WAYPOINT GUIDANCE BASED PLANAR PATH FOLLOWING AND OBSTACLE AVOIDANCE OF AUTONOMOUS UNDERWATER VEHICLE

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Keywords: Underwater robotics, Path planning, AUV, Obstacle avoidance, Potential field, Line-of-sight.

Abstract: This paper presents waypoint guidance based planar path following and obstacle avoidance for Autonomous Underwater Vehicles (AUV). Guidance through waypoints by line-of-sight (LOS) method and artificial potential field method (APFM) are used to develop the algorithm. Both LOS and PFM are simple and computationally inexpensive and can be used for real-time implementation. The basic LOS method has been modified for reference heading correction with a distance threshold in order to achieve minimal calculation for heading correction and smoother vehicle turn during course change at waypoints. An improved potential field method is also proposed for better obstacle avoidance for the AUV. Few points are taken from the path generated by the waypoint guidance and given as via points for the obstacle avoidance algorithm. The proposed algorithm basically follows the improved LOS method when there is no obstacle along the vehicle's path and switches to APFM when any obstacle is detected. The details of the algorithm and simulation results are presented.

1 INTRODUCTION

Applications of AUV have seen rapid growth in the last few decades. Guidance, navigation and control (GNC) are important to an autonomous vehicle's mission success and utility. However the effectiveness of AUV is still limited by the precision and accuracy of guidance schemes. The main purpose of the guidance is to receive the target related information from the navigation system and generate references for the vehicle control system so as the vehicle can move through a set of way points as per the given sequence. It may be a time variant trajectory tracking or time invariant path following. Guidance system also includes sophisticated features like obstacle avoidance, minimum time navigation, fuel optimization and weather routing (Fossen, 1994). Several guidance laws such as waypoint guidance by LOS, vision based guidance, Lyapunav based guidance, guidance using chemical signals and magnetometers, proportional navigation guidance, and electromagnetic guidance are being used for developing guidance strategies. Waypoint guidance by LOS is one the most widely used method for AUV due to its simplicity and computational advantages. But it has a major drawback of undesirable control energy consumption due to overshoot during course change at waypoints (Naeem et al., 2003). Fossen et al. (2003) presented a LOS method that uses straight lines and circular arcs in order to get smooth transition between two consecutive waypoints. Though the vehicle makes a better turn, its path is far away if a U-turn is made at a waypoint thus missing the waypoint. Bakaric et al. (2004) proposed a technique to avoid the missed waypoint and the overshoot issues by considering the next waypoint before the current waypoint is reached. In this method, the vehicle calculates the heading correction from the starting point itself though it is not essentially needed if the vehicle is too far away from the target point. Obstacle avoidance algorithm can also be incorporated in the design of waypoint guidance systems (Fossen, 2002). Road map, cell decomposition, optimal control and potential field methods are used for developing obstacle avoidance schemes. Artificial potential field method for obstacle avoidance was initially proposed by Khatib (1985). Koren and Bronstein (1992) discussed the potential field method and their inherent limitations. Potential field

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WAYPOINT GUIDANCE BASED PLANAR PATH FOLLOWING AND OBSTACLE AVOIDANCE OF AUTONOMOUS UNDERWATER VEHICLE.
DOI: 10.5220/0003531401910198
In *Proceedings of the 8th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2011), pages 191-198
ISBN: 978-989-8425-75-1

method is mostly used for on-line obstacle avoidance (Al-Sultan and Aliyu, 1996). Ge and Cui (2000) presented a new artificial potential field method for mobile robot path planning in order to avoid goal non reachable with obstacle nearby (GNRON) problem. Ding Fu-guang et al. (2005) developed a path planning method using virtual potential field concept for AUV. In most cases, the potential field methods are used for mobile robots and the potential of an obstacle is calculated at only one point. Hence an improved guidance strategy is required for better path following and obstacle avoidance for an AUV. In this paper, we propose an improved path following and obstacle avoidance strategy to address this. The waypoint guidance by LOS is modified by locating a distance threshold point in the direction of the waypoints. The vehicle can take any course angle correction only in between these threshold points and the waypoints. This reduces the computation of heading correction. Similarly, the obstacle avoidance can be improved by discretizing both the periphery of the obstacle and an arc of radius around the AUV into many points. The potential fields due to each point on an obstacle can be calculated and integrated to obtain a strengthened potential field for that particular obstacle.

