WSR Robust Control System with 2nd-order Dynamics

Kyunghan Chun[a]

[a]Department of Electronic Engineering, Daegu Catholic University, Gyeongbuk, Korea
[a]kchun@cu.ac.kr

Abstract: In this paper, we propose a sliding mode controller with a second-order dynamic approach for RAM (Rotate And Move) water strider robots. Under the premise that the water strider robot operates on the water surface, its dynamic characteristics are affected by disturbance. A robust RAM controller in consideration of this point has been proposed in the past. In this case, since it is designed mainly for simple robustness, it is not easy to apply when a controller that considers the dynamic characteristics during movement is required. In this paper, we design a RAM controller that can get the movement characteristics in the reaching mode as the second-order dynamic characteristics using the PI type law. The proposed controller is not only robust, but can be easily applied as a design method using secondary dynamic characteristics and can improve the response characteristics of the controller. The stability of the proposed controller is proved by the Lyapunov function, and from the simulation results, the proposed controller has the designed second order dynamic characteristics and the response characteristics are also improved compared to the conventional controller.

Keywords: WSR, sliding mode, RAM, 2nd-order

1. Introduction

Recently, a lot of interest has been shown in the field of biomimetic robots that mimic living organisms in nature [1]-[8]. In particular, the water strider robot, which imitates the water strider moving on water, was applied to the semiconductor process due to the peculiarity of its implementation method of superhydrophobicity in the supporting and driving legs of the water strider robot, which causes the system to have a weight limitation. Under this circumstance, the controller should be designed simply, and it is reflected in the implementation.

In order to implement the movement of the water strider robot on the water surface environment, the rotation and movement method is applied in consideration of the stability in the water surface. This is a method of implementing the movement of the robot by a simple mechanism which means move straight after rotation considering the operation environment and the robot structure because the water strider robot has a two-wheeled system. In particular, the movement speed was improved by selecting the shortest rotation direction from clockwise (CW) or counterclockwise (CCW) according to the proposed method for fast rotation [7].

In addition, by applying sliding mode control (SMC), the latest nonlinear control technique, robust control has been studied to improve the instability that may occur when moving on the surface of the water and improve the response speed. In this study, the sliding mode is designed to enable robust control, and the stability of the entire system is ensured by the additional design of the reaching mode. And the system is more stable on the water surface by using the saturation function instead of the conventional sign function [8].

In this paper, we propose a robust controller of a water strider robot with second order dynamics. When designing the characteristics of the reaching mode, the proposed controller candetermine the damping ratio and natural frequency representing the characteristics of the second order dynamics in the reaching mode, and it can be designed easily because it uses the characteristics of the secondary system which is famously well-known in the control study. Also, since these secondary dynamics have continuous characteristics, chattering of the system of sliding mode can be improved due to the conventional discontinuous reaching mode control input. The stability of the proposed controller is verified using the Lyapunov function, and through MATLAB-SIMULINK simulation, it shows a faster response characteristic than that of the previous sliding mode controller, and stable tracking response.

2. SMC with 2nd-order dynamics

<u>Model</u>

In the cylindrical coordinate system, the WSR dynamics is as follows

$$\ddot{\theta} = \frac{2W}{I} F = K_{\theta} u \tag{1}$$

$$\ddot{r} = \frac{2}{m}F = K_r u \quad (2)$$

where

$$K_\theta = \frac{2W}{I},\ K_r = \frac{2}{m},\ u = F$$

W is the location distance of driving leg from the WSR center, *I* is the inertial momentum, *m* is the weight of the WSR, and *F* is the control input from the driving motor.

RAM Method

Considering the 2-wheeled structure and moving on the water surface, move straight after rotation method is used.

Rotation)

If the rotation angle is under π, the same angle is applied

If the rotation angle is over π, the angle is recalculated by $\theta_e = -\text{sgn}(\theta_e)\left[2\pi - |\theta| + |\theta_d|\right]$

Movement)

The WSR movement is simple action to go straight toward the target point.

