Kinematic Walking and Posture Control of CR200 for Subsea Exploration in High Tidal Current

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***Abstract*—This paper presents kinematic walking and posture control of Crabster (CR200), 200 meter-class six-legged ROV, for seabed survey and underwater precision work in high tidal current. CR200 can overcome the high tidal current by controlling its body posture and walk without overturn. In order to control the body posture and walking, kinematic gait algorithm has been developed. It creates the joint paths of each leg for the desired body posture and position. In order to implement the gait algorithm, two types of graphic user interfaces (GUI) are developed: test program and pilot program. Test program is used for ground test of CR200. It performs basic function for controlling the posture and walking of CR200. Pilot program is developed based on the test program. It has many functions for sea trials of CR200 such as status monitoring of the robot, checking body posture through virtual 3D viewer, sensor power control and so on. In this paper, we will show the simulation and experimental result of the posture and walking control of CR200 based on the gait algorithm using the pilot program. From the results, we verified the effectiveness of the computation frame of the kinematics.**

Keywords—crabster, cr200, posture control, walking control, pilot program

I. Introduction

Recently, demands for the marine resource development is increased, so that there are lots of researches about remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) has been performed [1].

But in a coastal area with strong tidal current, most ROVs and AUVs with propeller-type thrusters have some difficulties to perform the precise underwater works such as inspection of shipwrecks, scour and survey of seafloor geography [2]-[6]. Especially in the West Sea of Korea, the current velocity goes up to 5~6knots and more than 7knots in specific area. The Korea Institute of Ocean Science and Technology (KIOST) has been developed the 200 meter-class six-legged ROV named CRABSTER200 (CR200) to overcome the weakness of ROVs and AUVs [7]. Its main missions are seabed survey and underwater precision work in high tidal current. The external appearance of CR200 is shown in Fig. 1.

CR200 can overcome the high tidal current by controlling the body posture against the current (Fig. 2). To make the desired posture and position, a kinematic gait algorithm has been developed. It creates the joint paths of six legs for the desired body posture based on kinematic parameters of CR200.

In this paper, we will show the kinematic gait algorithm for the posture and walking control. The posture of CR200 are controlled in six degrees of freedom; surge, sway, heave, roll, pitch, yaw and combination of the motions. And CR200 can walk eight directions and rotate two directions which are forward, backward, left, right, forward-left/right, backward-left/right, and turn left/right.

We also mention the GUI program for operating CR200 which is based on the kinematic gait algorithm. Finally, simulation and experimental results of the kinematic gait algorithm will be presented.

Fig. 1. Appearance of CR200

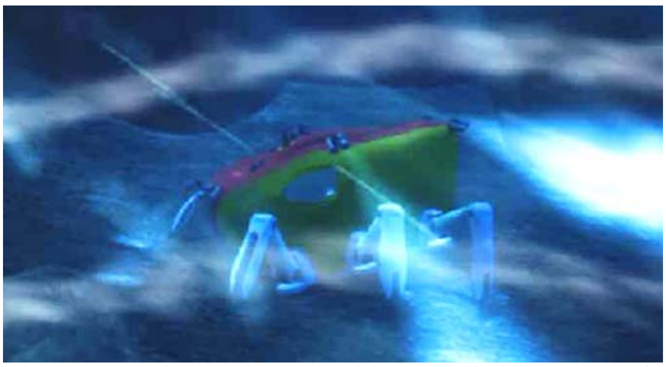

Fig. 2. Concept of overcoming strong tidal current by body posture control

II. System Configuration

CR200 is designed to survey the ocean floor precisely and perform various underwater works with manipulators.

The body of CR200 is 2.42m long, 2.45m wide and 1.3m height (Fig. 3). And a maximum height of CR200 is 1.8m when it stands up with straighten the legs. The weight of CR200 is about 650kg in the air and 200kg in the water. Body frame of CR200 is made of carbon fiber reinforced plastic (CFRP) which is lighter and stronger than conventional materials such as aluminum and stainless steel. The frame is designed as a shape of rib cage, so that the frame can protect inner devices from external load as well as distribute applied external load through the rib cage structure.

CR200 is operated by external power of 190 VDC through a tether cable. The tether cable consists of three conductors and four fiber optic cables. Its outer diameter is 26mm and total length is 500m. It can endure ten tons of maximum static loads.

