Motion control considering the effects of cable deflection caused by gravity and fluid resistance for Cable-restricted Underwater Vehicle

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***Abstract*—For efficiently observing the marine resources, we developed an observation device with low operational risk and a wide observable area. The observation device consists of a seafloor station and an underwater vehicle tethered by a cable. As experimental validation result, we found that the vehicle tethered by a cable was able to navigate with an error of less than 0.071m compared with the planned trajectory. The vehicle is controlled using the cable restraint condition and the forces exerted by the thrusters while considering the effect of the cable slack, without the need of any feedback signal.**

Keywords*—*Long-term observation, Cable-restricted Underwater Vehicle, Self-localization, Cable slack

I. INTRODUCTION

Marine resources such as hydrothermal deposit, and methane hydrate are in Japan's exclusive economic zone [1]. For investigating or observing the resources, Untethered underwater vehicles (AUVs) are used as practical tools [2][3][4]. However, in case of hardware or software failure, there is the risk to lose the AUVs. Moreover, it is difficult for AUVs to keep observing the same points during the exploration. For these reasons, long-term data of the resource can be not obtained because the AUVs cannot be used frequently for the investigation. As a method to obtain the long-term data, the operation of the AUVs with underwater stations has been proposed [5][6]. In these methods, when the battery capacity of the AUVs is low, the AUVs dock at an underwater station for charging. However, as we said before, potential hardware or software failure make risky these explorations. In order to obtain long-term data of the resource, the authors developed an observation device with low operational risk and a wide observation area [7]. Our device can observe the same point using an underwater vehicle tethered by a cable. In this paper, we explain the motion control of the underwater vehicle considering the effects of cable deflection, and we show the experimental results to evaluate the self-localization of the underwater vehicle tethered by a cable.

II. LONG-TERM OBSERVATION METHOD

A. Overview

The observation device proposed consists of an underwater station and an underwater vehicle, as shown in Fig.1. The underwater station is equipped with batteries for supplying the power to the vehicle through a restraint cable, as in Fig.1. The underwater vehicle is tethered to the underwater station by the reel cable. By keeping the same altitude as the reel of the station and applying a constant tension to the cable, the underwater vehicle can observe a circular area whose radius is the length of the unwound cable. By using the tethering restraint, the underwater vehicle can navigate the same trajectory with only simple motion control without self-localization data based on DVL or INS and route tracking control based on waypoints.

B. Trajectory for Underwater vehicle

The trajectory of the underwater vehicle tethered by a cable is shown in Fig.2. It navigates away from the reel by unwinding the cable, and then it comes closer again by winding the cable on the reel. To return to the reel, the vehicle changes the thrusters direction, and winds again the cable while approaching the starting position. During this operation, it observes the same points observed while unwinding the cable. When the length of the cable being unwound is maximum, the trajectory of the vehicle is a semicircle when switching from winding the cable to unwinding it or from unwinding it to winding it. To plan the trajectory of the vehicle, we constructed a theoretical formula based on the involute curve. The involute curve is the trajectory of the endpoint of a cable when the cable unwinds from a circular reel called the basic circle, and the position of the end point $\boldsymbol{p_i} = [x_i \quad y_i]^T$ is expressed by the following equation using the radius a of the basic circle and the angle θ from the initial position.

$$\boldsymbol{p_i} = a\begin{bmatrix} 1 & \theta \\ -\theta & 1 \end{bmatrix}\begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} \quad (1)$$