The rest of the paper is organized in four sections. In Section 2, the guidance based path following algorithm is described by modifying the waypoint guidance by LOS guidance law. Section 3 presents the development of obstacle avoidance algorithm using artificial potential field method. Here, the environment is taken as local minima free. Section 4 consists of simulation results for path planning and obstacle avoidance of an AUV. Finally, the conclusion and future work are given in section 5.

2 WAYPOINT GUIDANCE BY LINE OF SIGHT

We can define the LOS in terms of a desired heading angle (Fossen, 1994) as

$$\psi_r = \tan^{-1}\left(\frac{y_i - y}{x_i - x}\right), \tag{1}$$

where $WP(x_i, y_i)$ for $(i = 1 \ldots N)$ is the given set of waypoints. When the vehicle lies within the circle of acceptance with a radius ρ_o around the waypoint $WP(x_i, y_i)$, that is if the vehicle location $\mathrm{V}(x, y)$ satisfies:

$$dP_{i^2} = (x_i - x)^2 + (y_i - y)^2) \le \rho_{o^2}\,, \tag{2}$$

where dP_i is the distance between vehicle position and the current waypoint. Then the next waypoint $WP(x_{i+1}, y_{i+1})$ can be selected. The radius of circle of acceptance is taken as 2L, where L is the length of the vehicle. The basic LOS algorithm has a disadvantage that the vehicle will not turn smoothly during course change since the reference heading is calculated only with respect to the current waypoint. In order to achieve smoother turn at the waypoints, the waypoint guidance by LOS is modified by making some corrections on the reference heading determined from the basic LOS guidance law. The algorithm can be explained as follows. Let $SP(x, y)$ is the starting point, $GP(x, y)$ is the goal point, $WP(x_i, y_i)$ and $WP(x_{i+1}, y_{i+1})$ are the current and next waypoints as shown in Figure 1. Now the vehicle is located at $V(x, y)$. A distance threshold point $C_{Ai}(x_i, y_i)$ is located before the current waypoint in the direction of current waypoint. Similarly another threshold point $C_{Bi}(x_i, y_i)$ is located after the current waypoint in the direction of next waypoint. The distance threshold is taken as 10L. This is an adjustable constant and it is sufficient even if any sharp U-turn is needed. Let $A(x_{Ai}, y_{Ai})$ and $B(x_{Bi}, y_{Bi})$ are the auxiliary points at a distance ρ_o in the direction of next and current waypoints. The coordinates of the point A_i are given as (Bakaric et al., 2004):

$$\begin{aligned} y_{Ai} &= y_i + \rho_o \frac{\operatorname{sgn}(y_{i+1} - y_i)}{\sqrt{1 + \left(\frac{x_{i+1} - x_i}{y_{i+1} - y_i}\right)^2}} \quad if\,(y_i \ne y_{i+1}) \\ x_{Ai} &= x_i + \left(\frac{x_{i+1} - x_i}{y_{i+1} - y_i}\right)(y_{Ai} - y_i) \end{aligned} \tag{3}$$

Similarly,

$$\begin{aligned} x_{Ai} &= x_i + \rho_o \frac{\operatorname{sgn}(x_{i+1} - x_i)}{\sqrt{1 + \left(\frac{y_{i+1} - y_i}{x_{i+1} - x_i}\right)^2}} \quad if\,(x_i \ne x_{i+1}) \\ y_{Ai} &= y_i + \left(\frac{y_{i+1} - y_i}{x_{i+1} - x_i}\right)(x_{Ai} - x_i) \end{aligned} \tag{4}$$

