Proceedings of the 2008 IEEE/ASME
International Conference on Advanced Intelligent Mechatronics
July 2 - 5, 2008, Xi'an, China

Wireless Sensor Node for Real-Time Thickness Measurement and Localization of Oil Spills

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Abstract— **Marine pollution by oil spills is a devastating environmental hazard, requiring a low-cost efficient system for detection, real-time thickness measurement and localization of oil. Such a system is necessary to guide and speed-up the clean-up process. Knowing that none of the previous detection methods has managed to fully meet these requirements, it is necessary to devise a new technique to assist in management of oil spills. This paper presents a sensor device, capable of sensing, processing and transmitting information about an oil spill (location and thickness). The paper discusses two new methodologies of detection, which are based on the difference in absorbance spectral signatures and electric conductivity properties of oil and water. Measuring the resistance values of an array of photodiodes and the current intensities between an array of conducting strips both allow us to estimate the thickness of the oil. The experimental results, presented in this paper, illustrate the effectiveness of the proposed method under different lighting conditions. With the capability of forming a wireless ad-hoc sensor network, these proposed devices will produce together a real-time map of the current state of an oil spill, including its thickness level at different locations.**

Index Terms*— *Oil spills, Oil localization, Thickness measurement.

I. INTRODUCTION

Oil spills are among the most environmentally damaging events, highlighted by the dramatic accidents of Prestige, Erika, and Exxon Valdez. They are mainly caused by pipeline leaks, off shore drilling operations, ship spills, and routine ship and car maintenance operations. Oil spills have both short-term and long-term effects on many organisms. They can cause nausea and health problems to humans; such as fisherman that inhale its fume or contact it directly. They can also be absorbed by birds and mammals while trying to clean themselves and by fish while breathing through their gills. The most devastating long-term effect is biodiversity, which is caused by the bioaccumulation of oil through the food chain as predators, such as humans, eat a large number of organisms, such as fish or mammals, having sub-lethal quantities of oil stored in their bodies. Long-term effects also include damaging fish eggs, wiping out generations [1].

Since oil slicks spread rapidly and cannot be extracted once they become very thin, usually only 20% of the total quantity of the oil is recovered from a spill [1]. For this reason, treating oil spills properly necessitates a rapid and well-resourced response. Taking into account that a real clean up is not possible in most cases, containing the oil spill through booms reduces the extent of the damage. This is followed by sucking up the oil into a receiving tank using skimmers. Studies have shown that knowledge of the oil slick thickness at different locations, minutes after an oil spill occurs, reduces the clean-up costs since it helps guide the clean-up operation by indicating the real-time path for the most efficient treatment; starting with the thickest location of the oil slick. This is due to the fact that response personnel can plan countermeasures more effectively (different countermeasures are adopted for different oil thicknesses) in an attempt to limit the effects of the pollution [2]. Moreover, direct-contact measurement of the thickness, compared to the existing techniques, is more resistant to weather conditions and effective with different types of oil. While remote sensing, mainly using Synthetic Aperture Radar (SAR) and laser fluoro-sensor techniques, is the most common form of oil spill tracking, it suffers from many drawbacks, such as delayed response, high cost, and dependence on weather conditions, lighting conditions, and sea state [3].

In order to solve the problem at hand, a low-cost device was designed to be stored on board oil-carrying ships and off shore drills. Just after an oil spill occurs, a number of such devices can be thrown into the spill, sticking to the oil slick above the water surface. As the oil slick spreads, the devices will float around with the slick, sensing, processing and transmitting information about the oil spill. Creating a wireless ad-hoc sensor network between the devices will produce a map of the current state of the oil spill, including its thickness level at different locations in a short amount of time, guiding a fast and efficient treatment of the spill. Furthermore, the device is designed to provide accurate results under various atmospheric and oceanic conditions and in different geographic regions.