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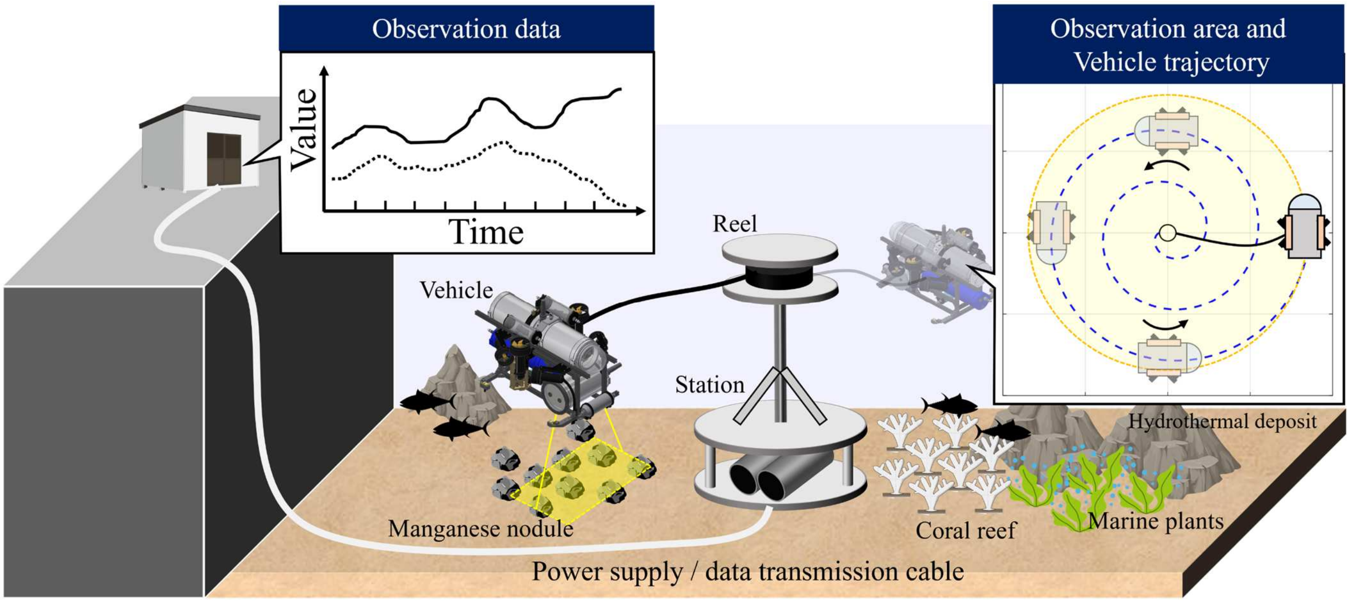

Fig. 1. Overview of long-term observation device using Cable-tethered Underwater Vehicle

In Eq. (1), the radius a of the basic circle is constant. In this research, we considered that the radius a of the basic circle changes with the cable diameter d_{ca} depending on the number of cable windings n. Therefore, the radius a_i of the basic circle is expressed by the following equation.

$$a_i = n \cdot d_{ca} + r_b \tag{2}$$

Here, r_b is the radius of the reel mounted on the underwater station, for which we chose a value that satisfies an allowable bending radius of the cable. During the navigation, the vehicle monitors the seafloor. The pattern of the images recorded is designed to have an overlapping area between adjacent positions, for example when the vehicle passes from two points along the same radial direction but at a different radius length. We also considered that the length of the cable changes depending on the number of cable windings n. Considering that the cable length L_{wi} when winding it and the cable length L_{uwi} when unwinding it change by the circumference length of the basic radius depending on n and the angle θ, it is expressed by the following equations.

$$L_{wi} = L_m - 2\pi\left\{n \cdot r_b + \frac{1}{2}n(n-1)d_{ca}\right\} \tag{3}$$

$$L_{uwi} = 2\pi n\left[r_b + \left\{N - \frac{1}{2}n(n-1)\right\}d_{ca}\right] \tag{4}$$

Here, L_m is the maximum length of the cable, which is the dominant parameter for the observation range of our device. By applying Eq. (2) through Eq. (4) to Eq. (1), the position $p_{wi} = [x_{wi} \quad y_{wi}]^T$ of the tethered underwater vehicle when winding the cable and the position $\boldsymbol{p_{uwi}} = [x_{uwi} \quad y_{uwi}]^T$ of the vehicle when unwinding the cable are expressed by the following equations.