Fig. 4 is represents equipment of CR200. Acoustic doppler current profiler (ADCP), Auto Heading Reference System (AHRS), ultra-short baseline (USBL) responder are for navigation. Acoustic camera, high resolution scanning sonar, cameras, LED lights are to obtain information of submarine topography. Tool sled is storing tools for underwater works such as welding, hoisting and etc., so that CR200 can work using those tools on seabed without supplying tools from a mother ship. Two junction boxes and two canisters are setup at the frame.

CR200 has six electric-driven legs and 30 joint totally, so that it can crawl as a crab or a lobster on seabed. The joint mechanism is described in Fig. 5. Every joint consists of electric motor, harmonic drive, incremental encoder and absolute encoder which is enable to guarantee the high angle resolution as well as to measure the reference joint angle. The front two of legs are arm-combined legs which have 7 functions with 6 degrees of freedom. And the other four legs are dedicated legs which have 4 degree of freedom. Every leg consists of 'Hip Yaw' joint (#1), 'Hip Roll' joint (#2), 'Shoulder Pitch' joint (#3) and 'Knee Roll' joint (#4), basically. The arm-combined legs have three more joints, especially: 'Wrist Roll' joint (#5), 'Wrist Yaw' joint (#6) and 'Gripper' (#7).

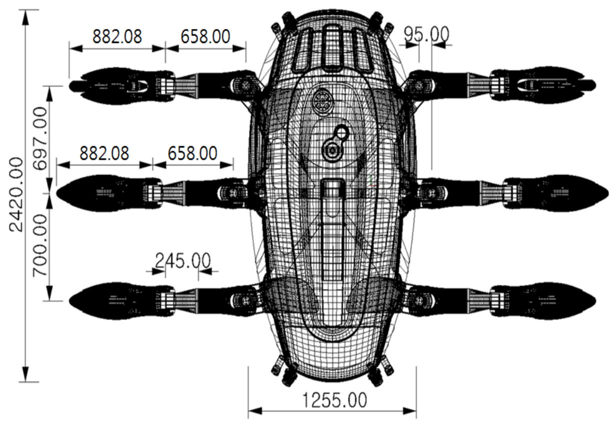

Fig. 3. Kinematic parameters of CR200

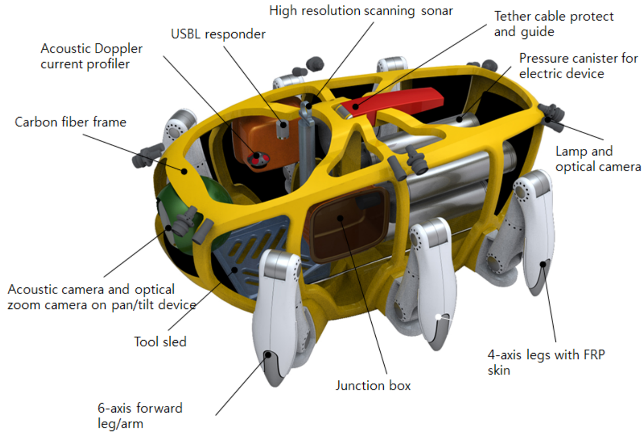

Fig. 4. Equipment of CR200

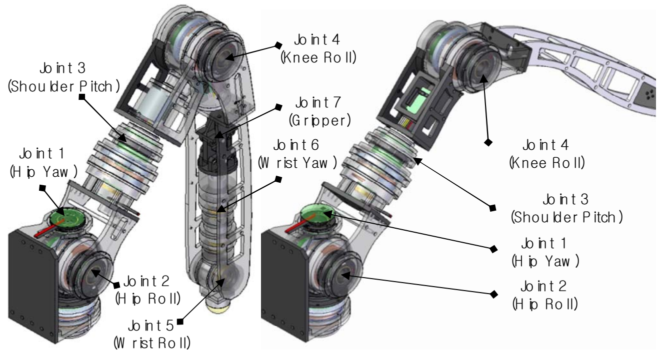

Fig. 5. Joint configuration of arm and leg of CR200 [8].