II. RELATED WORK

IR thermal sensing is based on the fact that oil films emit heat slower than the surrounding water during daytime. However, the process is reversed during night-time, making it vulnerable to lighting conditions. As mentioned in [4], the Advanced Spaceborne Thermal Emission and Reflection

Funded by the American University of Beirut ECE Department

Radiometer (ASTER) – used on NASA's Earth Observation System – relies on the thermal inertia and temperature differences between oil and water to identify oil spill locations. Since oil weathering (change in chemical composition of oil) may change, the difference in these characteristics over time and the warm-to-cool transition of oil – used as a reference for comparison – is not sharply defined, the accuracy of the performed measurements is limited [5].

Radar sensing, another remote sensing technique for detecting oil spills, is based on the backscatter of the microwave signal transmitted by the radar, making it strongly dependent on wind and sea state conditions. In [6], the ScanEx R&D Center has found a complete solution for the fast acquisition, processing and monitoring problem of oil spills using SAR imagery. The captured SAR images are prone to error due to short waves usually present on the seawater surface and the fact that oil films affect the viscosity of the seawater [3]. More importantly, SARs do not provide a thickness estimate for the oil spill.

Certain ultrasonic characteristics of oil can also be used to identify the oil in seawater and estimate its thickness in two ways. The first is based on applying an ultrasonic pulse to an oil film and measuring the amplitude or the phase angle of the reflected signal, knowing that the reflection coefficient of oil depends on its thickness and acoustic properties [7]. The second is based on measuring the time delay of an ultrasonic wave between the air-oil and oil-water boundaries. This approach was adopted in the design of the Laser Ultrasonic Remote Sensing of Oil Thickness (LURSOT) system [8], developed by the Industrial Materials Institute (IMI) of National Council Research Canada. Ocean currents, which cause changes in the phase of the reflected signal, lead to inaccurate results, limiting the usage of this technique.

Laser fluorosensors, such as the Scanning Laser Environmental Airborne Fluorosensor (SLEAF) [9], are based on the fact that different types of oil fluoresce at different wavelengths and have different deterministic spectral signatures. The captured fluorescence spectra are investigated through a principle component analysis to determine the presence of oil. However, these devices possess some drawbacks, such as their large size, heavy weight and high cost [2].

Hyperspectral imaging can be used to build a library of spectral signatures for different types of oil, to be used for oil detection [10]. Another multispectral technique determines the oil thickness by computing ratios between specific wavelengths in the absorbance spectrum of oil. According to [11], spectral ratios, which are less sensitive to light fluctuations than radiance, vary as a function of the properties of seawater and the spectral quality of incident light. Thus, assigning an absolute thickness to a specific spectral ratio is not accurate.

In conclusion, most of the current detection methods, addressing the stated problem, rely on remote sensing; thus, requiring the use of a dedicated aircraft, and are strongly affected by the lighting and weather conditions, in addition to being associated with a high cost.

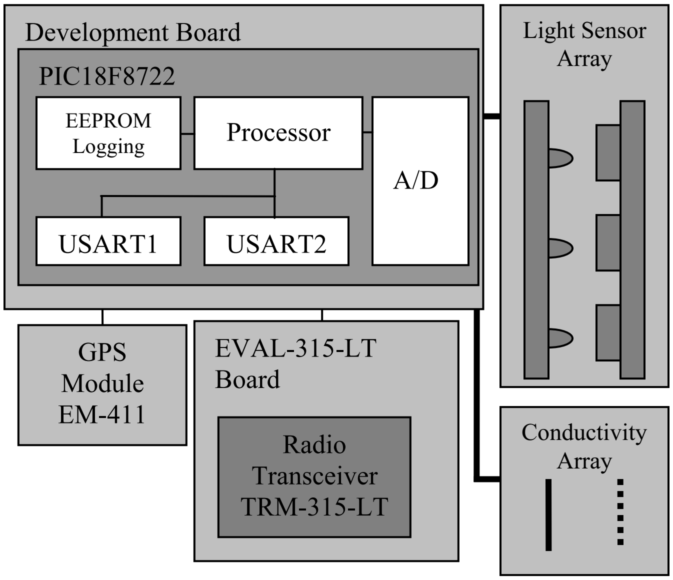

Fig. 1: Block Diagram of the Hardware System

There are a few direct-contact techniques for tracking oil spills that depend on capacitance and electric conductivity. The former, mentioned in [12], is based on the difference in the relative permittivity between oil and water. However, this technique requires on-site calibration and is dependent on the different types of oil. A method using electric conductivity uses a motor to immerse two electrodes in the oil above the water, until they reach the oil-water boundary and calculates the oil thickness according to the number of revolutions [13]. However, this method is dependent on the stability of the device above the water surface, which cannot be achieved due to oceanic waves and wind speeds.

