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A Study on the Selective Guidance Scheme for Remote/Autonomous Retrieval of Underwater Platform

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Abstract : The path guidance method is one of important technologies for autonomous navigation system. The localization errors in structured environments may bring about the path-following error; it can be caused the underwater platform such as AUV collision with a structure and the path generation failure. In this paper, the selective guidance method is proposed to solve these guidance problems. The suggested method optionally used both the LOS guidance and steering control in direction of cross-track error. Generally, the AUV used the LOS guidance method for steering control. However, the AUV conducts the steering control in direction of cross-track error if the path error is bigger than threshold value (turning radius of AUV). The proposed method was verified by comparing with the conventional LOS guidance method at real sea environment, and it showed the satisfactory path-following performance near the underwater structure.

Key Words : Autonomous underwater vehicle (AUV), Line-of-sight (LOS), Autonomous navigation, Obstacle avoidance

1. Introduction

Recently, underwater structures are increasing due to the resource extraction and military purposes. However, the regularly facilities management and inspection require many costs and risks. Therefore, the AUV (Autonomous Underwater Vehicle) technologies are needed for underwater infrastructure inspection and management.[1-3] However, the autonomous navigation technology using the AUV is challenging problem. An AUV is continuously influenced by fluids (e.g., tidal current, speed resistance and turbulence) during the operation. In addition, available sensors are very limited, and accumulation error of inertial sensor is faster than ground environment. Furthermore, several inertial sensors (e.g., gyro sensor and geomagnetic sensor) are easily distorted by the underwater structures.[4,5] In this condition, the path guidance method is one of important technologies for autonomous navigation system in structured environment. The AUV can occur the position errors due to the long-term dead reckoning, drastic steering angle change and sensor signal distortion. These localization errors may bring about the path-following error, and the AUV can recognize this path-following errors after position

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correction using more accurate sensors. After position correction, the AUV attempts to reduce the path-following error using path guidance method, however conventional guidance method can bring about the AUV collision with a structure, and guidance failure. Therefore, an alternative path guidance method for structured environment is needed to reduce the guidance failure and collision probability.[6-8)]

In this paper, the selective path guidance method is proposed to solve this problem as shown in Fig. 1. The AUV collision and guidance failure can be occurred due to the large localization error around the structured environment. Basically, the proposed guidance method uses the LOS (Line-of-sight) method to follow a given trajectory. However, this method takes a lot of time to reduce the path-following error. Moreover, it has the possibility of structure collision and guidance failure when i) *Case 1*; AUV is located out of its current path or ii) *Case 2*; the path-following error is bigger than LOS acceptance circle. In order to solve these problems, proposed method selectively changes the desired steering angle in direction of cross-track error (CTE), when path-following error is greater than a threshold value. This threshold value is defined as turning radius (TR) to consider the AUV characteristic and path overshoot.

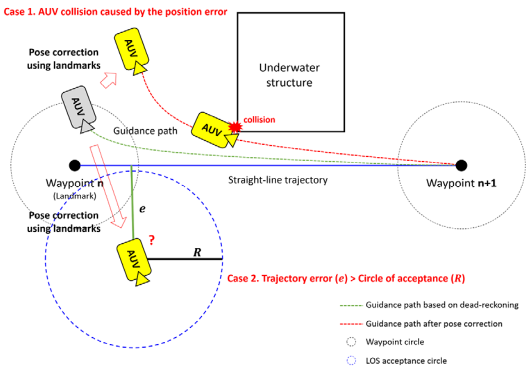


Fig. 1 The guidance problems near the structure

This paper is organized as follows: Section 2 briefly introduces the background skills for full autonomous navigations: localization and path planning scheme, and shows the techniques used in this research. Section 3 describes the detail of proposed path guidance strategy. This section is considered the LOS guidance and problems of this guidance method. And it suggests the selective guidance method at specific condition. Section 4 describes the experimental condition, procedure and result to verify the proposed path guidance method. Finally, section 5 presents a summary, conclusion and outlines of future work.