The coordinates of the point B_i can be given as

$$\begin{aligned} y_{Bi} &= y_i + \rho_o \frac{\operatorname{sgn}(y_{i-1} - y_i)}{\sqrt{1 + \left(\frac{x_{i-1} - x_i}{y_{i-1} - y_i}\right)^2}} \quad if\,(y_i \ne y_{i-1}) \\ x_{Bi} &= x_i + \left(\frac{x_{i-1} - x_i}{y_{i-1} - y_i}\right)(y_{Bi} - y_i) \end{aligned} \tag{5}$$

Similarly,

$$x_{Bi} = x_i + \rho_o \frac{\operatorname{sgn}(x_{i-1} - x_i)}{\sqrt{1 + \left(\dfrac{y_{i-1} - y_i}{x_{i-1} - x_i}\right)^2}} \quad if\,(x_i \neq x_{i-1})$$
$$y_{Bi} = y_i + \left(\frac{y_{i-1} - y_i}{x_{i-1} - x_i}\right)(x_{Bi} - x_i) \tag{6}$$

The distance between vehicle and the auxiliary points can be calculated as,

$$\begin{aligned} d_{Ai}^2 &= (x_{Ai} - x)^2 + (y_{Ai} - y)^2 \\ d_{Bi}^2 &= (x_{Bi} - x)^2 + (y_{Bi} - y)^2 \end{aligned} \tag{7}$$

The normalized difference between the auxiliary and the distance threshold points can be given as,

$$\begin{aligned} \varepsilon_{Ai} &= \frac{d_{Ai} - d_{Pi}}{\rho_o} \\ \varepsilon_{Bi} &= \frac{d_{Bi} - d_{CBi}}{\rho_o}, \end{aligned} \tag{8}$$

where ε_{Ai} and ε_{Bi} are the normalized difference factors and d_{CBi} is the distance between the vehicle position and the distance threshold point $C_{Bi}(x_i, y_i)$. If both the current and next waypoints are in the same direction, the normalized difference factor becomes 1, and no heading correction is required. If the next waypoint lies in the direction of current waypoint, this factor is near to 1. Whenever a sharp turn is needed, this factor gets the value near to -1. The heading correction ψ_c is zero at the distance threshold points and at the waypoints. A linear curve fitting is done in order to find the different values for heading correction. The values are taken as distance factor and angle factors. The sign of the heading correction ψ_{sc} can be determined as

$$\begin{aligned} \psi_{sc} &= \operatorname{sgn}\{(x_{Ai} - x).(y_i - y) - (y_{Ai} - y).(x_i - x)\} \\ \psi_{sc} &= \operatorname{sgn}\{(x_{Bi} - x).(y_i - y) - (y_{Bi} - y).(x_i - x)\} \end{aligned} \tag{9}$$

The heading correction ψ_c can be calculated as

$$\begin{aligned} \psi_c &= (\psi_{sc}).f_{Ad}(d_{Pi}).f_A(\varepsilon_{Ai}) \\ \psi_c &= (\psi_{sc}).f_{Bd}(d_{Pi}).f_A(\varepsilon_{Bi}) \end{aligned} \tag{10}$$

where the distant factors $f_{Ad}(d_{Pi})$, $f_{Bd}(d_{Pi})$ and the angle factors $f_A(\varepsilon_{Ai}), f_B(\varepsilon_{Bi})$ are determined using Figure 2, 3 and 4. Finally the desired heading is calculated as (Bakaric et al., 2004)

$$\psi_d = \psi_r + \psi_c \tag{11}$$

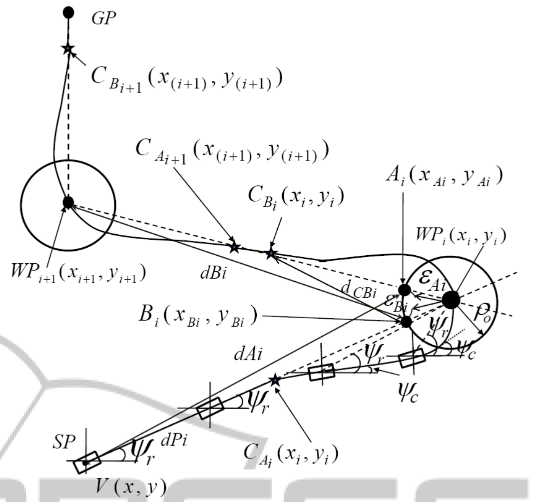

Figure 1: Calculation of heading correction for smooth turn during course change at waypoints.