III. Posture and Walking Control

A. *Kinematics*

When CR200 encounters strong tidal current during operation, it can change the body posture using legs to overcome the current. Desired body posture is obtained by distance from body coordinates to end of the leg coordinates at desired posture. Forward kinematics is used to obtain the distance from center of the body to the tiptoe. And inverse kinematics is used to obtain angle of each joints. In order to solve the kinematics, D-H parameters should be defined. Table I and Fig. 6 presents the D-H (Denavit-Hatenberg) parameters and kinematic coordinates of the body and each legs of CR200 [9],[10].

Table. I. D-H parameters of CR200

J.	θ_{ij}	α_{ij}	a_{ij}	d_{ij}	**Angle Limit**
1	90°	90°	0	0	-90° ~ 90°
2	90°	90°	0	0	-45° ~ 90°
3	0	-90°	0	0.658	-180° ~ 180°
4	-90°	0	0.882	0	-170° ~ 90°

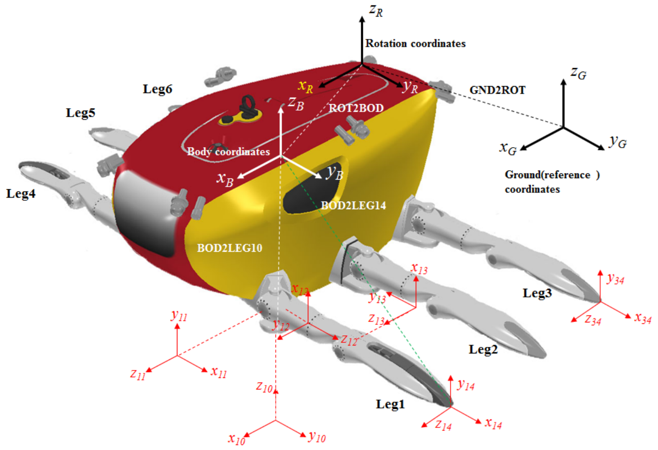

Fig. 6. Coordinates system of CR200

Gait of CR200 is implemented by solving a forward and inverse kinematics and generating the joint paths from the reference posture. Eq. (1) presents transformation matrix ${}^{B}T_{i4}$ for calculating distance from the body coordinates to end of the leg coordinates.

$$ {}^{B}T_{i4} = {}^{B}T_{i0}\,{}^{i0}T_{i4} = {}^{B}A_{i0}\,{}^{i0}A_{i1}\,{}^{i1}A_{i2}\,{}^{i2}A_{i3}\,{}^{i3}A_{i4} \tag{1} $$

$$ {}^{B}T_{i0} = \begin{bmatrix} I_{3\times3} & {}^{B}p_{i0} \\ 0_{1\times3} & 1 \end{bmatrix},\ {}^{B}p_{i0} = \begin{bmatrix} {}^{B}x_{i0} & {}^{B}y_{i0} & {}^{B}z_{i0} \end{bmatrix}^{T} \tag{2} $$

$$ {}^{i(j-1)}A_{ij} = \begin{bmatrix} \cos\theta_{ij} & -\cos\alpha_{ij}\sin\theta_{ij} & \sin\alpha_{ij}\sin\theta_{ij} & a_{ij}\cos\theta_{ij} \\ \sin\theta_{ij} & \cos\alpha_{ij}\cos\theta_{ij} & -\sin\alpha_{ij}\cos\theta_{ij} & a_{ij}\sin\theta_{ij} \\ 0 & \sin\alpha_{ij} & \cos\alpha_{ij} & d_{ij} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

Where, ${}^{B}T_{i0}$ is a transformation matrix from the body coordinates to a base coordinates of i^{th} leg. ${}^{i0}T_{i4}$ is transformation matrix from base coordinates of leg to end of the leg coordinates. In Eq. (2), ${}^{B}p_{i0}$ is a position vector of the leg base coordinates. Eq. (3) is represents a transformation matrix between each joint.