2. Background of Localization and Path Planning Scheme for AUV

Many skills are required for full autonomous navigation in structured environments. In particular, more precise and reliable localization technique is needed to minimize the risk of collision and sensor error. The AUV localization in structured environments is challenging problem because inertial measurement unit (IMU) can be easily distorted by the near the structures. Specially, in a narrow space or inside of structures, the conventional acoustic based systems (e.g., ultra-short baseline system, long baseline system) are limited due to the diffused reflection and multi-path effects. The alternative method for underwater localization structured environment is a landmark-aided inertial navigation sensor (INS) using sonar or vision information.[9)] These methods are categorized as a natural landmark aided localization using underwater terrain information, and an artificial landmark aided localization that calibrates the position using the sonar and vision markers. Although a marker installation is not required for the natural landmark aided localization technique, it has the disadvantage of being vulnerable to changes in the natural landmark by the sheath and aquatic organisms and being less precise due to similar natural environments. On the other hand, in the case of the artificial landmark aided localization, an AUV recognize the markers with precise positioning better than natural landmark method. However, it is difficult to install and maintain artificial markers. An active vision marker or chemical treatment (e.g., anti-barnacle) are used to improve maintenance performance.[10,11] Improving the location precision of inertial navigation system in the underwater structure environment is necessary as the image sonar and active vision markers cannot be calibrated throughout the navigation when performing the underwater autonomous navigation of the AUV. Therefore, for this purpose, the location correction was attempted through ring gyro, AHRS (Attitude Heading Reference System) sensor-based attitude and acceleration estimation, DVL (Doppler Velocity Log) and Depth sensor, and the location accuracy was improved through Extended Kalman Filter-based sensor data convergence based on the sampling rate of different sensors and error model of each sensor.

The integrated block diagram for implementing the underwater complex navigation can be express as shown in Fig. 2. An inertial navigation system

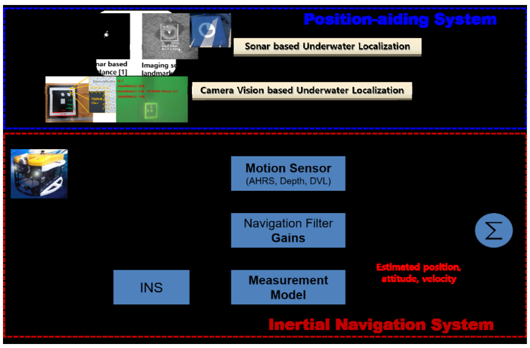
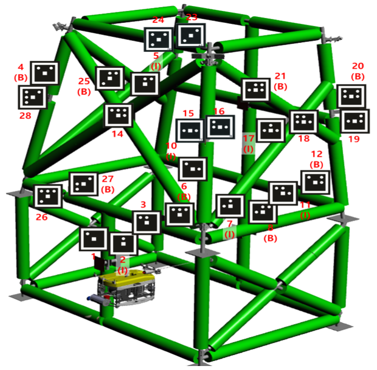


Fig. 2 Integrated block diagram for underwater complex navigation

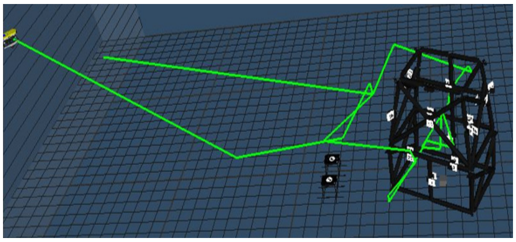
combined with DVL, ARS, and depth sensor is constructed as the primary navigation system for out test-bed AUV, as seen in Fig. 2. Two position-aiding methods are applied to prevent the position divergence of inertial navigation system: one is optical camera vision based underwater localization method, where the markers are attached on the jacket structure, and the other one is an acoustic camera vision based localization method with the markers installed on the seafloor around the jacket structure.[12)]

