A new path following method of AUV using line-of-sight with sideway

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***Abstract*—In this paper, we propose a new guidance law based on Line-of-Sight (LOS) guidance, i.e., Line-of-Sight-With-Sideway (LOSWS) for autonomous underwater vehicle (AUV) with sideway motion in small water area, such as fish pond. It is able to maximize the use of kinetic characteristic in sideway and realize a more precise path following. In addition, to overcome the demerit of course angle variation which is required to "through" *π*-axis or -*π*-axis, we also propose a reference point course angle updating algorithm to implement the optimal steering path. The simulation results in MATLAB validate that the proposed methods can achieve a better performance compare to conventional LOS and PID-LOS guidance.**

Keywords—path following, guidance, Line-of-Sight, LOSWS, optimal steering path

I. INTRODUCTION

In general, there are always path following or trajectory following missions with operation of autonomous underwater vehicle (AUV). For path following, the path points only need to obtain positions, or both of position and attitudes which are independent to time. Of course, it is also able to consider about time constraint in local planning. For trajectory following, however, the time constraint is necessary to trajectory points. Thus, the trajectory points could be seen as special path points. Because it is permitted that there is no time constraint during the path following, path following is feasible to be implemented and more adaptive to the complex ocean and lake environment compare to trajectory following with strict time constraint. Therefore, path following becomes an increasingly important problem in research field of AUV. And one of the key subproblem of path following is how to guide the AUV to reference path or reference point based on a particular guidance law.

The last two decades have seen a growing trend towards path following guidance. In 2003, Fossen applied Line-of-Sight (LOS) to path following control to avoid solve the path following problem directly in [1]. After four years, Lionel proposed a nonlinear path following control in [2]. The key idea is to explicitly control the rate of progression of a "virtual target" to be tracked along the path, thus overcoming the "singularity" problems. Moreira declared in [3] that LOS with a dynamic acceptance circle radius would spend less convergence time to increase the following speed. In 2012, Jia introduced an adaptive feedback control based on neural network which achieve a precise 3-D path following in [4]. Lekkas presented a LOS guidance with variable lookahead distance which can make AUV move into path point faster in [5]. However, variable lookahead distance would lead some constraints into control system which is unable to be solved by classic control law. To get over the constraint problems, Pavlov used a model predictive control with LOS to solve the constraints problems in [6]. Xia suggests an improved LOS trajectory following control to deal with highly coupled nonlinearities, ocean currents-induced uncertainties, and input saturation for under-actuated AUV in [7]. In 2016, Moe considered the unknown influence of current and combined the guidance law, adaptive feedback linearization control as well as sliding mode control to realize the path following with only velocity feedback in [8]. Peng maintained in [9] that it is able to employ a projection neural network for computing optimal guidance signals in real time. Furthermore, a multi-objective model predictive control (MPC) framework was developed by Shen to accommodate the prioritized speed profile of path following tasks in [10]. Liu investigated the underactuated AUV path following in [11]. A MPC-based path following under the state constraints was proposed. Recently, in [12], to determine the effects of reinforcement learning in improving AUV, Jiang implemented the generative adversarial imitation learning algorithm for AUV path following. Nevertheless, the work above are aiming at torpedo form AUV without direct sideway propulsion. On the other hand, sideway motion can realize the larger use of AUV kinetic characteristic and the smaller following error with fixed course angle. It promises that AUV with sideway motion can finish path following mission more precise and rapid. Unfortunately, there are few achievements about path following of AUV with sideway motion. Path following has a wide range of applications in many fields. For example, in pond aquaculture applications, AUV is used to detect underwater biomass throughout the pond. However, due to the small pond area and short air route, AUV is required to have a good path tracking and control capability to adapt to narrow waters. In this work, we propose a new guidance method based on LOS for AUV with sideway motion. In addition, we also discuss about reference point updating and propose a new algorithm to

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realize a more efficient path following. Our contributions can be summarized as follow:

A. A new guidance law based on LOS.

A new guidance law based on LOS for AUV with sideway motion, i.e., Line-of-Sight With Sideway (LOSWS), is proposed. It is able to reduce the following error by making the kinetic characteristic maximization.