This heading correction is calculated between the points C_{Ai}, C_{Bi} and the current waypoints. In this way the LOS guidance algorithm is improved to turn the vehicle smoothly at both sides of the waypoints.

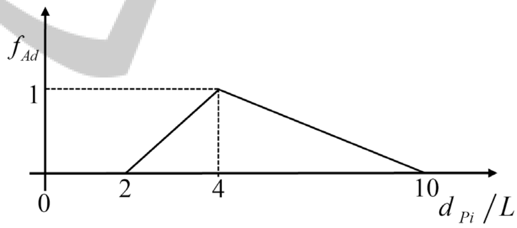

Figure 2: Distance factor for the auxiliary point A_i.

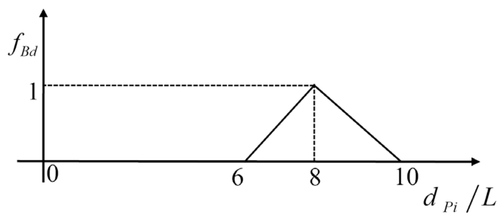

Figure 3: Distance factor for the auxiliary point B_i.

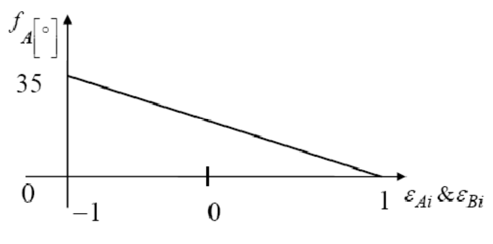

Figure 4: Angle factors for calculating heading correction.

3 OBSTACLE AVOIDANCE BY POTENTIAL FIELD METHOD

The objective of the obstacle avoidance algorithm is to find an obstacle free path by avoiding the obstacles so that the vehicle can reach the desired goal position without collision. The artificial potential field method is used for developing the obstacle avoidance algorithm. The main idea of this potential field method is to generate attraction and repulsion potentials for the target and the obstacles. The target has an attraction potential and the obstacles have repulsion potentials. By determining the point at which the minimum potential exists among the total potentials, the vehicle can be commanded to that point. The total potential can be calculated by integrating the attraction and repulsive potentials at few points around the periphery of the vehicle.

The obstacle avoidance algorithm has been developed in 2D space based on the artificial potential field method with static obstacles. The following assumptions are made for the implementation of the algorithm.

- The vehicle is assumed to be flat-fish type AUV.
- The obstacles are assumed as static and they are in circular shape of various sizes
- Forward looking sonar data is used for developing the control algorithm.
- The vehicle cannot move in sideways.
- The vehicle is neutrally buoyant and there are no external disturbances

The following steps give the methodology of the obstacle avoidance algorithm.

- Discretize the arc of radius r around the AUV into N points $(q_i: 1 = 1,2, \ldots N)$ over a range of interest defined by θ_u, and θ_l. (Refer Figure. (5))
- Compute the attractive potential U_{att} at these points. The attraction influence tends to pull the vehicle towards the target position. The most commonly used attractive potential field is of the form (Ge and Cui, 2000):

$$U_{att_{(i)}}(q) = \frac{1}{2}\xi d_{a(i)}{}^{2}, \tag{12}$$

where $d_{a(i)} = \left| q_i - q_a \right|$ is the distance between q_i th point around the vehicle and the goal point q_a . ξ is an adjustable constant.

