Surface Water Wave Detector for Floating Devices with Capacitive Sensor
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Abstract — Water wave monitoring is essential in collecting marine parameters for oceanography studies and early warning systems on security and safety, such as drowning detection, weather detection, and gas leakage from underwater pipeline detection, because these activities create different water wave patterns that can be further analyzed. The current wave detection methods, such as underwater pressure and resistive sensors, have lower durability as they require direct contact with the water. Monocular camera wave detection can detect the line where water waves propagate. However, a static platform is required to perform monitoring operations. This research aims to develop a continuous capacitive sensor system that a buoy can implement for contactless water surface wave detection and to develop a water wave direction detection algorithm by Principal Component Analysis (PCA) calculation. Capacitive sensors arranged in a circular shape and a compass module are implemented inside the prototype buoy. Each capacitive sensor detects the real-time wave height change by changing the capacitance value. The capacitance values from all the capacitive sensors and the North of the compass sensor are sent to the embedded server for further computations. Processes carried out in the embedded server are initial calibration, centroid calculation, PCA calculations for water wave detection, and data visualization on the webpage. The prototype buoy with a capacitive sensor system and compass sensor developed can detect the four positions tested in the experiment with a mean square error of 38.42° and a mean absolute error of 5.85°.

Keywords — Surface water wave detector; capacitive sensor system; principal component analysis; water wave direction detection.

I. INTRODUCTION
Most actions that induce water surface variation produce water waves in the process. These activities can be caused by nature, such as gravity quakes beneath the water, or by individuals, such as swimming, chemical disposal, drowning, and other activities. Water waves produced by various activities will differ in amplitude, frequency, direction, and duration. As a result, numerous activities may be determined by recording and studying the water surface wave. An immediate reaction may also be provided to avoid future hazards and injury if abnormal actions occur in the regions under monitoring [1].

Oceanography has frequently implemented the water wave monitoring feature to study water wave characteristics. However, water wave monitoring can also be implemented in other fields to act as a detection system, such as drowning and chemical disposal, as the struggling movements and pouring action of chemical disposal will induce water surface waves, which can be further analyzed for identification purposes.

Remote areas such as dams, reservoirs, and lakes do not have continuous surveillance systems to ensure the safety and security of the area. Besides, monitoring activities around remote areas is challenging, but these regions are essential in providing water resources, generating hydroelectricity, and preserving biological diversity. Moreover, weather changes also induce different changes in water waves, allowing the water wave detection feature to be implemented into the weather detection tool. Gas leakage in underwater pipelines can also be detected via the changes in water wave patterns because gas fountains will be created on the water's surface due to the high pressure of gas leakage [2]. Furthermore, underwater information can be analyzed and obtained using water surface waves [3].

A wider application and longer durability can be achieved by developing water wave monitoring devices that do not require a static platform and direct contact with water. Contactless sensing techniques that apply visual and light methods require a static platform and a specific distance from the water surface to perform the detection actions [4]. Cameras and light reflection water wave detection usually
must be fixed in a static position, and pre-calibration must be
done for accurate measurement [5]–[8]. Besides, the weather
condition is also a major constraint for the light reflection
detection method [9]. Water wave detection methods such as
the Kinect sensing method [10] and CCD camera sensing
method [11] require the liquid to be dyed or other particles
into the liquid to lower the water transparency so that the
change in water surface waves can be captured. Another
contactless sensing method, which is radar detection, such as
[9], [12], [13], also requires static positioning and is
vulnerable to constructive and destructive scattering as the
detection is based on the backscattering method. However,
pressure sensing methods [14] and [15] require exposure to
the water. A single unit of pressure sensor can only detect the
water level change at a specific point. Multiple pressure
sensors need to be installed underwater to detect the direction
of water waves [16]. The changes in concentration of
electrolyte will be affecting those pressure sensors that
operate and detect based on the changes in chemical
properties [17]. The flexibility of static platform methods is
low as once the setup of the system is completed, the system
needs to be dismantled to change to another monitoring area.
Besides, a larger monitoring area requires a higher number of
monitoring devices and platforms to achieve full coverage.
Static platform detection methods are also challenging when
applied to areas in which a static platform is challenging to be
created, such as oceans, dams, and lakes.

The non-static monitoring devices can be flexible in
changes in the monitoring area. The structure of a buoy is
suitable for wave detection because of the flexibility to be
located at any point in the surveillance area. However, buoys
commonly used nowadays, such as [18]–[20], implement
gyrosopes and accelerometers for detection operations. The
buoys with huge size and mass cause the deployment to be
challenging and require special equipment [21]. Furthermore,
the fouling effect is also a significant problem buoy faces [22].

