Path planning for an autonomous underwater vehicle in pole inspection

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Present study consists a pre-mission time optimal inspection path planning for visual inspection of a well-characterized submerged vertical pole using an autonomous underwater vehicle. Target environment, which is the entire surface of a submerged pole, is modelled as a planar map for easy path planning. Proposed inspection path planning utilizes the concept of grid-based coverage path planning, where the target environment is break into many same size grid cells. Various inspection path patterns are designed manually based on boustrophedon and spiral motions with different sweep direction and turning pattern. They are analysed in term of trajectory length, inspection time, and coverage percentage to choose the best inspection path among them. Calculation results show that the chosen inspection path can cover 99% of the entire pole surface with shortest distance travelled and shortest operational time.

[Keywords: inspection path planning; autonomous underwater vehicle; underwater pole inspection; grid-based coverage path planning]

Introduction

Oil and gas industry bring profitable economic benefit. Offshore platform is needed to extract and process oil and gas on the ocean. However, marine fouling organisms are found on the submerged legs of oil and gas offshore platform1. This unwanted marine growth is one of the critical factors affecting the service lifetime of offshore platforms2. It will lead to increased tube diameter, increased drag coefficient, increased structural weight and reduced natural frequency of the platform legs3.

For safe operation of offshore platform, periodic preventative measure of marine growth rate is needed. The measured marine growth rate is useful to schedule the marine growth removal job effectively. Conventionally, underwater pole inspection on platform leg is done by commercial divers or remote operated vehicle (ROV). However, marine growth formed rough and sharp surface, which leads to high life risk of human divers. On the other hand, the long connecting cable between ROV and control station, which can get stuck has increase the operational difficulties of ROV.

Therefore, underwater pole inspection system using autonomous underwater vehicle (AUV) is considered4. Compared to other underwater inspection system, underwater inspection system using AUV is exceptionally good because there is no operators and divers needed, and no connecting cable required. By using an AUV, underwater pole inspection can be completed with lower cost, lower life risk, and higher efficiency. However, an AUV has limited battery capacity on board, thus limited operating time. Therefore, an effective predefined trajectory is needed for the AUV to inspect the entire surface of the submerged pole with shortest time and shortest distance travelled.

To the author best knowledge, there are no coverage path planning (CPP) designed specifically for underwater pole inspection. However, CPP in painting, vacuum cleaning, and seabed mapping are similar problems, thus provides experiences and references upon the design of inspection path for underwater pole. There are various offline algorithms of CPP, i.e. cellular decomposition CPP, grid based CPP and optimal CPP.

Cellular decomposition CPP divides the target environment into several non-intersecting sections called cells, in the way that each of the cells can be covered by simple motion. As a result, the mission to cover the entire target environment is reduced to cover each of the cells. Choset and Pignon used simple back-and-forth boustrophedon motion to cover the cells5. Besides, Fang and Anstee proposed the method to break the target environment into cells effectively using Voronoi diagram6.
Grid based CPP breaks the target environment into many same size grid cells. Choi et al. break the target environment into robot-sized cells and then uses spiral path to cover all the grid cells. Furthermore, Zelinsky et al. used path transform methodology to cover all the grid cells. This method propagates a wave from the goal cell (end point) to all other grid cells in the target environment. All the grid cells are weighted with sum of distance from goal cell with distance from obstacles. Then, the robot will cover all the grid cells by following steepest ascent path. This strategy can specify the location of start point and end point.

Optimal CPP finds path that maximizing coverage while at the same time minimizing energy consumption, path length, or completion time. Minimizing the number of sharp turning is the most significant factor in reducing completion time because the robot needs to slow down to make a sharp turning, which will undeniably cost a significant of time. Furthermore, sweep direction of coverage path is also one of the critical issues because different sweep direction will produce different number of turns, even they have same path length.

Mao et al. used heuristic path planning to reduce the number of turns created by template-based path planning. On the other hand, Huang allocate different sweep direction to different cells to reduce the sum of sub-region altitudes, so that the number of turns in the path is minimized. Moreover, Jimenez et al. used genetic algorithm to generate the optimal path based on the value of the fitness function, which is designed in term of total distance travelled and total time taken.

Present study is a reliable inspection path planning specifically for underwater pole inspection using an AUV, which can provide maximum coverage and time optimal. This research work is first reported in. The proposed inspection path planning utilizes the concept of grid-based coverage path planning, where the target environment is break into many same size grid cells.