From the Eq. (1), in order to obtain the end-position of the leg based on a ground coordinates, transformation matrix is obtained as follow.

$$ {}^{B}T_{i4} = \left({}^{G}T_{B}\right)^{-1}\,{}^{G}T_{i4} = \left({}^{G}T_{B}\right)^{-1}\,{}^{G}T_{B}^{init}\,{}^{B}T_{i4}^{init} \tag{4} $$

${}^{G}T_{B}^{init}$ is a transformation matrix from the ground coordinates to an initial coordinates of center of the body. ${}^{B}T_{i4}^{init}$ is a transformation matrix from the body coordinates to initial coordinates of end of the leg. ${}^{G}T_{B}$ in Eq. (4) could be written as Eq. (5) using a transformation matrix of the ground coordinates to initial rotation coordinates.

$$ {}^{G}T_{B} = {}^{G}T_{R}^{init}\,{}^{R}T_{B} = {}^{G}T_{B}^{p}\,{}^{B}T_{R}^{init}\,{}^{R}T_{B} \tag{5} $$

$$ {}^{G}T_{B}^{p} = \begin{bmatrix} {}^{G}R_{B} & G_{P_B} \\ 0_{1\times3} & 1 \end{bmatrix},\ G_{P_B} = \begin{bmatrix} G_{x_B} & G_{y_B} & G_{z_B} \end{bmatrix}^{T} \tag{6} $$

${}^{G}T_{B}^{p}$ of Eq. 6 is a transformation matrix based on ground coordinates, considering the position displacement when changing posture. And ${}^{R}T_{B}$ of Eq. 6 can be expressed as Eq. 7 considering the rotation transformation matrix R_{ypr}.

$$ {}^{R}T_{B} = R_{yaw}R_{pitch}R_{roll}\,{}^{R}T_{B}^{init} = R_{ypr}\left({}^{B}T_{R}^{init}\right)^{-1} \tag{7} $$

$$ R_{roll} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\psi & -\sin\psi & 0 \\ 0 & \sin\psi & \cos\psi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ R_{pitch} = \begin{bmatrix} \cos\chi & 0 & \sin\chi & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\chi & 0 & \cos\chi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8} $$

$$ R_{yaw} = \begin{bmatrix} \cos\varphi & -\sin\varphi & 0 & 0 \\ \sin\varphi & \cos\varphi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Using Eq. (4), (5) and (7), a transformation matrix from the body coordinates to end of the leg coordinates can be obtained as Eq. (9).

$$ {}^{B}T_{i4} = \left({}^{G}T_{B}^{p}\,{}^{B}T_{R}^{init}\,R_{ypr}\left({}^{B}T_{R}^{init}\right)^{-1}\right)^{-1}\,{}^{G}T_{B}^{init}\,{}^{B}T_{i4}^{init} \tag{9} $$

Substituting a variation $dp_B = [dx, dy, dz, d\psi, d\varphi, d\chi]$ of body position (dx, dy, dz) and posture ($d\psi, d\varphi, d\chi$) into the Eq. (6) and (8), a position vector $P_{Li4} = [x_{Li4}\ \ y_{Li4}\ \ z_{Li4}]$ of tiptoe for a desired body position and posture can be obtained. Solving an inverse kinematics using P_{Li4} and the initial position, joint angle of each leg can be obtained. In order to control thirty joint angles, we can implement the desired position and the posture. Fig. (7) shows a numerical inverse kinematics method.