Sliding Mode Control

Rotation)

For rotation control, the angle error is

$$\theta_e = \theta_d - \theta \quad (3)$$

where θ_d is the desired angle and the angle sliding function is

$$s_\theta = \dot{\theta}_e + \lambda_\theta \theta_e \quad (4)$$

In the sliding surface $s_\theta = 0$, the angular error will converge to zero for $\lambda_\theta > 0$. For reaching mode, we use 2nd-order reaching law to achieve good tracking performance [9] which is

$$\dot{s}_\theta = -K_{P_\theta} s_\theta - K_{I_\theta} \int s_\theta \, dt \quad (5)$$

And to show the 2nd-order dynamics, we differentiate (5) and get the result is

$$\ddot{s}_\theta + K_{P_\theta} \dot{s}_\theta + K_{I_\theta} s_\theta = 0 \quad (6)$$

where the parameter K_{P_θ}, K_{I_θ} can be calculated from the values of damping ratio and natural frequency which are well-known in the 2nd-order dynamics of the automatic control theory.

For the sliding mode control, the angle controller is proposed as follows

$$u_\theta = \frac{1}{k_\theta}\left[-\lambda_\theta \dot{\theta} + K_{P_\theta} s_\theta + K_{I_\theta} \int s_\theta \, dt\right] \quad (7)$$

where K_{P_θ}, K_{I_θ} are positive and the integrator resets when crossing the sliding surface.

Theorem 1. For the system (1) and the angle sliding function (4), the proposed angle controller (7) satisfies the sliding condition.

Proof)

Let the angle Lyapunov function $V_\theta = \frac{1}{2} s_\theta^2$ and differentiating the function results in

$$\dot{V}_\theta = s_\theta \dot{s}_\theta \quad (8)$$

where the derivative of the angle sliding function is

$$\begin{aligned}\dot{s}_\theta &= \ddot{\theta}_e + \lambda_\theta \dot{\theta}_e \\ &= -\ddot{\theta} - \lambda\dot{\theta}\end{aligned} \quad (9)$$

with the assumption that the reference input is constant and by applying (1), (7), the derivative of the angle sliding function becomes as follows

$$\begin{aligned}\dot{s}_\theta &= \lambda_\theta \dot{\theta} - K_{P_\theta} s_\theta - K_{I_\theta} \int s_\theta \, dt - \lambda\dot{\theta} \\ &= -K_{P_\theta} s_\theta - K_{I_\theta} \int s_\theta \, dt\end{aligned} \quad (10)$$

And for the sliding condition, we apply the result (10) to the derivative of the Lypunov function (8)

$$\dot{V}_\theta = s_\theta \left(-K_{P_\theta} s_\theta - K_{I_\theta} \int s_\theta \, dt \right) < 0 \quad (11)$$

which always satisfies the sliding condition because K_{P_θ}, K_{I_θ} are positive and the integrator resets when crossing the sliding surface.

Q.E.D

Movement)

For movement control, the distance error is

$$r_e = r_d - r \quad (12)$$

where r_d is the desired distance to the target and the distance sliding function is

$$s_r = \dot{r}_e + \lambda_r r_e \quad (13)$$

In the sliding surface $s_r = 0$, the distance error will converge to zero for $\lambda_r > 0$. For reaching mode, we use 2nd-order reaching law to achieve good tracking performance [9] which is

$$\dot{s}_r = -K_{P_r} s_r - K_{I_r} \int s_r \, dt \quad (14)$$

And to show the 2nd-order dynamics, we differentiate (14) and get the result is

$$\ddot{s}_r + K_{P_r} \dot{s}_r + K_{I_r} s_r = 0 \quad (15)$$

where the parameter K_{P_r}, K_{I_r} can be calculated from the values of damping ratio and natural frequency which determine the 2nd-order dynamics.

For the sliding mode control, the distance controller is proposed as follows

$$u_r = \frac{1}{k_r} \left[-\lambda_r \dot{r} + K_{P_r} s_r + K_{I_r} \int s_r \, dt \right] \quad (16)$$

where K_{P_r}, K_{I_r} are positive and the integrator resets when crossing the sliding surface.

