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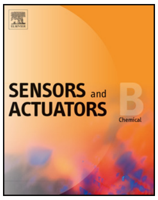

Data analysis from a low-cost optical sensor for continuous marine monitoring[☆]

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ABSTRACT

Continuous monitoring of aquatic environments has increased in recent times and is likely to continue in the immediate future. To obtain the most desirable outcomes from *in situ* monitoring it would be ideal to assemble sensor webs of low-cost and robust sensors with a high spatial resolution that produce relevant, timely and accurate data. In this paper, data analytics techniques are employed on data retrieved from a low-cost and robust optical sensor, measuring the side scattering and transmission of light through water. The sensor was deployed in estuarine waters to generate useful evidence of bulk water parameter events. These techniques are easily scalable for use in real-time for sensor webs to give decision makers additional information (both spatially and temporally), to help inform grab sampling times and other environmental monitoring considerations. Results are presented which show the optical data can be used to observe opacity changes in the water and these changes are correlated with turbidity events. In addition estimates of sunrise and sunset times can be given, as well as indications of sunlight hours. Data from multiple long-term deployments in Dublin Bay are used in this study.

1. Introduction

Increasing environmental pressures due to climate change, with the inherent water challenges therein, give a strong scientific and economic argument for the expansion of real-time continuous aquatic monitoring. The adoption of the Water Framework Directive by EU Member States [1], along with other Directives, means that monitoring of EU water bodies must increase in the near future. While these factors will drive an increase in environmental monitoring, it should be noted that the high costs associated with physical sample collection, the transportation to and analyses in laboratories is one of the main reasons for the low level of continuous monitoring in the past [2]. The fact that these techniques are standardised for legal and regulatory procedures and their high level of precision and accuracy in the laboratory, underlines their importance to date. Despite the desire for more regular information from a monitoring programme very often appropriate funding is not available to achieve these objectives. This means that new technologies must emerge to meet the demand for greater spatial and temporal information on the quality of our waters.

Potential solutions to some of these issues are *in situ* sensors, which are capable of continuously monitoring aquatic environments, and whose use is increasing in the recent past. These sensors can provide real-time information and supply a higher calibre of long-term data for water quality trends [3]. Recent investigations show sensor webs consisting of *in situ*, autonomous sensors deployed at a high spatial frequency, operating long-term and providing real-time alerts for key events are realisable [4]. The data handling, communication and analysis are all vital to the viability of sensor webs and must be suited to the particular task at hand. Challenges that remain for such large scale sensor networks include: sensor expense, bio-fouling, power needs, type of measurable parameters and calibration issues. The key issue remains the ability to measure and detect environmental pollutants as accurately, efficiently and effectively in the field with continuous monitors as is possible in the laboratory [5].

The success of sensor network depends on the ability to produce reliable, inexpensive *in situ* sensors which supply data that can be processed in real-time to provide accurate interpretation of water quality events. Recent developments have been made to reduce the cost of *in situ* sensors including fluorometers for the measurement of phytoplankton [6], chemical sensors for pH measurements [7] and the use of optical refractive index measurements for generic

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water event detection [8]. The authors previously described the development of a low-cost optical sensor for marine monitoring [9] which is capable of discerning changes in bulk water quality parameters including opacity and colour.

Water opacity may change through a number of different factors including: increased sediment concentrations from aquatic or terrestrial sources, the on-set of harmful algal blooms (HABs), the presence of hydrocarbons in the water body and storm water run-off. Opacity changes in water are largely driven by the turbidity level, which is now seen as a crucial water pollutant. Turbidity is often used as a surrogate for suspended solids concentration [10] and both are key influences on the population and ecosystem dynamics of plankton in estuarine systems [11]. Changes in the concentration of re-suspended pollutants (e.g. heavy metals and sediments) and in variations of microbial populations are linked with localised and sustained rises in turbidity [12]. A strong correlation has been found between total suspended solids concentration and the amount of attached bacteria, which is important for determining the levels of bacteria like *Escherichia coli* and faecal coliforms, in a number of aquatic systems [13]. As re-suspension of sediments can lead to increased *E. coli* concentrations, better knowledge of turbidity concentration dynamics can enhance the understanding of *E. coli* in surface waters [13].

This paper illustrates how by employing data analytics techniques on the data retrieved from a low-cost, optical sensor, extremely useful results on bulk water parameter events can be generated. These techniques are easily scalable for use in a real-time network of such sensors to provide decision makers with valuable information, to inform sampling times and other environmental monitoring considerations.

2. Experimental

2.1. Optical colourimetric sensor

A low-cost optical sensor, the optical colourimetric sensor (OCS), with the capability of determining changes in water opacity and colour, was designed and built. The sensor features; an LED array light source, photodiode detectors, a robust design, flexible electronic control, in-built antifouling measures and a custom built data logger. The construction and analytic performance of this sensor in terms of opacity and colour, along with a comparison to other sensing modalities, has been described in detail elsewhere [9].

