Sensors and Actuators B 150 (2010) 425–435

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Wireless aquatic navigator for detection and analysis (WANDA)

Cormac Fay [a], King-Tong Lau [a], Stephen Beirne [a], Ciarán Ó Conaire [a], Kevin McGuinness [a], Brian Corcoran [a], Noel E. O'Connor [a], Dermot Diamond [a,*], Scott McGovern [b], Greg Coleman [b], Rod Shepherd [b], Gursel Alici [b], Geoff Spinks [b], Gordon Wallace [b]

[a] CLARITY: Centre for Sensor Web Technologies, Dublin City University, Glasnevin, Dublin 9, Ireland
[b] Intelligent Polymer Research Institute, ARC Centre of Excellence for Electromaterials Science, University of Wollongong, NSW, Australia

ARTICLE INFO

Article history:
Received 18 January 2010
Received in revised form 5 May 2010
Accepted 10 June 2010
Available online 7 July 2010

Keywords:
Water monitoring
Polymer actuator
Wireless sensing
Biomimetics
pH detection
Optical sensing
Digital imaging
Colorimetric reagent

ABSTRACT

The cost of monitoring and detecting pollutants in natural waters is of major concern. Current and forthcoming bodies of legislation will continue to drive demand for spatial and selective monitoring of our environment, as the focus increasingly moves towards effective enforcement of legislation through detection of harmful events, and unambiguous identification of perpetrators. However, these monitoring demands are not being met due to the infrastructure and maintenance costs of conventional sensing models. Advanced autonomous platforms capable of performing complex analytical measurements at remote locations still require individual power, wireless communication, processor and electronic transducer units, along with regular maintenance visits. Hence the cost base for these systems is prohibitively high, and the spatial density and frequency of measurements are insufficient to meet requirements. In this paper, we present a more cost effective approach for water quality monitoring using a low cost mobile sensing/communications platform together with very low cost stand-alone 'satellite' indicator stations that have an integrated colorimetric sensing material. The mobile platform is equipped with a wireless video camera that is used to interrogate each station to harvest information about the water quality. In simulation experiments, the first cycle of measurements is carried out to identify a 'normal' condition followed by a second cycle during which the platform successfully detected and communicated the presence of a chemical contaminant that had been localised at one of the satellite stations.

1. Introduction

It has been long recognised that the interaction between industrialised societies and the environment can be negative, in that concentrations of people in urbanised areas, with co-located industries will have a negative impact on the overall quality of the environment. An important aspect of this interaction is the release of pollutants into local water bodies, such as rivers and lakes, which can adversely affect the health of people and cause devastating fish kills [1–6]. Consequently, environmental protection is a priority in modern society, and an extensive, and growing, body of legislation exists that specifies the limits of key chemical and biological pollutants in various types of water (potable, drinking, ground, etc.) [7–9].

Arising from the enforcement of this body of legislation is a growing need to police these pollutant limits, through analytical measurements that are used to determine the water quality [10]. However, these measurements are almost always achieved by taking samples from a relatively small number of designated locations, and analysing the composition at a centralised laboratory facility equipped with sophisticated state-of-the-art equipment. There are good reasons for employing this strategy, principally because of the high precision and accuracy of the measurements, which are vital for obtaining legally binding decisions against polluters. However, because of the expense involved to manage the analytical facilities and monitoring programmes, this model is inherently not scalable, and measurements are very restricted in terms of the number of locations and sampling frequency [11,12].

In recent years, we have developed autonomous analyser platforms that can perform complex analytical measurements at remote locations, and make the resulting data globally available via websites. However, the cost base for these devices is still relatively high as it includes pumps, valves, microfluidics, optical detection, reagents, standards, electronics, power, and wireless communications, all housed within a robust enclosure [13–15]. In this paper, we present a radically different approach to remote water quality monitoring based on a low cost, biomimetic robotic fish, known as WANDA (wireless aquatic navigator for detection and analysis). The WANDA platform is capable of movement via a polymer actuator based tailfin [16], and can report what it 'sees' via an integrated

* Corresponding author.
E-mail address: dermot.diamond@dcu.ie (D. Diamond).

