A sensor design based on the principle of laser ranging to measure the thickness of sea oil spill

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Abstract: This study aims to design a marine oil film thickness measurement sensor based on pulsed laser ranging technology to address the potential ecological threats posed by oil spill incidents in marine environments. By employing an advanced measurement approach, the sensor continuously monitors the thickness of oil films on the ocean surface, offering an effective means for environmental protection and oil spill emergency response. The research team conducted a comprehensive analysis of key influencing factors and mechanisms during the measurement process, providing theoretical support for the sensor's design and application. The sensor system comprises five main components: the Sensor Control Unit, Laser Ranging Unit, Wireless Serial Communication Unit, Upper Computer Data Reception Unit, and Upper Computer Data Processing Software. Through module testing and measurements in an experimental water tank, the study validates the measurement accuracy of the sensor. Experimental results demonstrate that the relative error remains within the range of 2% to 3% across various oil film thickness measurements, confirming the feasibility of the sensor in measuring thicker oil films in practical applications. Further validation in actual water tank experiments underscores the sensor's performance and stability, thereby offering robust support for marine environmental monitoring and emergency response efforts.

Keywords: Marine oil spill; oil film thickness measurement; pulsed laser ranging technology; environmental protection; sensor design

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1 Introduction

Protecting the marine environment is a prerequisite for ocean development. As human activities in the oceans continue to increase, the occurrence of marine oil spills, which have the most significant impact on the marine environment, is also inevitable during ocean development processes. For instance, notable oil spill incidents occurred in the Gulf of Mexico on April 20, 2020, due to an oil platform explosion, and in Israel on March 4, 2021[1]. Oil spills disperse within the affected maritime area under the influence of waves and currents. Simultaneously, oil components undergo evaporation, dissolution, and sedimentation, leading to extensive environmental contamination[2]. Marine oil spills are unavoidable accidents in the course of petroleum industry development[3], causing significant harm to the marine environment and ecosystems[4]. The severity and classification of oil spill incidents are determined by the volume of spilled oil. Additionally, the spill volume plays a crucial role in emergency response and scientific decision-making at spill sites[5]. Among the key parameters of oil spills, the thickness of the oil film is of utmost importance. This paper introduces a sensor design that employs pulsed laser ranging technology as the primary approach to achieve real-time, in-situ measurement of marine oil film thickness.

The team led by Carl E. Brown [6] devised a Laser-Ultrasonic Remote Sensing Oil Thickness (LURSOT) sensor. It couples a set of detection lasers with photoelectric interferometers to measure the displacement generated on the oil film's surface, thereby calculating the thickness of the oil spill. However, variations in the chemical composition of different petroleum products can lead to differences in the speed of sound within the oil film, affecting measurement accuracy. S. A. PELYUSHENKO's team [7] constructed a Multi-Frequency Imaging Radiometer System (MIRS), which compares the temperature difference between water and oil film surfaces with theoretical values to determine oil film thickness. This method is primarily limited by the poor angular resolution of microwave sensors, resulting in lower accuracy.

Abdul-Wahab's team [8] designed an oil film thickness measurement device based on the difference in conductivity between oil and water layers. However, this approach overlooks the effects of waves and currents in the ocean, leading to substantial measurement deviations. Sun Changsen's team [9] developed a Scanning White Light Interferometer (SWLI) that calculates oil film thickness by analyzing the peak span difference between interference patterns on the oil film surface and the oil-water interface. Kukhtarev's team [10] experimentally verified that the analytical expression describing intensity distribution in an interference pattern can determine oil film thickness. The team led by Lu Yingcheng [11] established a remote sensing quantitative inversion model for oil film thickness based on spectral reflectance and its variability. Ye Zhou's team [12] confirmed that the spectral reflection characteristics of oil films, along with oil type and thickness, can be differentiated through reflectance curve analysis. Furthermore, the vertically incident differential laser triangulation method for oil film thickness measurement developed by Wu Di's team[13], as well as the fixed-point oil spill collection device designed by Li Ying's team[14], are both subject to real-world marine environments, exhibiting substantial measurement deviations during water surface fluctuations. Therefore, we propose a sensor for real-time, in-situ measurement of marine oil film thickness. In comparison to existing oil film thickness measurement methods, this approach offers rapid response and real-time capabilities while minimizing the effects of wave-induced interference due to its structural design.

2 Principle and Design

The ocean oil film thickness measurement sensor designed in this study is based on the technology of pulsed laser ranging. By utilizing this technology, the sensor measures the difference between the reference position of the measurement slider when no oil film is present and the actual position of the measurement slider when an oil film exists. This difference provides the thickness of the measured oil film.

