Modeling for the Crabster leg with hydrodynamics force

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***Abstract*— The KRISO (Korea Research Institute of Ships & Ocean engineering) developed the Crabster which is an underwater walking robot with six legs in 2013. This robot is operated on the seabed with high tide and high turbidity environments which is unknown environments. This paper deals with modeling of the Crabster leg with hydrodynamics force for active control and feedback control. Joints of friction and buoyancy model are derived with experiments. Motor currents are used to the modeling process. Finally, the derived model is verified with walking pattern data of the Crabster.**

Keywords – Crabster; modeling; hydrodynamics force; underwater robot, leg

I. INTRODUCTION

The Crabster(Figure 1) is operated on the seabed with high tide and high turbidity environments as western sea in South Korea[1]. Terrain structures and lipid status are not observed using underwater device as underwater optical cameras and ultrasonic cameras in this sea. Thus, the Crabster must have ability to react for the unknown environment as active controls and force controls for stable walking and maintaining posture. This study deals with modeling for the Crabster leg with hydrodynamics force as buoyancy for dynamical approach as active controls and force controls.

Many research for dynamical approach of joint robots has been studied. In 2006, Helmick studied comparison of estimation performance for robot arm with 5-axis using force/torque sensor with 6-axis, torque sensor of joint, strain gauge of link, motor current and model of the robot arm [2]. In 1994 and 1995, Schjølberg and McMillan studied modeling of underwater ROV (Remotely Operated Vehicle) arm and underwater ROV-installed arm by considering fluid dynamics effects [3]. In 1996, Abderrahim studied simulation study by considering added mass and drag for the 2-axis joint robot [4][5]. In 1998, McLain studied theoretical Analysis and experimental measurement based on visualization of the fluid for added mass and drag [6]. Most existing research has been conducted with theory approach and simulation studies. This approach is suitable to carry out prior to making the robot but approach using the actual robot is inappropriate. In this study, Dynamic Modeling was performed for estimation of kinetic coefficient using the actual robot unlike previous studies.

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As experimental approach, this study used for the motion information data of Crabster legs as joints angular position, angular velocity and motor current. First dynamic model of the Carbster leg was derived using Euler-Lagrangian equation [7][8]. And then friction and gravity model with coefficient were derived based on experiments. Finally, dynamic model was verified with walking pattern data of the Crabster in the floating state.

II. CRABSTER LEG AND DYNAMIC MODELING

A. Crabster leg

The Crabster leg (Figure 2) is the core part as composing the Crabster system. It is used to change the posture of body and to walk for moving in the air and underwater. The Crabster leg is fabricated using BLCD (Brushless DC) motors for precise control. Motor current and angular position and angular velocity of leg joints are measured by the motor driver. In this study, the current was used for the derivation of kinetic coefficient. The specification of Crabster leg is summarized in the Table 1. The joint structure of Crabster leg is shown in the Figure 3. The detailed specification of Crabster leg is described in existing papers [9]-[11]. Leg joint 1, 2 and 4 are used when the Crabster move. The leg joint 3 is used when the Crabster changes or maintains posture in inclined plane or rough terrain. In this study, the leg structure is simplified to three joints except for joint 3 and then it is applies to dynamic modeling.

Figure 1. Crabster

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TABLE I. SPECIFICATIONS OF CRABSTER LEG

Parameter	Specification
Link length(mm)	Link 1 : 658mm Link 2 : 877mm
Weight(Kg)	40
Degree of freedom	4
Joint angular speed(deg/sec)	Joint 1 : 240 Joint 2-3 : 180
Range of motion	Joint 1 : -90° ~ 90° Joint 2 : -45° ~ 90° Joint 3 : -90° ~ 90° Joint 4 : -150° ~ 90°
Frame material	Aluminum alloy 6061T6