0925-4005/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.snb.2010.06.021

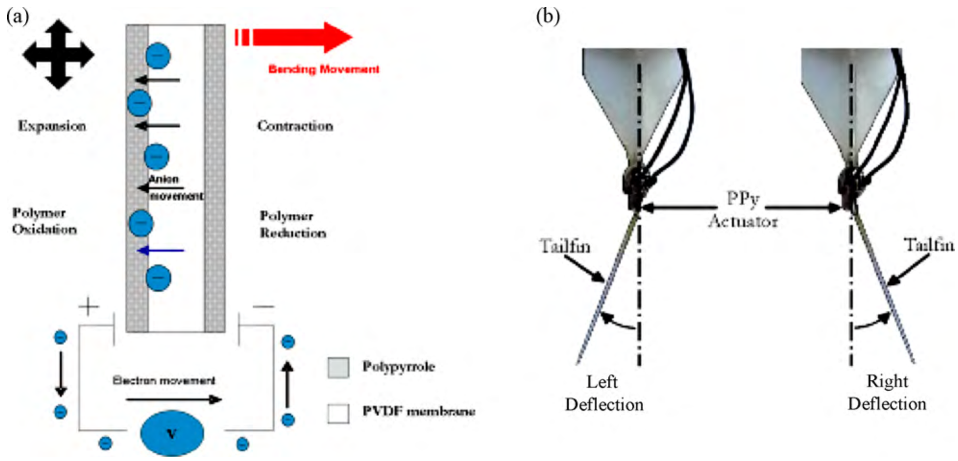

Fig. 1. (a) Cross-sectional diagram showing bending principle of the tri-layer conducting polymer actuators. Applying a low electrical potential 'V' causes oxidation of one polypyrrole layer and reduction of the other resulting in a bending movement. (b) Images showing the resulting bending movement of WANDA's polymer actuators when a rigid tailfin is attached.

low-power wireless video camera. The biomimetic fish can be used in conjunction with very low cost, dispersed, colorimetric 'satellite' sensors integrated into an easily recognised 3D form that enable very effective shape-identification algorithms [17] to be employed to distinguish the sensor from its surroundings. Once the sensor has been located, the camera is used to interrogate its condition and make the resulting data available via a wireless link. In this manner, a single, low-power robotic platform can harvest analytical information about the local chemical and/or biological environment at multiple locations using very low cost sensors.

In this paper, we demonstrate the principle of this approach using dispersed colorimetric sensors to probe changes in the local pH at several locations. Specifically, a water container of sufficient size (to allow for manoeuvrability) is setup within a laboratory setting. Several colorimetric sensors are then dispersed within the water container whereby an initial sensing patrol by WANDA allows for reference measurements of the sensors in uncontaminated conditions. A subsequent sensing patrol takes place whereby the water surrounding one station is acidified, resulting in a colorimetric change that is sensed by the camera. The results of the two patrols are compared showing that a change in pH has occurred in the water surrounding the station.

2. Robotic fish platform

The mobile wireless sensor platform used combines many disciplines into one practical device including materials science, wireless communications, vision systems, chemistry, systems control, biomimetics and robotics. However, in this paper, we will focus on three of these:

- the biomimetic novel propulsion method;
- the ability to navigate and sense chemical events;
- system construction and control.

2.1. Propulsion method

Conducting polymer actuators (or artificial muscles) based on polypyrrole (PPy) [18] have been utilised within the propulsive element of the tailfin of WANDA. With the application of an oscillating voltage (e.g. a low voltage square wave, ±1 V 1 Hz), a bi-directional bending movement is derived from the actuators as one side becomes oxidised, and the other side is reduced. This oxidation/reduction process is accompanied by swelling/contraction of the respective polymer layers, due to movement of anions and water of hydration associated with the maintenance of overall charge neutrality, see Fig. 1a. In such a system, the direction of bending is controlled by the polarity of the applied voltage. If a rigid tail fin is attached to a pair of actuators (Fig. 1b) the force generated can enable a transfer of energy from the bending motion of the actuator to the water.

2.2. Navigation and sensing

The WANDA platform is equipped with a wireless video camera for two main purposes. The first is for navigation as, through the video images, one can estimate the location of the device while building a map of the environment. This technique, known as simultaneous localisation and mapping (SLAM), has received continuous attention for the last two decades [19,20].

The second purpose of the onboard camera is to harvest information about the chemistry of the water body it moves through. In this study, we achieve this through the use of a number of sensing stations fitted with a chemo-responsive dye which responds colorimetrically to changes in the chemistry of the local environment. By using the onboard camera, a mobile device can easily detect differences in colour and, in turn, this can be related to the levels of certain chemicals in that region of the water body. Previous works [21–25] have shown that it is possible to monitor changes of pH in a laboratory using a colour camera, and we have therefore selected this measurement as the proof of principle test for the platform.

2.3. System construction and control

A primary goal for the research was to control the movement of WANDA using a biomimetic polymer actuator. Fig. 2 shows the assembly of the WANDA fish platform presented in schematic (Fig. 2a) and photographic (Fig. 2b) formats for clarity. The main components, i.e. wireless camera and control circuitry, are housed within a waterproof container (a truncated 50 ml syringe). Connected to the casing's bung are the PPy actuators to which the tailfin (cut from a thin plastic sheet) is attached. The range of the WANDA device is dictated by the wireless camera allowing for a transmission length of 100 m [26]. The control circuitry is powered from the wireless camera's battery allowing for a continuous operation (PPy bi-directional actuation of 1 Hz with wireless video transmission) of WANDA for a period of ca. 3.5 h in its current configuration.