III. SYSTEM DESIGN

A. Hardware Components

The block diagram of the proposed device is shown in Fig. 1. In addition to the Light Sensor and Conductivity arrays, responsible for measuring the thickness of the oil, it includes a GPS module, used to locate the geographical position of the sensor in the oil spill and a Radio Transceiver, used to transmit the information about the oil spill, including the thickness and position of the oil. It also includes a PIC microcontroller; used to process the measurements collected by the light sensor array and the conductivity array, in order to determine the thickness of the oil, based on the devised detection algorithms (discussed later).

For the GPS module, the EM-411, manufactured by GlobalSat, was chosen, mainly because of its relatively low cost, number of channels, short synchronization time, and the built-in antenna features. For the transceiver, the EVAL-315-LT evaluation board was selected, due to its low power consumption, large transmission range, and its serial interface. For the microcontroller, the ET-PIC Stamp evaluation kit is used, because of its compact form, the PIC18F8722 microcontroller it includes, its two serial port interfaces, and its 16-channel 10 bit A/D converter.

B. *Thickness Measurement Sensors*

Two independent sensors were designed in order to determine the thickness of the oil, namely using a Light Sensor Array and a Conductivity array.

1) Light Sensor Array: This is an active optical color sensor, based on the concept of the variation of intensity and the properties of light propagating in a certain medium. The amount of received power of light on the receiving surface per unit area, on the other end of the propagating medium, is referred to as Illuminance and depends on the angle at which the light strikes the surface of the receiver, the distance between the transmitter and the receiver of the light source, and the radiant energy of the light that is emitted by the source and propagated as an electromagnetic wave. Since blue light exhibits very low absorption in water [14] and high absorption in oil [15] [16], the decision was to use blue LEDs as the source of light. Since the required low-cost receiver of blue light should only detect wavelengths in a narrow range between 440 nm and 490nm, the most suitable receiver was found to be the LDR, whose resistance varies inversely (in an exponential fashion) with the change in intensity of the light received on its surface. Therefore, a longitudinal array of LED-LDR pairs were used, through which the change in the resistances of the LDRs can be measured to detect the oil level, based on the fact that when the blue light passes through the water, the LDR resistance is decreased, and when it passes through the oil, its resistance is increased.

Although this detection method requires the measurement of resistances, the actual measurements, in the implemented system design, are voltages. Since the value of an LDR can vary on the order of hundreds, it would be impossible to physically implement a current source to change the LDR resistance to voltage that can be entered to the microcontroller. Therefore, to get the LDRs' resistance values, we measured the voltage (V_L) on the LDR (R_L) using a voltage divider configuration fed with a known voltage (V_{dd}=5V), where we put each of the LDRs in series with another resistor Rc, of known value as shown in equation (1). Thus, the resistance of the LDR is calculated using equation (2).

$$V_L = \frac{V_{dd} \times R_L}{R_C + R_L} \quad (1)$$

$$R_L = \frac{V_L}{V_{dd} - V_L} R_C \quad (2)$$

In order for V_L to vary linearly with R_L in equation (1), R_C should have a very large value. However, this would lead to a very small value of V_L, which would be difficult to read using the A/D input of the microcontroller. Conversely, making the value of R_C very small would make V_L independent of R_L, and thus irrelevant to our analysis. Therefore, we have chosen the value of R_C to be 1 kΩ, which is in between our range of possible LDR values under different lighting conditions. This will enable us to retrieve the LDR resistance values through simple calculations in the micro-controller, using equation 2.

