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Oil Thickness Measurement Using Laser Refraction

Vasantha-Kumar[1], Sungjae Park[2], Jinhwan Koh[3*]
[1]Department of Electronic Engineering, Gyeongsang National University
[2]WOOHYUN SHIP DESIGN TECHNOLOGY
[3]Department of Electronic Engineering, ERI, Gyeongsang National University

레이저 굴절을 이용한 기름 두께 측정

바산타쿠마르[1], 박성재[2], 고진환[3*]
[1]경상국립대학교 전자공학과, [2]우현선박기술, [3]경상국립대학교 전자공학과, 공학연구원

Abstract The problem of oil spills from ships is a serious cause of marine pollution. Therefore, estimating the thickness of oil is necessary to determine the overall runoff. Usually, measures can be taken against the spread of oil for the measurement of the thickness of the oil strip. Further, Snell's law can be used to quantify the rays refracted in oil. This study proposed a quantitative study of oil thickness based on the above mentioned approach. In particular, the test is performed by passing a laser beam through an air/oil/water layer. When a laser beam travels from one medium to another, it is refracted by an amount proportional to the difference in refractive indices of the mediums. Subsequently, Snell's law is used to calculate the position of the refracted laser beam, and the position is recorded by a camera module remotely controlled by a microcontroller. The captured image of the beam position is image processed to obtain the X and Y coordinates of the beam ray position using Python OpenCV. After measuring the X and Y coordinates, the oil thickness is calculated. However, the experimental results indicate that the error in the estimation of oil thickness by the proposed method is around 0.1%.

요 약 선박에서 유출된 석유 문제는 해양 오염의 심각한 원인이다. 기름의 두께를 추정하는 것은 전체의 유출량을 결정하는 데 매우 필요하다. 기름띠의 두께를 측정하는 것은 기름 확산에 대책을 강구할 수 있다는 것을 의미한다. 스넬의 법칙은 기름에서 굴절되는 광선을 계량화하는 데 사용될 수 있다. 이 접근법에 기초하여, 오일 두께에 대한 정량적 연구가 제안되었다. 테스트는 레이저 빔이 공기/기름/물 층을 통과하도록 하여 수행된다. 레이저 빔이 한 매체에서 다른 매체로 이동할 때, 빛은 매체의 굴절률 차이에 의해 굴절된다. 스넬의 법칙은 굴절된 레이저 빔의 위치를 계산하는 데 사용되며 마이크로컨트롤러에 의해 원격으로 제어되는 카메라 모듈에 의해 위치가 기록된다. 빔 위치의 캡처된 영상은 Python OpenCV를 사용하여 빔 광선 위치의 X 및 Y 좌표를 얻기 위해 영상처리된다. X 및 Y 좌표를 측정한 후 오일 두께를 계산한다. 실험 결과에 따르면 제안된 방법의 추정오차는 약 0.1% 이다.

Keywords : Thickness Measurement, Oil Thickness, Laser Refraction, Oil Spill, Remote Sensing

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*Corresponding Author : Jinhwan Koh(GyeongSang National University)
email: jikoh@gnu.ac.kr
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1. Introduction

Huge oil tankers carry oil around the world through sea routes, and due to the high volume of traffic at sea, accidental oil spills are not uncommon. Spills of natural gas from offshore platforms, oil reserves, and pipelines contribute to the pollution of our oceans. Synthetic aperture radar (SAR) for a space borne sensor for operational oil spill detection identifies oil slicks in wind speeds ranging from light to 12–14 m/s. Maximum wind speed for oil slick detection is dependent on the kind and age of the oil. They work focus only on the employment of manual and automated methodologies to discern between oil slicks pattern-based looks and oil spill detection [1]. The Biscay-LMLN was developed to estimate surface ocean circulation in the Bay of Biscay; as a result, surface drifter movements aid in the estimation of oil slick drift trajectory and contribute to the fight against oil pollution disasters, but they fail to measure the thickness of the oil slick [2].

Mariano et al. proposed a technique for creating initial conditions (ICs) of oil location as well as a Monte Carlo approach for parameterizing all oil removal procedures such as evaporation were developed and assessed. Their simulations demonstrated the well-known fact that ICs are critical for accurate oil spill forecasting [3]. Because of the inherent difficulties of the oil spill prediction problem, the focus was solely on technique rather than precise oil spill forecasts and thickness measurement.