$$\boldsymbol{p_{wi}} = \begin{bmatrix} a_i & -(L_{wi} - a_i\theta) \\ (L_{wi} - a_i\theta) & a_i \end{bmatrix}\begin{bmatrix}\cos\theta \\ \sin\theta\end{bmatrix} \tag{5}$$

$$\boldsymbol{p_{uwi}} = \begin{bmatrix} a_i & -(L_{uwi} + a_i\theta) \\ (L_{uwi} + a_i\theta) & a_i \end{bmatrix}\begin{bmatrix}\cos\theta \\ \sin\theta\end{bmatrix} \tag{6}$$

Furthemore, the position $\boldsymbol{p_{ci}} = [x_{ci} \quad y_{ci}]^T$ of the vehicle when winding the cable or unwinding the cable is expressed by the following equation using the maximum length of the cable L_m and the angle θ.

$$\boldsymbol{p_{ci}} = L_m\begin{bmatrix}\cos\theta \\ \sin\theta\end{bmatrix} \tag{7}$$

In Eq. (7), the range of θ is from 0 deg to 180 deg because the trajectory of the vehicle when winding the cable or unwinding the cable is a semicircle with the radius of the maximum length of the cable.

C. *Required Thrust force for motion control*

The underwater vehicle used in this research navigates without waypoint or sensor information from DVL or INS. We describe the required thrust of the vehicle which is tethered by a cable in surge direction and in sway direction to navigate without sensor information like DVL or INS. The required thrust in the surge direction F_x is the dominant parameter for the vehicle's velocity, and this parameter must be set so that the images from the camera mounted on the vehicle satisfy a certain overlap ratio. The required velocity V_x of the vehicle for the captured image to satisfy a certain overlap ratio is expressed by the following equation using the shooting range d_s of the camera, the shooting cycle T_s of the camera, and overlap ratio α_{OL}.