The path planning skill to visit multiple waypoints in a structure is required to achieve multiple tasks. Most important point when AUV passing through paths inside a structure is minimization of collision risk. The AUV can reduce the collision probability by generating a path that maximizes the Euclidean distance(e.g., repulsive potential field algorithm), or making waypoints to see the many landmarks.[13,14]

In Fig. 3, it shows the jacket structure environment for experiment and the path scheduler. The Fig. 3(a) is the jacket which is used for autonomous navigation experiment. It has twenty-eight active vision marker for position correction and installed on seabed 17 m. Fig. 3(b) is the waypoints for autonomous navigation. The path scheduler chooses the lowest Euclidean distance cost path using Genetic algorithm, and connect the landmarks in a straight line. Finding the optimal waypoint sequence is also important when AUV given the several tasks (unordered waypoints). It can be viewed as the Travelling salesman problem when given the Euclidean distances between tasks. However, the exact solution is difficult to determine because the problem is an non-deterministic polynomial (NP) hard problem. Usually, this problem can be solved using heuristic search algorithm.



(a) Jacket structure environment for experiment



(b) The path scheduler

Fig. 3 Jacket structure and path scheduler for experiment

In this paper, artificial landmark-aided localization scheme used to correct position in jacket structure. The twenty-eight active vision markers are installed at hotspot positions in jacket structure such as routes of entrance, exit, depth change points, and high potential collision points. These artificial landmarks function as the waypoints because it is installed at hot spot, and the AUV can correct its own position whenever AUV is departure from waypoint and AUV is arrive to waypoint as shown in Fig. 3(a). When user choose the several markers, which are interested, the AUV made the path considering the Euclidean distance. To consider Euclidean distance, the AUV solves this NP hard problem using genetic algorithm, and AUV choose the path, which has the lowest Euclidean distance cost. Therefore, using this array of the waypoints, AUV makes the straight line path, and the AUV followed this path using line-of-sight guidance law as shown in Fig. 3(b).

3. Selective Guidance Scheme for Structure Environment

In this section, the selective guidance method is suggested to guarantee the vehicle safe and guidance path near the underwater structures. This algorithm assumes that the trajectory has straight-line path that links two waypoints, and used the look ahead-based steering method. In addition, it is no considered roll, pitch motion and the AUV dynamics model (except the TR) to get the less computationally intensive.

3.1 LOS for straight-line paths

As shown in Fig. 4, the LOS vector $x_d(t)$ for AUV guidance at time t is sum of the path-tangential angle and the velocity-path angle. Using the path-following error $e(t)$ and the circle of acceptance R, the $\Delta(t)$ can be calculated.

Generally, the AUV conducts the path-following by using the LOS guidance method except specific conditions. A LOS vector from the vehicle to the next waypoint on the path between two waypoints can be used for steering control.[15] In Fig. 4, we only interested in 2D steering control, the pose state vector of AUV $x(t)$ at time step t, the previous waypoint p_k and the next waypoint p_{k+1} are defined as follows:

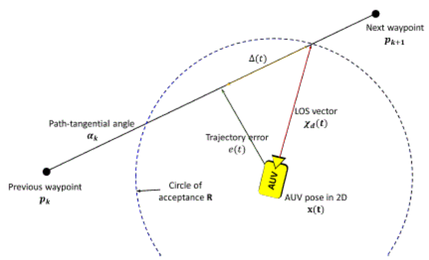


Fig. 4 LOS guidance method

$$\mathrm{x}(t) = [x(t)\ \ y(t)\ \ \theta(t)]^T \qquad (1)$$
$$p_k = [x_k\ y_k\ \theta_k]^T$$
$$p_{k+1} = [x_{k+1}\ y_{k+1}\ \theta_{k+1}]^T$$

