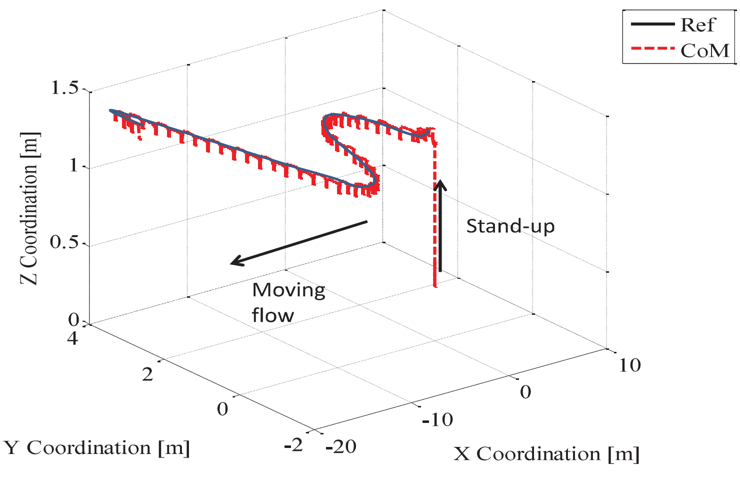

Fig. 7. Sample of BMC for omnidirectional walking mode

5. Conclusion

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

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