Zhixia and Fengqi proposed a multiperiod mixed-integer linear programming (MILP) model that combined with predictions from an oil weathering model [4]. The oil spill response-planning model predicts the optimal time trajectories of the oil slick's volume, area, transport, and use levels, but often fails to estimate the oil slick thickness.

Mervin and Carl review the developments in several remote sensing technologies as well as the merits and demerits of active and passive systems in the estimation of oil spread, location, and oil thickness measurements [5].

Yingcheng et al. propose a realistic model to represent the quantitative link between oil slick thickness and spectral reflectance based on the theoretical relationship, parameter analysis, and methodology [6]. This model has a minimal thickness range for estimating oil slick thickness.

Guillem and Yolanda proposes the Multi-angle Imaging SpectroRadiometer (MISR) to identify oil leaks [7]. The Terra satellite's MISR sensor uses cameras and works on bidirectional reflectance principle. However, the findings recognizes spectrally inside the red band region.

Ying et al. propose hyperspectral data to detect and evaluate reflectance using an Analytical Spectral Devices (ASD) hyperspectral analyzer to enhance offshore oil slick remote sensing [8].

Mahdi et al. proposes a capacitive-based sensor for in-situ and real-time oil thickness monitoring for interior applications [9]. Sensor may detect the thickness of oils of various viscosities by detecting the interface layers separating air, oil, and water.

Alessandro et al. presented yet another contact-based approach for determining oil thickness [10]. An array of conductive plates was utilized to measure oil thickness by altering the received voltage. Furthermore, the proposed technique was unable to deal with oil fouling and corrosion.

Hovig et al. propose a capacitive sensing based method on the concept of several methods for measuring liquid levels and thicknesses [11]. Electrical corrosion is prevented by avoiding direct contact. However, since the sensor is designed to function in open water, which is affected by climatic conditions and unpredictable oil mixes after oil spills, such systems require constant calibration.

Table 1 compares various oil thickness estimation methods and their merits and demerits. Because the sensor is required to work in open water, under dynamic climatic conditions, and against unexpected oil combinations following oil spills, contact-based technology relies on sensing analogue capacitance values; additionally, the systems require continuous calibration.

To summarize, while contact-based sensors aid in the detection of relative oil thickness, their flexibility and precision are severely limited due to variables such as reliance on calibration features, oil fouling, ageing, and temporal drift. Airborne and space-based remote sensing methods are utilized to provide a worldwide estimate of oil thickness. In this work, we present a light refraction-based remote sensing approach that employs light refraction to detect the thickness of oil up to 11mm thick with an error of 0.1%.

Table 1. Represents the various methods of oil thickness measurements and compare their merits and demerits.

Types	Methodology	Merits	Demerits
Visual imagine observation.	By utilizing airborne vehicles, visual observation.	Simple and Effective from low altitude	Affected by Climatic condition & reflection.
Hyperspectral Imaging.	High correlation between oil spill spectral reflectance and oil spill thickness.	Effective from low altitudes. Measure up to 20-30mm.	Complex Affected by Sea climatic condition
Optical remote sensing model	Light refraction-based remote sensing approach	Simple and cost effective	Sea state & climatic condition.
Capacitance sensors Method.	Based on the discrete thickness sensing via discrete horizontal electrodes.	Can measure up to 50-80 mm.	Complex & Needs calibration.
Conductive -Based Method.	Metallic array is used on electric conductivity.	Can measure up to 50 -80 mm.	Complex and Depend on aqueous solutions property

2. Experiment

2.1 Data Analysis

When a laser beam directed from a fixed position at a constant angle θ_1 towards the oil-water setup, the laser beam gets refracted and reflected when light travels from rarer to denser medium and vice versa. Considering only the refracted beam as shown in Fig. 1. Let the angle made by refracted laser beam be θ_2 in oil medium θ_3 be in water medium. To estimate the unknown oil thickness t, let us consider the triangle A, B, C from Fig. 1(a) the angle of refraction θ_2 and θ_3 in oil and water medium can be calculated using Snell's law. The position of $\triangle D$ from Fig. 1 can be estimated for different values of oil thicknesses t, by solving for angles θ_2 and θ_3 are obtain shown below. Applying Snell's law to obtain θ_2 and θ_3 as follows.