B. A new reference point course angle updating algorithm.

A new reference point course angle updating algorithm is presented, which can realize a more efficient path following and a further lower following error.

The first section of this paper will introduce the background and discuss the relevant work. Then, we will introduce the overview of the path following in section II. And in section III, we will introduce the origin of LOSWS and show the detail and effect of reference point course angle updating algorithm. The simulation results of above two methods for different path following missions will be presented in section IV. Finally, the paper will be concluded in section VI.

II. DIAGRAM OF LOSWS WITH REFERENCE POINT UPDATING ALGORITHM

The guidance diagram is shown in Fig.1. The input data is reference points $p_1, p_2, \dots p_n$, which are defined as $p_i = (x_i, y_i)$. The reference path will be generated by reference points. Reference path and current system state will be used to calculate the desired heading speed u_d, course angle ψ_d, and sideway displacement y_d by reference updating algorithm and LOSWS guidance law.

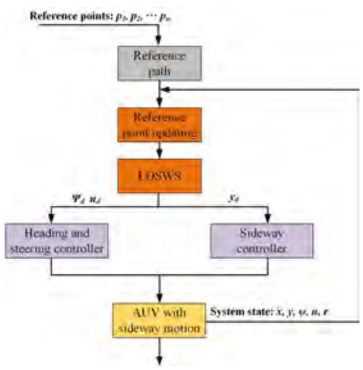


Fig.1 Diagram of path following based on LOSWS with reference point updating algorithm.

The three inputs above will be send to heading controller, steering controller and sideway controller respectively. Then, controllers will drive AUV and the system state will be updated. The system state contains five variables, which are x-position x, y-position y, course angle ψ, heading speed u and course angle rate r. The new system state will be feed backward.

III. ORIGIN AND DETAIL OF LOSWS AND COURSE ANGLE UPDATING ALGORITHM

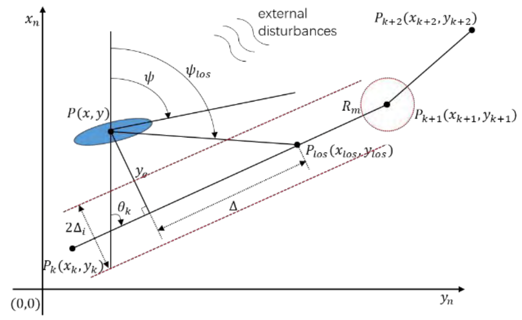
The origin of LOSWS is shown in Fig.2, where P is current position point of AUV, P_k is current reference point , P_{k+1} is next reference point, ψ is current course angle, y_e is following error, Δ represents forward sight distance, θ_k is current reference path direction and R_m is acceptance circle radius. As shown in Fig.2 (a), it is same as LOS, system will guide AUV moves into acceptance circle when it is beyond sideway support area. The sideway support area refers to the area between two parallel red dotted lines which are also parallel to current reference path. The distance from current reference path to each parallel red dotted line is both Δ_i which determines the area range. But different from LOS, the proposed LOSWS requires not only desired heading speed u_d and desired course angle ψ_d, but also desired sideway displacement y_d to confirm the sideway motion.

