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Swing-Free Control of Mobile Harbor Crane with Accelerometer Feedback

Ki-Ru Park[1] and Dong-Soo Kwon[2]

[1] Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Korea
(Tel : +82-42-350-3082; E-mail: parkkr@robot.kaist.ac.kr)
[2] Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Korea
(Tel : +82-42-350-3042; E-mail: kwonds@kaist.ac.kr)

Abstract: Recently, as the amount of trade among nations has increased, a greater amount of the transport by ship is required and container ships have been enlarged to satisfy this requirement. However, there are some nations or harbors that have the problem of lack of sufficient area for the anchoring of large ships. To solve this problem, the Mobile Harbor (MH) has been proposed conceptually at KAIST. Since the MH should work on the sea, there are more problems than those of a common fixed harbor. One of the main problems is the swing of the payload, such as container boxes, as a result of the continuous sea-induced moving of the floating base. In this paper, we focus on reducing the swing of the crane due to external disturbances that are caused by the continuously moving base. We use an accelerometer to measure the swing angle of the crane and an observer is designed to estimate both the angle and the angular velocity of the swing. A sliding mode controller is also designed to stabilize the swing robustly with continuous bounded disturbance; the system simulation and experimental results are discussed.

Keywords: Swing-Free, Anti Sway, Crane control, Mobile Harbor, Accelerometer

1. INTRODUCTION

Recently, a global trend in the development of container ships and terminals has been the separation between hub harbors and middle feeder harbors. Therefore, increased productivity through innovation is required and the ability to transport large containers from ships will be the main competitive factor for the future of harbors and of the trade industry. However, there are some nations or harbors that will continue to have difficulties due to the lack of sufficient area for the anchoring of large ships. To solve this problem, the Mobile Harbor (MH) has been proposed conceptually at KAIST; an example of this MH is shown in Fig. 1. The concept of the MH is a floating platform that has the capability of transporting cargo to a local harbor from a large ship that is anchored in a nearby sea. Since the MH works on the sea, there are more problems than are found in common fixed harbors. One of the main problems is the swing of the payload, such as container boxes, due to the continuous sea-induced movement of the floating base.

In this study, we focused on reducing the swing of the crane that is caused by external disturbance due to the continuously moving base.

Fig. 1 The concept of the Mobile Harbor System

During the previous two decades, many studies have been performed on reducing the swing of cranes for the improvement of transport speed and safety. One of the main approaches is to make an adequate trajectory of the trolley that compensates for the swing caused by trolley's movement; this method is called Input Shaping or Command shaping [1-2]. The advantages of this method are a reduction of the swing without any sensors and the fact that this method is very robust with cranes that have a natural frequency that only depends on the length of the cable with constant gravity. However, this method cannot deal with any disturbances such as wind and a plant's uncertainty. Therefore, this approach cannot possibly be adequate to this problem, which deals with disturbances.

There are also feedback control approaches that use not only linear controllers [3] but also non-linear controllers [4-6]. The feedback approaches can control the swing with external disturbances including transporting of the trolley. Nevertheless, there is no consideration of continuous external disturbances, which should be considered in this problem. In addition, there have been few studies that have performed experiments with real cranes or modeled cranes that have flexible cables. The main reason why few experiments have been performed is the lack of a sensor that can measure swing.

Several sensors for measuring swing have been proposed. The most widely used sensors are vision based sensors [7]. However, vision based systems are very expensive and hard to work with in bad weather that causes lack of light. Furthermore, the permanency of such a sensor system for long-term use is not guaranteed. Another approach is using an inclinometer that can sense the tilt angle of the spreader that is tilted by the length difference of the fixed points of the cable between the trolley and the spreader [3, 8]. This approach is a very efficient and robust way to estimate the swing. However, if the differences between fixed points are very small or the length of the cable is very long relative to that difference, the tilt angle cannot be measured sensitively without high resolution and high accuracy of the inclinometer. In addition, common inclinometers have slow response time when measuring the swing angle and its angular velocity. Therefore, an expensive inclinometer is required to satisfy this problem.

In this paper, a tri-axial accelerometer is used for estimating the swing. It is economical and has a short response time. In the proposed method, the swing angle can be measured even when the difference of the fixed points between the trolley and spreader are almost zero and the length of the cable is relatively high compared to that difference. A device to observe and estimate the swing angle with the accelerometer is designed. A sliding mode controller is designed to reduce the swing due to the continuously moving base. Simulation and experimental results for the small model of the overhead crane are also included.