Figure 2. Crabster leg

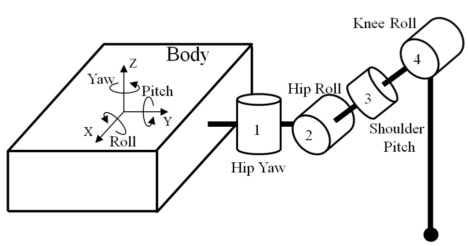

Figure 3. structure of crabster leg

B. Dynamic modeling

The general dynamic model of land robot is considered as equation (1). Where τ is a joint torque, q is a joint angular position, $\dot{q}$ is a joint angular speed, $\ddot{q}$ is a joint angular acceleration, $M(q)$ is the inertial matrix, $C(q,\dot{q})$ is the centrifugal/Coriolis matrix, $G(q)$ is gravity vector, $\tau_F(q,\dot{q})$ is friction vector, $J^T(q)$ is the manipulator Jacobian matrix, f_{Ext} is external force vector. The general dynamic model of underwater robot is considered as equation (2). Where $M_A(q)$ is the added inertial matrix, $C_A(q,\dot{q})$ is the added centrifugal/Coriolis force matrix, $G_B(q)$ is combined gravity and buoyancy vector, $\tau_D(q,\dot{q})$ is fluid drag force vector, $\tau_L(q,\dot{q})$ is hydraulic lift force vector, $\tau_V(q,\dot{q})$ is vortex vector. Underwater robots are considered with above fluid effects but it is hard to consider about all fluid effects. In mots existing research about underwater robot arms, links of robot arm have been simplified to rectangular or circular cylinder shape [12][13]. The Crabster leg also has the complicated shape. In this research, the Crabster leg was assumed to circular cylinder shape. Equations (3)-(5) are dynamic model of the Craster leg. These were derived from the Euler-Lagrangian equation. Where m_2 and L_2 are the link weight and length from joint 2 axis to joint 4 axis , m_3 and L_3 are the link weight from joint 4 axis to the tiptoe.

$$\tau = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + \tau_F(q,\dot{q}) + J^T(q) f_{Ext} \quad (1)$$

$$\begin{aligned}\tau = &\left[M(q) + M_A(q)\right]\ddot{q} + \left[C(q,\dot{q}) + C_A(q,\dot{q})\right]\dot{q} + G_B(q) \\ &+\tau_F(q,\dot{q}) + \tau_D(q,\dot{q}) + \tau_L(q,\dot{q}) + \tau_V(q,\dot{q}) + J^T(q) f_{Ext}\end{aligned} \quad (2)$$

$$M = \begin{bmatrix} M_{11} & M_{21} & M_{31} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} \quad (3)$$

$$\begin{aligned}M_{11} = &m_3(L_2^2\cos(\theta_2)^2 + L_2L_3\cos(\frac{1}{2}\theta_3)^2 + L_2L_3\cos(\theta_2 + \frac{1}{2}\theta_3)^2 \\ &- L_2L_3 + \frac{1}{3}L_3^2\cos(\theta_2+\theta_3)^2) + \frac{1}{3}m_2L_2^2\cos(\theta_2)^2\end{aligned}$$

$$M_{12} = M_{13} = M_{21} = M_{31} = 0$$

$$M_{22} = \frac{1}{3}m_2L_2^2 + m_3L_2^2 + \frac{1}{3}m_3L_3^2 + m_3L_2L_3\cos(\theta_3)$$

$$M_{23} = M_{32} = m_3L_3(\frac{1}{3}L_3 + \frac{1}{2}L_2\cos(\theta_3))$$

$$M_{33} = \frac{1}{3}m_3L_3^2$$

$$C = \begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} \quad (4)$$

$$\begin{aligned}C_1 = &-\dot{\theta}_1\dot{\theta}_2(m_3L_2^2\sin(2\theta_2) + L_2L_3\sin(2\theta_2+\theta_3) + \frac{1}{3}L_3\sin(2\theta_2 \\ &+ 2\theta_3)) + \frac{1}{3}m_2L_2^2\sin(2\theta_2) - L_2L_3\dot{\theta}_1\dot{\theta}_3(\frac{1}{2}L_2\sin(\theta_3) \\ &+ \frac{1}{2}L_2\sin(2\theta_2+\theta_3) + \frac{1}{3}L_3\sin(2\theta_2+2\theta_3))\end{aligned}$$

$$C_2 = \frac{1}{6} m_2 L_2^2 \dot{\theta}_1^2 \sin(2\theta_2) - \frac{1}{2} m_3 L_2 L_3 \dot{\theta}_3^2 - m_3 L_2 L_3 \dot{\theta}_2 \dot{\theta}_3 \sin(\theta_3)$$

$$C_3 = m_3 L_3 (\frac{1}{4} L_2 \sin(\theta_3) + \frac{1}{4} L_2 \dot{\theta}_2^2 \sin(\theta_2 + 2\theta_3) + \frac{1}{6} L_3 \dot{\theta}_1^2 \sin(2\theta_2 + 2\theta_3) + \frac{1}{2} L_2 \sin(\theta_3) \dot{\theta}_2^2)$$

$$G = \begin{bmatrix} G_1 \\ G_2 \\ G_3 \end{bmatrix} \quad (5)$$

$$G_1 = 0$$

$$G_2 = g(\frac{1}{2} m_3 L_3 \cos(\theta_2 + \theta_3) + \frac{1}{2} m_2 L_2 \cos(\theta_2) + m_3 L_2 \cos(\theta_2))$$