By coupling the propulsion method with machine vision techniques, autonomous control is achievable. Further, by interpreting the scene with data captured by the onboard camera using a

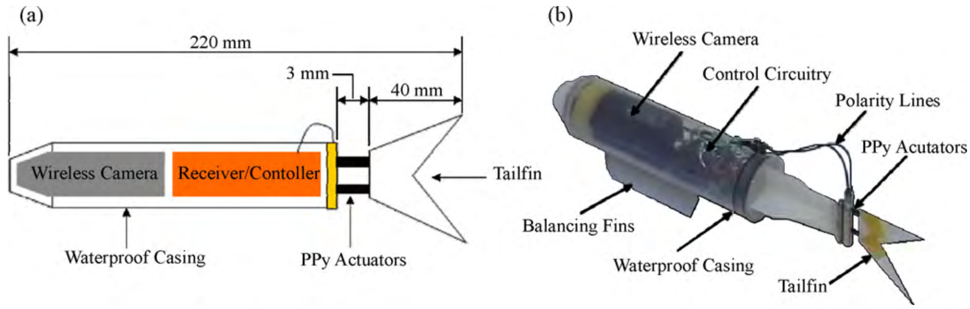

Fig. 2. (a) Diagram showing the wireless camera, controller, casing, PPy actuators, and tailfin arrangement on the WANDA device. Dimensions added for size reference. (b) Image of WANDA assembly for visual reference. Major components labelled including left balancing fin (right balancing fin obscured from view).

combination of image processing algorithms, WANDA can avoid obstacles, track towards objects of interest and/or perform chemical analysis. To achieve this, commands are sent from the base station to the tailfin control circuitry on board WANDA (Fig. 3) and, in turn, alter the tailfin's state, resulting in motion.

In this study, WANDA moves through a fixed patrol route in a water container under remote control from the base station. When a chemical indicator station appears within the camera's field of view, colorimetric analysis is performed on the pixels representing the chemically responsive dye. This returns a quantitative estimation of the pH of the immediate environment surrounding the chemical indicator station.

3. Experimental

3.1. Materials and equipment

A standard colour reference chart (X-Rite Colour Checker Passport) is used as reference for colorimetric analysis. The wireless camera (ZTV ZT830T) transmits a video stream from WANDA to the receiver (AEE AR101 placed ca. 4 m from the water container), which forwards it to the video capture card (Avermedia C038). The main processor (Dell Latitude D630) interrogates the signal and sends a direction command via radio (EZ Radio ER900TRS 250 m possible range [27]) to the microcontroller (PIC16F683) on WANDA which, in turn, controls the tailfin (polypyrrole) movement.

The water container (Intex 59416NP) used for experimentation, was cylindrically shaped with a diameter of 114 cm, a height of 25 cm and filled 8 cm with water allowing sufficient room for WANDA to manoeuvre. One molar HCl solution was made from 37% HCl (Scharlau AC0741) and ultra pure water (Millipore Milli-Q), and this was used to change the local pH near one of the pH sensing stations.

Three identical pH sensing stations were constructed as shown in Fig. 4. The stations consist of a standard 20 ml vial affixed (Loctite 3430) to a heavy metallic base with a strip of Universal Indicator (Johnson Universal pH Indicator) attached around the centre of the vial. The strip was modified with ethyl cellulose (Sigma–Aldrich 28244) to reduce leaching effects. This was achieved by dissolving 100 mg of ethyl cellulose in 10 ml of solvent (ethanol). After manually coating the strip, a thin layer of porous ethyl cellulose resulted, allowing efficient exchange of H^+ ions but inhibits loss of the much larger dye molecules.

Software components used as part of overall system integration include:

- Java runtime edition [28]—standard java programming package.
- Javax.comm [29]—serial port communications.
- Direct show java (DSJ) [30]—video capture.
- Java advanced imaging [31]—video processing and analysis.