Buoys that use three-axis accelerometers and gyroscopes for
detection also have lower accuracy as these sensors are easily
affected by inconsistency of the starting point and positions
of accelerometers, gyroscope drift, lateral sensitivity, and
lever-arm effect [18]. Triboelectric nanogenerators (TENGs)
can also perform detection on water waves by detecting the
current changes due to friction [23], [24]. However, the small
current generated by TENGs requires high accuracy and
precision devices to perform the measurement.

Most water wave detection methods cannot obtain the
direction of water waves referred to as North. Monocular
camera water wave detection in [25] can detect wave
propagation lines of the water, but there is no reference to the
North. The North referencing is important to provide an actual
direction whenever the detection system is attached to a
dynamic platform, where the orientation of the sensor will be
facing a different direction from time to time. Capacitive
sensors detect based on the fringing field [26],[27], which
allows the water level sensing action to be carried out without
any direct contact with water [28].

This project aims to propose a solution for water surface
wave detection with contactless close monitoring features
using capacitive sensors. In this project, a prototype buoy is
developed, and the functionalities are experimented in an
inflatable pool. The four cardinal positions can be detected by
the buoy developed without being directly in contact with the
water with capacitive sensors do not involve any moveable
parts, which is advantageous compared to the pressure
sensing methods. The structure of pressure sensors consists of
moveable parts that will be worn and torn after a certain
period of usage. The PCA calculations will be carried out
based on the water wave patterns captured by the capacitive
sensors system. The results will then be compared with the
absolute North direction to identify the actual water wave
direction. The results that refer to the North are more
informative than wave detection using monocular vision
because monocular vision can only calculate the propagation
line of the water waves without knowing the actual direction
referring to the North. This research aims to develop a
continuous capacitive sensor system for water wave detection
and develop a surface water wave direction detection
algorithm.

II. MATERIAL AND METHODS

A. Hardware Structure

The cross-sectional shapes with edges are inappropriate for
the outer structure of buoys because these shapes contain a
flat surface that allows the water waves to be reflected to the
source of the wave generated. Construction and destruction of
water waves will reduce the accuracy of the wave patterns
captured. Besides, forces from water waves can be easily
exerted onto the buoy with a flat surface, which will cause the
buoy to be pushed towards the shore. The cylindrical buoy is
selected because the cross-section of the buoy is an edgeless
circle. The edgeless shape allows the water waves to
propagate through the buoy without creating strong
reflections and exerting much force on the buoy. The material
used for the outer structure must also be an insulator, as
capacitive sensors cannot operate whenever attached to a
conductive material due to the short circuit between the
electrodes.

A cylindrical buoy is designed with a height of 80 cm and
a diameter of 15.24 cm. The height of 80 cm is separated into
three portions, which are the components region (20 cm),
sensing region (30 cm), and weight region (30 cm). A UPVC
pipe with 6 6-inch diameter, also known as 15.24 cm
diameter, is used for developing the buoy because it can provide
an internal space of 14593 cm³, sufficient to include all the
components and circuitry of the system. Besides, UPVC pipe
is selected instead of PVC because the wall thickness of
UPVC is thinner than PVC, which decreases the gap between
the capacitive sensor and the water to allow higher sensitivity
for water level detection. Weights are also located at the
bottom of the buoy to ensure that the buoy can sink in the
water partially. Waterbased polymer is also applied to the
outer surface of the buoy to increase its hydrophobicity [29].
Fig. 1 shows the external structure of the buoy for this project.

The hardware for the detection system includes a
Raspberry Pi 4B to function as the embedded server, an
Arduino Uno microcontroller to function as the core of the
data acquisition system, a TCA9548A multiplexer, 4
FDC11004 Capacitance-to-digital converters (CDCs) and 16
capacitive sensors.
Fig. 1  External structure

Fig. 2 shows the internal system of the buoy. CDCs are introduced in the prototype to convert the capacitance changes into digital signals, which are more stable to transmit within the system.

Fig. 2  Internal structure

B. Multi-Tier Architecture System

Multi-Tier architecture, also known as the n-tier architecture, is commonly used in software development [30]. Three-tier architecture, which consists of data management, application, and client tier, is widely used. In this project, a multi-tier system is introduced, which consists of a data tier, logic tier, and presentation tier. The block diagram for the multi-tier system implemented in this project is shown in Fig. 3.

![Fig. 3  Block diagram for multi-tier system](image)

The data tier functions to perform data collection from all the sensors. The logic tier performs arithmetic calculations to process the raw data to the desired output, while the presentation tier functions to visualize and display the processed data. When the prototype buoy is powered, the buoy will be deployed into the water in the environment under surveillance. The calibration setup for the capacitive sensors is also included in the system to reduce the offset for all the capacitive sensors. From Fig. 3 above, whenever the capacitive sensor detects changes in capacitance due to the changes in water wave height, the capacitance changes measured will be converted to digital input by FDC1004 converters. The data are then captured and stored in an array in the data acquisition system by sequentially obtaining the data from all the FDC1004 converters implemented through a multiplexer. Besides, the direction of the North will be detected and stored in the array. All data collected from the capacitive sensors and the direction of the North measured from the compass sensor are converted into a single string and then sent to the embedded system through serial communication.