$$G_3 = \frac{1}{2} g m_3 L_3 \cos(\theta_2 + \theta_3)$$

III. DERIVATION OF DYNAMIC MODEL COEFFICIENT

All dynamic effects must be considered for the dynamic modeling. But it is very hard to consider all effects. Thus, in this study, derivation of dynamic coefficient for only mechanical friction, gravity and gravity combined buoyancy were considered based on experiments. Experiment for derivation of gravity coefficient was performed with air condition and underwater condition. Each Motor current and angular position and angular velocity of leg of joint was applied to derivation of dynamic model coefficient.

A. Experiment environment

The environments for the experiment were as follows. The extra Crabster leg was applied to derivation of dynamic coefficient. An industrial embedded PC (PCI-104) was used for the leg control. Derivation experiments of coupled gravity with buoyancy effect is performed the fresh water tank. This tank is 3.2m depth and no current. Underwater cable and connector are applied to supply power and communicate. An air pressure sensor was installed for monitoring the inside pressure of leg.

B. Friction model

The friction effect can be divided as static frictions and dynamic friction. In this study, only dynamic friction is considered to the derivation of dynamic coefficient. Each joint of Craster leg is installed with bearings and a harmonic drive for the transmission of power and also is used with O-ring for the waterproof. Friction effects are generated when a joint is rotated. They are comprised of viscous friction, static friction and Coulomb friction. It is difficult to derive accurate mathematic model with all friction effects [5]. Friction model must be derived with minimized inertial force and centrifugal/Coriolis force except for link parts. But in this study, a fully assembled leg was used in this study because the Crabster leg has waterproof when the leg is fully assembled.

The environments for the experiment of friction model derivation were as follows. Each joint axis was aligned with the direction of gravity. Range of joint motion was fixed as shown Figure 4. Angular speed of joint was changed with step per 6deg/sec. Drive current of joint motor were measured as figure. Average values for constant velocity sections in measured current data were used to derivation of friction model except for acceleration and decelerate sections. Friction model of each joint were derived as equation (6) using polynomial curve fitting function (polyfit) in MATLAB. The friction model of joint 1, 2 and 4 are shown as Figure 5-7.

$$\begin{bmatrix} +y_{j1} = (-0.0001)x^2 + 0.197x + 0.6896 \\ -y_{j1} = 0.004x^2 + 0.0318x - 0.5758 \\ +y_{j2} = (-0.0006)x^2 + 0.0521x + 0.984 \\ -y_{j2} = 0.0006x^2 + 0.0467x - 1.1634 \\ +y_{j4} = 0.0005x^2 + 0.011x + 0.9658 \\ -y_{j4} = (-0.0007)x^2 + 0.0094x - 0.9954 \end{bmatrix} \quad (6)$$

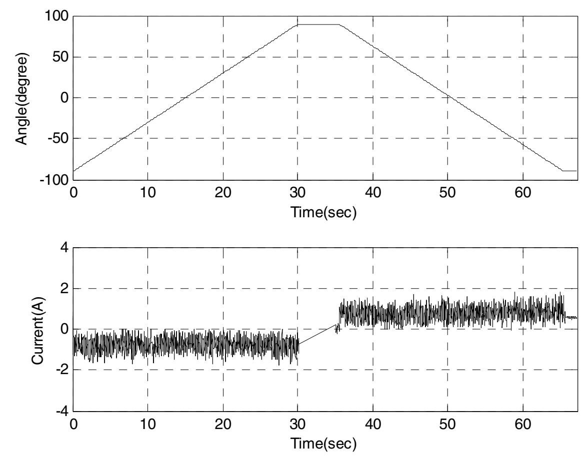

Figure 4. Sampling data for friction model (Joint 1, 6 deg/sec)