2. SYSTEM MODELING

An overhead crane is installed on a floating body. The displacement of the trolley caused by the rotational movement of the floating body is shown in Fig. 2. The floating body can be considered as relatively fixed in Cartesian space because of docking at both the target container and the ground of the sea. Therefore, the displacement of the center of gyration in absolute coordinates can be neglected.

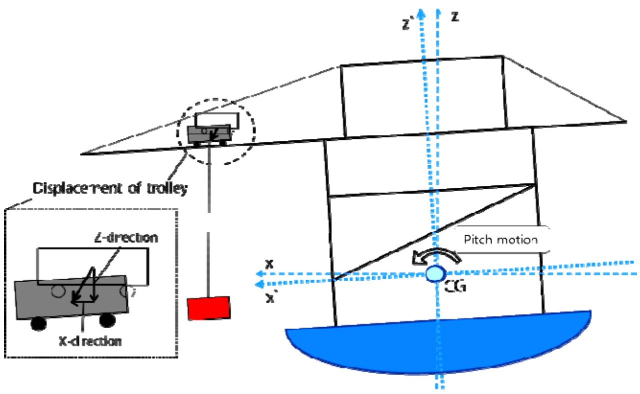


Fig. 2 Diagram of the crane's movement with rotational movement of the floating body

The displacement of the trolley can take place along both the x and the z axis. Although the displacement along the z-axis can also cause swing of the payload, this motion can be considered one of the disturbances of the control system. Actually, some of the motion can be compensated for by the posture control system that is proposed in the MH system to maintain system posture in absolute rotational coordinates. Thus, we only considered the displacement along the x-axis in this modeling.

The swing of the crane can be considered to be like a

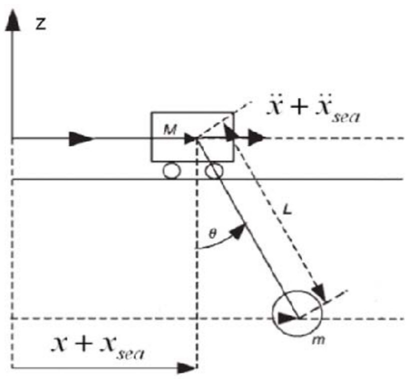


Fig. 3 Modeling of the crane dynamics with sea-induced base movement in a plane

spherical pendulum that has uncoupled dynamics with sufficiently small swing angle. Therefore, we considered the swing of the crane in a plane as shown in Fig. 3 to simplify the problem. A solution in one plane can be applied to the other plane independently.

The x indicates the relative distance between the crane base and the trolley; the x_{sea} is the displacement of the trolley caused by sea waves with respect to the absolute position, as explained before in Fig. 1. We assumed that there is no friction or air resistance and that the cable is always stretched, so that it can be considered as rigid. To remove the effect of the variable mass of the payload, the trolley system is considered as a servo system that can internally control the motor in order to make it follow the desired acceleration; its response time is relatively higher than the response time of the crane dynamics. Therefore, the control input of the trolley can be treated like the acceleration of the trolley, as described in the equation below.

$$u = \ddot{x} \tag{1}$$

From these assumptions, the derived system equation is,

$$\ddot{x}_{abs} = u + \ddot{x}_{sea} \tag{2}$$

$$L\ddot{\theta} + \cos(\theta)\ddot{x}_{abs} + g\sin(\theta) = 0 \tag{3}$$

The value x_{abs} is the combination of the relative displacement of the trolley from the base and the displacement of the trolley caused by the sea in absolute coordinates.

The above equations can be translated into state-space form by setting state variables as,

$$x_1 = x_{abs},\ x_2 = \dot{x}_{abs},\ x_3 = \theta,\ x_4 = \dot{\theta} \tag{4}$$

The full equation can be derived based on the state variables.

$$\begin{aligned}\dot{x}_1 &= x_2\\ \dot{x}_2 &= u + \delta\\ \dot{x}_3 &= x_4\\ \dot{x}_4 &= -\frac{1}{L}(g\sin x_3 + u\cos x_3 + \delta\cos x_3)\end{aligned} \tag{5}$$

In this formulation, we have assumed that the state of x_1 can be measured by the gyro sensor, the tilt sensor attached on the center of the gyration point, and the encoder information of the servo system. The delta is the uncertain acceleration along the x-axis caused by the rotation of the base and other disturbances in the system such as displacement along the z-axis of the trolley.