The ψ_d is the same as LOS which is calculated by

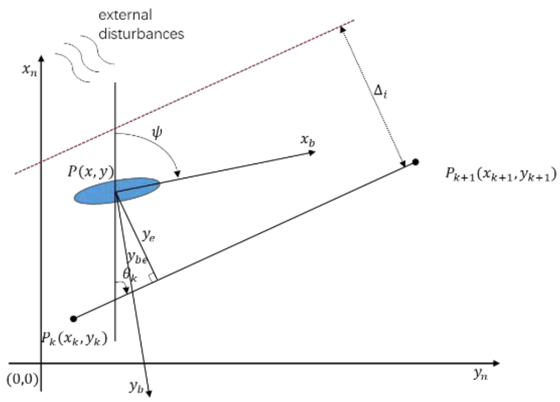
$$\psi_d = \psi_{LOS} = atan2(y_{LOS} - y, x_{LOS} - x) \tag{1}$$

where x and y are current position coordinates in x-axis and y-axis of AUV. And x_{LOS} and y_{LOS} are coordinates of P_{LOS} which is a point on current reference path.

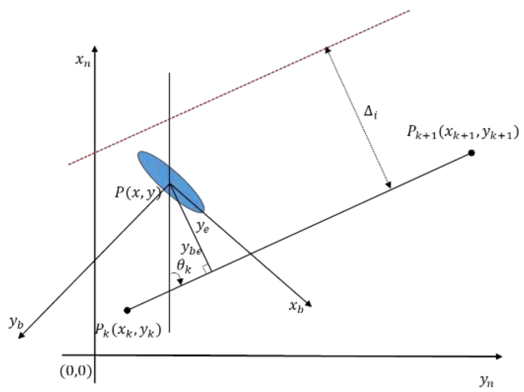
During LOSWS guidance, sideway controller is supposed to work when AUV moves into the sideway support area as shown in Fig.2 (b). At meantime, desired course angle ψ_d is equal to θ_k and desired sideway displacement y_d is equal to y_e.



(a) Follow law beyond the sideway support area



(b) Follow law in the sideway support area



(c) Overlarge difference between course angle and path direction

Fig.2 Origin of path following based on LOSWS

It should be mentioned that regarding the sideway support area as the only condition to activate sideway controller may lead to inefficient path following. As shown in Fig.2 (c), AUV would be away from the reference path because of sideway controller in this situation. As mentioned above, ψ_d should be calculated as follow

$$\begin{cases} \psi_d = \psi_{los} = atan2(y_{los} - y, x_{los} - x), & |y_e| > \Delta_i \text{ or } |\psi - \theta_k| > \theta_i \\ \psi_d = \theta_k, & |y_e| \le \Delta_i \text{ and } |\psi - \theta_k| \le \theta_i \end{cases} \quad (2)$$

where θ_i determines the course angle deviation constraint. The sideway controller should work when both of conditions above are met.

However, as shown in Fig.3, there is a "small circle" path when AUV encounters a special course angle variation during path following. The cause of this phenomenon is process of course angle change will be required "through" the π-axis or -π-axis. But the course angle is defined at (-π, π], so it is not able to realize the optimal steering path as shown in Fig.4.

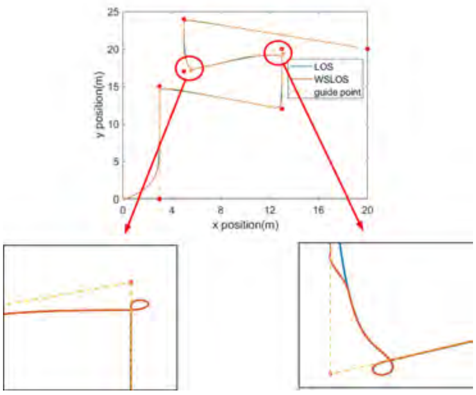


Fig.3 "Small circle" during path following with a course angle variation greater than 90°