Theorem 2. For the system (2) and the distance sliding function (13), the proposed distance controller (16) satisfies the sliding condition.

Proof)

Let the distance Lyapunov function $V_r = \frac{1}{2}s_r^2$ and differentiating the function results in

$$\dot{V}_r = s_r \dot{s}_r \quad (17)$$

where the derivative of the distance sliding function is

$$\begin{aligned} \dot{s}_r &= \ddot{r}_e + \lambda_r \dot{r}_e \\ &= -\ddot{r} - \lambda_r \dot{r} \end{aligned} \quad (18)$$

with the assumption that the reference input is constant and by applying (2), (16), the derivative of the distance sliding function becomes as follows

$$\begin{aligned} \dot{s}_r &= \lambda_r \dot{r} - K_{P_r} s_r - K_{I_r} \int s_r \, dt - \lambda_r \dot{r} \\ &= -K_{P_r} s_r - K_{I_r} \int s_r \, dt \end{aligned} \quad (19)$$

And for the sliding condition, we apply the result (19) to the derivative of the distance Lypunov function (17)

$$\dot{V}_r = s_r \left(-K_{P_r} s_r - K_{I_r} \int s_r \, dt \right) < 0 \quad (20)$$

which always satisfies the sliding condition because K_{P_r}, K_{I_r} are positive and the integrator resets when crossing the sliding surface.

Q.E.D

3. Simulation

For simulation, the model is (1), (2) and the dc motor is used in [7]. All parameters are

$$m : 5.03\text{g}, W : 0.025\text{m}, \; m_R : 0.3\text{g}, \; \text{a=0.25}, \; h : 0.015\text{m}, \; \theta_{uw} = \frac{\pi}{2}\text{rad}, \; I = \frac{mW^2}{6} \quad (21)$$

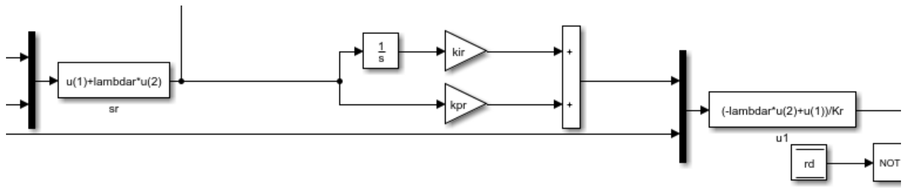
andfinally the computed force is

$$F = 1.4921 \times 10^{-10} n^2 \quad (22)$$

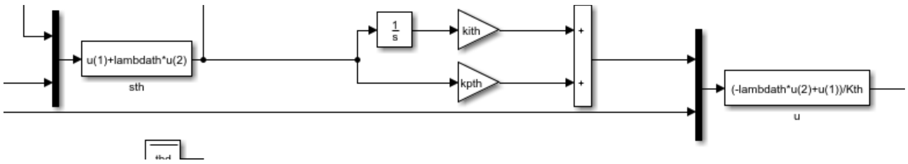
Where n is motor speed (r/min).

For the simulation of WSR robust control system with the 2nd-order dynamics, the model and the controllers are implemented by using MATLAB/SIMULINK and the target point is assumed as (-5,-5) for the comparison with [8]. The block diagram of the robust control system with the 2nd-order dynamics is shown in Figure 1 where (a) is for rotation controller and (b) is for movement controller. Although the structures are same, but the each parameters are properly chosen

$$\lambda_\theta = 5, \; K_{P_\theta} = 5, \; K_{I_\theta} = 0.1, \; \lambda_r = 1, \; K_{P_r} = 1, \; K_{I_\theta} = 0.1 \quad (23)$$