2) Conductivity Array: This is a passive sensor, based on the difference in electric conductivity properties of different aqueous solutions. The conductivity of water is dependent on the concentration of dissolved salts and other chemical species that ionize in it. Since sea water possesses a high electric conductivity and oil possesses a low electric conductivity, the current passing through sea water is high (On) and the current passing through oil is low (Off). Therefore, a longitudinal array of conductive metal pairs – similar to that of the longitudinal array of LED-LDR pairs – is used, composed of two plates. One plate is fully covered with conductive material and fed by a constant voltage, and another plate is covered with equidistant strips of the same conductive material, separated by strips of non-conductive material having the same thickness. Each strip of conductive metal along with the fully-conducting plate makes up a conductive metal pair. By measuring the intensity of the current passing through each conductive pair, which is low when the pair is separated by oil and high when it is separated by sea water, we can detect the presence of oil of a certain depth. As in the case of the Light Sensor Array, voltages are being measured. Therefore, each conductive pair is connected to a resistor (R_D) to transform the measured current to voltage. R_D should have a small resistance value in order not to attain high voltages at the A/D input of the microcontroller.

Since the aqueous solution between each conductive pair does not act like a perfect switch, where it is On in the case of water and Off in the case of Oil, it is better to measure conductivity using resistance, where the aqueous solution acts like a resistor, which is high in the case of oil and low in the case of water. Therefore, measuring the voltage on R_D is almost equivalent to the voltage divider configuration used for the light sensor array. However, no initial calculation (to convert voltage into current intensity) is needed since the measured voltage is linear to the current intensity, which is required for the analysis. In order to prevent ground looping, which can be caused by the existence of a large number of resistors in series with each metal strip, the resistors are connected to a multiplexer, through which only one of the resistors is connected to ground at the same time. The multiplexer receives a signal from the microcontroller through which the voltages of the resistances are measured successively.

IV. THICKNESS DETECTION ALGORITHMS

A. *Light Sensor Array*

Algorithm 1 describes the analysis of the measured data using the Light Sensor Array in order to determine the thickness of the oil. It first takes the averages of k voltage measurements. Then, it calculates the LDR values from the corresponding voltage measurements using equation (2). Since a small error in voltage measurement may produce a large change in the resistance value (V_L=4.98; R_L=249 kΩ, while V_L=4.99; R_L=499 kΩ), the algorithm replaces all R_L values larger than R_M = 1 MΩ by 1 MΩ, which is 1000 times larger than R_C, and was the maximum resistor value obtained through direct experimental measurement. The logarithm of each resistance is taken to account for the exponential response of LDRs with the change in intensity. This is followed by determining the ratio of the resistances between the case when the blue LEDs are turned off (R_D) and when they are turned on (R_B). This will remove the offset in the resistance values, caused by changing lighting conditions, and will eliminate the need for on-site calibration of the LDRs before detection. Every one of these ratios R(i) is then divided by its previous one and the changes between these ratios are enlarged using an exponential. The maximum of these ratios corresponds to the pair of consecutive LDRs where the oil-water boundary exists. Therefore, the thickness of the oil is determined with a quantization error equal to D/2, where D is the distance between two consecutive LDRs.

B. *Conductivity Array*

Algorithm 2 describes the analysis of the measured data using the Conductivity Array in order to determine the thickness of the oil. It first takes the averages of k voltage measurements on R_D. Since we want to use this sensor in a digital manner, by reading a low voltage (through oil) as an Off signal and a high voltage (through water) as an On signal, we set a threshold value for the voltage on R_D, below which we have oil. This threshold value depends on the value of the resistance used, the material the conductor is made of, and the distance between a conducting strip and the fully conducting plate. The thickness of the oil is determined with a quantization error equal to D/2, where D is the distance between two consecutive conducting strips.