$$\frac{\eta_1}{\sin\theta_1} = \frac{\eta_2}{\sin\theta_2} = \frac{\eta_3}{\sin\theta_3} \quad (1)$$

$$\sin\theta_2 = \left(\frac{\eta_2}{\eta_1} sin\theta_1\right),$$

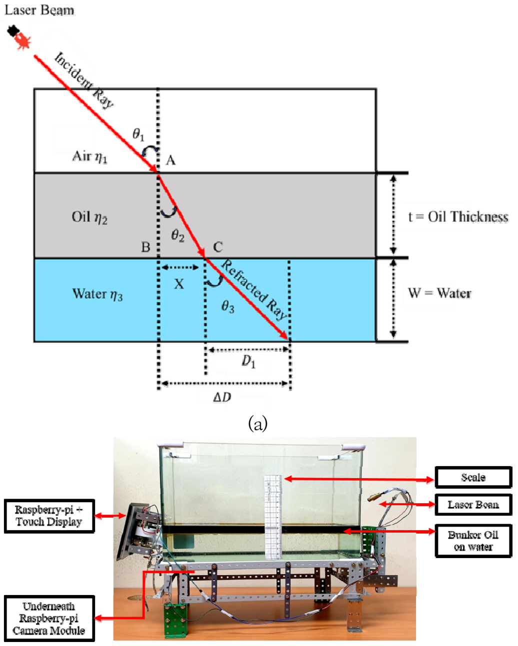
Where t the thickness of the oil, let η_1 and η_2 be the refractive index of air, oil and water. Wherein θ_1 angle of incident θ_2 and θ_3 angle of refraction in air, oil and water medium respectively. The angle of refraction θ_3 in water can be calculated using Eq. (2),

$$\sin\theta_3 = \left(\frac{\eta_3}{\eta_1} sin\theta_1\right), \quad (2)$$

From Fig. 1 we can say that $X = t * \tan\theta_2$, $D_1 = W * \tan\theta_3$ and $\triangle D = X + D_1$ therefore solving for is given by

$$\begin{aligned}\triangle D &= X + D_1\\ &= t * \tan\theta_2 + W * \tan\theta_3\\ &= t * \left(\frac{\frac{\eta_2}{\eta_1} sin\theta_1}{\sqrt{1-\left(\frac{\eta_2}{\eta_1} sin\theta_1\right)^2}} \right) + \\ & W * \left(\frac{\frac{\eta_3}{\eta_1} sin\theta_1}{\sqrt{1-\left(\frac{\eta_3}{\eta_1} sin\theta_1\right)^2}} \right)\end{aligned} \tag{3}$$

$$t = \left\{ \frac{\triangle D - \left(W * \left(\frac{\frac{\eta_3}{\eta_1} sin\theta_1}{\sqrt{1-\left(\frac{\eta_3}{\eta_1} sin\theta_1\right)^2}} \right) \right)}{\left(\frac{\frac{\eta_2}{\eta_1} sin\theta_1}{\sqrt{1-\left(\frac{\eta_2}{\eta_1} sin\theta_1\right)^2}} \right)} \right\} \tag{4}$$



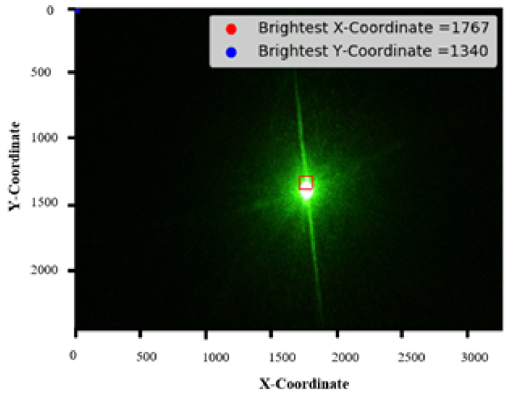
(a)

(b)

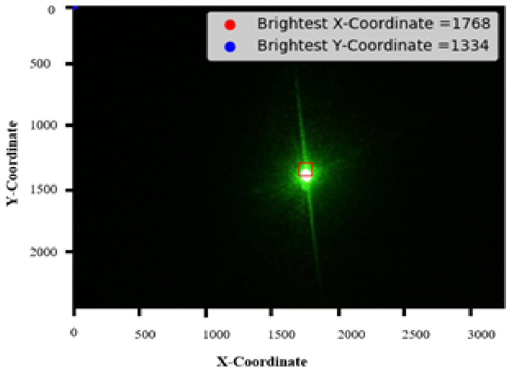
Fig. 1. Represents complete experimental setup and estimating of oil thickness t using refraction of light through a different medium.
(a) Estimating of oil thickness t using refraction of light through a different medium.
(b) Experimental Setup Side view.