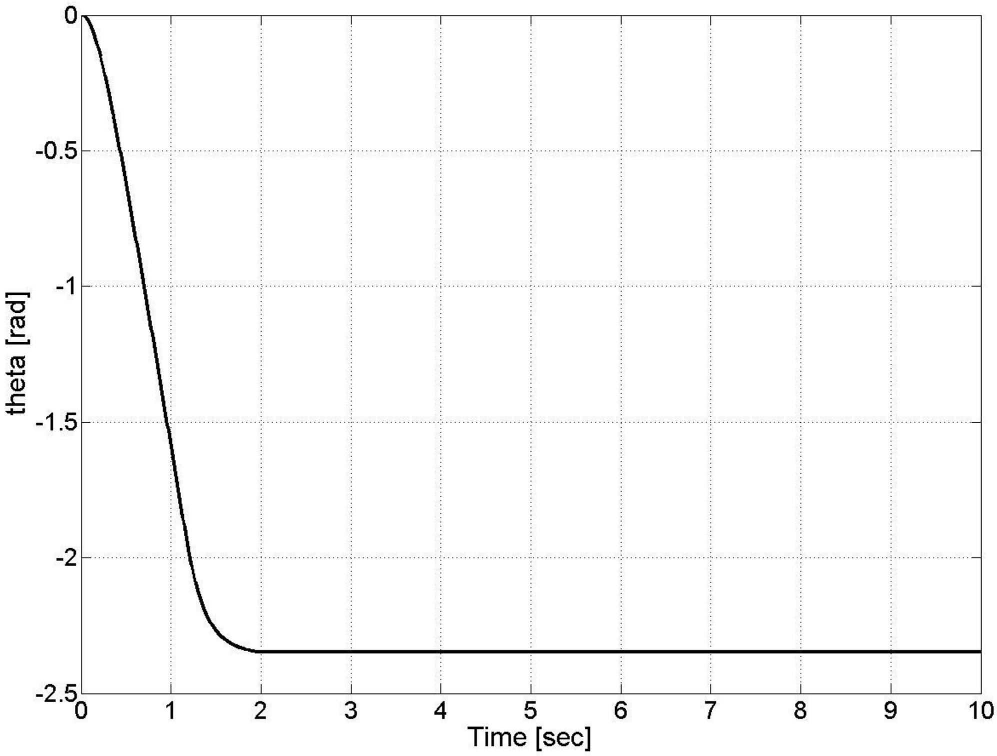
(a) Rotation controller



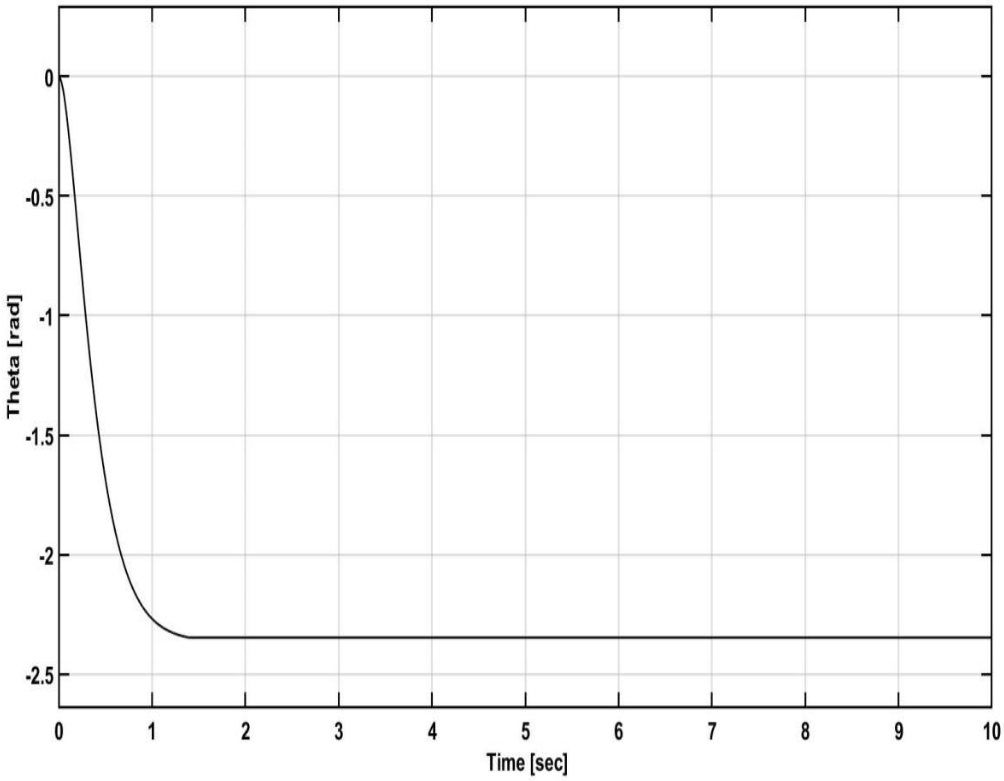
(b) Movement controller

Figure 1. Block diagram of robust control system with the 2nd-order dynamics

For showing RAM control, the angle and the x, y positions are displayed in the Figure 2-4. In Figure 2, rotation results are compared with [8] and (a) is [8] and (b) is the proposed controller and the result shows that two methods are all good rotation at first in the RAM action and the proposed controller shows the fast response 1.4s that is faster than 2s of [8].