3. OBSERVER DESIGN WITH ACCELEROMETER FEEDBACK

3.1 Design of High-Gain Observer

Full-state feedback control is required to control the swing of the payload caused by uncertain disturbances. In the previous state-space formulation, states x_3 and x_4, which are related to the swing angle, should be estimated by sensors. In this study, a tri-axial accelerometer is chosen, as explained in the introduction.

The swing angle is extracted from the distributed value of the accelerometer between the gravity direction (z-axis) and the x-axis, as indicated in Fig. 4.

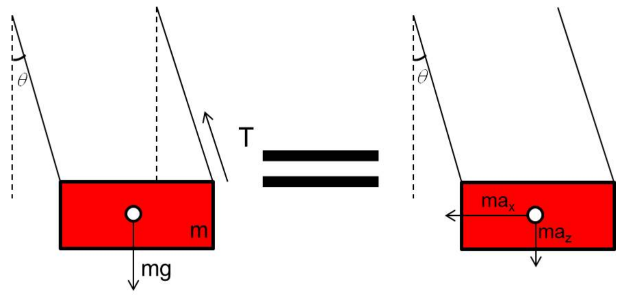


Fig. 4 Distributed value of the accelerometer between the z and the x directions to measure swing angle

From the above figure, the swing angle *theta* can be derived by Newton's second law, as follows:

$$\sum F_x = T\sin\theta = ma_x \,, \tag{6}$$

$$\sum F_y = T\cos\theta - mg = ma_z \,. \tag{7}$$

Therefore, the swing angle *theta* is

$$\theta = \tan^{-1}\left(\frac{a_x}{a_z + g}\right) \cdot \tag{8}$$

In this equation, the acceleration of the trolley is automatically included by the tension T so that the swing angle can be independently observed without any pre-knowledge of such elements as the trolley's movement, the hoist length or the trolley's structure.

A robust estimate of the angle and the angular velocity of the swing can be achieved through the design of the observer. Based on system equation (5), a high gain observer is designed with an abstracted angle of swing, as follows:

$$\dot{\hat{x}}_3 = \hat{x}_4 + \frac{\alpha_1}{\varepsilon}(y - \hat{x}_3)\,, \tag{9}$$

$$\dot{\hat{x}}_4 = -\frac{g\sin\hat{x}_3}{L} - u(\cos\hat{x}_3 / L) + \frac{\alpha_2}{\varepsilon^2}(y - \hat{x}_3)\,. \tag{10}$$

where $\varepsilon > 0, \varepsilon \ll 1 \text{ and } \alpha_1, \alpha_2 > 0$ are constants to be chosen. Then, the error dynamics, $e = \hat{x} - x$, are obtained as follows:

$$\begin{aligned} \dot{e}_3 &= e_4 - \frac{\alpha_1}{\varepsilon} e_3, \\ \dot{e}_4 &= -\frac{\alpha_2}{\varepsilon^2} e_3 - \frac{g}{L}(\sin\hat{x}_3 - \sin x_3) \\ &\quad - \frac{u}{L}(\cos\hat{x}_3 - \cos x_3) \end{aligned} \tag{11}$$

The nonlinear term in equation (11) is the bounded value, as follows:

$$\begin{aligned} &\left| -\frac{g}{L}(\sin\hat{x}_3 - \sin x_3) - \frac{u}{L}(\cos\hat{x}_3 - \cos x_3) \right| \\ &\qquad \le \left|\frac{g}{L}\right| |2| + \left|\frac{u}{L}\right| |2| \end{aligned} \tag{12}$$

The control input u is also bounded by system limitations, so the nonlinear term is bounded by a simple constant value defined by the maximum control input, hoist length and gravity.