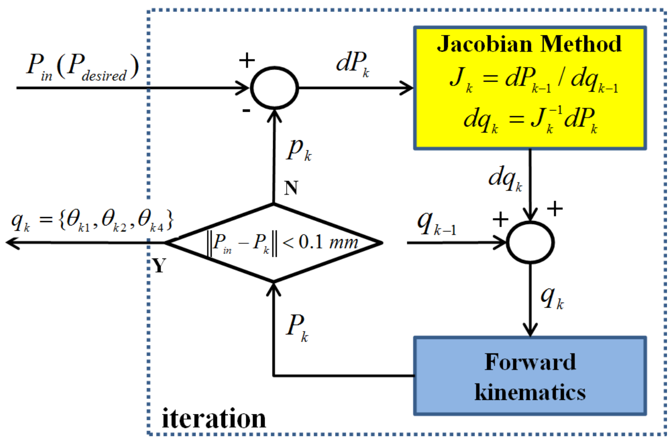

Fig.7. Numerical inverse kinematics method

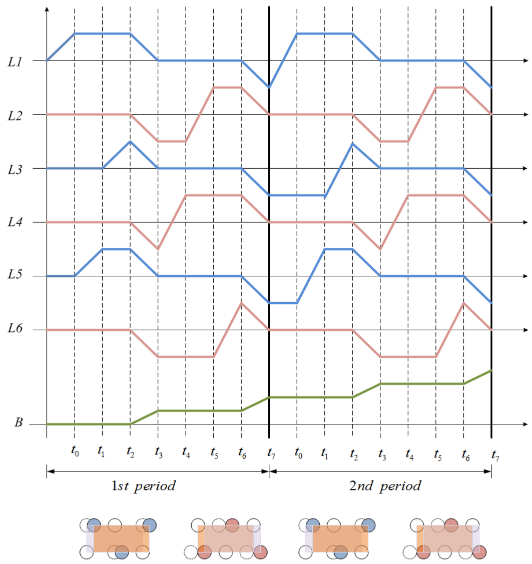

Fig. 8. Pattern diagram of 8-phase discontinuous periodic gait.

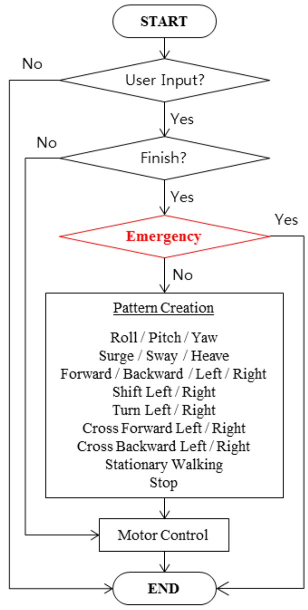

Fig. 9. Flowchart of operating sequence

B. Gait Control Algorithm

Since CR200 is a hexapod robot, there are several gait patterns such as three, four and five-point gait. This paper the control algorithm for walking is focused on the five-point gait pattern. And it is based on eight-phase discontinuous periodic gait. The gait pattern applied in CR200 is planned by certain schedule which is Leg#1→Leg#5→Leg#3→Body→ Leg#4→ Leg#2→Leg #6→Body. Fig. 8 is a pattern diagram of the eight-phase discontinuous periodic gait. The pattern consists of time for liftoff from ground of leg, time for transfer to the desired point, time for placement to the ground and time for body motion. In order to generating gait pattern for CR200, certain aspects should be considered:

1. After finish the previous pattern, than the next pattern is started. Pattern is not overlap.
2. The body is propelled forward with all legs on the ground.

CR200 posture and walking control is performed using Eq. (10) which is control the leg from current position to the desired position according to time variation.

$$P_{Li4}^{k} = P_{Li4}^{init} + 0.5\left(P_{Li4}^{des} - P_{Li4}^{init}\right)\left(1 - \cos\left(\frac{t^{k}}{T}\pi\right)\right) \qquad (10)$$

Where, T is a time for completion of leg moving and t^k is a time for control status. The Cosine function of Eq. (10) is grant an acceleration and a deceleration of leg movements in order to increase a stability of CR200.

Through the gait control algorithm, we control CR200 with 100Hz of control frequency by open loop control method. Using inverse kinematics, the position of end-point of each leg is converted to the joint angle. And it is delivered to motor controller of each joint in every cycle.

IV. Operating Program

We have developed two types of graphic user interfaces (GUI) using C++ language to implement the kinematic gait control algorithm of CR200. The one is test program and the other one is pilot program. Each program is connected to CR200 by LAN (local area network). Operating sequence of two programs is same and it is shows in Fig. 9. First, check a user input. If there's a user input than check a gait status, finished or moving. If the gait status is finished, check an emergency status. If it is not an emergency situation than create a gait pattern according to the user input. In the process of pattern creation, joint angle of each leg for desired position and posture are obtained. After pattern creation of gait, motor control command for joint angle control is sent to each motor driver.

The GUI of the test program is shown in Fig. 10. Test program is developed for ground test of CR200. The Ground test is a basic test of CR200 such as motor driver setting, individual operation of legs, sensor feedback check, posture and walking control and etc. Test program can be operated in laptop, so that operator of CR200 can operate robot in any place where under wireless LAN connection.