- Obtain the location and size of the obstacle from the sonar data and discretize its periphery into K points $(p_j: 1 = 1,2, \ldots K)$.
- Compute the repulsive potential U_{obs} at q_i due to the obstacle point p_j . The repulsive potential fields are intended to generate a high potential around the obstacle, such that the gradient flow points away from the obstacle. The repulsion influence tends to push the vehicle away from the obstacles. The repulsive potential at q_i due to the obstacle point p_j is given as (Ge and Cui, 2000)

$$U_{obs_{(i,j)}}(q) = \begin{cases} \frac{1}{2}\eta\left(\frac{1}{d_{o(i,j)}} - \frac{1}{d_t}\right)^2 d_{a(i)}^2, & if \quad d_{o_{(i,j)}} \le d_t \\ 0, & if \quad d_{o_{(i,j)}} > d_t \end{cases} \tag{13}$$

where $d_{o(i,j)} = \left| q_i - p_j \right|$, is the distance between q_i th point around the vehicle and p_j th point on the periphery of the obstacle, d_t is the influence distance, η is an adjustable constant.

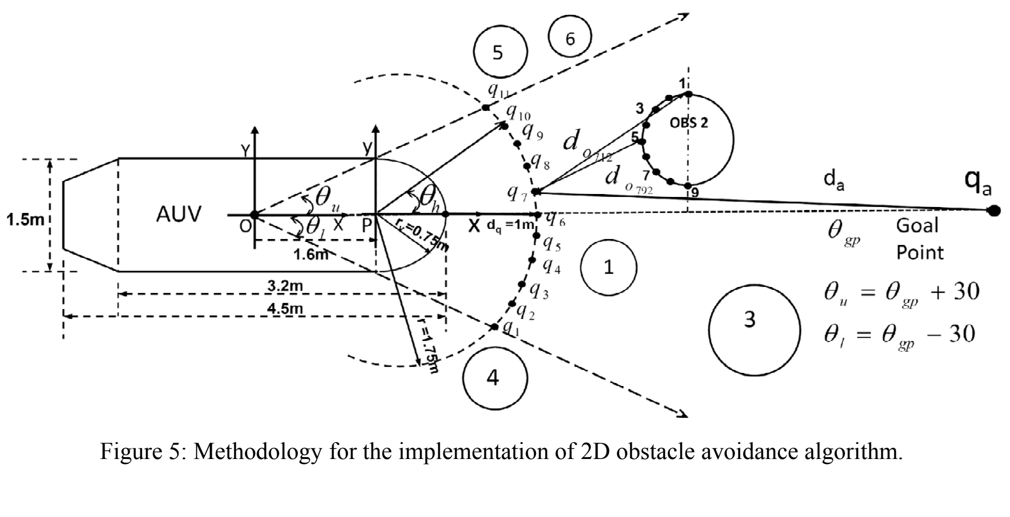

Figure 5: Methodology for the implementation of 2D obstacle avoidance algorithm.

- Compute the actual repulsive potential U_{rep} at q_i due to the obstacle

$$U_{rep_{(i)}}(q) = \sum_{j=1}^{K} U_{obs_{(i,j)}}(q) \tag{14}$$

- Compute the total potential U_{tot} at each point around the vehicle. The total potential at a point around the vehicle is represented as a sum of attractive potential and all the repulsive potentials. Here the repulsive potential results from the superposition of the individual repulsive potentials generated by the obstacles.

$$U_{tot_{(i)}}(q) = U_{att_{(i)}}(q) + \sum_{m=1}^{R} U_{rep_{(i,m)}}(q) \tag{15}$$

where m=1,2…,R. R is the number of obstacles, $U_{att(i)}(q)$ represents the attractive potential and $U_{rep_{(i,m)}}(q)$ represents the repulsive potentials generated by the obstacle m. The above steps can be represented in a single equation as,

$$U_{tot_{(i)}}(q) = U_{att_{(i)}}(q) + \sum_{m=1}^{R}\sum_{j=1}^{K} \begin{cases} \frac{1}{2}\eta\left(\frac{1}{d_{o_{(i,j,m)}}} - \frac{1}{d_t}\right)^2 d_{a(i)}^2, & if\ d_{o_{(i,j,m)}} \le d_t \\ 0, & if\ d_{o_{(i,j,m)}} > d_t \end{cases} \tag{16}$$

where i=1,2,…,N; j=1,2,…,K and m=1,2,…,R. In this way, obtain the total potential for all the points around the vehicle and predict the next one step ahead by determining the minimum potential $U_{\min tot}$.

$$U_{\min tot} = \min(U_{tot}) \tag{17}$$

- Represent the minimum potential point in Cartesian space.
- Command the vehicle to the position calculated in the previous step.
- Repeat the above steps till the goal is reached.