Fig. 1(b) illustrates the whole setup for this research, including the laser beam and its wavelength (λ =550 nm–600 nm). The tank is now filled with water and oil flowing at a certain thickness, as seen, and the setup can estimate the thickness of the oil t. As a laser beam ray is directed towards the setup at a constant angle of incident, the angle of the incident and θ_1 the angle of refraction in θ_2 oil and the wavelength of the beam be λ respectively, and Fig. 1.(a) represents the characteristics of the laser beam being retracted when travelling from one medium to another medium (air, oil and water).

To measure oil thickness, we are only interested in the refracted beam and ignore the reflecting beam. The image of the refracted beam $\triangle D$ is captured by the Raspberry Pi camera module v2 with the python command "Raspistill –o image.jpg," and the X and Y coordinates of the brightest point in the captured image are measured with Python OpenCV. The thickness of the oil is determined and evaluated after the X and Y coordinates are obtained the calculated oil thicknesses t will then be compared to the estimated thicknesses. The incidence angle θ_1 fixed is constant value (60^0) in this experiment, with the independent variable being oil thickness t and the subject variable being beam refraction angle θ_2 and θ_3. Eq. (4) explains the theoretical relationship between the thickness of the oil spill, the angle of refraction, and various positions of the beam $\triangle D$, which are captured by a camera module and image analyzed to obtain the X and Y coordinates of beam orientation. In this experiment, we utilize bunker C oil, which is another name for ship fuel oil. Bunker fuels A, B, and C are types of fuel oil differentiated by their boiling temperatures, carbon-chain lengths, and viscosities, all of which contribute to their utility. The refractive index of bunker-C oil is $(\eta_2) = 1.5132$, the refractive index of air $(\eta_1) = 1.0003$, the refractive index of water $(\eta_3) = 1.3330$ and constant water level (W) set to $9.0\,cm$ scale respectively.



(a)



(b)

Fig. 2. Finding the Brightest point on X, Y coordinated for oil thickness of 1 mm and 2 mm.

3. Results and Discuss

The measured data and relative error in thickness were summarized in table 2. We may conclude that there is a non-linear connection between Y coordinates and oil thickness after acquiring the X and Y coordinates values via image processing owing to variation in oil thickness. As oil thickness varies, so do the Y coordinates, and vice versa. Fig. 3 gives the relation between Y coordinates and oil thickness through the experimental result and the relation between Y coordinates and oil thickness through analysis. The data estimated are almost the same and thus this the developed quantitative remote sensing model which can be able to measure the thickness of the oil.

Table 2. Varying oil thickness and the resulting Y coordinate and their percentage error

Oil Thickness	Measured Y coordinates	Analytic Y coordinate	Estimated Oil Thickness (mm)	Relative error in thickness
1 mm	1340	1340.0729	1.00005440	5.44E-05
2 mm	1334	1332.8490	1.99827436	8.63E-04
3 mm	1324	1325.0283	3.00232998	7.77E-04
4 mm	1316	1316.6108	4.00185653	4.64E-04
5 mm	1308	1307.5965	4.99845756	3.08E-04
6 mm	1297	1297.9854	6.00455852	7.60E-04
7 mm	1290	1287.7775	6.98793992	1.72E-03
8 mm	1275	1276.9728	8.01237835	1.55E-03
9 mm	1265	1265.5713	9.00406458	4.52E-04
10 mm	1257	1253.573	9.97273667	2.73E-03
11 mm	1239	1240.9779	11.0175600	1.60E-03
				Percentage error = 0.10246

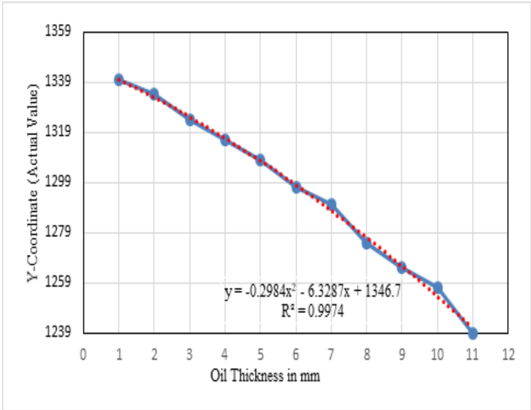


Fig. 3. Oil Thickness vs. Y coordinates obtained from experimentation.

