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Weng, Yang; Matsuda, Takumi; Sekimori, Yuki; Pajarinen, Joni; Peters, Jan; Maki, Toshihiro

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Pointing Error Control of Underwater Wireless Optical Communication on Mobile Platform

Yang Weng, *Student Member, IEEE,* Takumi Matsuda, *Member, IEEE,* Yuki Sekimori, Joni Pajarinen, Jan Peters, *Fellow, IEEE,* and Toshihiro Maki, *Member, IEEE*

***Abstract*—This letter discusses pointing errors in underwater optical communication caused by environmental disturbances and uncertainties that cannot be well measured and controlled in previous optical alignment methods. The bore-sight and jitter effects are identified in the motion model of the mobile platform. We propose to use the sensor suite that includes a pressure sensor, super short baseline (SSBL) acoustic system, Doppler velocity log (DVL), and fiber optic gyro (FOG) to observe and estimate pointing errors during communication. The pointing errors updated by the particle filter can be shared with the pointing, acquisition, and tracking (PAT) system and thruster system. The sea experiments reveal that the proposed method can measure pointing errors and limit error growth by maneuvering the mobile platform.**

***Index Terms*—Autonomous underwater vehicles, Underwater wireless optical communication, Optical beam alignment, Bore-sight, Jitter**

I. Introduction

In recent years, underwater wireless optical communication (UWOC) has gradually attracted the attention of the underwater technology research community. UWOC can provide a much higher data rate service than the traditional acoustic communication, which currently dominates underwater [1]. In 2018, a light-emitting diode (LED) based system developed by Lu *et al.* achieved a data rate of 205 Mbps in the sea environment [2]. In 2021, Fei *et al.* experimentally demonstrated a laser diode (LD) based 3 Gbps UWOC over 100 meters in a water tank [3]. Although the effective transmission distance of optical signals is relatively short, this is acceptable for mobile platforms, such as autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), and underwater gliders. Considering that the deployment of multi-platform formations for joint underwater surveys may become the standard in the future, UWOC is an attractive solution for sharing real-time data between mobile platforms.

Achieving wireless optical communication between mobile platforms requires establishing a line-of-sight (LOS) link. The underwater optical link is affected by various factors, such as inherent and apparent optical properties [4]. Gabriel *et al.* simulated the trajectories of emitted photons in seawater to study the effects of absorption and scattering on underwater optical signals [5]. Guo *et al.* investigated the signal scintillation due to fluctuations in the sea environment, such as turbidity, salinity, temperature, and air bubble [6]. Based on well-studied underwater channel characteristics, the pointing, acquisition, and tracking (PAT) system is proposed for underwater optical link alignment [7][8]. The main concept is to develop a real-time beam director system to rapidly steer the optical beam towards the target and maintain the LOS link based on detected light intensity.

However, the current PAT system cannot estimate the pointing error caused by environmental disturbances and uncertainties. The bore-sight and jitter effect is still a problem as the random nature of the sea environment cannot be measured and controlled [4]. As far as we know, sensor data measured by mobile platforms has not been considered for sharing with PAT systems to improve the stability of the link. The onboard sensor suite that includes pressure sensors, super short baseline (SSBL), Doppler velocity log (DVL), and fiber optic gyro (FOG) can provide continuous and real-time observation of the environment and target platform [9]. There is also no mobile platform-based control strategy to reduce pointing errors.

We propose to combine the mobile platform and PAT system in the LOS link alignment task. The pointing error is identified in the motion model of the mobile platform so that the platform can measure it using the sensor suite. The estimation results updated by the particle filter can be shared with the PAT system and platform control unit. The thrusters are used to adjust the position and orientation of the platform to control the pointing error. We deployed the proposed method on the AUV Tri-TON and the autonomous surface vehicle (ASV) BUTTORI in the sea experiments. The experiment results show that our method can measure pointing errors caused by the environment and limit error growth by maneuvering the mobile platform. The residual pointing error can be covered by the current PAT system.

To summarize, the main contributions of introducing pointing error control on mobile platforms are:

1) reduce the dimension of the link alignment task from a three-dimensional space to a two-dimensional plane;

2) measure and estimate bore-sight and jitter effects caused by environmental disturbances and uncertainties;

3) maneuver the mobile platform to limit the growth of pointing errors;

The remainder of this paper is organized as follows. Section

Yang Weng, Takumi Matsuda, Yuki Sekimori and Toshihiro Maki are with the Institute of Industrial Science, The University of Tokyo, Tokyo, Japan (e-mail: yangweng@iis.u-tokyo.ac.jp; matsuda@iis.u-tokyo.ac.jp; sekimori@iis.u-tokyo.ac.jp; maki@iis.u-tokyo.ac.jp). Takumi Matsuda is also with the School of Science and Technology, Meiji University, Japan (tmatsuda@meiji.ac.jp).

