# Bioinspired Underwater Navigation Using Polarization Patterns Within Snell's Window

CHENG Hao-yuan[a, b, *], YU Shi-min[a, b], YU Hao[c], ZHU Jin-chi[a, b], CHU Jin-kui[c]

[a] Department of Mechanical and Electrical Engineering, Ocean University of China, Qingdao 266100, China

[b] Key Laboratory of Ocean Engineering of Shandong Province, Ocean University of China, Qingdao 266100, China

[c] Key Laboratory for Micro/Nano Technology and System of Liaoning Province, Dalian University of Technology, Dalian 116024, China

Received April 12, 2023; revised June 15, 2023; accepted July 13, 2023



**Abstract**

Aiming at the requirement of autonomous navigation capability of the underwater unmanned vehicle (UUV), a novel bionic method for underwater navigation based on polarization pattern within Snell's wind þ ᴀ ᵀ window. Then, we carry out static and dynamic experiments of u polarization information detection equipment. Finally, we obtain underwater polarization patterns and conduct the tracking experiment at different water depths. The experimental results of the underwater polarization patterns are consistent with the simulation, which proves the correctness of the proposed model. At the water depth of 5 m, the average angle and position error of the tracking experiment are 14.3508° and 4.0812 m, respectively. It is illustrated that underwater polarization navigation is realizable and the precision can meet the real-time navigation requirements of UUV. This study promotes the improvement of underwater navigation ability and the development of marine equipment.

**Key words:** underwater navigation, polarization pattern, heading determination, tracking experiment

**Citation:** Cheng, H.Y., Yu, S.M., Yu, H., Zhu, J.C., Chu, J.K., 2023. Bioinspired underwater navigation using polarization patterns within Snell's window. China Ocean Eng., 37(4): 628–636, doi: https://doi.org/10.1007/s13344-023-0053-z

## 1 Introduction

The ocean area of the earth is vast and there are still a large number of sea areas to be explored and exploited. There (Paull et al., 2014). The attitude error obtained by the inertial navigation system accumulates over time (Stutters et al., 2008). The geomagnetic navigation system cannot work in uncertain magnetic fields (Wu et al., 2018). Therefore, it is necessary to develop a new navigation system that does not rely on satellite navigation and can effectively improve inertial navigation. This new navigation technology needs to have comprehensive advantages in cost, coverage, accuracy, anti-interference, and viability.

Physicists have found that after undergoing atmospheric scattering, air-water interface refraction, and underwater scattering, sunlight eventually forms a particular pattern of underwater polarization. When viewed upward from calm water, the field of view above the water surface is compressed to a conical area of approximately 97.5° due to the refraction effect. This field of view is called Snell's window. The polarization pattern in Snell's window under a calm water surface is usually relatively stable under certain conditions and contains important orientation information, which can be used by underwater organisms and even humans. It has

Foundation item: This work was financially supported by the National Natural Science Foundation of China (Grant No. 52175265).

*Corresponding author. E-mail: chenghaoyuan@ouc.edu.cn

been proven that polarization has great superiority in the water (Cheng et al., 2021b; Zhang et al., 2021). Many creatures have evolved for millions of years and natural selection has given them many navigational skills. In the water, a variety of creatures can use polarization for navigation, predation, disguise, and communication (Shashar et al., 2000; Waterman, 2006; Cartron et al., 2013). Among them, a grass shrimp named Palaemonetes vulgaris (Goddard and Forward, 1991; Horváth and Varjú, 1995) can perceive the underwater polarization pattern in Snell’s window and uses this pattern as a direction cue to move away from the coastline predators. In the process of migration, rainbow trout (Hawryshyn and Bolger, 1990; Browman and Hawryshyn, 1994; Parkyn et al., 2003) can make use of underwater polarization patterns to realize navigation. The vision system of mantis shrimp (Bok et al., 2014; Gagnon et al., 2015) can detect and analyze visible light, ultraviolet light, linearly and circularly polarized light, which enables it to accurately capture prey, avoid natural enemies, and even navigate in

with lf +r¾ M Ş ö lByst = lns to real ö l ö tion of polarized light. $I$ is the total intensity of light, $Q$ quantifies the fraction of linear polarization parallel to a reference plane, gives the proportion of linear polarization at 45° to the reference plane, and describes the fraction of right-handed circular polarization. The Stokes vector form of incident light can be written as follows:

where

ple, the AOP patterns can be obtained by polarization camera and coordinate transformation. Different azimuth values of polarization can be distinguished by pixel values. The characteristic region of the solar meridian has an obvious edge, which shows a significant mutation of the gray value in image processing. We can acquire the characteristic region of the solar meridian by setting the characteristic threshold value. Next, we detect the edge of the characteristic region of the solar meridian based on the Canny operator. The azimuth of the solar meridian is obtained by using the Hough transform and symmetry distribution relation (Fig. 2). Then, we can calculate the heading angle by combining the north finder data.