Algorithm 1: Thickness using Light Sensor Array:

```
Data: matrix $V_B$ and matrix $V_D$ of voltages with and
      without blue light respectively,
      $V_{dd}$, voltage for the voltage divider,
      $R_C$, resistance in series with the LDR,
      D, distance between two consecutive LDRs.
      $R_M$, max possible value for a resistor
Result: Thickness of the Oil (same unit as d)
Initialization: Set m to the number of LDR's used
                Set k to the number of times each
                measurement is repeated
                Set max to 0, index to -1.
for i = 1, ...m do
    $L_B(i) = \text{average}(V_B(i),k)$
    $L_D(i) = \text{average}(V_D(i),k)$
end
for i = 1, ...m do
    $R_B(i) = \frac{L_B(i)}{V_{dd} - L_B(i)} \times R_C$
    if $R_B(i) > R_M$ then
        $R_B(i) = \log(100 \times R_M, 10)$
    else
        $R_B(i) = \log(100 \times R_B(i), 10)$
    $R_D(i) = \frac{L_D(i)}{V_{dd} - L_D(i)} R_C$
    if $R_D(i) > R_M$ then
        $R_D(i) = \log(100 \times R_M, 10)$
    else
        $R_D(i) = \log(100 \times R_D(i), 10)$
    $R(i) = \frac{R_D(i)}{R_B(i)}$
end
for i = 1, ...m-1 do
    $\text{Ratio}(i) = 10^{\frac{R(i+1)}{R(i)}}$
    if Ratio(i) > max then
        index = i
        max = Ratio(i)
end
return (index) × D
```

Algorithm 2: Thickness using Conductivity Array:

```
Data: matrix $V_R$ of voltages across the resistor in series
      with each conducting pair,
      $V_T$, min threshold voltage for water,
      D, distance between two consecutive
      conducting strips.
Result: Thickness of the Oil (same unit as d)
Initialization: Set m to the number of conducting pairs
                Set k to the number of times each
                measurement is repeated
                Set index to -1.
for i = 1, ...m do
    $V(i) = \text{average}(V_R(i), k)$
    if $V(i) < V_T$ then
        index = i
    else  break
end
return (index) × D
```

V. EXPERIMENTAL SETUP & RESULTS

A. *Experimental Setup*

The designed prototype is presented in Fig. 2. The experiments were carried out in an experimental tank, containing sea water and oil, under different light conditions and oil thicknesses. The 16 LDR-LED pairs used are aligned with each other, having their centers exactly D = 2 cm apart from each other. The LDRs have a diameter of 10mm and the LEDs have a diameter of 5 mm. The distance between an LDR and its corresponding LED is exactly 7.6 cm. The LEDs are supplied by 4V (DC), because the light source should generate enough radiant energy that can pass through the oil and reach the receiver with adequate intensity so that any variation in transparency/opacity due to oil is detectable. The

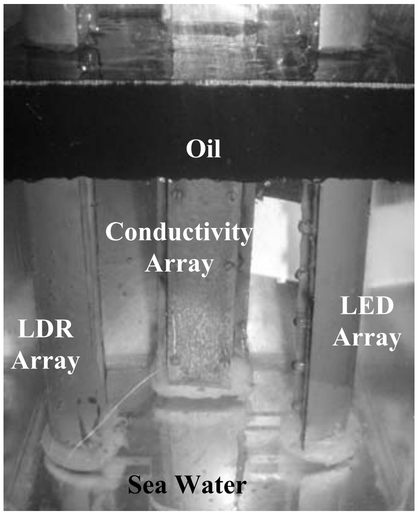

Fig. 2: System Prototype

TABLE I
PERCENTAGE DIFFERENCE BETWEEN THE PEAK OF EACH CURVE AND THE CLOSEST OBTAINED RATIO

	Light	Dark
3 cm	11.28%	51.07%
5 cm	147.89%	411.50%
7 cm	283.13%	521.17%

center of the first LDR is D = 2 cm below the surface of the water under flat sea conditions.