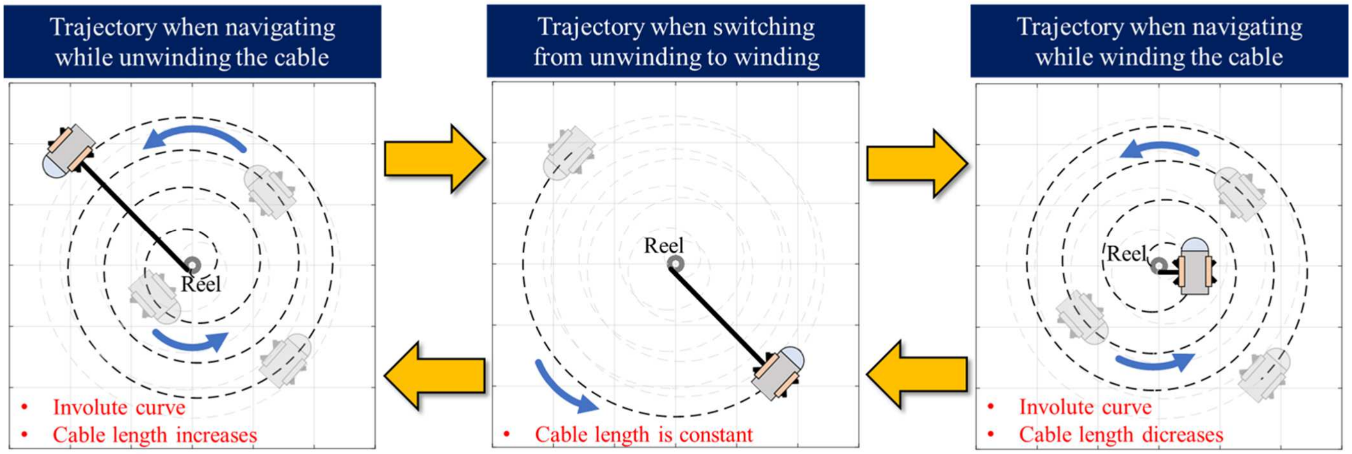

Fig. 2. Trajectory of Cable-restricted Underwater Vehicle

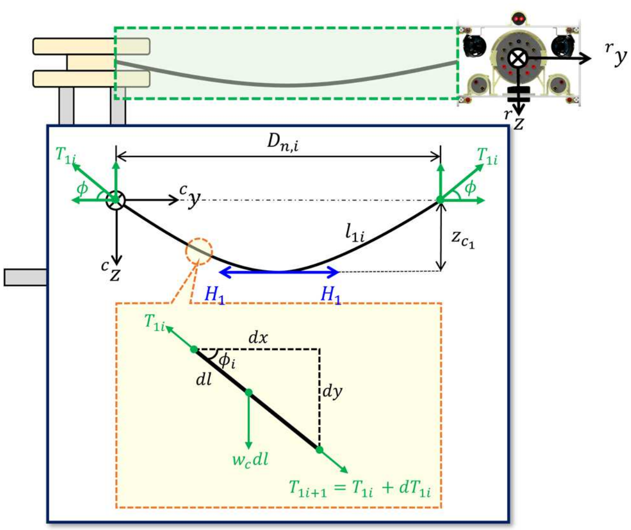

Fig. 3. Cable tension due to the gravity

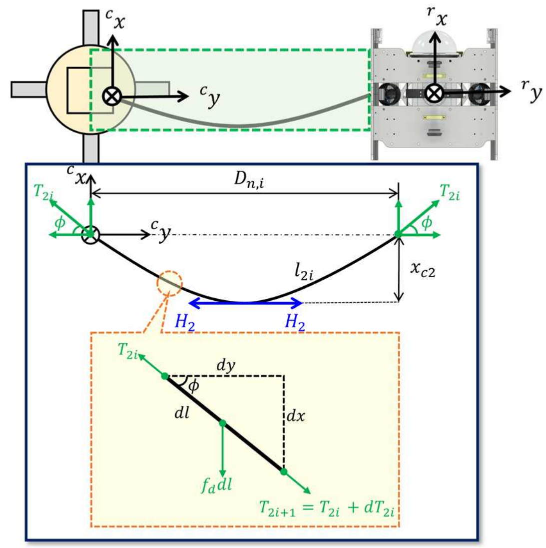

Fig. 4. Cable tension due to fluid resistance

$$V_x \leq \frac{d_s(1-\alpha_{OL})}{T_s} \tag{8}$$

By substituting the velocity V_x of the vehicle obtained by Eq. (8) into equation of motion, the required thrust in the surge direction F_x is expersssed by the following the equation.

$$F_x = D_x|V_x|V_x \tag{9}$$

Here, D_x is the fluid drag force of the vehicle, and this parameter estimated from the results of the limit cycle test. The required thrust in the sway direction F_y is the dominant parameter for the positioning accuracy of the vehicle. In order to determine this parameter, we focused on the deflection generated in the cable. The weight and fluid drag of the cable increases with its length being unwound, so the deflection which generated in the cable increases. It is difficult for the vehicle to follow the trajectory calculated by Eq. (5) to Eq. (6) because the positioning accuracy of the vehicle deteriorates by increasing the deflection of the cable. The cable model of the underwater vehicle tethered to the underwater station is shown in Fig.3 and Fig.4. Based on the assumptions that the flexibility of the cable is not considered, the deflection of the cable is ideal, and the velocity of the vehicle is very slow and static, the cable can be considered to have a catenary shape [8]. The deflection z_{c1} and the length which is unwound from the reel l_{1i} generated by the gravity is expressed by the following equations using weight per unit length w_c of the cable in water, the horizontal tension H_1 at the lowest point of the cable, and the distance $D_{n,i}$ between the center of the vehicle and the reel.

$$z_{c1} = \frac{H_1}{w_c}\left[\cosh\left(\frac{w_c D_{n,i}}{2H_1}\right) - \cosh\left\{\frac{w_c}{H_1}\left(\frac{D_{n,i}}{2} - y\right)\right\}\right] \tag{10}$$

$$l_{1i} = \frac{H_1}{w_c}\left[\sinh\left(\frac{w_c D_{n,i}}{2H_1}\right) - \sinh\left\{\frac{w_c}{H_1}\left(\frac{D_{n,i}}{2} - y\right)\right\}\right] \tag{11}$$