Joni Pajarinen and Jan Peters are with Intelligent Autonomous Systems Laboratory, TU Darmstadt, Darmstadt, Germany (e-mail: joni.pajarinen@aalto.fi; jan.peters@tu-darmstadt.de). Joni Pajarinen is also with the Department of Electrical Engineering and Automation, Aalto University, Finland.

II introduces pointing errors based on the underwater platform motion model. In Section III, a method to measure and control pointing error using platform sensors is proposed. A detailed field experiment is conducted and discussed in Section IV. The conclusions are given in Section V.

II. Model

A motion model of the mobile platform during the link alignment task is presented in this section. The pointing error due to external disturbances is identified in this model for measurement and control. As shown in Fig. 1, the LOS can only be established when the omnidirectional receiver is at least partially covered by the sector-shaped beam. We present the model of the LOS establishment between mobile platforms on a horizontal plane. The pressure sensor is one of the few sensors that can provide accurate measurements underwater [9]. Determination of absolute depth allows the mobile platforms to establish the LOS link at a specific depth, which reduces the alignment task from a three-dimensional space to a two-dimensional plane.

During underwater optical communication, the receiver is expected to be located at the optimal point (x^O, y^O) to detect higher light intensity, which can increase the Signal-to-Noise Ratio (SNR) and limit the Bit Error Rate (BER) in communication. The optimal point is at the center of the beam, and link distance l_o is affected by various factors such as absorption, scattering, scintillation, source power, and hardware [10][11]. Ocean waves, turbulence, and uncertainties of the mobile platform can cause the position of the transceiver to shift, which optical communication systems cannot detect.

The pointing errors caused by external disturbances consist of two components: bore-sight and jitter. The bore-sight is the displacement between the optical beam center and the center of the receiver due to the inaccurate receiver location information [12]. The jitter is the random offset of the beam center at the detector plane, which is mainly caused by platform vibration [4]. The position of the mobile platform may fluctuate due to the ocean currents and uncertainties in the dynamic model. The misalignment due to pointing errors can be modeled using the beam spread function (BSF) [13]:

$$\begin{aligned} &BSF(l_R, r_R) \\ &= E(l_R, r_R)exp(-cl_R) + \frac{1}{2\pi}\int_0^\infty E(l_R, v)exp(-cl_R) \\ &\times \left\{ exp\left[\int_0^l b\widetilde{\beta}(v(l_R - l))dl\right] - 1\right\} J_0(vr_R)vdv \end{aligned} \quad (1)$$

where $E(l_R, r_R)$ and $E(l_R, v)$ are irradiance distributions in spatial coordinates and spatial frequency domain, l_R is the link distance between transceivers, r_R is the distance from the receiver to the center of optical beam. The parameter b and c are the scattering and attenuation coefficients, and $\widetilde{\beta}$ is the scattering phase function.

Displacement and jitter in distance l_R and r_R can affect the received light intensity and even interrupt the link during optical communication. We define the pointing error d_Δ to represent the displacement and jitter from optimal point, and the mobile platform tries to control its position to mitigate this error:

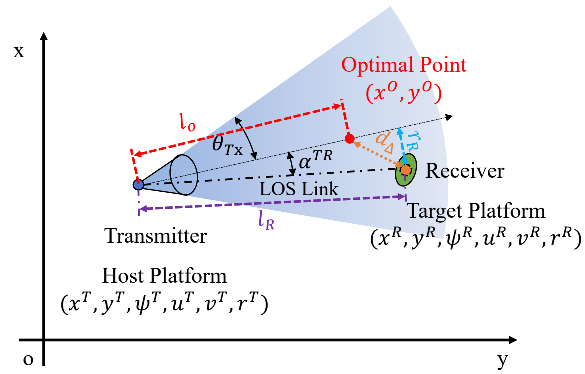


Fig. 1. The establishment of a LOS link between two underwater mobile platforms on a horizontal plane at the same depth.

$$d_\Delta = (x_\Delta^2 + y_\Delta^2)^{\frac{1}{2}} \quad (2)$$

where

$$x_\Delta = x^R - (x^T + l_o \cos\psi^T) \quad (3)$$

and

$$y_\Delta = y^R - (y^T + l_o \sin\psi^T) \quad (4)$$

where (x^T, y^T) and (x^R, y^R) is the position of the host and target platform on the horizontal plane, respectively. The yaw angle of the host platform is represented by ψ^T.