Each of the 32 conductive pairs used has a thickness of 0.5 cm and are separated by a 0.5 cm thick non-conductive strip. The stripped-plate is separated from the fully conducting plate by a distance of 6.5mm. While a large distance would produce a low current, which is difficult to measure accurately, a smaller distance could make the oil get stuck between the plates, producing inaccurate results. The resistance R_D, the voltage of which was measured in the conductance array, had a value of 4.7Ω. Both the LDRs and the conductive pairs are numbered in increasing order from top to bottom. The center of the first strip is 1 cm below the surface of the water. The conductive metal used was copper, which slowly underwent some electrolysis; thus, it would be worn out after a few hours of continuous use. However, using a different type of metal or plating with mercury or carbon will significantly reduce the rate of electrolysis. Moreover, taking 30 measurements for each conductive pair successively and repeating this process every 10 min will increase the life of the conductivity plates to 2 or 3 days, which is the required life span of the sensor device.

B. Experimental Results and Analysis

1) Light Sensor Array: The experiments were conducted using the light sensor array, under light and dark environments, and with different thicknesses of oil. The thickness levels examined are 2 cm apart from each other, because the resolution of the device is equivalent to the distance between the centers of two consecutive LDRs in the array. Fig. 3 and 4 summarize the results of these experiments after using algorithm 1. These graphs show the ratios explained in algorithm 1, where the maximum peaks of these ratios represent the estimated thickness, which can be read on the x-axis of the graph. Each of the three curves, in both figures, has its peak at its corresponding thickness read on the x-axis. Therefore, the conducted experiments have not produced any errors.

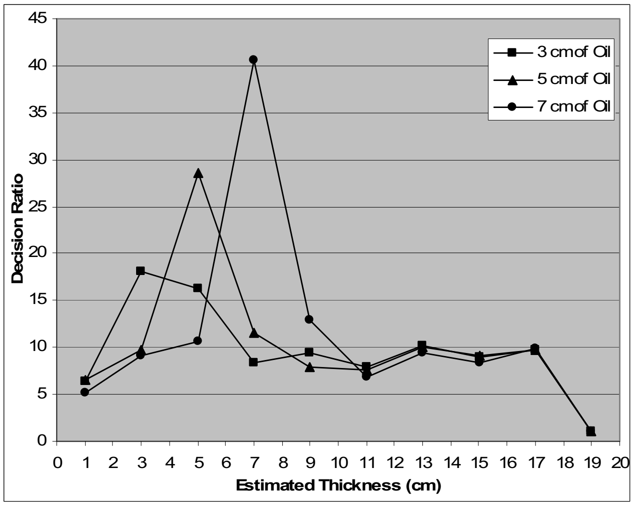

Fig. 3: Thickness Measurement Using LDRs (Light Environment)

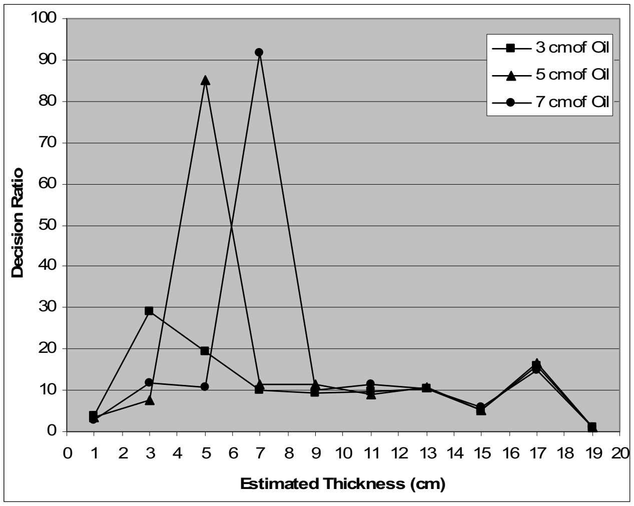

Fig. 4: Thickness Measurement Using LDRs (Dark Environment)

Table I shows the percentage difference between the peak of each curve and the closest (second) obtained ratio. The table shows that even if the highest ratio, below the maximum ratio, increases, due to experimental errors, by the given percentage in the table, the results of the algorithm would still have given correct estimates of the thickness.