Using the LOS guidance method, the desired steering angle assignment is separated into two parts:

$$\chi_d(t) = \chi_p + \chi_r(t) \qquad (2)$$

where $\chi_d(t)$ is the path-tangential angle and $\chi_r(t)$ is a velocity-path relative angle.

$$\chi_p = \alpha_k \qquad (3)$$

$$\chi_r(t) := \tan^{-1}\left(\frac{-e(t)}{\Delta(t)}\right) \qquad (4)$$

Here, $e(t)$ means a length between trajectory and vehicle, where

$$\Delta(t) = \sqrt{R^2 - e(t)^2} \qquad (5)$$

3.2 Problem of LOS guidance method

Fig. 5 shows the alternative steering control to prevent guidance problems. When the path-following error is greater than TR (threshold value), AUV conducts the steering control in direction of XTE (cross track error). After the path-following error is

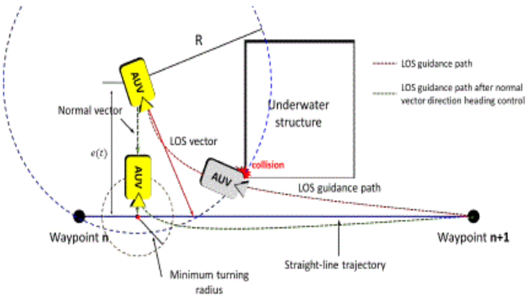


Fig. 5 The proposed guidance method

converged into the TR, the steering control method is switched to the LOS guidance.

During the path-following, the AUV guidance can suffer the two problems as shown in Fig. 5. One is a structure collision problem due to the LOS characteristic. The LOS has a terminal point guidance characteristic: it gradually reduces AUV path errors along the path-following. This characteristic doesn't cause great problems in an open water condition. However, it may cause a collision when AUV operates in structure environments. The other problem is guidance failure. The LOS guidance needs two conditions to calculate the steering angle and velocity: AUV is located between previous waypoint and current waypoint, and the path-following error is smaller than LOS circle. However, AUV may fail to correspond with these conditions when the vehicle significantly corrects it is own position using accurate position sensors. To solve this problem, the proposed method uses the alternative steering control in direction of XTE at specific conditions.

3.3 Alternative path guidance with turing radius citation

The suggested selective steering control considers the magnitude of XTE before follow the trajectory. When the magnitude of XTE is greater than a threshold, the AUV conducts alternative steering control in direction of XTE until the path-following error is smaller than TR. The vehicle velocity is considering the distance between vehicle position and XTE point. After the path-following error is converged into the threshold, the steering control method is switched to the LOS guidance as shown in Fig. 4. In order to reduce of rapid rudder adjustment and path overshoot, threshold selection is important.

In order to switch the guidance method, a simplified TR is considered as the criterion of the threshold. It is defined along to the vehicle speeds and actuation constraints. Because it is hard to know the TR value in cases, it is simply defined by using a forward velocity (u), steering velocity(r) and minimum turning radius (MTR) as follows:

$$\mathrm{TR} = MTR + g_v \times |u| + g_w \times |r| \tag{6}$$

where, g_v and g_w are weight parameters along to the velocities. The proposed guidance method is expected not only can solve the AUV collision problem and guidance failure, but also reduces the overall path-following error.