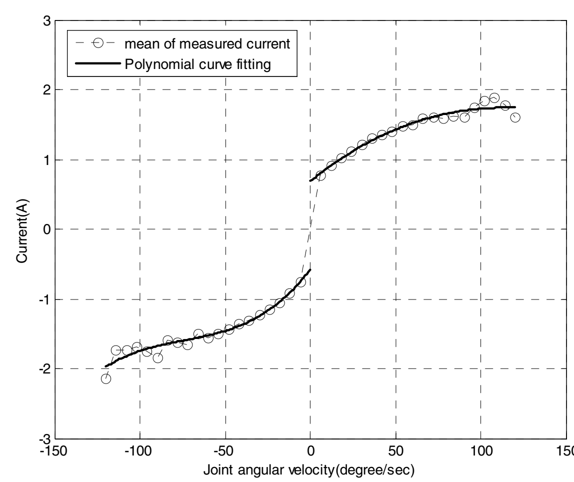

Figure 5. Friction model of joint 1

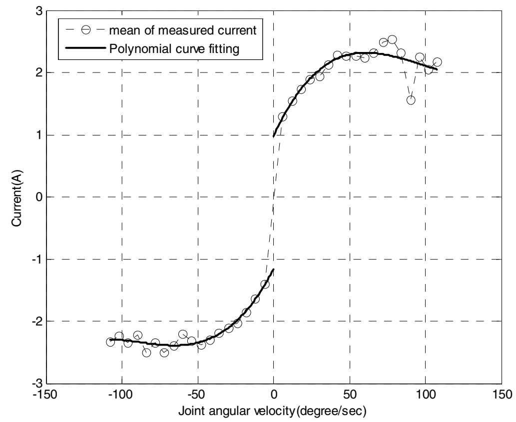

Figure 6. Friction model of joint 2

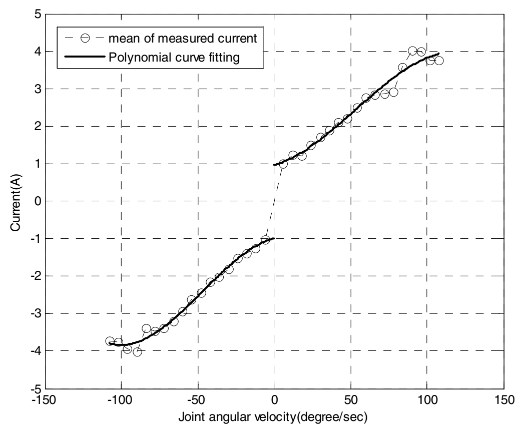

Figure 7. Friction model of joint 4

C. *Gravity model*

The gravity model τ_G can be derived using equation (5). It can be transformed to equation (7)-(8). Equations (8)-(12) are motor torque formula and transformed formula for coefficient of gravity, where Y is the unknown parameter which is the combination link mess with length of mess center. It is coefficient of gravity model and derived in this study. $A(\theta)$ is the observation matrix which can be measured. τ_M is a motor torque. k is a motor constant. i is a motor current. i_G is a measurement vector. It is motor current which is decided with joint posture of leg. Unknown X is derived to lumped factors using Least squares method as equation (12). Joint 2 and joint 4 were used for data sampling of observation vector (joint position) and measurement vector (motor current) in the air and underwater as Figure 8. Each Joint rotational axis was aligned with a horizontal plane. Joint position was moved per 5 degrees and maintained for 5 seconds. The gravity model coefficient of joint 2 and joint 4 are [0.0606, -0.2508, -0.0931] and [–0.086] in the air and also [0.0155; -0.1241; -0.0455] and [–0.0536] in underwater using data sampling of observation vector and measurement vector and equation (12). And then simulations were performed using the derived coefficients for verification as Figure 9 and Figure 10. Where, FW and BW are forward rotation and backward rotation of joint respectively. There is hysteresis in the simulation results. These causes are assumed that the leg to act as weight in the air and to act as buoyancy in underwater.

$$\tau_G = \begin{bmatrix} 0 & 0 & 0 \\ m_2 L_2 & m_3 L_2 & m_3 L_3 \\ 0 & 0 & m_3 L_3 \end{bmatrix} \begin{bmatrix} \frac{1}{2} g\cos(\theta_2) \\ g\cos(\theta_2) \\ \frac{1}{2} g\cos(\theta_2+\theta_3) \end{bmatrix} \quad (7)$$