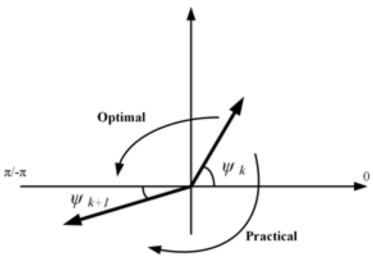


Fig.4 Optimal steering path and practical steering path

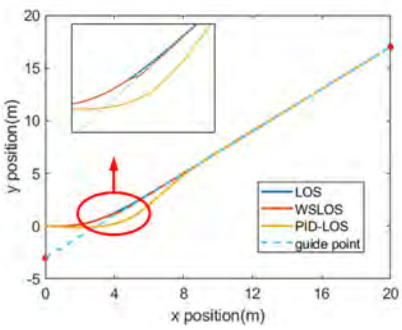
To overcome the demerit, we propose a reference point course angle updating algorithm. The main idea of proposed algorithm is that make the reference course angle map to (-3π, 3π] when it is require to "through" the π-axis or -π-axis. After course angle "passing" the π-axis or -π-axis, the course angle would be mapped return to (-π, π]. The detail of algorithm is presented as follow:

input: ψ *and* ψ_{ref}, *output: new* ψ_{ref}
1) *if* $\psi > \pi$
   do: $\psi = \psi - 2\pi$
   else if $\psi < \pi$
   do: $\psi = \psi + 2\pi$
2) *if* $\psi - \psi_{ref} > \pi$
   do: $\psi_{ref} = \psi_{ref} + 2\pi$
   else if $\psi - \psi_{ref} < -\pi$
   do: $\psi_{ref} = \psi_{ref} - 2\pi$
3) *end*

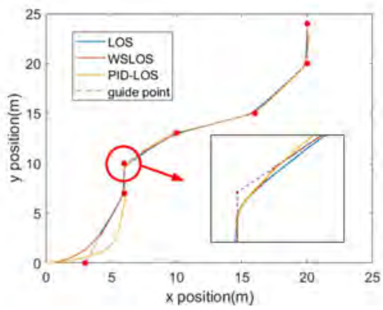
IV. DISCUSSION AND ANALYSIS OF SIMULATION RESULTS

We then validate the LOSWS guidance law and compare the simulation results between different scheme in MATLAB. For comparison, we also introduce a PID-based LOS guidance law into the simulation. In simulation, initial position of AUV is all $(x_0, y_0) = (0,0)$, acceptance circle radius R_m is set to 1m, Δ is set to 2m and desired heading speed $u_d = 0.5\ m/s$. For LOSWS, Δ_i is set to 0.5m, and θ_i is set to π/18. The control law is set to nonlinear model predictive control (NMPC). Sampling period is set to 0.1 second. The prediction horizon and control horizon of NMPC for forward thruster is set to 10 and 2 respectively. The prediction horizon and control horizon of NMPC for side-way is set to 50 and 5 respectively. Forward thrust force is restricted during [-20N, 20N] and side-way thrust force is restricted during [-1N, 1N].

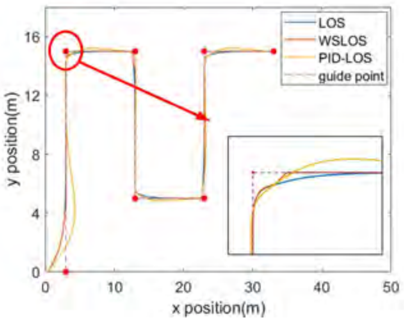
The simulation results are presented in Fig.5. The first path is a line contains two reference points as shown in Fig.5(a). Compare to LOS and PID-LOS guidance, it is able to see that there is an obvious sideway displacement when AUV is close enough to reference path with LOSWS. In next path, we try to add more points into reference path and there is a course angle variation between adjacent path. Every angle variation between adjacent path is lower than 90°. As shown in Fig.5(b), it is similar to path 1, AUV will obtain an obvious sideway displacement when it is satisfied the sideway support conditions. And the similar results is presented by Fig.5(c) and Fig.5(d) with course angle variation which is equal to 90° and greater than 90°. It should be mentioned that PID-LOS cannot finish the whole path following because of the larger angle variation. So there is no simulation results of PID-LOS in Fig.5(d).