(a) Conventional SMC

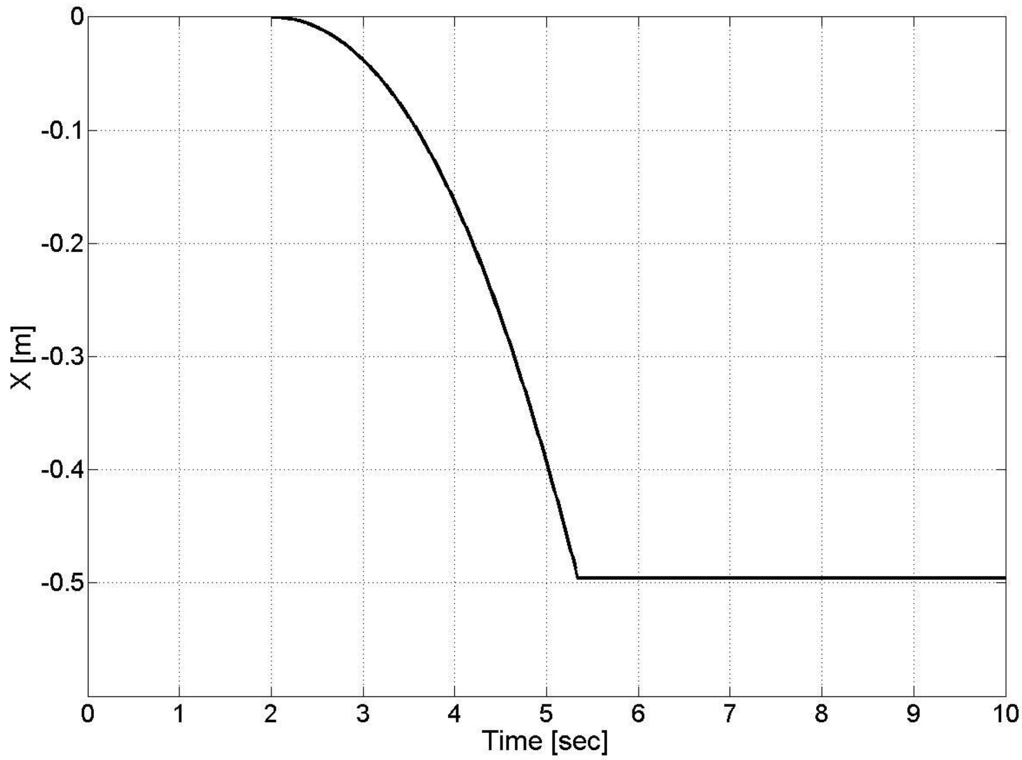


(b) Proposed rotation controller

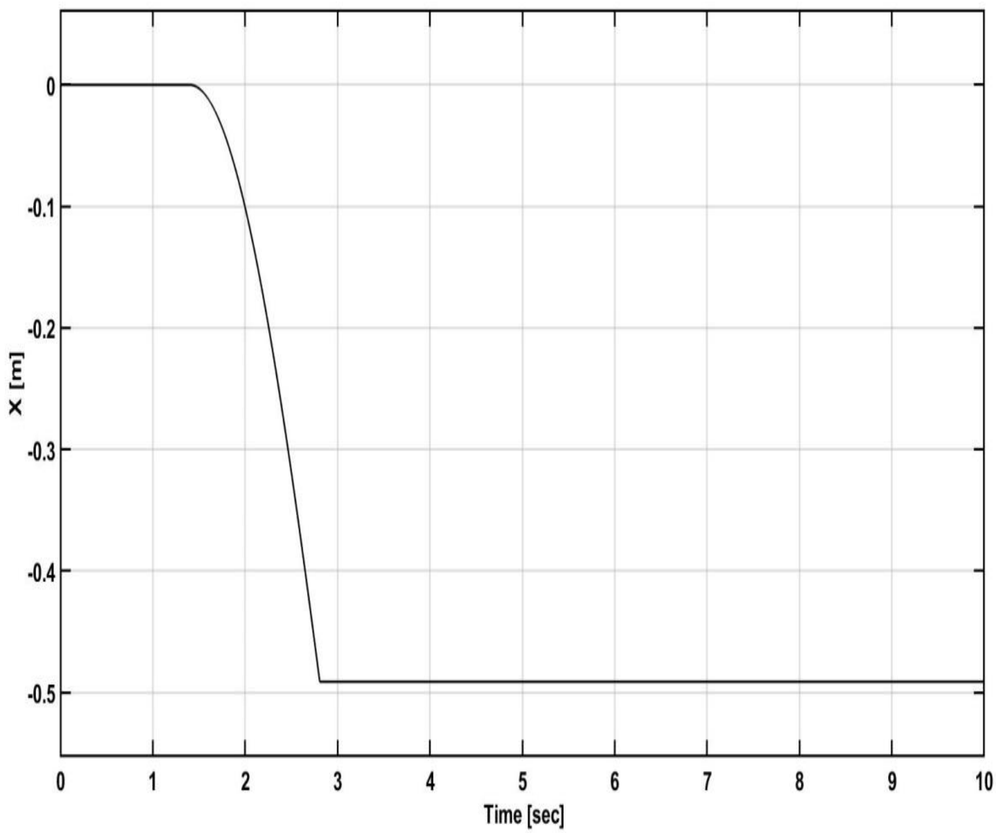
Figure 2. Rotation

The angle target is -2.355 (CW) rad which means -135 deg (CW). Actually the target angle is 225 deg (CCW) from the angle error definition and target point (-5,-5), but the value is larger than 135 deg (CW) which is from the fast rotation algorithm. So the fast rotation algorithm select -135 deg (CW) rotation.

In Figure 3-4, the moving control applied which are next step in the RAM action. Figure 3 shows the x movement and Figure 4 shows y movement. Like Figure 2, (a) is [8] and (b) is the proposed controller in the Figure 3 and 4. Both methods are exactly going straightly to the target point ((a) from 2s and (b) from 1.4s) because this is 2nd step (movement) after finishing 1st step (rotation) in the RAM action, which means the robot directs exactly toward the target point after finishing the rotation. Both are good tracking performance and [8] reaches to the target point at 5.3s and the proposed controller arrives at 2.8s, which are almost half time than the previous method.