**Material and Methods**

Mainly, there are five steps to design the inspection path for an AUV in pole inspection. First, the design specification of inspection path is defined. Then, the planar map of target environment is constructed. After that, various patterns of inspection path are designed manually based on boustrophedon and spiral motions with different sweep direction and turning pattern. Next, the designed inspection paths are analysed in term of trajectory length, inspection time, and coverage percentage. Last step is to choose the best inspection path according to the analysed result and design specification. The detail of these five steps are discussed in this section.

First, the design specification of inspection path is defined. The designed inspection path should be able to provide maximum coverage on the surface of a submerged pole while minimize the AUV’s operational time. The coverage percentage should be more than 90%. By following the designed path, the AUV should be able to inspect the entire pole’s surface visually in 360 degree without any physical contact. To ensure the quality of data collected, the perpendicular distance between AUV and pole surface, \( l_p \) should be maintained at a fixed value.

In this research work, the pole to be inspected is assumed to be a fixed diameter and vertical pole. The existence of bracing system and unexpected obstacles are ignored. Since the AUV is going to go around the target pole in 360 degree and inspect it from a fixed distance, the target environment is taken as a three-dimensional (3D) curve region surrounding the entire pole’s surface from a fixed distance.

Due to the fact that the target environment is simple and well characterized, it is modelled as a two-dimensional (2D) map for easy path planning. The modelled planar map is shown in Figure 1, where \( h_p \) is the height of the submerged section of the target pole and \( d_p \) is the diameter of the target pole. The target environment is a 3D region, any horizontal straight-line motion across the planar map is a circular motion with radius \( r \).

The concept of grid based CPP is used in designing the inspection path. The planar map is divided into
many same size grid cells. The size of the grid cells is designed to be equal or less than the size of the field of view of the underwater camera equipped by the AUV, as shown in Figure 2. The height of a grid cell, \( h_c \), is designed to be less than or equal to the vertical field of view, \( vFOV \), of the camera whereas the width of grid cell, \( w_c \), is designed to be less than or equal to the horizontal field of view, \( hFOV \), of the camera.

When the camera on the AUV reaches the centre of a grid cell, it will be able to capture the entire surface of the grid cell. Once it goes through the centre of all the grid cells, the entire target environment is captured. As a result, the mission to design a path which can inspect the entire pole’s surface is reduced to the mission to design a path which is able to pass through the centre of all the grid cells in the planar map.

The pattern of inspection path is designed manually rather than create an algorithm to generate the path automatically. Five patterns of inspection paths are designed manually based on the defined design specification, as shown in Figure 3 – 7. For easy explanation, they are named Path A, Path B, Path C, Path D, and Path E respectively. Notice that the resolution of grid cells shown is not the actual resolution.
resolution. They are drawn to reveal the pattern of designed path. The actual grid cells resolution will be discussed later.

Path A and Path B are designed based on back-and-forth boustrophedon motion. The sweep direction of Path A is in horizontal direction whereas sweep direction of Path B is in vertical direction. Both Path A and Path B undergo 90° sharp turning. On the other hand, Path C is designed using spiral path along a vertical axis. Path C is similar to the shape of an open ends helical spring. Path D and Path E are designed based on Path A and Path B. Unlike Path A and Path B, Path D and Path E use smooth turning instead of 90° sharp turning.

Step four is to analysis the five designed inspection paths. To analyses the inspection paths, first one needs to define the resolution of grid cells. The grid cells resolution is based on the parameters of target pole, as shown in equation (1) and (2), where $n_r$ is the number of rows of the grid cells and $n_c$ is the number of columns of the grid cells. Both $n_r$ and $n_c$ must be whole number. If fractional number is obtained from equation (1) and (2), one needs to round it to next whole number. After that, the size of a grid cell can be calculated using equation (3) and (4).

\[ n_r = \frac{h_p}{v\text{FOV}} \quad \ldots (1) \]

\[ n_c = \frac{2\pi}{h\text{FOV}} \quad \ldots (2) \]

\[ h_c = \frac{h_p}{n_r} \quad \ldots (3) \]

\[ w_c = \frac{2\pi r}{n_c} \quad \ldots (4) \]

Basically, the five designed inspection paths are formed by five types of simple motion across a grid cell. They are horizontal straight-line motion, vertical straight-line motion, inclined straight-line motion, 90° sharp turning, and circular smooth turning, as shown in Figure 8 – 12. Therefore, one can first calculate the trajectory length and time taken of these single grid cell motions, then use the calculated values to find the total trajectory length and total inspection time needed for the whole inspection path.
The equations of trajectory length and time taken for the five single grid cell motions are shown in Table 1. During derivation of these equation, the speed of the AUV, \( v \) is assumed to be a constant for all single grid cell motions except when making a 90\(^\circ\) sharp turning. During sharp turning, the AUV will need to slow down until stop, and then accelerates to another direction. The magnitudes of both acceleration and deceleration are taken as a same constant value, \( a \). The turning process for both sharp and smooth turning will be done within a grid cell. Besides, the trajectory length of inclined straight-line motion is the arc length of a cylindrical helix. Therefore, the arc length equation of cylindrical helix is used as the equation of trajectory length.