4. Experimental Results

4.1 Experimental environments

The experimental environment and vehicle are shown in Fig. 6. The jacket structure was deployed at seabed (17 m depth), and AUV conducted the autonomous navigation around this structure. During the full autonomous navigation, the AUV estimated own pose using dead reckoning of DVL aiding INS, and corrected the position using vision information. Nevertheless, the AUV often collided with structures during autonomous navigation due to the positioning error and path-following error.[16)]

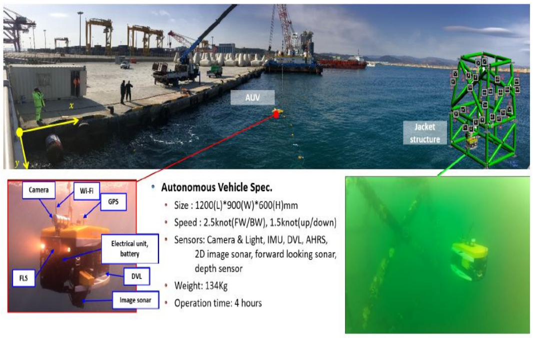


Fig. 6 Experimental environment and specification of AUV in the area of sea

In order to verify the proposed guidance method, the AUV guidance experiment was conducted in seawater as shown in Fig. 6. The experimental area was a Yeongil-bay harbor at Pohang, Korea (36.110755N, 129.439204E), and the underwater jacket structure was deployed at seabed (17 m depth). The structure size was and vision landmarks were attached at twenty-eight points, but only twelve markers used in this experiment for check the guidance performance (same horizontal plane, 12 m depth). The self-made platform was used to verify the performance of selective guidance method and was equipped with INS and vision camera. This vehicle can autonomously navigate the underwater environments. The vehicle navigation system estimates own position using dead reckoning of DVL (Doppler Velocity Log) aiding INS, and corrects the pose information using vision data.[15-16)] The size of this AUV was ($L \times W \times H$) 2 m×0.9 m×0.6 m and the cruising speed was 1.5 knots. The MTR was a stationary state (including the vehicle volume) and the weight parameters g_v and g_w were 0.5 and 0.3 which were determined using kinematics and dynamics report. Therefore, *TR* of this vehicle is calculated as follows:

$$\mathrm{TR} = 0.9 + 0.5 \times |u| + 0.3 \times |r| \tag{7}$$

4.2 Experimental procedure

The experimental procedure as shown in Fig. 7. The AUV sequentially navigated the structured environments using INS and vision landmarks (from (1) to (9)). The AUV predicts own position by dead reckoning using INS in every step. Whenever AUV shows the vision marker, AUV corrected own position. If path-following error is greater than TR, AUV conducts the steering control in direction of XTE.

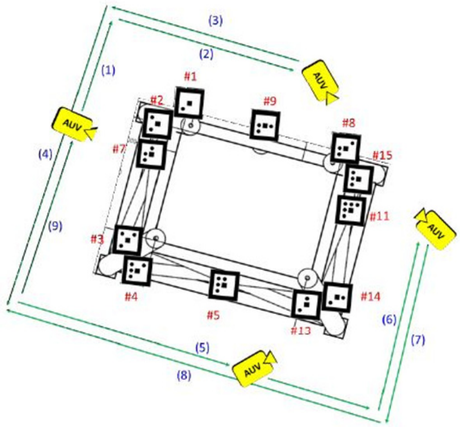


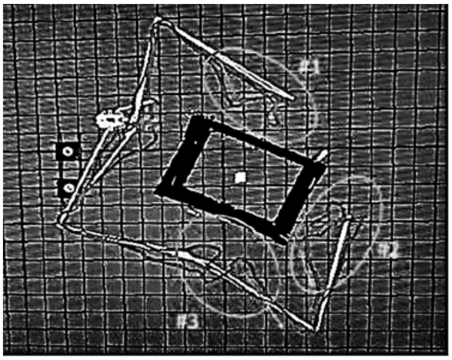
Fig. 7 Experimental procedure

The experimental procedure is as follows: The AUV started the navigation at first vision marker position (#7), and moved around the jacket structure (#7 → #2 → #8 → #1 → #3→ #13 → #15 → #14 → #4 → #25). Among the AUV navigation, AUV predicted own position by dead reckoning based on DVL aiding INS information, and corrected the dead reckoning errors using the updated pose information using vision markers. In spite of this navigation system, the position estimation error accumulated quickly owing to the structure effect.