Then, the stability and convergence of the error dynamics can be shown by following the Lyapunov function:

$$V(e_3, e_4) = \frac{\alpha_2}{2\varepsilon^2} e_3^{\,2} + \frac{e_4^{\,2}}{2}\,. \tag{13}$$

Then,

$$\begin{aligned} \dot{V} &= \frac{\alpha_2}{\varepsilon^2} e_3 (e_4 - \frac{\alpha_1}{\varepsilon} e_3) + e_4 \{ -\frac{\alpha_2}{\varepsilon^2} e_3 \\ &\quad - \frac{g}{L}(\sin\hat{x}_3 - \sin x_3) - \frac{u}{L}(\cos\hat{x}_3 - \cos x_3) \} \\ &\le -\frac{\alpha_1\alpha_2}{\varepsilon^3} e_3^{\,2} + C|e_4|\,. \end{aligned} \tag{14}$$

The value C is the constant value defined by the system constraints, as elaborated in equation (12). As shown in the observer above, the observer parameters will be designed such that $\varepsilon > 0, \varepsilon \ll 1 \text{ and } \alpha_1, \alpha_2 > 0$ so that the value of $\alpha_1\alpha_2 / \varepsilon^3$ is sufficiently higher than *C*. Therefore, the value $\dot{V}$ is negative except for the point $e_3 = e_4 = 0$. It can be said that the observer is uniform, asymptotic and stable.

3.2 Simulation

The simulation to verify the observer was performed using MATLAB Simulink. The observer dynamics equations (9) and (10), and system dynamics equation (5) are applied numerically in the simulation.

The sampling time of the simulation is 0.001 second; white measurement noise was added to verify that the observer can be robust against accelerometer noise. The results for certain observer parameters and initial conditions are shown in Fig. 5. From these results, it can be said that the convergence speed of the observer value is sufficiently faster than the system dynamics, which have a value of about 0.5Hz.

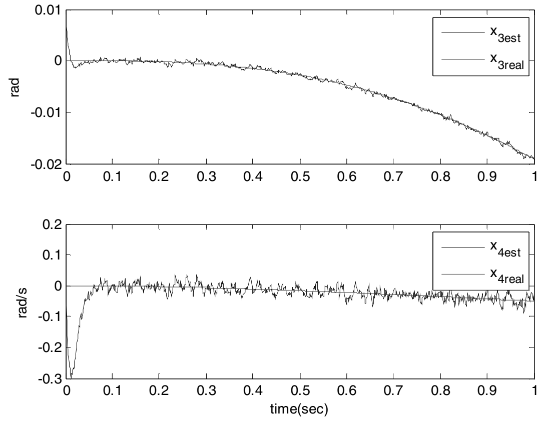


Fig. 5 Observer simulation results of state x_3 and x_4, where $\varepsilon = 0.01, \alpha_1 = 2, \alpha_2 = 1, L = 5, \hat{x}_{3,t=0} = 0.01$, $\hat{x}_{4,t=0} = 0.1, x_{3,t=0} = 0.1, other\ I.C = 0$.

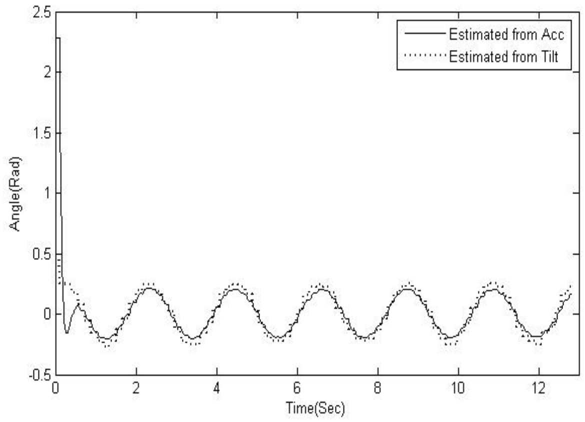


Fig. 6 Experimental results of proposed observer from accelerometer value and values derived from tilt sensor.

3.3 Experiment

The validity of the proposed observer is also verified by experiment. We used a miniature crane model that will be described in section 5; the tri-axial accelerometer, LIS3LV02D, has a sensitivity of more than 0.001g.