The bore-sight and jitter caused by external disturbances can be identified in this model. The value of (x^R, y^R) may become inaccurate if there is no continuous observation of the receiver position. Jitter in position (x^T, y^T) and yaw orientation ψ^T occurs because of ocean currents and turbulence.

III. Method

We propose to utilize the equipment in the underwater platform to measure and control the pointing error problem caused by external disturbances. As shown in Fig. 2, the pointing error estimate will be shared with the PAT system and the thruster system. The depth measured by the pressure sensor is used to maintain the mobile platform on a set horizontal plane for the link establishment. A DVL measures the ground velocity, including surge velocity u^T, sway velocity v^T. A FOG is used for measuring yaw orientation ψ^T and yaw angular velocity r^T. The acoustic positioning is implemented to obtain the initial receiver location information and continuously observe the state of the target platform during optical communication. The two-way travel time (TWTT) ranging can measure the relative distance l_R and bearing angle α^{TR} between the host and target platforms [14][15]. The position of the target platform (x^R, y^R) can be shared through acoustic communication.

A particle filter algorithm is used to estimate the current state based on measurement [15]. In the prediction phase, the

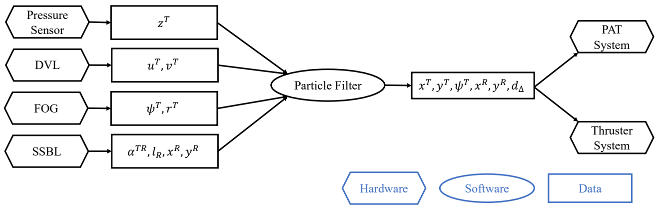


Fig. 2. Mobile platform based pointing error measurement and control method. The environmental parameters and platform status are measured by four different sensors, estimated by the particle filter algorithm, and then the results are transmitted to the PAT system and the thruster system for link establishment.

particle filter updates the position and orientation from time t to $t + \Delta t$ by measurement results:

$$x^{T,i}_{t+\Delta t} = x^{T,i}_t + (u^{T,i}_t \cos\psi^{T,i}_t - v^{T,i}_t \sin\psi^{T,i}_t)\Delta t \tag{5}$$

$$y^{T,i}_{t+\Delta t} = y^{T,i}_t + (u^{T,i}_t \sin\psi^{T,i}_t + v^{T,i}_t \cos\psi^{T,i}_t)\Delta t \tag{6}$$

$$\psi^{T,i}_{t+\Delta t} = \psi^{T,i}_t + r^{T,i}_t \Delta t \tag{7}$$

where i indicates the ith particles in the estimator.

Once the TWTT acoustic ranging results are available, the estimator calculates the difference between observed values and prediction values for weighting and resampling all particles:

$$W^i = W^i_d \cdot W^i_\psi \tag{8}$$

$$W^i_d = \max\left\{\exp\left(\frac{k_d^2}{2} + \frac{-(\Delta d^i)^2}{2(\sigma_d)^2}\right), 1\right\} \tag{9}$$

$$W^i_\psi = \max\left\{\exp\left(\frac{k_\psi^2}{2} + \frac{-(\Delta \psi^i)^2}{2(\sigma_\psi)^2}\right), 1\right\} \tag{10}$$

where Δd and $\Delta\psi$ are the difference in relative distance and direction between observation and prediction, respectively. k_d and k_ψ are parameters for judging outliers.

Then, the host platform can estimate the current pointing errors by:

$$\hat{x}_\Delta = \hat{x}^R - (\overline{x}^{T,i} + l_o \cos\overline{\psi}^{T,i}) \tag{11}$$

$$\hat{y}_\Delta = \hat{y}^R - (\overline{y}^{T,i} + l_o \sin\overline{\psi}^{T,i}) \tag{12}$$

where the variables with overline symbols are averaged from all particles and the hat symbol indicates the variable from estimation results.

With this method, the pointing error due to external disturbances and uncertainties can be measured and estimated by mobile platforms. Based on the continuous measurements from the sensor suite, the mobile platform can maneuver the propellers to control the bore-sight and jitter problems.

Fig. 3. Sea experiments at Hiratsuka Port, Japan. The yellow platform is the hovering AUV Tri-TON, and the red platform is the ASV BUTTORI.