The principle of pulsed laser ranging is illustrated. It primarily consists of a pulse modulator, laser emitter, and laser receiver. By calculating the flight time of pulsed laser light between the measuring target, emitter, and receiver, the distance can be determined[15].

Assuming the speed of pulsed laser light in a certain medium is denoted as c, and the time it takes for the pulsed laser light to travel back and forth between the emission point A and the point of measurement B is represented as t, the distance D between emission point A and measurement point B can be calculated using the following formula[16]:

$$D = \frac{ct}{2} \tag{1}$$

In this equation,

D represents the distance between the emission point and the measurement point,

c is the speed of light in the medium,

t is the round-trip time of the pulsed laser light, and denotes the system response time. This equation serves to capture the intricate factors influencing the accuracy of the pulsed laser ranging measurements and provides a comprehensive understanding of the measurement process.

This formula represents the relationship between the distance and the time of flight of the pulsed laser light in the specified medium.

Building upon the principle of pulsed laser ranging, the research conducted by the team led by Gao Yong [17] comprehensively analyzed the measurement process. They investigated key influencing factors and their underlying mechanisms. Furthermore, they formulated the following equation to express the ranging capability:

$$E = \frac{L^4 \times \exp(2\beta L)}{M} \tag{2}$$

In this equation,

E is the ranging capability,

M represents the radiation coefficient of the target radiation area and the distribution of radiation flux,

L is the measurement range,

β is the medium average attenuation coefficient.

The described ocean oil film thickness measurement sensor system consists of five main components. These components include the Sensor Control Unit, Laser Ranging Unit, Wireless Serial Communication Unit, Upper Computer Data Reception Unit, and Upper Computer Data Processing Software.

The prototype's housing is designed using SolidWorks software. The sensor's housing consists of a total of 14 components. The design focuses on maintaining the center of gravity and buoyant center along the vertical axis relative to the water surface, ensuring stability upon immersion and preventing tilting. The bottom conical structure facilitates breaking through the oil film and water layer. Within 3 to 10 seconds of immersion, a water-soluble, rigid pressure disc at the bottom of the cage dissolves, allowing the slider to rise along its track due to buoyant materials. Ultimately, the oil film is clamped between the sensor's top cover and slider blades, enabling the measurement of oil film thickness.

The Sensor Control Unit employs a Cyclone IV series FPGA device, specifically the EP4CE10F17C8N model. Its primary function is to collect data from the Laser Ranging Unit and transmit it to the Wireless Serial Communication Unit. The Laser Ranging Unit employs a VL53L0X module, capable of measuring distances up to 2 meters with a resolution of 1 millimeter. The Wireless Serial Communication Unit utilizes an ATK-LORA-01 module operating within the frequency range of 410 to 441 megahertz. The Upper Computer Software is developed using LabVIEW, with VIAS functions employed for serial communication.

3 Results

The underwater release system is demonstrated. The underwater release system employs water-soluble rigid pressure discs. Upon the dissolution of these discs, the blades are released, and buoyant materials facilitate their upward movement. Through experimentation, it has been determined that the water-soluble rigid pressure discs dissolve within 3 to 8 seconds upon immersion.

The measurement module is tested by measuring values through the movement of the measurement slider within the measuring rail. According to the test data, the relative error is within the range of 2% to 3%, demonstrating the capability to measure relatively thick oil films with reasonable accuracy.

As illustrated in Figure 1, the sensor's practical measurements in an experimental water tank are presented. The experimental oil used is Yuchai Power APICD-40 model diesel engine oil. The experiments involve adding a suitable quantity of oil observed by a ruler, resulting in oil film thicknesses of 1 millimeter, 3 millimeters, and 5 millimeters. Once the oil is added, the sensor is immersed in the testing water tank for measurement. To ensure rigorous testing, the sensor underwent a systematic immersion process in the testing water tank for each measurement, followed by retrieval and meticulous cleaning before subsequent tests. This rigorous approach validates the sensor's ability to consistently deliver precise measurements, a fundamental requirement for its application in dynamic marine environments. The sensor performs 100 measurements for each thickness. Analysis of the collected data reveals that the average relative error between the measured mean and the reference value is 1.7117%. Notably, the average relative error, calculated after excluding the maximum and minimum values from each data set, significantly diminishes in comparison to the reference value. These experimental results not only underscore the sensor's accuracy but also establish its practical feasibility for quantifying oil film thickness. This critical aspect confirms the sensor's suitability for oil spill response initiatives and marine environmental monitoring. The sensor's precise measurement of oil film thickness is paramount for effective environmental protection. Timely and accurate detection of oil spills empowers rapid response measures, ultimately mitigating the ecological consequences on marine ecosystems. Consequently, the sensor emerges as a pivotal tool for environmental preservation.