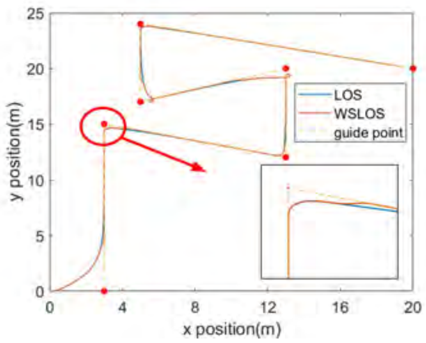
(a) Path 1, a line contains two reference points



(b) Path 2, a curve with course angle variations which are lower than 90°



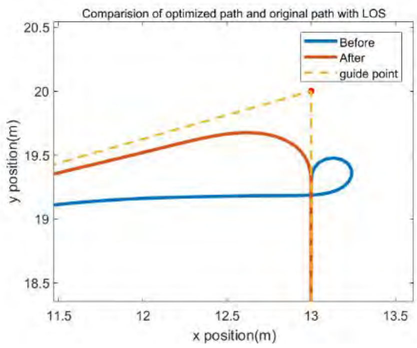
(c) Path 3, a curve with course angle variations which are 90°



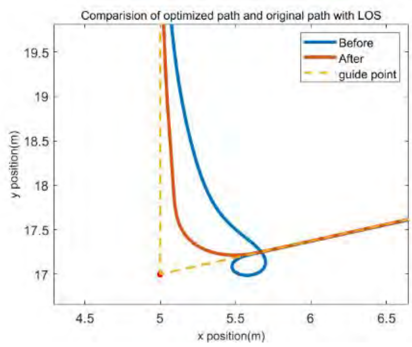
(d) Path 4, a curve with course angle variations which are greater than 90°

Fig.5 Simulation with different path

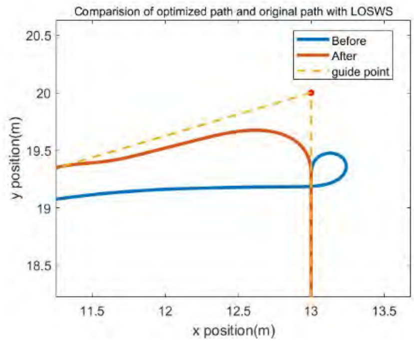
The results of proposed optimization algorithm are given as follow. As shown in Fig.6, both of the path following with LOS and LOSWS avoid a circle path when encountering a special course angle variation whether it is required to "through" the π-axis or -π-axis. Which means that steering path is chosen as optimal path as shown in Fig.4. And obviously, the following error is decreased.



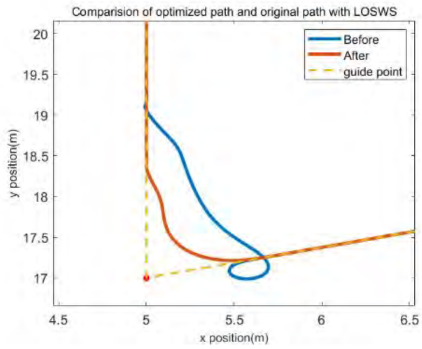
(a) Course angle variation "through" π-axis with LOS



(b) Course angle variation "through" -π-axis with LOS



(c) Course angle variation "through" π-axis with LOSWS



(d) Course angle variation "through" -π-axis with LOSWS

Fig.6 Path before and after optimized by proposed algorithm with LOS and LOSWS

To describe the following error more directly, we calculate the integration of following error which can describe global error with one value during the whole path following. The calculate formular is as follow

$$Error_{integral} = \sum_{t=0}^{t_{final}} T_s \times Error_t \tag{3}$$

where T_s is sampling period, $Error_t$ is following error at current time.