$$\tau_G = Y \cdot A(\theta) \quad (8)$$

$$\tau_M = ki \quad (9)$$

$$i = \frac{\tau_M}{k} \quad (10)$$

$$i_G = X \cdot A(\theta) \quad (11)$$

$$X = i_G \cdot A(\theta)^{-1} \quad (12)$$

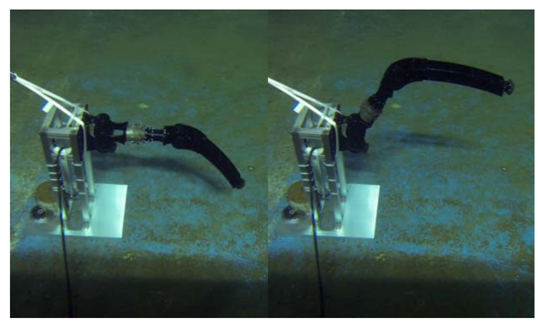

Figure 8. Experiment environments for gravity combined buoyancy

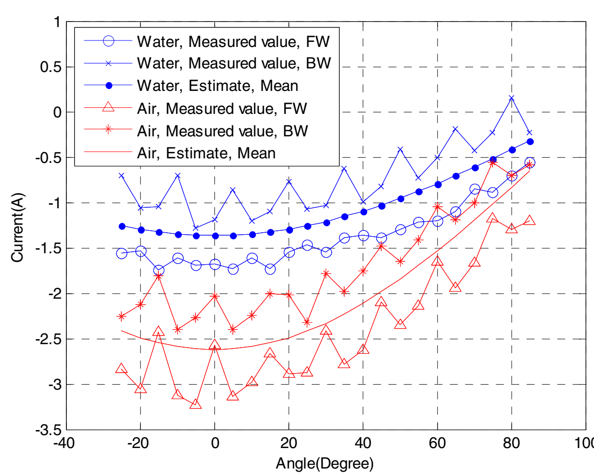

Figure 9. Gravity model of joint 2

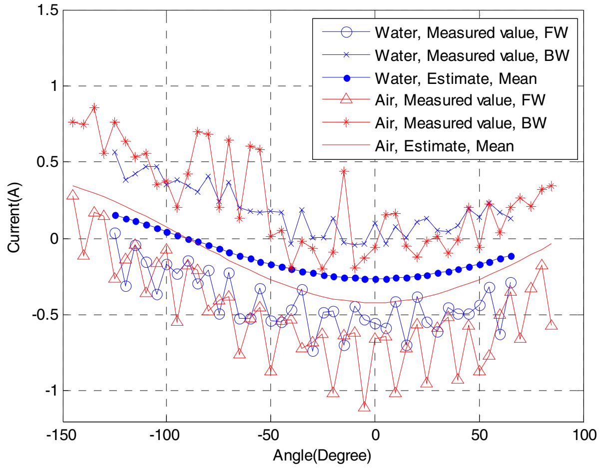

Figure 10. Gravity model of joint 4

D. *Verification of the dynamic model*

Verification of derived dynamic coefficient was performed with walking pattern data of the Crabster in the floating state. Figure 11 is shown for measured data and simulated data of motor current using dynamic model with friction and gravity model. Where, J1, J2 and J4 are Joint 1, Joint 2 and Joint 4 in. In case of joint 2, measured data and estimated data are approximate. But in case of joint 1, there are errors. The Cause of error is assumed that only friction model was used without inertia model and centrifugal/Coriolis model. In case of joint 4, there are errors also. The cause of error is assumed due to irregular static friction force.

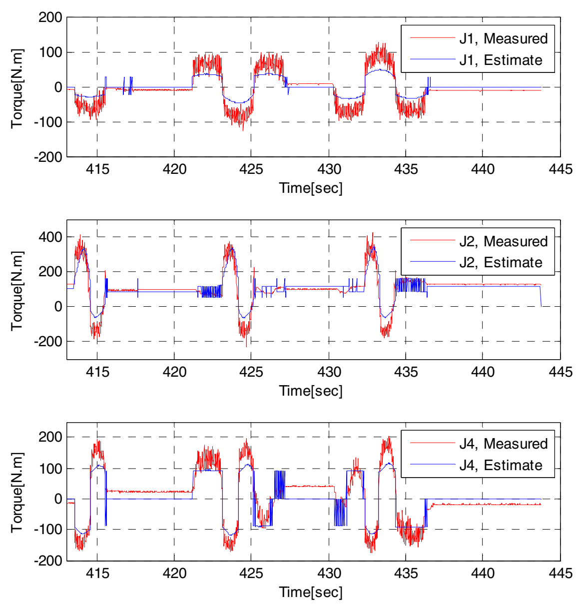

Figure 11. Verification of the dynamic model with measured data

IV. CONCLUSION

This paper performed modeling of the Crabster leg with hydrodynamics force by considering friction model and gravity and gravity combined buoyancy based on experiment. As experimental approach, motion information data of Crabster legs as joints angular position, angular velocity and motor current used to modeling process. Euler-Lagrangian equation was used to derivation of dynamic model of the Carbster leg. And then, friction and gravity models were derived based on some experiments using the Crabster leg. Finally, dynamic model with friction and gravity model was verified with pattern data of the Crabster in the floating state. This study will utilize to active controls and force controls for the Carbster. In order to complete congruous model with the real model, it is need to improve the dynamic model of the Crabster leg persistingly.

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