We collected accelerometer data from the 12-bit AD converter after low pass filtering. The accelerometer was attached on the top side of the payload and the communication between the PC and the accelerometer was performed by Bluetooth wireless communication. The tilt sensor, DAS M1, was also attached on the top of the payload, in order to compare the estimated angle from the accelerometer. We estimated the swing angle from the tilt sensor by the geometry derived in the studies performed by Kim et al [3]. The experimental data was collected during the oscillating motion of the payload. All of the parameters are set as the same values as those in the previous simulation. As shown in Fig. 6, the observer values converged quickly to the exact values that were derived from the tilt sensor; the observer followed those values safely. From these results, it can be said that the performance of the observer is sufficiently faster than the system dynamics and that the stability of the observer has also been experimentally proved.

4. DESIGN OF SLIDING MODE CONTROLLER

4.1 Control of the underactuated system

To control the crane during a non-linear disturbance, a robust controller for the system should be designed. However, it is out of the scope of this study to propose a new type of controller to control the crane system. Many studies have already been performed that have looked at the control of general underactuated systems, which is the same type of system as our crane system [5, 6]. Among those studies, non-linear controller approaches have been found to be more adaptable for our case, which has non-linear, bounded disturbances as well as a non-linear system. Therefore, we refer to the approach that was performed by Wang et al. [6] using a hierarchical sliding-mode controller (HSMC). This method makes it easy to control the trade-off problem between the movement of the trolley to a target point and the smaller angle of swing due to the simple surface weight factors such as alpha and beta. Detailed descriptions of the controller and proof of the stability, which are contained in the Wang's study, are omitted in this paper.

4.2 Design of hierarchical sliding mode controller

Parameters that were defined in Wang's study can be obtained from our modeled crane system, as follows:

$$f_1 = -\ddot{x}_d\,,\ b_1 = 1, d_1 = \delta, f_2 = -\frac{g\sin x_3}{L},\quad b_2 = -\frac{\cos x_3}{L},\ d_2 = -\frac{\delta\cos x_3}{L} \tag{15}$$

The first-level sliding surface pair is set as follows:

$$s_1 = c_1 e_1 + e_2 \tag{16}$$

$$s_2 = c_2 x_3 + x_4 \tag{17}$$

where $e = x_1 - x_d$, x_d is the desired position of the trolley in absolute coordinates. Then, the second-level sliding surface of the HSMC is also constructed as follows:

$$S = \alpha s_1 + \beta s_2 \tag{18}$$

From the surface pairs, the equivalent control law is derived for each surface, as follows:

$$u_{eq1} = \ddot{x}_d - c_1 x_2 \tag{19}$$

$$u_{eq2} = \frac{-g\sin x_3 + Lc_2 x_4}{\cos x_3} \tag{20}$$

The switching control law is also given as follows:

$$u_{sw} = -(\alpha - \beta\cos x_3 / L)^{-1}[-u_{eq1}\beta\cos x_3 / L + \alpha u_{eq2} + \eta\,\mathrm{sgn}(S) + kS] \tag{21}$$

Then, we can set the control input u as follows:

$$u = u_{eq1} + u_{eq2} + u_{sw} \qquad (22)$$

If we set $\eta > \sup|\alpha d_1 + \beta d_2|$ in equation (21), the stability of the system is proved by Lyapunov stability [6]. Therefore, the controller derived in equation (22) can be used to control the crane system.

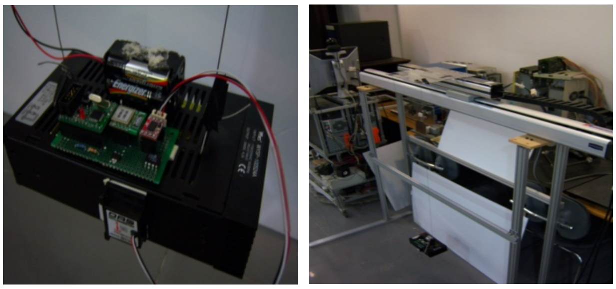


Fig. 7 Accelerometer and tilt sensor attached on the payload (left); miniature crane model (right)

5. EXPERIMENT & RESULT

A small size crane model has been constructed to verify both the designed observer and the designed controller, as shown in Fig. 7. The system was composed of two linear actuating robots that were able to independently realize both the sea-induced base movement and the trolley's relative movement with respect to the base. The payload was attached to the trolley with two wires so that the swing characteristics were sufficiently similar to those of the real container crane system. Sea induced movement was applied using a simple sinusoidal function with specific amplitude and frequency. Table 1 shows the system parameters for this experiment. The accelerometer was attached on the top of the payload, the same as in the observer experiment. Observer parameters are the same as those in the previous experiment, in section 3. The system was controlled every 10ms with the same sampling rate data from the accelerometer. During the control experiment, the maximum input value was limited to less than $2m/s^2$. Table 2 shows the control parameters of the HSMC that were used in this experiment.