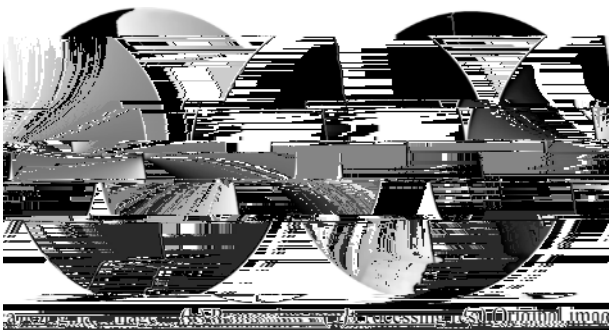


**Fig. 2.** Solar meridian extraction results.

In this way, we obtain polarization navigation data through the AOP pattern. The azimuth of the polarization or the direction of the solar meridian obtained by the polarization detection method can determine the reference angle between the carrier axis and solar meridian, which is the relative angle. The angle between the body axis and the true north can be obtained by means of compass-assisted orienta

**Fig. 7.** Positioning system of underwater tracking experiment.

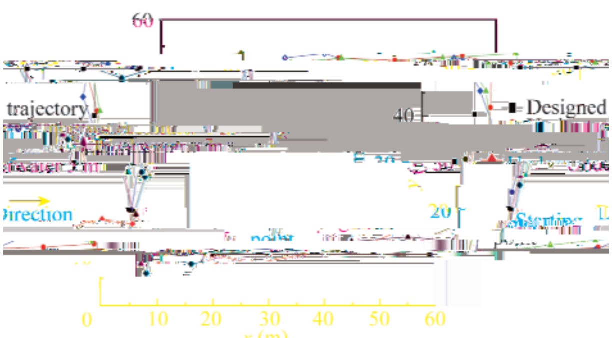
igation error of the strapdown system and compensate for it to get the optimal navigation structure of attitude, speed, and position.

Whether polarization navigation technology can be realized underwater depends on the stability of detected underwater polarization patterns. If the polarization pattern, such as DOP or AOP, is robust in the general underwater environment, the navigation information contained in the pattern can be obtained by image processing to realize underwater polarization navigation. To prove that underwater polarization patterns are regular and further serve for underwater navigation, we captured the underwater polarization patterns at different time (Fig. 8) and depths (Fig. 9) in the real underwater environment. The underwater experiment was performed under clear weather conditions at a depth of 1 m, 3 m, and 5 m. The wind was southeast and the speed was about 5 m/s. There were some waves on the surface of the ocean. The underwater environment in the experiment was complex. The water was semi-turbid and the visibility was poor owing to the absorption and scattering of light by various particles. The ocean wave, shoreline, seabed, and waterproof device had a negative influence on the experiment due to their impacts on the light. The maximum DOP occurs at sunrise and sunset (Cheng et al., 2020b), and thus we experimented within this time range. We used a long exposure time to overcome the low light in the water. Experimental results show that underwater polarization patterns are regular and the navigation based on them is realizable. Underwater polarization patterns within Snell’s window, whose main affecting factor is the sun position, are stable and similar to atmospheric polarization patterns. Underwater light is partially polarized except for the neutral points. The DOP is concentric around the sun position and symmetrical about the solar principal plane. The AOP is negative about the solar principal plane and keeps the robustness in most cases. However, polarization patterns cannot be maintained at deep water because there is an increase in multiple scattering. At deep waters, polarization characteristics cannot be maintained (Shashar et al., 2004). Snell’s window is dark and shows no apparent color or structure (Lynch, 2015). With depth increase, the effect of sun position on both the DOP (Ivanoff and Waterman, 1958) and AOP (Waterman, 1955) diminishes. Although there are some noisy points in the patterns and the DOP value is low, we can still distinguish the patterns, especially AOP. It proves the feasibility of underwater polarization navigation. Thus, we choose AOP patterns within Snell’s window to conduct the navigation.

**Fig. 8.** Underwater DOP (a) and AOP (b) patterns at different time.

**Fig. 9.** Underwater DOP (a) and AOP (b) patterns at different depths.

After proving the regularity of underwater polarization patterns, we conducted the underwater tracking experiment and realize underwater positioning. We controlled the ROV to move horizontally so that the polarization camera is straight up toward the sky and can capture the underwater polarization patterns within Snell’s window. GPS served as a reference for the polarization navigation information to verify the relevant position accuracy. We used the computer to control the ROV to dive at a specified depth and started to cruise at a designed route. The experimental target trajectory was a square with a side length of 40 m and a total length of 160 m. We collected the angle and position data every 10 m and the experiment trajectory at different depths are shown in Fig. 10. Then, we compared the measurement with the GPS and obtained the error of the method (Table 4). With depth increase, the errors of angle and position of underwater polarization navigation increase, which are consistent with the results of underwater polarization pattern. However, the practical trajectory is similar to the designed trajectory within this depth range and the precision can meet the real-time navigation requirements of UUV (Miller et al., 2010). The polarization navigation method is greatly affected by depth because the patterns are getting blurry with depth increase. It shows that underwater polarization navigation is feasible and has great potential within this depth range. As a new bionic visual navigation method, it exactly cannot work at much larger depths. But as photoelectric detection devices improve and underwater image enhancement technology develops, the polarization navigation will be able to work in deeper waters and plays a more important role. The results suggest that the underwater polarization pattern contains rich navigation information and can be used for navigation. However, many optical effects such as surface waves, water particles, and sea bottom reduce the performance of the method. In the future, the disturbance of multiple optical effects will be taken into consideration in the navigation model to improve the robustness and precision of the proposed method.



improvement in turbid water by the fusion technology of Mueller