The above steps can be explained using Figure 5 as an example. Let the starting, goal positions are given and the obstacle information are received from sensor. Initially the vehicle is at the start position. In this methodology, the vehicle is always aimed towards the target. In order to determine the next position, an arc around the AUV is discretized into eleven (N=11) equidistant points. The way of selecting few points around the vehicle is shown in Figure 5. The angle (θ) between the starting point and goal point is calculated in the horizontal plane.

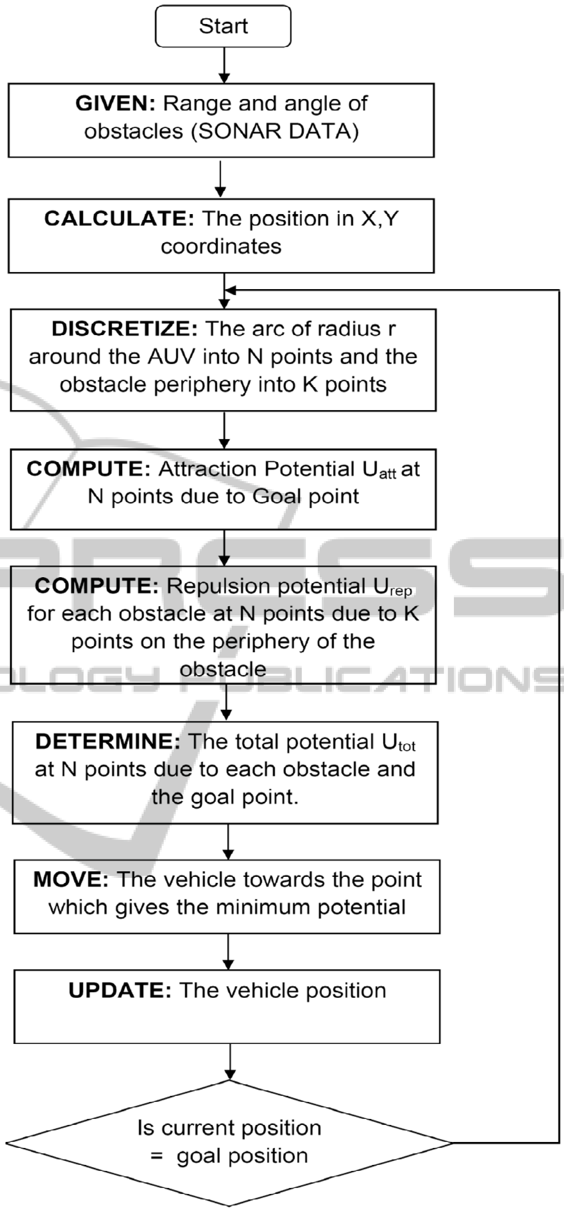

Figure 6: Flow chart for the obstacle avoidance algorithm.

A range of interest is determined by the distance influence threshold and the angles $(\theta + \theta_u)$ and $(\theta - \theta_l)$, where $\theta_u = 30^\circ$ and $\theta_l = 30^\circ$ are the upper and lower limit angles and they can be adjusted in order to define the obstacle region. The obstacles are considered only if they are within this region. The obstacles 2, 3 and 4 are existing in this region and the rests are out of the region. Now there are 1 one-step ahead points with radial distance of two meter around the vehicle and 15 degrees apart. (i.e., θ_h = -75, -60, -45, -30, -15, 0, 15, 30, 45, 60, 75 degrees). So each point is having a heading angle of 15 degree. The points (q_i) on the semicircle in terms of Cartesian co-ordinates can be represented as

$$\begin{aligned} x_i &= r\cos\theta_h \\ y_i &= r\sin\theta_h , \end{aligned} \tag{18}$$