The required thrust f_{y1} of the vehicle in the sway direction, for preventing large deflections due to the gravity, is expressed by the following equation.

$$f_{y1} = \sqrt{\frac{{w_c}^2 y^2}{12({l_1}^2 - {z_{c1}}^2 - y^2)}} \tag{12}$$

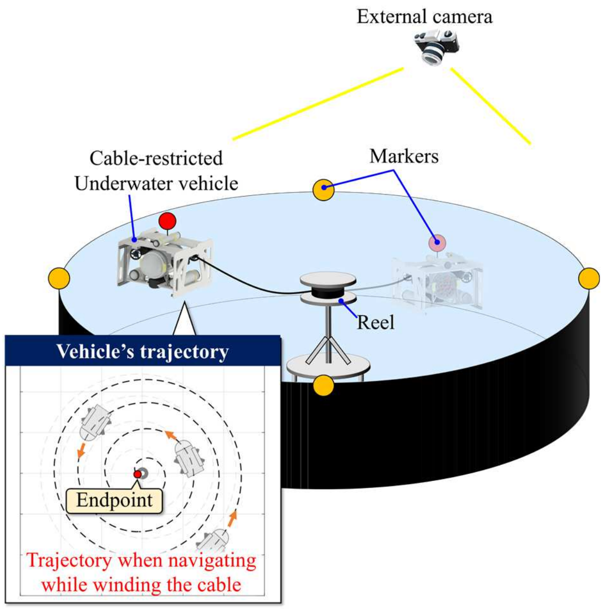

Fig.5. Experimental setup

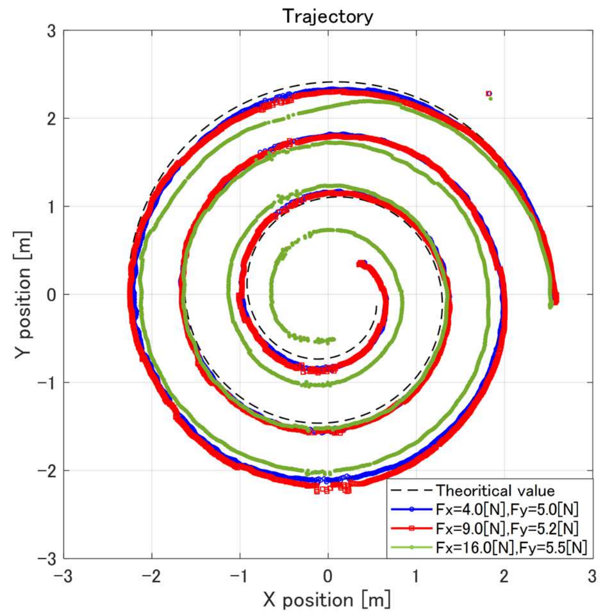

Fig. 6. Trajectory result of the vehicle

TABLE I. THRUST VALUE FOR UNDERWATER VEHICLE

	Thrust value for vehicle		
Surge thrust value F_x	4.0N (0.1m/s)	9.0N (0.15m/s)	16.0N (0.2m/s)
Sway thrust value F_y	5.0N	5.2N	5.5N

The deflection x_{c2} and the length which is unwound from the reel l_{2i} generated by the fluid drag force is expressed by the following equation using the horizontal tension H_2 at the lowest point of the cable, the fluid drag coefficient C_D, the density of water ρ_w, the diameter of the cable d_c, the velocity V_x of the vehicle, the distance $D_{n,i}$ between the center of the vehicle and the reel.