The OCS is constructed from low-cost, robust materials (stainless steel 308 and 304, PVC-U, copper, rubber and IP 67/IP 68 rated enclosures). The body is foam-filled and acts as flotation, the electronics compartment is double sealed and the sensor head is stainless steel protected by copper plating. Fig. 1 gives an exploded view of the key sections of the sensor (including a photo of the system prior to a deployment). The sensor has a total length of 130 cm. Deployed attached to a pier/pontoon the sensing elements are submerged to a depth of 1 m, with the electronics and communications housing above the water. A schematic of the sensor head (which houses the detection abilities of the OCS) is shown in Fig. 2. As the sensor was designed to be deployed in the marine environment the sensor head is covered with a copper shroud which has strong anti-fouling properties [14] to minimise bio-films forming on components [15] thereby enabling longer deployment periods.

The light source consists of an array five LEDs: IR ($\lambda_{PEAK} = 850$ nm, FWHM = 45 nm), red ($\lambda_{PEAK} = 627$ nm, FWHM = 45 nm), amber ($\lambda_{PEAK} = 583$ nm, FWHM = 36 nm), green ($\lambda_{PEAK} = 515$ nm, FWHM = 30 nm) and blue ($\lambda_{PEAK} = 430$ nm, FWHM = 60 nm), which provide coverage across the spectrum. Two silicon photodiode (with a spectral response >20% efficiency in the range from 410 nm to 1080 nm) are the optical detection elements. The photodiodes are placed at 90° and 0° to the optical path of the LEDs light emission and this allows for the transmission and side scattering of the light through the water to be recorded simultaneously. Each LED is turned on in series and a measurement taken, in addition an ambient light measurement is taken with all LEDs off. A T-shaped piece of copper tubing encases the LED array and the photodiodes to prevent non-scattered light from entering the 90° photodiode, additionally it provides extra anti-fouling.

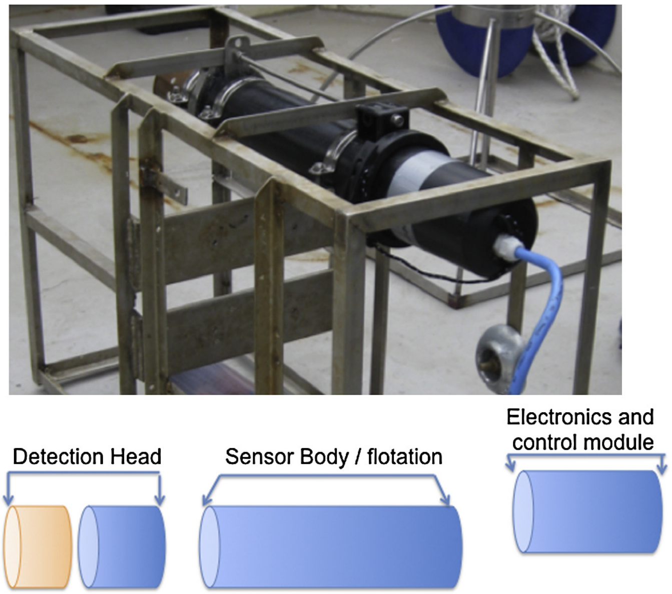

Fig. 1. An exploded view of the optical colourimetric sensor (OCS), showing the three main sections and a photo illustrating the OCS before deployment at sea.

The sensor is functionally controlled by a micro-controller, through the use of a Wixel (a programmable module from Pololu Robotics and Electronics). It regulates the on/off cycle of the LEDs and reads the photodiodes output signals via an analogue to digital converter. Both photodiode signals are measured for every LED, as well as the background light level (i.e. the signal level with all LEDs off). This allows for reconfigurable control of the photodiode sensitivity, LEDs cycle and frequency. The data is outputted via RS232 and captured by a data logger based on a “Raspberry Pi$^{®}$ (R-Pi)” single board computer, which saves the data to an SD card while simultaneously transmitting the data locally over Wi-Fi for downloading via a smart device. The sensor was powered using a cable connected to the mains power supply via an adaptor.

2.2. Field deployment

Poolbeg Marina is in a busy port environment in the Liffey estuary and in an area of less intense ship traffic, a deployment took

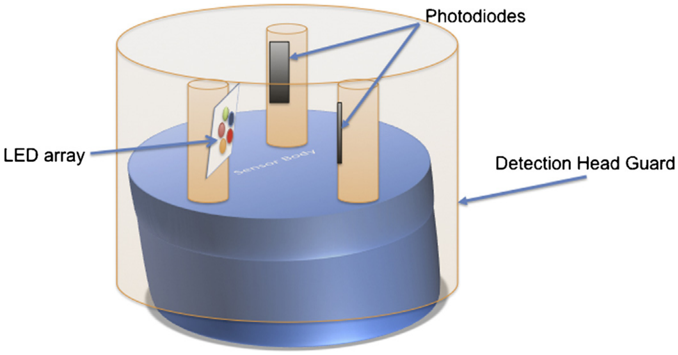

Fig. 2. Sketch of the OCS detection head, showing the basic configuration of the LEDs and photodiodes.