The results of three guidance law without proposed algorithm optimization are shown in Fig.7. For path 1 (line contains 2 points), there is little difference between LOS and LOSWS, but the performance of LOSWS is still better than LOS. And the performance of PID-LOS is much worse. However, for path 2 and path 3, the difference between LOS and LOSWS is increasing. It is due to the complexity and length of path are growing. At the meantime, the following error is accumulating correspondingly. But for path 4, the performance of LOS and LOSWS is both not ideal and the difference also becomes fewer. Fortunately, this will be improved by applying the proposed algorithm.

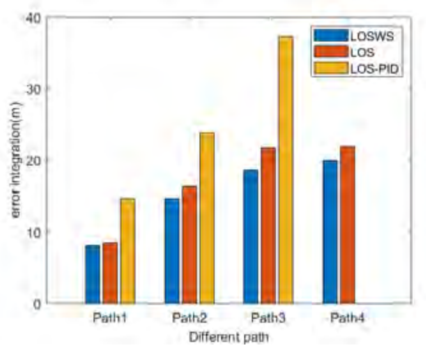


Fig.7 Error integration of three guidance law without proposed algorithm optimization

As shown in Fig.8, for the same path (path 4), after optimization of the proposed course angle updating algorithm, the following error decreases obviously both with LOS and LOSWS. In addition, the performance of proposed LOSWS guidance law is still greater than LOS. It should be mentioned again that PID-LOS cannot finish the whole path following for path 4, thus the results of error integration with PID-LOS are not given.

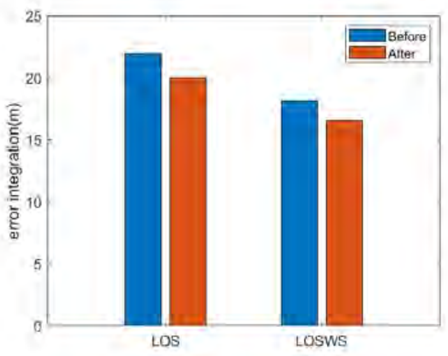


Fig.8 Comparison of after and before optimization of proposed algorithm

The exact results of error integration are shown in the following table.

TABLE I. ERROR INTEGRATION WITHOUT PROPOSED ALGORITHM

Path	Error integration with different guidance law (m)		
	LOSWS	***LOS***	***PID-LOS***
Path 1	8.1461	8.5552	14.6413
Path 2	14.6605	16.3833	23.8439
Path 3	18.6982	21.8202	37.2709
Path 4	20.0119	21.9296	/

TABLE II. ERROR INTEGRATION OF PATH 4

	Error integration with different guidance law (m)	
	LOSWS	***LOS***
With algorithm optimization	16.5753	18.1196
Without algorithm optimization	20.0119	21.9296

V. CONCLUSION

In this paper, the aim is to explore a new guidance law for AUV with sideway motion to maximization the use of AUV kinetic characteristic and to realize a more precise path following. The simulation results has shown that the proposed guidance law, LOSWS, can implement path following with a lower following error for different path. The second major finding is that when the course angle is required to change a lot (to “through” the π-axis or -π-axis), there will be a “small circle” path in steering. To overcome this demerit, we also introduce a reference point course angle updating algorithm to realize a optimal steering path. The simulation results of LOSWS validate the proposed guidance law are better than conventional LOS guidance. And there is also an obvious decrease of following error after the optimization of algorithm for both LOS and LOSWS with still a lower error of LOSWS. Obviously, this method can be used in the narrow water area, such as fish ponds and urban rivers.

However, the proposed scheme is still with a low computing speed during simulation. It is not benefit to practical situation much less to the special situation which contains a real-time, change rapidly etc. conditions. Further work needs to be done to establish whether sideway support conditions could be dynamic during the path following to reduce computing amount, so that it is able to realize a faster convergence speed or even meet the time constraints to realize trajectory-following. At the meantime, a beacon supported scenario will further enhance accuracy for path following. It is worthy to consider the results in such dynamic scenarios.

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