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Original Article

Low-cost wave characterization modules for oil spill response

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Abstract

Marine oil spills can be remediated by mechanical skimmers in calm waters, but performance degrades with increased wave height. We have developed and demonstrated a system that quantifies local wave characteristics with an uncertainty of four inches of heave. Our system is intended for the measurement of wave characteristics during oil spill recovery. It conveys this information to coordinators and responders in real time via WiFi and remote reporting through a satellite network. This information will allow for enhanced situational awareness during an oil spill response, assisting stakeholders and optimizing mechanical skimming operations. Our wave characterization module (WCM) uses accelerometer outputs from a very small inertial measurement unit (IMU) to generate wave statistics and calculate wave characteristics. It is configured such that a WCM can either be attached to a skimmer float or incorporated into a microbuoy. Wave height and period are transmitted via WiFi and/or a satellite-enabled mesh-grid network to a cloud-hosted geographic information system (GIS). Here, we discuss the bare-bones sensors-plus-algorithm approach we developed by using spring-mass systems to approximate the wave height and period regime of interest. We then describe open water tests carried out using that development system both mounted to a weir skimmer mockup and packaged in a microbuoy. Finally, we present controlled tests in the wave tank at Ohmsett, the National Oil Spill Response Test Facility in New Jersey, with the WCMs communicating the wave characteristics via WiFi to tankside laptops and via satellite to the cloud-based GIS. Snapshot determinations of wave height calculated using the scalar magnitude of the three-axis accelerometer in the IMU were within four inches of the benchmark wave measurement system at Ohmsett.

Keywords: Oil spill; Wave characterization module; Inertial measurement unit; Microbuoy.

1. Introduction

Marine oil spills can rapidly be contained by booms and remediated by mechanical skimmers. However, these are most effective in calm waters [1] with performance dropping off with increased wave height and decreased wave period [2,3]. Although much of this technology is mature, a variety of research is underway to develop and evaluate improved oil recovery technology [4,5]. Legacy sea-state monitoring systems with large discrete instrumentation packages provide decades of work refining algorithms which interpret sensor output that can be effectively leveraged.

There are a number of free-form buoy devices available on the market that have various sensors and communicate their data remotely. The iSphere and Argosphere communicate both their location and the sea surface temperature [6]. Buoys with wave characterization capabilities include the Seawatch Buoys from Fugro OCEANOR [7], the Waverider buoys from Datawell BV [8], and the TRIAXYS buoys from AXYS Technologies [9]. The TRIAXYS g3 Wave Sensor provides numerous wave parameters and typical wave statistics features. The majority of these buoys are over 0.5 m in diameter and employ moorings, requiring special equipment to deploy. The Mini Directional Waverider GPS by Datawell [10] has the capacity for satellite communication and uses GPS to characterize wave movements. As they are highly sensitive to lateral movement, these buoys require an additional external antenna to determine wave height accurately. A recent review of measurement platforms for sea surface elevation, especially

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accelerometer buoys, can be found in [11], and in [12], eleven platforms for measurement of spectral wave parameters are compared. There is also work underway around the world to develop small buoys for measurement of wave characteristics [13,14] and tracking oil spills [15,16] using GPS and satellite communication.

Wearables are the current leading edge of the Internet of Things with an increased emphasis on battery-charge life despite the imperative to include more sensing capability. The key enablers are tiny, low-power sensor hubs which fuse the inputs of several different types of microelectromechanical systems (MEMS) sensors, such as accelerometers, gyroscopes, and magnetometers, all without engaging the main processor and thereby reducing power consumption by up to 95%. This recent proliferation of highly capable, but small and low power, MEMS sensor hubs now makes it feasible to implement a very low cost WCM for buoys, skimmers, booms and the like in order to provide highly accurate and hyper-localized measurements of wave characteristics in real time during oil spill remediation.