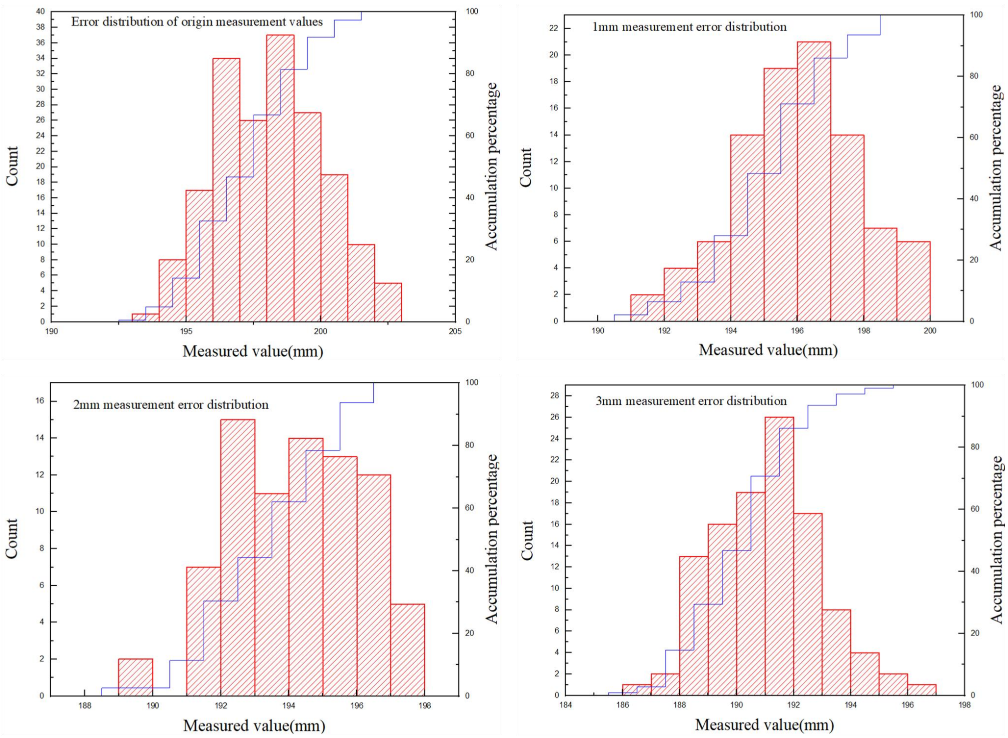

Figure 1. Measurement data error distribution diagram

4 Discussion

The developed marine oil film thickness measurement sensor system exhibits a robust design comprising essential components for accurate and real-time measurement. The integration of the Cyclone IV series FPGA device (EP4CE10F17C8N) as the Sensor Control Unit facilitates efficient data collection and transmission between the laser ranging unit and the wireless serial communication unit. The laser ranging unit, utilizing the VL53L0X module, extends the measurement capabilities with a maximum range of 2 meters and a high resolution of 1 millimeter. By leveraging the ATK-LORA-01 module in the wireless serial communication unit, reliable wireless data transmission within the frequency range of 410 to 441 megahertz is achieved.

The Upper Computer Data Processing Software, implemented using LabVIEW programming, offers a user-friendly interface for data analysis and manipulation. The utilization of VIAS functions for serial communication streamlines the interaction between the sensor and upper computer software. The VI program structure, as depicted in Figure 5, underscores the systematic approach adopted for effective communication and data processing.

The housing design, realized through SolidWorks software, ensures stability and functionality in marine environments. The carefully engineered design addresses buoyancy control and stability by positioning the center of gravity and buoyant center along the vertical axis relative to the water surface. This design consideration prevents tilting upon immersion. The incorporation of a conical structure at the bottom of the sensor aids in breaking through the oil film and water layer, enabling swift measurements. Moreover, the water-soluble rigid pressure disc dissolution mechanism, verified to occur within 3 to 8 seconds, further emphasizes the efficiency and readiness of the sensor for measurement.

The practical measurements conducted within the experimental water tank demonstrate the sensor's capability to accurately measure various oil film thicknesses. The validation experiments, conducted with Yuchai Power APICD-40 model diesel engine oil, yielded a minimal average relative error of 1.7117%. Notably, the approach of excluding maximum and minimum values from each data set leads to a significant reduction in relative error, enhancing the precision of measurements.

In conclusion, the developed marine oil film thickness measurement sensor system, with its innovative design and thorough testing, holds promise for effective oil film thickness measurements in marine environments. The combination of advanced technologies, such as pulsed laser ranging, wireless communication, and intelligent software, contributes to enhanced accuracy, efficiency, and environmental monitoring capabilities.

Data Availability Statement: Data from this research will be available upon request to the authors.

Conflicts of Interest: The authors declare no conflict of interest.

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