where r =r_v+d_q, (r_v=radius of the AUV nose (0.75m), d_q=radial distance of the points q_i around the vehicle). These points are used to "predict" the next one step ahead. The distance (d_a) between a point on the arc (q_i) and the goal point is measured and the attractive potential is calculated using eq. (12). To calculate the repulsive potential, sixteen (K=16) points are taken on the periphery of the obstacle 2. Using eq. (13), the repulsive potential is calculated at each point on the arc (q_i) by measuring the distance (d_o) between this point and the point (p_j) on the obstacle 2. The actual repulsion potential due to the obstacle 2 at the point on the arc is the sum of individual potential calculated by using the eq. (13). In this way, the actual potentials for other obstacles within the region of interest are also calculated. Since U_{tot} is the sum of the attractive and repulsive potentials, we need to add all the actual repulsion potentials due to the obstacles 1, 2, and 3 at the point (q_i) and this has to be added with attractive potential corresponding to the point on the arc (q_i). Once the total potentials are computed for N points, then the vehicle is moved to the point at which U_{tot} has minimum value. The algorithm is shown as flowchart in Figure 6.

4 SIMULATION RESULTS

In order to illustrate the performance of the way point guidance based path planning algorithm, simulations are carried out by taking the length of the vehicle as L=4.5 m and the desired forward speed u_d = 2 m/s. The path of the modified waypoint guidance by LOS method and the basic LOS are shown in Figure 7. The minimum distance between starting point, waypoints and goal point can be fixed by adjusting the distance threshold value. From Figure 7, it can be seen that the vehicle takes a smooth turn at the waypoints using the modified waypoint guidance by LOS method. A close-up view of the course change at waypoint-3 is shown in Figure 8. The vehicle computes for heading correction only between the distance threshold and waypoints though the line showing the path between waypoint and goal point is not via the threshold point C_B. It can be seen that there is a smooth transition exists at waypoints and also passes through it. The simulations are carried out for obstacle avoidance algorithm and the results have been shown in Figure 9 and 10. Here the obstacles are considered along the path of the vehicle in a manner such a way that there will be no local minima.

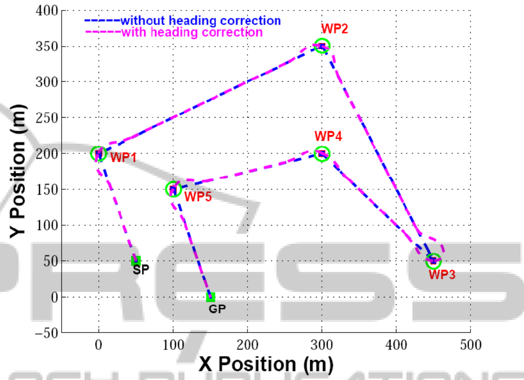

Figure 7: Waypoint guidance with and without heading correction.

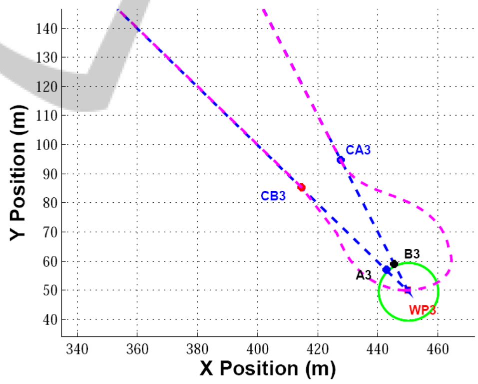

Figure 8: Close-up view of the modified waypoint guidance by LOS at waypoint 3.

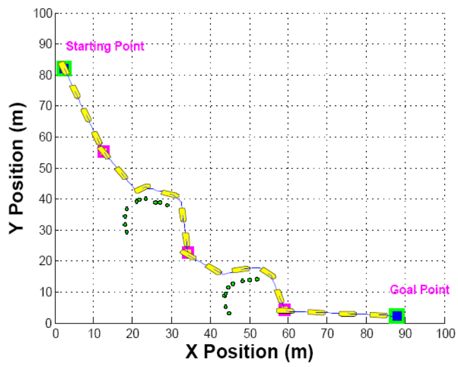

Figure 9: 2D Obstacle avoidance of AUV with circular obstacles of same size.