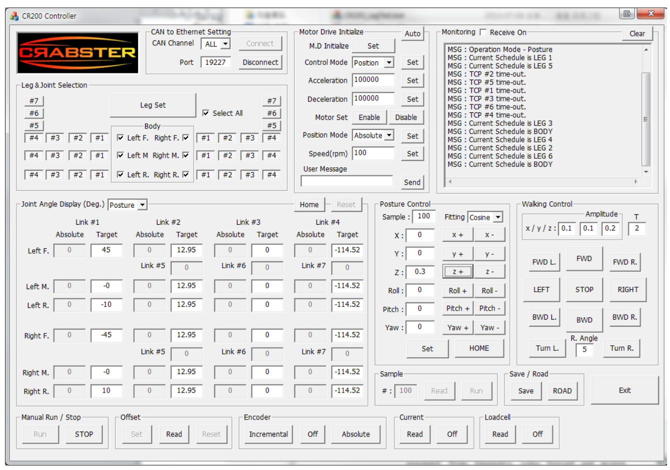

Fig. 10. Graphic user interface of test program.

Fig. 11. Graphic user interface of pilot program.

The GUI of the pilot program is shown in Fig. 11. Pilot program is developed based on the test program. It has many functions for sea trials of CR200 such as robot status and attitude monitoring (joint angle, joint current, COP data, navigation data, pressure data of legs, temperature data of canisters, 3D viewer of virtual robot posture), tool sled control, sensor power control, light power control, data logging, and so on. The user input is defined by controlling of joysticks for posture control and walking control. Fig. 12 and 13 shows commands of each joystick.

V. Simulation and Experiments

A. Simulation

Before the experiment, we performed a simulation using MATLAB® of MathWorks Inc. to guarantee a performance of the gait algorithm. For the simulation of the posture control, 6 kinds of posture were simulated which is roll, pitch, yaw, surge, sway and heave. Angle variation of roll, pitch and yaw is 4° and displacement of surge, sway and heave is 10cm. The result of simulation is shows in Fig. 13.

B. Experments

The implemented kinematic gait algorithm was tested on the ground before underwater demonstration. An omni-directional walking and posture control were performed same as simulation. The posture control experiment of CR200 is performed in six degrees of freedom; surge, sway, heave, roll, pitch, yaw and combination of the motions. And walking experiment of CR200 is performed eight directions and two directions of rotation which are forward, backward, left, right, cross forward left/right, cross backward left/right, and turn left/right. As can be seen in the Fig. 14 and 15, the postures are followed well the designed gait algorithm. Fig. 16 shows an experiment result of walking (forward). Through the gait simulation, we also notice that it is possible to calculate the location of the CR200 when it walks using kinematics [11].

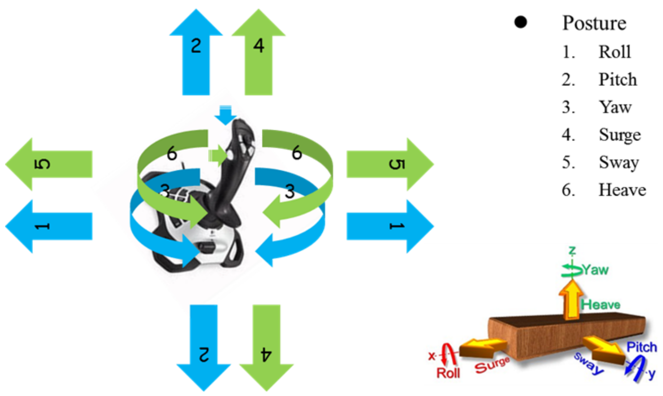

Fig. 12. Joystick commands for posture control.

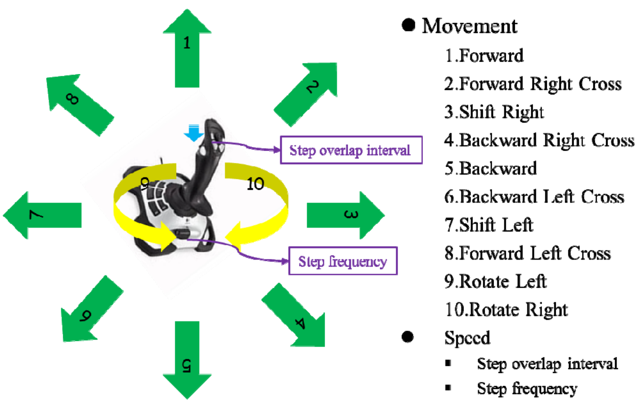

Fig. 13. Joystick commands for walking control.