$$x_{c2} = -\frac{1}{2H_2} C_D \rho_w d_c \left(\frac{V_x}{D_{n,i}}\right)^2 \left(\frac{1}{12} y^4 + \frac{D_{n,i}^3}{24} y\right) \tag{13}$$

$$l_{2i} = y\sqrt{\frac{1}{2304{H_2}^2}\left(C_D \rho_w d_c {V_x}^2\right)^2 {D_{n,i}}^4 + 1} \tag{14}$$

The required thrust f_{y2} of the vehicle in the sway direction or preventing large deflections due to fluid drag force is expressed by the following equation.

$$f_{y2} = \frac{1}{48\sqrt{l_{2i}^2 - y^2}} C_D \rho_w d_c {V_x}^2 {D_{n,i}}^2 y \tag{15}$$

Therefore, the required thrust F_y of the vehicle in the sway direction considering the effects of the deflection by the gravity and fluid drag force is the sum of the thrust value obtained from Eq. (12) and Eq. (15).

TABLE I. POSITION ERROR OF THE VEHICLE AGAINST THEORITICAL VALUE

Thrust values for vehicle	***Root Mean Square Error (RMSE)***		
	Position X [m]	Position Y [m]	Distance [m]
$F_x = 4.0$[N], $F_y = 5.0$[N]	0.045	0.045	0.045
$F_x = 9.0$[N], $F_y = 5.2$[N]	0.045	0.055	0.071
$F_x = 16.0$[N], $F_y = 5.5$[N]	0.127	0.127	0.182

III. EXPERIMENTAL VALIDATION

To evaluate the trajectory of the underwater vehicle tethered by the cable based on the cable constraint and motion control, we carried out some experiments in a water tank with a diameter of 6.0 m and a depth of 1.0 m. We placed markers for measuring the trajectory of the vehicle around the water tank and on the vehicle as shown in Fig.5, and we obtained the position by motion tracking based on the image data the through an external camera. We placed a reel device with a radius of 128 mm in the center of the water tank, and the vehicle was tethered by a cable with 12 mm in diameter and 2.7 m in length. In this experiment, we used the parameters shown in Table1 as thrust value inputs to the vehicle and we measured the trajectory of the vehicle from the starting position until it reached the reel. As a starting position, we selected the position, where the cable wound on the reel in advance.

Fig.6 shows the trajectories calculated from Eq. (5) and measured by motion tracking. When the thrust value of the vehicle input by the operator $F_x = 4.0$ N, $F_y = 5.0$ N and $F_x = 9.0$ N, $F_y = 5.2$ N, the vehicle was able to navigate while winding the cable around the reel device, and the trajectory was able to follow the planned route calculated from Eq. (5). On the other hand, when the thrust value of the vehicle input by the operator $F_x = 16.0$ N, $F_y = 5.5$ N, the trajectory was significantly different compared with the planned route calculated from Eq. (5). This is because when the vehicle navigates, the cable wound around the part supporting the device instead of the reel. A possible reason why the cable cannot wind around the reel, is that the required thrust in the sway direction was the dead zone of thrusters, and the vehicle could not output enough thrust to prevent the deflection of the cable. Table2 shows the root mean square error (RMSE) of the self-localization compared with the theoretical position calculated from Eq. (5) when the thrust input to the vehicle is changed. The RMSE of the distance at $F_x = 4.0$ N, $F_y = 5.0$ N and $F_x = 9.0$ N, $F_y = 5.2$ N, when the vehicle was able to navigate with the cable wound around the reel, was less than 0.071 m. It can be confirmed that the vehicle was able to follow the planned route with high accuracy, by using only the cable restraint condition and motion control.

IV. CONCLUSION

In order to obtain long-term data of the marine resources, we have developed an observation device that can observe a wide area with lower operational risk than existing investigation methods. In this paper, we proposed a method using the underwater vehicle tethered by a cable to navigate with only the cable restraint condition and motion control, and explained the required thrust for the vehicle to prevent the deflection of the cable. The results of the evaluation experiment showed that the vehicle can navigate with an error of less than about 0.07 m compared with the planned route when the cable can wind around the reel and can navigate using only cable restraint condition and motion control without sensor data from DVL or INS.

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