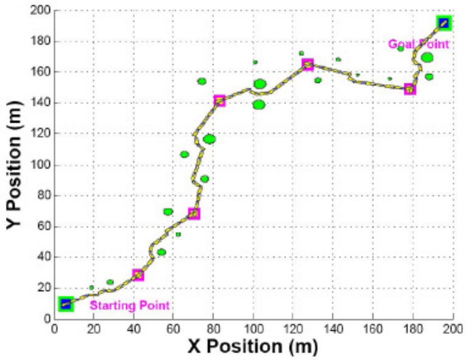

Figure 10: 2D Obstacle avoidance of AUV with circular obstacles of various sizes.

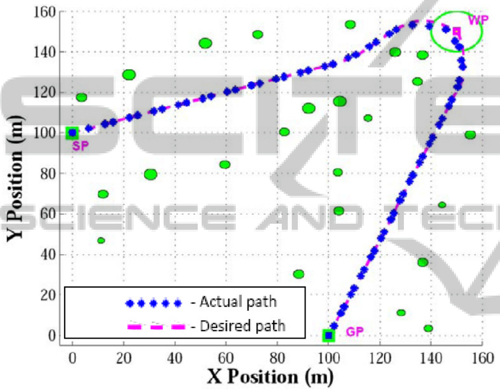

Figure 11: Obstacle avoidance with improved waypoint guidance data – No obstacle in the desired path.

In order to showcase the position and orientation of the vehicle during maneuvering the vehicle is considered as a flat fish type AUV. It has been observed that the vehicle is able to reach the desired goal position successfully after avoiding the obstacles by maintaining the orientation. Few points are taken from the path generated by the improved waypoint guidance. These points are given as waypoints for the obstacle avoidance algorithm. The corresponding results are shown in Figure 11 and 12. It has been observed that the obstacle avoidance algorithm follows the path if there is no obstacle in the path. In case of any obstacles found, it avoids the obstacles and follows the path.

5 CONCLUSIONS AND FUTURE WORK

A waypoint guidance based path following is developed by improving the basic LOS method for smooth turn during course change at waypoints. Simulation results show that it is possible to achieve

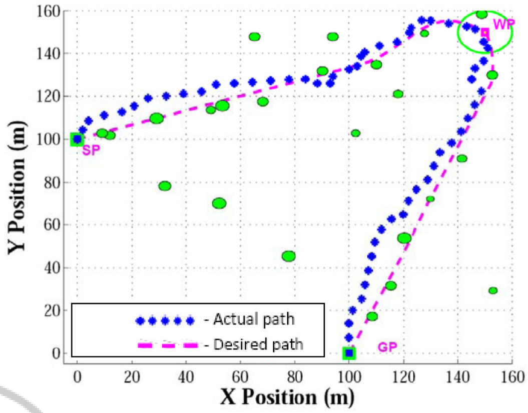

Figure 12: Obstacle avoidance for the obstacles of various sizes in the desired path with the improved waypoint guidance data.

a better and smooth transition though a sharp turn is required and computation for heading correction is needed for minimal distance only. These path points can be used to generate a trajectory and can be used for better vehicle control so that the vehicle will follow the trajectory. This algorithm also eliminates the problem of changing the waypoints by the mission planner in order to avoid a sharp turn. An obstacle avoidance algorithm has been developed by adding some improvements to the artificial potential field method. The desired path generated by the waypoint guidance algorithm can be given to the obstacle avoidance algorithm. This algorithm helps the vehicle to avoid the obstacles and reach the target successfully. Both the algorithms are simple and appropriate for real-time implementation. These algorithms are being improved to address the issues of local minima as well as dynamic environments. Hardware in the loop (HIL) simulations will be carried out in order to validate these algorithms for real time implementation. The results will be presented in the near future.

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