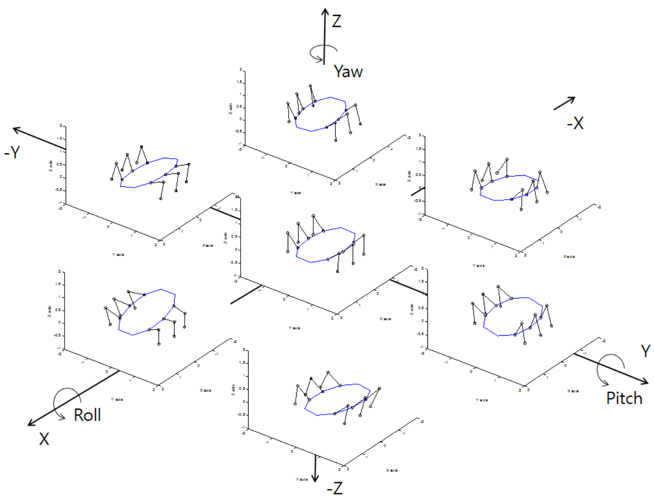

Fig. 14. Simulation result of the posture control.

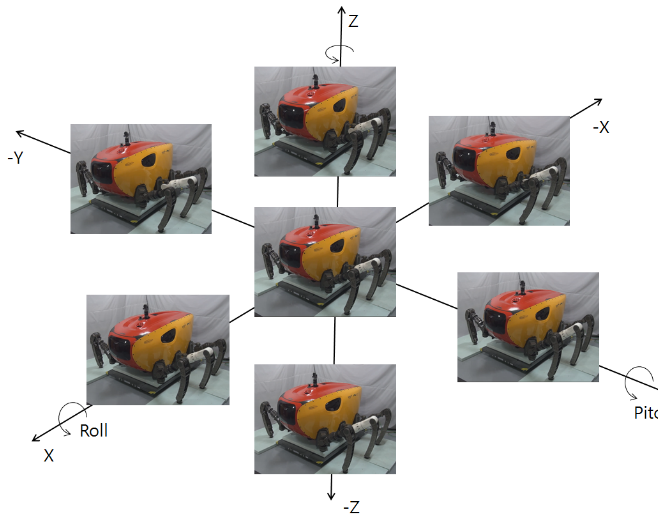

Fig. 15. Experimental result of the posture control

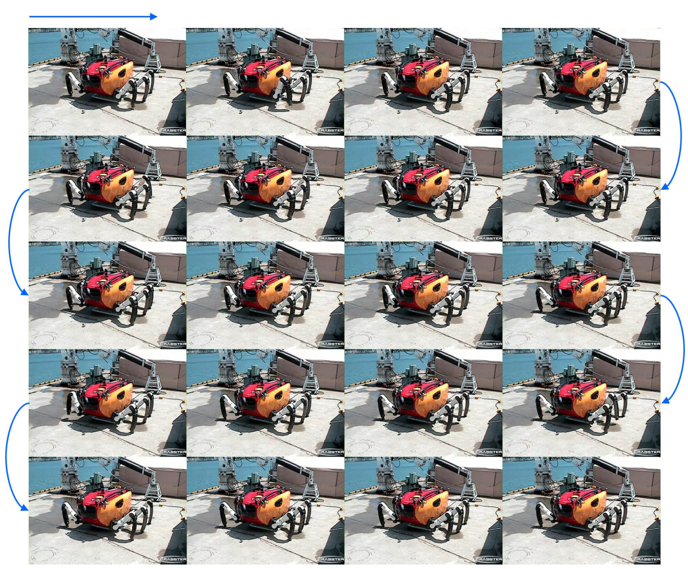
Fig. 16. Experimental result of the walking control (Forward).

VI. CONCLUSION

In this paper, we describe the method for controlling posture and walking of CR200. Kinematics and gait algorithm for CR200 is presented and we obtained the joint angle for the desired position and posture using forward and inverse kinematic methods. In order to operate to CR200 and implement of the kinematic algorithm, test program and pilot program are showed. The implemented programs and gait algorithm are validated through simulation and experiments. Through the simulation and experimental results, we verified the effectiveness of the computation frame of the kinematics. Therefore, we judge that the kinematic posture and walking control algorithms is affordable to apply for the body control against the current and the robot is stable more than conventional ROVs and AUVs in current environment.

ACKNOWLEDGMENT

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