To choose the best inspection path among the five designed paths, they are analysed in term of three performance indexes. They are trajectory length, inspection time, and coverage percentage. The equation for performance indexes of five designed inspection paths are shown in Table 2. At start point, the AUV will need to accelerate from stop, whereas at end point, the AUV will need to decelerate until stop. Therefore, additional time is added into the inspection time of all the five paths.

Last step is to compare the five designed inspection paths in term of their performance indexes. The comparison is divided into two parts. First part compares the performance indexes of inspection paths in different pole design.

Second part compares the performance indexes of inspection paths in different camera resolution. In both the two parts of comparison, we assume that \( l = 0.5m \), \( v_{F0V} = 0.5m \), \( v = 0.2ms^{-1} \), and \( a = 0.2ms^{-2} \).

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In order to compare the performance indexes of the five inspection paths in different pole design, the parameters of three jacket platform design are adopted. Table 3 shows the jacket leg parameters of the three jacket platforms. For easy explanation, they are called Jacket A, Jacket B, and Jacket C in the remaining text. Jacket A is an equilateral triangle jacket platform with

![Table 1 — Trajectory length and time taken for single cell motions](image)

![Table 2 — Performance indexes of designed inspection path](image)

![Table 3 — Jacket leg parameters of the three jacket platforms](image)
1:8 leg batter in the orthogonal directions. The three jacket legs are 0.914 meter in diameter with 19.812 meter in vertical height. Its vertical height is measured from water surface to mudline without consider the length of jacket leg above water and below mudline. Moreover, Jacket B is a four-legged jacket platform with 1:12 apparent batter. The four jacket legs are 0.838 meter in diameter with 33 meter in vertical height. Besides, Jacket C is a steel jacket structure with eight jacket legs. The jacket legs are 1.067 meter in diameter with 35.052 meter in vertical height. The four corner legs battered 1:8 in the orthogonal directions. Although the three jacket platforms’ leg are battered, they are assumed vertical in this paper. The proposed inspection path can be fit into the real-time jacket leg inspection by only minor adjustment.

### Results and Discussion

The comparison results are shown in this section. They will be explained through table and graph. The results are divided into two parts, which are performance indexes of inspection paths in different design of jacket leg and performance indexes of inspection paths in different resolutions of camera. The best inspection path will be chosen among them based on the calculated results.

Table 4 shows the performance indexes of five designed inspection paths in three different jacket legs. Path E has shorter inspection time and shorter trajectory length than other inspection paths. Due to its sweep direction, the difference of inspection time between Path E and other paths becomes more obvious when inspecting higher jacket leg, which is Jacket C. This shows that the sweep direction of inspection path should follows the direction of longest dimension of the target environment.

Path B has second shortest inspection time among the five designed inspection paths. By changing 90° sharp turning in Path B to circular smooth turning, Path E yield. Its inspection time is reduced by approximately 2 percent after the change. However,
during smooth turning, the camera is unable to reach the centre of grid cell, thus cannot capture the entire surface of the grid cell. Therefore, its coverage percentage is reduced by approximately 0.2 percent.

Although Path E is unable to provide complete coverage, its coverage percentage is more than 99.8 percent, which is satisfied compared to defined path specification.

The effect of changing the sharp turning into smooth turning is more obvious in Path A and path D. The inspection time is reduced by approximately 6 percent after smoothing the turning. This is because there are greater number of turning in Path A than Path B.

Table 5 shows the performance indexes of designed inspection paths in using different resolutions of camera whereas Figure 14 shows the graph of their inspection time ratio. As shown in the graph, higher the ratio of camera resolution, better the inspection time of Path E compared to others.

Although Path C is the path with shortest inspection time when 1:1 camera resolution is used, the difference
of inspection time between Path E and Path C is small. Note that performance indexes of Path C remain the same regardless of camera resolution.

In short, Path E is chosen as proposed inspection path in underwater pole inspection task because it can cover 99 percent of the pole surface with shortest inspection time and shortest distance travelled.

Conclusion

In short, a time optimal inspection path is design specified for underwater pole inspection mission using AUV. The path is designed based on a well-characterized planar map. The designed inspection trajectory can provide 99 percent coverage with minima operational time needed.

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