Whenever none or all of the LDRs are covered with oil, the algorithm will compute a maximum ratio at some random thickness; thus, producing a wrong result. Therefore this method is not suitable for the “no oil” and the “all-oil” cases. The Conductivity array presented next is capable of detecting the “no oil” and the “all-oil” cases. The resolution of the sensor could have been improved by reducing the distance between the centers of the LDRs. Since the used LDRs have a 10 mm diameter, this separation could not be less than 1 cm. However, for cleaning efforts, knowing the thickness up to 2

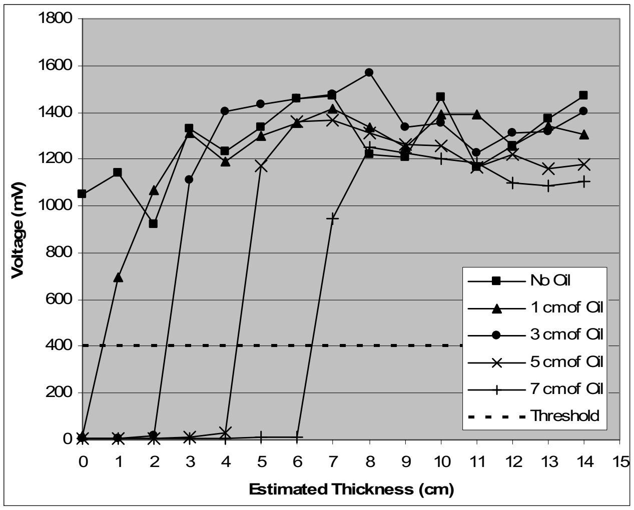

Fig. 5: Thickness Measurement Using the Conductivity Array

TABLE II
PERCENTAGE DIFFERENCE BETWEEN THE FIRST VOLTAGE ABOVE THE THRESHOLD AND THE THRESHOLD

No Oil	61.81%
1 cm	42.47%
3 cm	64.04%
5 cm	65.93%
7 cm	57.64%

cm resolution is acceptable. Note that the conductivity array can be designed to provide 1 mm resolution.

2) Conductivity Array: The experiments using the conductivity array were carried out under different thicknesses of oil, namely under no oil, 1 cm, 3 cm, 5 cm, and 7 cm. Fig. 5 summarizes the results of these experiments after using algorithm 2. The first voltage above the assigned threshold at 400 mV represents the estimated thickness, which can be read on the x-axis of the graph. As shown in the graph, each curve has its estimate at its corresponding thickness read on x-axis. Therefore, no errors were obtained during this experiment. Analyzing the measurements over all thickness levels and for all conductance pairs, the average voltage on the strips that were in the water was found to be 1276.14 mV and the standard deviation of these measurements was 193.73 mV. On the other hand, the average voltage on the strips that were immerged in the oil was 10.56 mV and the standard deviation of these measurements was 9.04 mV. Based on these values, the threshold was chosen to be between $10.56+3\times 9.04=37.68$ mV and $1276.14-3\times 193.73=694.95$ mV. Taking into account that other types of oil might have slightly higher conductivity levels, we decided to set a safe threshold at around 400 mV.

Moreover, Table II shows the percentage difference between the first voltage above the threshold and the threshold. This means that even if voltage on the first conducting strip decreased, due to errors in the measurements, by the given percentage in the table, the results of the algorithm would still have given correct estimates of the thickness. The advantage of this method over the previous one is its high revolution and ability to detect the "no oil" and "all-oil" cases. The experiments carried out were under calm conditions with negligible water movement. Clearly, additional testing is needed under wavy conditions. However, it is worth noting that large oil spills typically form a thick shield over the water with significant surface tension which inhibits the formation of waves.

VI. CONCLUSION

In this paper a device capable of localizing and determining the oil thickness is presented. The device consists of two measurement methods that rely on the difference between the characteristics of oil and water. The difference in blue light absorbance is detected using a light sensor array. While the difference in electric conductivity is detected using a conductance array. The algorithms of these techniques were presented and evaluated using extensive experiments. The obtained results were shown to be accurate and repeatable in the presence of different lighting conditions.

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