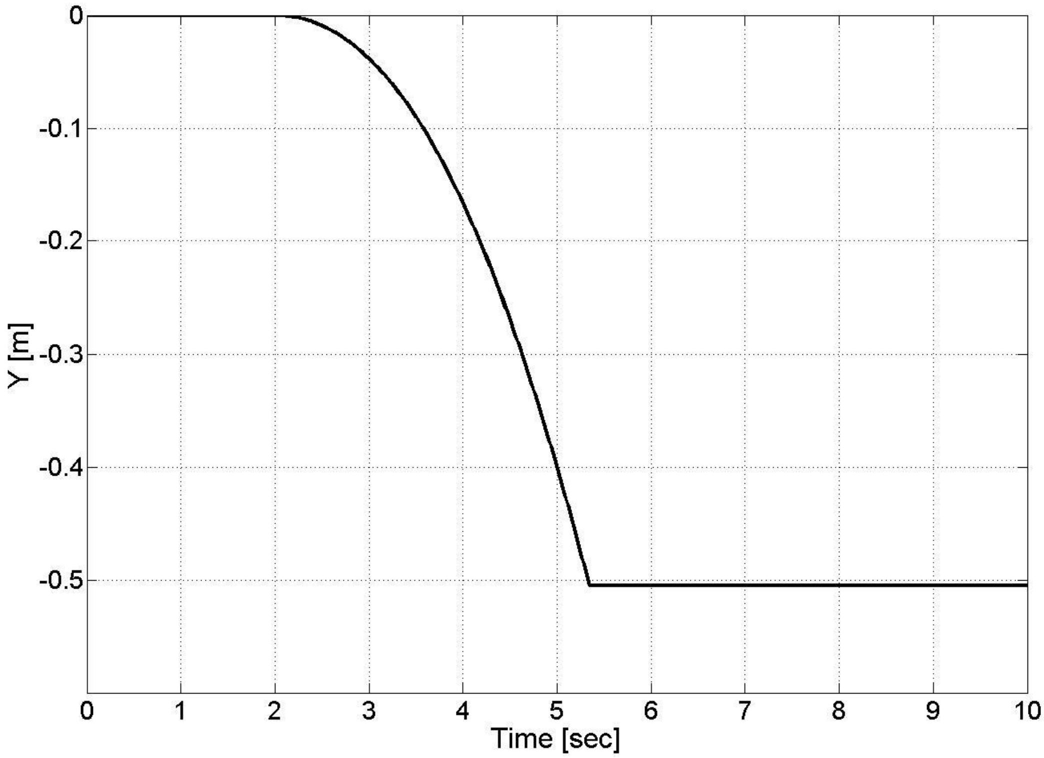


(a) Conventional SMC

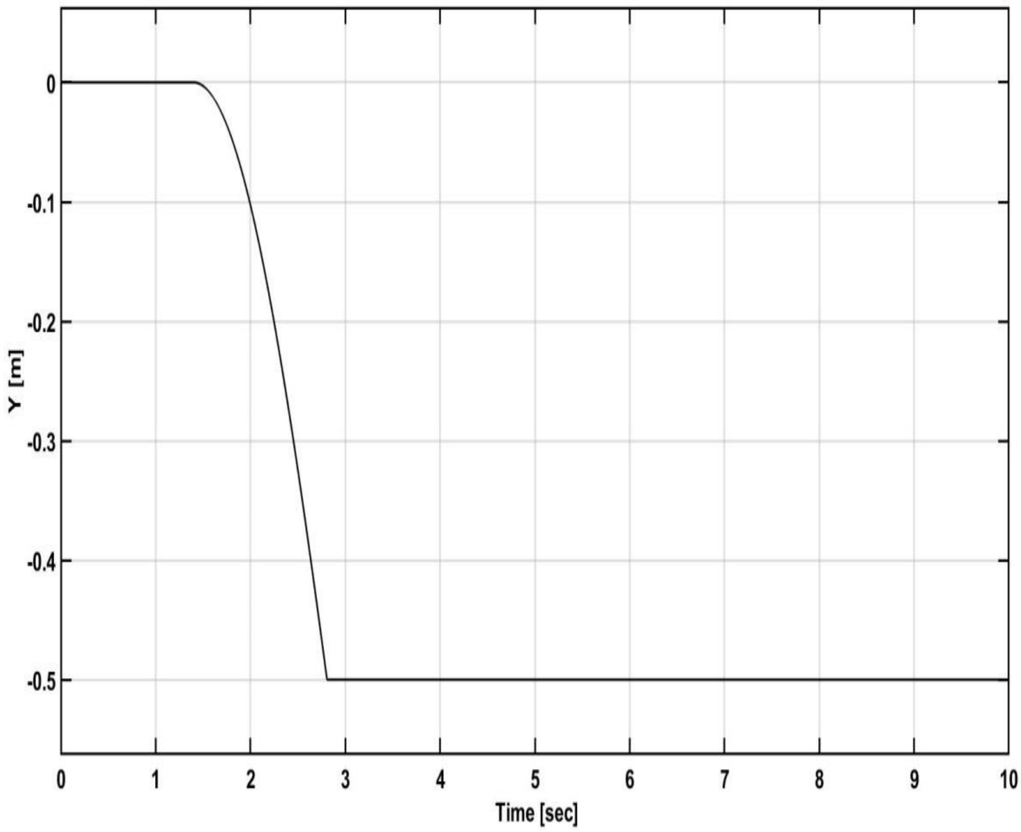


(b) Proposed distance controller

Figure 3. Movement(X-asix)



(a) Conventional SMC



(b) Proposed distance controller

Figure 4. Movement(Y-axis)

4. Conclusion

In this paper, we propose a sliding mode controller with a reaching mode with 2nd-order dynamics. The proposed controller has faster response characteristics than the PID controller or conventional sliding mode controller, and at the same time, the robust control is possible. In particular, the chattering of the conventional sliding mode controller can be improved by having the reaching mode applying the designed 2nd-order dynamic characteristics. The water strider robot to be applied has a lot of disturbances in that its operating environment is on the surface of the water, and it also needs a fast response characteristic of the controller due to the two-wheeled structure. The stability of the proposed controller is verified using the Lyapunov function, and the results are compared with the conventional sliding mode controller to verify the tracking performance. For comparison, the same target point was set and tested, and as a result, it was confirmed that the tracking performance was stably displayed and the response characteristic was faster than that of the conventional sliding mode controller.

ACKNOWLEDGMENT

This work was supported by research grants from the Daegu Catholic University in2019.

References