4. Sea State Analysis

Owens proposed the sea state is the overall condition of a large body of water's free surface, including wind waves and swells, at a specific location and time in oceanography. Statistics such as wave height, period, and power spectrum are used to describe a sea state. The state of the sea changes over time as the wind or swell conditions vary. An experienced observer, such as a skilled mariner, or instruments such as weather buoys, wave radar, or remote sensing satellites, can assess the sea state. The statistics for buoy measurements are calculated for a time interval during which the sea state can be assumed to be constant. Environmental contours of extreme conditions use historical data to forecast expected behaviour for a specific return period. The creation of these contours necessitates the projection of a finite data set into the future using probability and statistics techniques. Environmental contours of extreme sea states can be utilized to analyse the design-response of offshore constructions using numerical or physical model simulations and sea state wave height classified are shown below in the table. 3 [12].

Table 3. Sea state wave height characteristics.

Wave height	Wave characteristics
0 meters	Calm (Glassy)
0 to 0.1 meter	Calm (Ripple)
0.5 to 1.25 meters	Medium
1.25 to 2.5 meters	Moderate
2.5 to 4 meters	Rough

Fig. 4 represents a flow chart of estimation of variance (σ^2) which is then compared and validated with sea state wave characteristics. The three different cases considered as calm (Ripple) with variance (σ_1^2), medium wave with variance (σ_2^2) and moderate wave (σ_3^2) respectively. The calculated σ^2 is the compared to estimate the relation between them if $\sigma^2 < \sigma_1^2$ then validate the result and report if not again calculate the σ^2 and compared with σ_2^2 of medium wave and the cycle repeats until different values are estimated and validated.

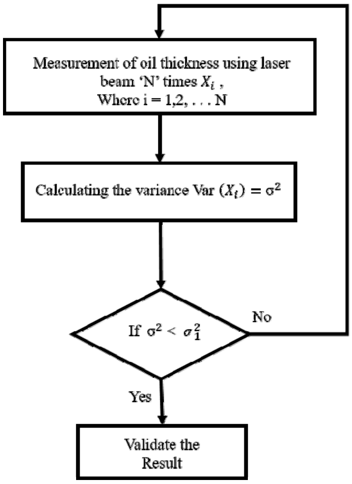


Fig. 4. Comparing the variance with the variance of sea state wave characteristics

5. Conclusion

Oil spills have become a major environmental problem as the transport of crude oil by sea has increased. In the event of an oil leak, the most valuable details available are in determining the extent of the spill and how it is dispersing. The thickness of the oil spill provides the information needed to assess all of these requirements. As a result, accurate measurements of the thickness provide useful information for calculating spill volume and monitoring spill dispersion. The proposed method's operational research shows measured oil thicknesses relative to thicknesses determined numerically, and the experimental findings demonstrate the proposed method's precision, with an error of less than 0.1% and accurate measurement of oil slick thicknesses on water ranging from 1 mm to 11 mm is estimated. Furthermore the measured value's variance is smaller than that of a calm ripple wave in the sea, allowing the proposed method to be used to measure oil thickness in calm ripple waves.

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Vasantha Kumar [Regular member]

- Aug. 2012 : V.T.Univ., Electrical Dept., Bangalore, India. M. Tech.
- Sep. 2019 ~ Current : Gyeongsang National University, Department of Electronic Engineering, Jinju, South Korea. pursuing PhD

〈Research Interests〉
Radar Signal Processing and Sensors

Sung Jai Park [Regular member]

- Mar 1988 ~ Feb 1995 : Dept. of Naval Architecture, BS
- Feb 2021 ~ Current : CEO WooHyun Ship Design Technology

〈Research Interests〉
Ship design, oil extractor, FEM-based design, 3D printing technology

Jinhwan Koh [Regular member]

- Dec 1999 : Dept. Electrical Engineering and Computer Science, Ph.D.
- Mar 2003 ~ Current : Professor, Dept Electronic Engineering, GyeongSang National University, ERI.

〈Research Interests〉
Radar system, electromagnetic wave processing, remote sensing, artificial intelligence