Table 1 System parameters.

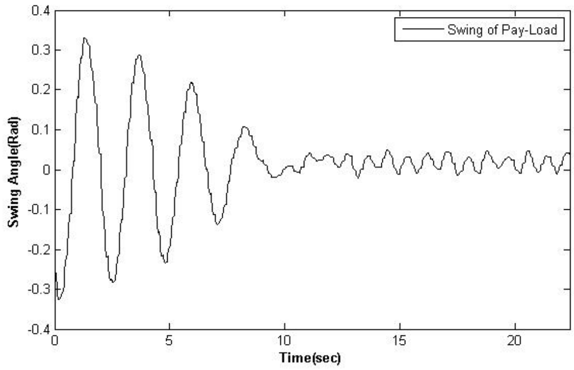
Parameter	Value
L	1m
g	$9.8m/s^2$
Sea wave height	0.02m
Sea wave frequency	0.5Hz

Table 2 Control parameters.

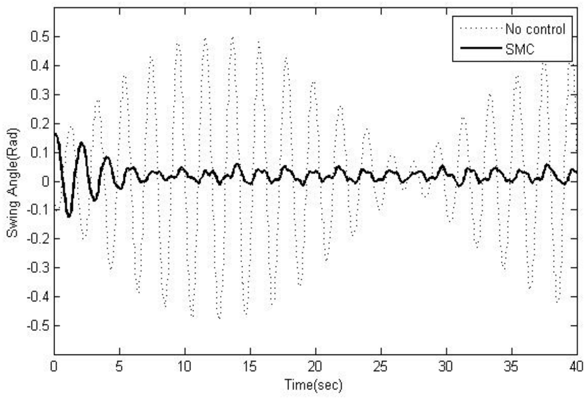
Parameter	Value
c_1	1
c_2	2
α	0.5
β	2
η	3
K	0.1

The experiment was performed in two ways. One way was to proceed without sea wave motion and another was to proceed with sea wave motion. The sinusoidal sea wave motion was executed by the upper linear robot and the trolley's motion was executed by the lower linear robot (larger one). Experimental results are shown in Fig. 8.

From graph (a) in Fig. 8, it can bee seen that the swing of the payload is reduced after about ten seconds. Although the control parameters were not optimized at this point, the stability of the controller and the validity of the proposed observer were proved. It is shown that there is small residual vibration after convergence. This is because of the sensory noise of the accelerometer and the chattering problem of the sliding mode control. The actual swing angle of the payload was negligible. The robustness of the control system was also proved, as shown in graph (b) in the Fig. 8. Although the swing of the payload is periodically increased to a high angle without the controller, the controller can maintain the swing angle in the negligible areas. The robustness of the controller was also tested by external disturbance, which are caused by humans during sea induced motion. In such cases, the swing angle was also found to converge safely to zero. This means that the proposed control system is robust against any external disturbances such as winds and sea waves.



(a)



(b)

Fig. 8 Experimental results for the whole control system: (a) SMC without sea induced motion, (b) Response of SMC and No control with sea induced motion

6. CONCLUSION & FURTHER WORK

In this study, we verified that an accelerometer can be used to estimate the swing of the crane without any pre-knowledge about the crane to be controlled. This conclusion means that the proposed approach can be easily adapted to other crane areas that use symmetric wires like those in our system.

An observer was proposed to estimate the swing angle of the crane with distributed values of the accelerometer between the z and the x axis. The validity of the observer was proved by both simulation and experiment.

In addition, a controller was designed to stabilize the swing of the crane with sea-induced base movement, which can be considered as a continuous non-linear disturbance. The validity of the proposed method was also proved with a real, miniature crane.

However, the parameters of the designed controller were not optimized for efficient tasks, which could have a trade-off between smaller swing angle and faster transport. In addition, an experiment on real water is also needed, because the real movement of the base is not sinusoidal, as was assumed in this study. We will consider these important aspects in future work.

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