The embedded system then converts the received data into float values. The capacitance sensor data are then used to calculate the centroid value. The sliding window technique is used to store 100 data of centroids in a buffer for calculating water wave direction using Principal Component Analysis (PCA). The selection of PCA algorithm is based on the advantages of lower time consumption [31]. The PCA-detected water wave direction is displayed in the polar graph once the buffer collects 100 centroid values. The difference angle between the compass North direction and PCA detected wave direction is also calculated for analysis. A webpage shown in Fig. 4 is developed to visualize the processed data through two graphs, which are cartesian and polar graphs. The
measurement from each capacitive sensor is used as radians for each 22.5° in the polar graph. The centroid value, capacitive sensor values, compass data, and water wave direction are plotted on both graphs. A CSV file is used to act as a data storage for all the data, which will be used as references for future analysis.

![Webpage for the water wave pattern visualization](image)

**Fig. 4** Webpage for the water wave pattern visualization

### III. RESULTS AND DISCUSSIONS

Fig. 5 shows the top view of the capacitive wave detector. The acceptance region of the four cardinal directions is ±22.5°. The acceptance range is calculated by dividing the total degree of a circle with eight directions, consisting of four cardinal and four ordinal directions.

The average water wave direction and compass direction for the data obtained from Table 1 are 173.82° and 136.65°, respectively. The average clockwise angle from the water wave direction to the compass is 322.83°, which has an error value of 7.83° when compared to the expected clockwise angle from the water wave direction to the compass, which is 315°.

<table>
<thead>
<tr>
<th>Polar Graph</th>
<th>Waveform Changes for Waves Generated From Position 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Frames (s)</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**TABLE I**

 wastewater
Four positions are tested, and the results in Table 2 and 3 show that all the directions can be detected. The error is calculated by taking the average clockwise angle from the wave direction to the compass and then subtracting it from the expected clockwise angle from the wave direction to the compass, which is 315°. Table 4 shows the measurements of errors from the experiment carried out. The mean square errors for the wave direction detection are 38.42°. The mean absolute error is 5.85°.

<table>
<thead>
<tr>
<th>Wave direction (Position)</th>
<th>Average Wave Direction (°)</th>
<th>Average Compass Direction (°)</th>
<th>Average clockwise angle from Wave Direction to Compass (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>173.82</td>
<td>136.65</td>
<td>322.83</td>
</tr>
<tr>
<td>2</td>
<td>271.61</td>
<td>224.08</td>
<td>312.47</td>
</tr>
<tr>
<td>3</td>
<td>354.57</td>
<td>316.85</td>
<td>322.28</td>
</tr>
<tr>
<td>4</td>
<td>82.58</td>
<td>43.32</td>
<td>320.74</td>
</tr>
</tbody>
</table>
Several possible sources of error contributed to the inaccuracy of water wave detection. The first possible source is that the human-generated water waves are inconsistent and irregular because there are different amplitudes and frequencies for each wave generated. Another possible source of error is that noise water waves are reflected from the wall of the inflatable pool to the buoy, which affects the generated wave due to wave constructions and destructions.

The results obtained and shown in Table 2 indicate that four directions can be detected using a capacitive sensor system with PCA calculations without being directly in contact with the water, which is advantageous compared to the pressure sensing methods [15], [16]. The water wave direction detection implemented using a capacitive sensor system is not required to keep a distance away from water, which is much more flexible than the light and visual detection methods proposed [4], [10]. The wave direction detected using a capacitive sensors system with PCA calculations is more informative than wave detection using monocular vision proposed in [25] because monocular vision can only calculate a line where the water waves are propagating without knowing the actual direction referring to the North.

### IV. CONCLUSION

Water wave detection is commonly used in oceanography, early warning systems in remote areas, and weather detection. This project aims to develop a real-time capacitive sensor system for water wave pattern acquisition and a surface water wave direction detection algorithm. Previous works on contactless water wave detection methods show lower flexibility in the field of applications. On the other hand, most non-contactless methods have lower durability as corrosion caused by the water will occur on the sensors after a certain period of usage. Besides, most previous works studied do not have the wave wave direction detection with the North referencing without any direct contact between the sensor and water. A static platform is not required for the buoy to operate. The prototype developed is much more advantageous than the previous works included because the previous works studied do not contain a contactless sensing method that can operate without the need for a static platform and, simultaneously, provide water wave direction that refers to the North. The area of the proposed solution can also be implemented further in the detection of water activities such as drowning and underwater gas pipeline leakage detection. However, detection algorithms must be proposed and analyzed to achieve accurate activity detection.

### ACKNOWLEDGMENT

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### REFERENCES