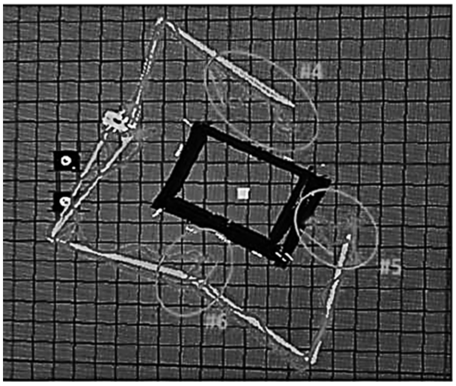
This path-following experiment was conducted two times. The AUV used the LOS guidance law only during the first time, and the AUV used the selective guidance scheme during the second time. We tried to verify the proposed method by comparing the two path-following results.

4.3 Results

Fig. 8 shows the AUV path-following results. Fig. 8(a) is AUV navigation with LOS guidance method and Fig. 8(b) is AUV navigation with selective guidance method. The red circles notate noticeable sections, and red arrows notate the directions of AUV movement.



(a) AUV navigation with LOS guidance method



(b) AUV navigation with proposed guidance method

Fig. 8 The AUV path following results

In case of Fig. 8(a), the AUV dramatically corrected the own position at #1~#3. However, the AUV gradually reduced the path errors using LOS. On the other hand, the AUV moved to the XTE direction to reduce the path error when it used the selective guidance method (#5 and #6). In case of #4 of Fig. 8(b), the AUV used the LOS guidance method due to the path error is smaller than TR.

Table 1 The path-following errors according to the guidance scheme

	LOS guidance (Fig. 8(a))	Proposed guidance (Fig. 8(b))
RMS error	0.6541 m	0.5212 m

Fig. 8 and Table 1 show the AUV path-following results according to the guidance method, respectively. Because of varying tidal current and different sea condition, we could not compare both guidance methods exactly. However, the characteristics of the both guidance methods can be clearly distinguished using navigation log data as shown in Fig. 7.

On the whole, the proposed guidance method near structured environment showed the satisfactory performance. In the almost sections, both of guidance methods showed the similar path-following performance, because they used the same LOS guidance method in ordinary situations. However, the proposed selective guidance methods showed the different guidance behavior when the AUV corrects own position using vision landmarks (#1~#6 in Fig. 8). Whenever the AUV position was updated at the vision landmarks, the AUV moved in the direction of LOS vector (cd) to smoothly minimize the path-following error using the LOS guidance (#1~#4). However, when the path- following error was bigger than TR, the AUV moved in the direction of XTE to reduce the path-following error (Red arrow direction of #5 and #6). After the path following error was smaller than TR, the AUV used the LOS guidance method to follow the trajectory. As the results, the path-following errors were significantly reduced than LOS guidance method only as shown in Table 1. Moreover, it is estimated that the collision possibility with structure was remarkably reduced.

5. Conclusions

In this paper, a selective AUV guidance method was suggested to overcome the several path-following problems in structured environments. The suggested method optionally used the LOS guidance or steering control in direction of XTE. Generally, the AUV used the LOS guidance method for path-following control. However, if the path error is bigger than TR, the AUV conducts the steering control in direction of XTE. By using the LOS guidance and steering control in direction of the XTE, the AUV guaranteed the satisfactory path-following results without AUV collision and guidance failure. The proposed method showed small path-following error by comparing with conventional LOS guidance method at real sea environment, and it showed the satisfactory path following performance near the underwater structure.

In the future work, the we will verify this proposed guidance method in real applications. Specially, we will use this algorithm to guide the AUV to follow the path in inner structures.

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Author contributions

J. W. Lee; Investigation, Software, Investigation and Writing-original. J. H. Li; Formal analysis, validation. J. H. Suh; Conceptualization, Funding acquisition, Project administration, Writing-review and editing.

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