[1] R.B. Suter, O. Rosenberg, S. Loeb, H. Wildman, and J.H.J. Long, “Locomotion on the water surface: Propulsive mechanisms of the fisher spider dolomes triton,” Journal of Experimental Biology, vol. 200, pp. 2523-2538, 1997.
[2] D.L. Hu, B. Chan, and J.W.M. Bush, “The hydrodynamics of water stider locomotion,” Nature, vol. 424, pp. 553-666, 2003.
[3] R.B. Suter and H. Wildman, “Locomotion on the water surface: Propulsive mechanisms of the fisher spider DOLOMES TRITON,” Journal of Experimental Biology, vol. 200, pp. 2523-2538, 1997.
[4] S.H. Suhr, Y.S. Song, S.J. Lee, and M. Sitti, Biologically inspired water strider robot, Robotics: Science and Systems, MIT, Boston, 2005.
[5] Y.S. Song, S.H. Suhr, and M. Sitti, “Modeling of the supporting legs for designing biomimetic water strider robots,” in Proceedings of IEEE International Conference on Robotics and Automation, Orlando, pp. 2303-2310, 2006.
[6] Y.S. Song and M. Sitti, “STRIDE: A highly maneuverable and non-tethered water strider robot,” in Proceedings of IEEE International Conference on Robotics and Automation, Roma, pp. 980-984, 2007.
[7] K. Chun and B. Kim, “Simple RAM Control for Water Strider Robot,” International Journal of Engineering and Technology, vol. 7(3.7), pp. 149-152, 2018.
[8] K. Chun and B. Kim, “Robust RAM Control for WSR on the Water Surface,” International Journal of Engineering and Technology, vol. 7(3.7), pp. 303-306, 2018.
[9] K. Chun, Y.J. Lee, and B.Y. Choi, “A Variable Structure Controller with a PI-type Reaching Law,” Journal of Institute of Control, Robotics and Systems, vol. 3(3), pp. 214-218, 1997.