The goal of our work was to develop a system that quantifies local wave characteristics with an uncertainty of four inches of heave. Our system is intended for the measurement of wave characteristics during oil spill recovery. It conveys this information to coordinators and responders in real time via WiFi and remote reporting through a satellite network. This information will allow for enhanced situational awareness during an oil spill response, assisting stakeholders and optimizing mechanical skimming operations.

Previous work has created a family of devices and applications based on a successful geo-referencing identification (GRID) tagging system for the autonomous and long-term global tracking of remote assets without the need for local infrastructure [17]. The WCMs described here augmented the latest generation of these GRID and satellite-enabled GRID (GRIDSAT) tags with integrated IMUs, containing three-axis accelerometers to measure wave characteristics, and associated microcontroller units (MCUs), with wave characterization algorithms to record, interpret and report wave data. The WCMs are designed to be mounted on commercially available mechanical skimmers to measure wave characteristics during oil spill response and recovery operations, providing quantitative feedback to operators and stakeholders.

The WCM uses accelerometer outputs from a very small IMU to calculate wave statistics, and is configured such that a WCM can be either attached to a skimmer float or incorporated into a microbuoy. Wave height and period are transmitted via WiFi and/or a satellite-enabled mesh-grid network to a cloud-hosted geographic information system (GIS). In this paper, we discuss the bare-bones sensors-plus-algorithm approach we developed by using spring-mass systems which approximate the wave height and period regime of interest. We then describe open water tests carried out using that development system both mounted to a weir skimmer mockup and packaged in a microbuoy. Finally, we present controlled tests in the wave tank at Ohmsett with the WCMs communicating the wave characteristics via WiFi to tankside laptops and via satellite to the cloud-based GIS. Snapshot determinations of wave height calculated using the scalar magnitude of the three-axis accelerometer in the IMU were within four inches of the benchmark wave measurement system at Ohmsett.

2. Algorithm development

2.1. Wave characterization

An ocean wave is a flow of energy traveling from its source, carried by the water. Therefore, anything floating on top of a wave, such as a buoy, moves in an elliptical rise-and-fall pattern [18]. This allows us to measure wave elevation from the surface of the ocean. A WCM-Buoy or WCM attached to a skimmer floating on the ocean's surface can be equipped with an accelerometer to measure its movement from crest to trough, which corresponds to the same movement of the wave at that particular point.

The sea surface is a superposition of waves of varying heights and periods moving in differing directions. Although simple sinusoidal motions can be readily analyzed by elementary methods, their regularity does not approximate the variability of ocean waves. When the wind blows and the waves swell in response, a wide range of heights and periods is developed, so at a fixed location in the ocean, the wave signals that a WCM outputs will be irregular. Though individual waves could be identified, there will always be significant variability in height and period from wave to wave. Thus, it is necessary to treat the characteristics of the sea surface in statistical terms [19–24].

We employ a modern machine-learning approach to ensure that the WCM can accurately output wave height for a variety of real-world situations. In some cases, like simple swell, the basic wave parameters would be straightforward to extract from the IMU sensor data. However, once the WCM is attached to a piece of equipment, the actual motion will be modified by the interaction of that equipment with the wave. This means that somewhat different IMU signal features need to be exploited, but a machine-learning approach is sufficiently robust to accommodate this. Moreover, we can also interpret complex wave fields where a simple one-dimensional wave model would fail. Rather than specifying IMU signal features that correlate with simple wave properties *a priori*, our approach is to train the algorithms with mockup and open-water wave data and then load the optimal feature set into the firmware. This will allow new situations and equipment to be incorporated in the future without modifying the WCM hardware.

The ocean surface is composed of a combination of wave components individually generated by the wind in different regions of the ocean propagating to the point of observation. Complex wave distributions are difficult to obtain in explicit form from a random wave model, but numerical algorithms based on the regression approximation work well. This method of calculating wave distributions is the only known method that gives correct answers valid for general spectra. We selected the Wave Analysis for Fatigue and Oceanogra-