IV. Experiment and Discussion

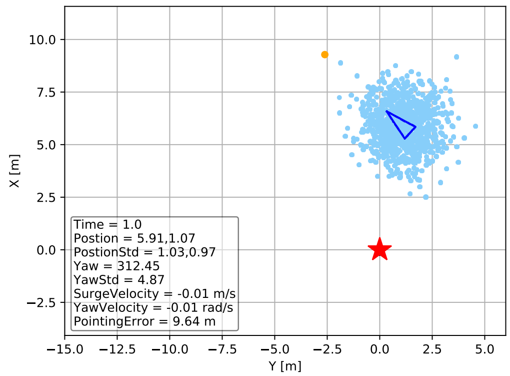
We conducted sea experiments to test the pointing error control on the mobile platform. The hovering AUV Tri-TON was used as the host platform, while the ASV BUTTORI served as the target platform for underwater optical communication. To shorten the pointing error d_Δ in the experiment, an motion planning method was deployed on the AUV Tri-TON, which was validated in simulations in previous studies [16][17]. No global navigation satellite system service or radio communications were used since it is not available underwater. The expected link distance l_o was set to 5 meters.

As shown in Fig. 4, AUV Tri-TON was deployed at a random initial position of (5.91, 1.07) meters in one of the experiments. The distance between the target platform and the optimal point was 9.64 meters. Then, the AUV Tri-TON started to align with the BUTTORI and controlled the pointing error. Based on our model, the environmental parameters and platform status were measured by four different sensors, some of which were presented in the bottom left corner of Fig. 4. The pointing error estimated by the particle filter was passed to the thruster system to adjust the motion of the mobile platform. At the 16.0 second of the sea experiment, the pointing error d_Δ was reduced to 0.60 meters. As shown in Fig. 5, the AUV Tri-TON kept the pointing error within 1.5 meters. From 20 to 60 seconds in this sea experiment, the mean of the pointing error was 0.68 meters and the corresponding standard deviation was 0.37 meters.

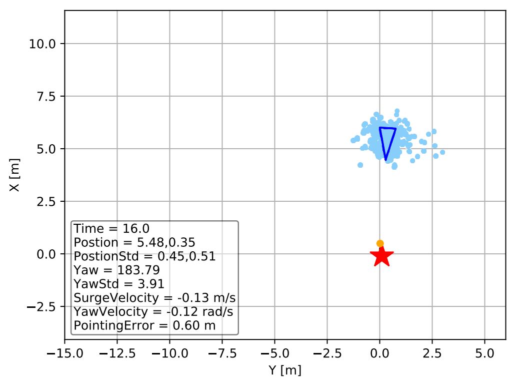
The sea experiments show that the sensors on the mobile platform can measure pointing errors caused by external disturbances. The thrusters successfully adjust the platform to limit the growth of pointing errors. In addition, the measured pointing error can be provided to the PAT system. The pointing error in the yaw direction is shown in Fig. 6. The residual pointing error in the sea experiment can be handled by the current PAT system [7].

V. Conclusion

In this letter, we propose to measure and control the pointing error of optical communication between underwater mobile platforms, which previous studies have not discussed. Mobile platforms are considered in the link alignment task



(a) Sea experiment at 1.0 s



(b) Sea experiment at 16.0 s

Fig. 4. The states of AUV in the sea experiment (a) 1.0 s and (b) 16.0 s. The AUV Tri-TON is represented by the blue triangle, and the sharp corner of the triangle is the head of the vehicle. The red star marker is the ASV BUTTORI. The particle filter estimation results of the AUV Tri-TON are depicted by cyan dots. The orange point is the optimal point defined in this research for optical communication. The parameters listed in the bottom left corner are the time in the experiment, the position of the AUV Tri-TON (x^T, y^T), the standard deviation of particle filter estimation results in the position, the yaw orientation ψ^T, the standard deviation of particle filter estimation results in yaw, the surge velocity u^T measured by DVL, the yaw angular velocity r^T measured by FOG, and the pointing error $d_\triangle$.

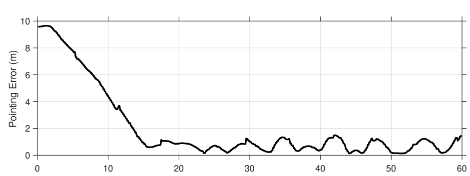


Fig. 5. The pointing error $d_\triangle$ in the sea experiment.

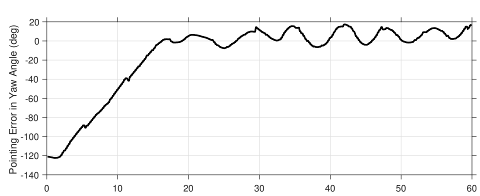


Fig. 6. The pointing error in the yaw direction. Clockwise angles are expressed as positive values.

and combined with the PAT system to maintain link stability. When boresight and jitter effects caused by environmental disturbances are identified in the motion model, we utilize the equipment in the mobile platform to measure and control the pointing error. The field experiment demonstrated that the pointing error can be measured by the mobile platforms and can be controlled by the platform motion and the optical PAT system.

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