3.2. Image processing

The video stream is captured from the capture card at a standard size of 640 × 480 pixels, 15 frames per second (fps), 24-bit colour depth (8 × 8 × 8) and in raw RGB format as any artefacts arising from compression algorithms (such as the MPEG family) may distort the

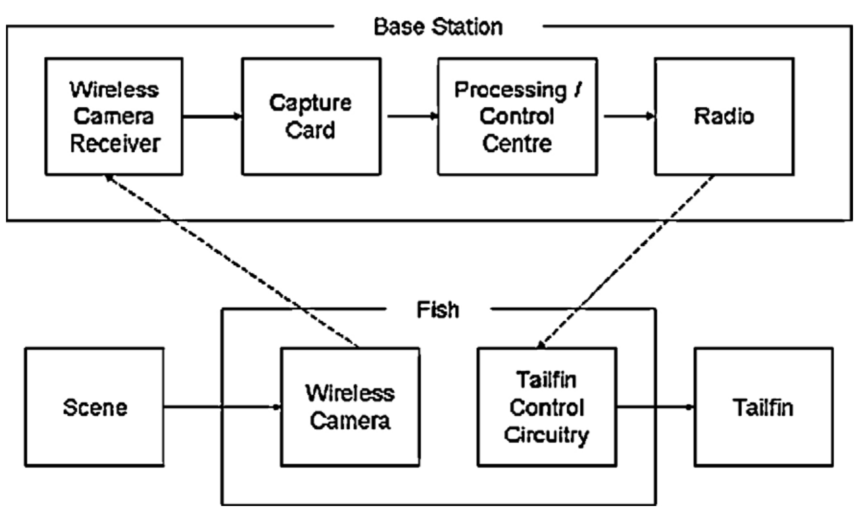

Fig. 3. Block diagram illustrating the full closed loop control system of WANDA and sub unit interactions thereof. A captured 'scene' is relayed via the 'wireless camera' on the 'fish' to the 'wireless camera receiver' on the 'base station'. The 'capture card' forwards the image to a pc or 'processing/control centre' where it extracts and analyses data. Decisions are made based on this data and forwarded via the 'radio' to the 'tailfin control circuitry' on board the 'fish' where it alters the 'tailfin' state resulting in controlled directional movement.

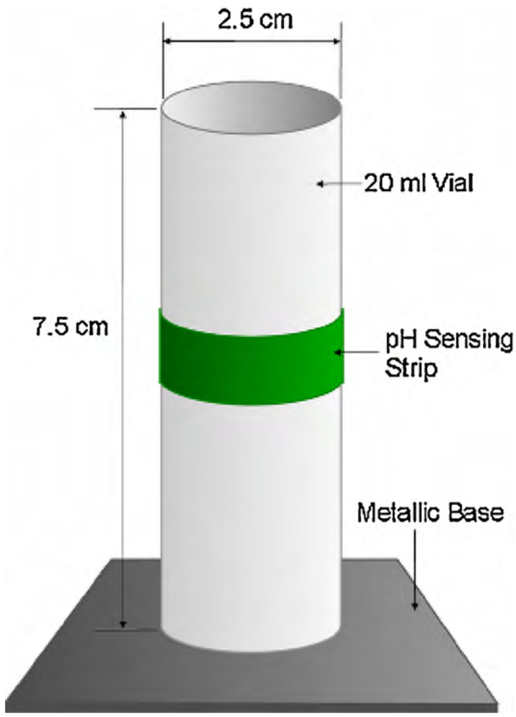

Fig. 4. Diagram showing the construction of a pH sensing station used during patrols. A standard 20 ml cylindrical vial is affixed to a heavy metallic base used as an anchor. One strip of universal pH indicator coated with ethyl cellulose is attached around the centre of the vial. Dimensions added for size reference.

estimated values. Fig. 5a shows a captured image of a submerged sensor station. For colorimetric analysis, it is necessary to extract the image region representing the pH sensing strip (see Fig. 4). To achieve this (Fig. 5c) a number of image processing steps were combined to segment the region of interest (i.e. to identify all pixels that represent the pH chemo-responsive material of the sensor station). Firstly, a region of interest is selected containing the indicator material and background. After that, to aid in the segmentation process, noise reduction techniques were applied; a median filter [32] followed by a standard 3 × 3 grey level morphological dilation [33]. Subsequently, a transformation from the RGB colour space to the HSI colour space [34] is performed to assist colorimetric analysis, i.e. to investigate if a more robust model to variable lighting intensities can be used, see Section 4.1. Since the pH material will only change colour between green and red when acid is introduced (Fig. 6), a band pass filter was applied to the Hue channel (from 0 to 2.09 rad, see Fig. 7 for quantitative values in relation to colours [35]). Next, a standard region labelling algorithm was applied to the Hue channel. This gave a grey level image whereby neighbouring pixels of similar colour/hue were connected together into one region. These regions were then ranked in order of their total number of pixels. The second largest region was taken to represent the indicator material as the largest represented the background. A binary mask image was created with white pixels set as the indicator region, see Fig. 5b. Following this, a binary morphological erosion process [36] was applied to remove edge pixels that may belong to the background and thus interfere with analysis. Fig. 5c shows the final step

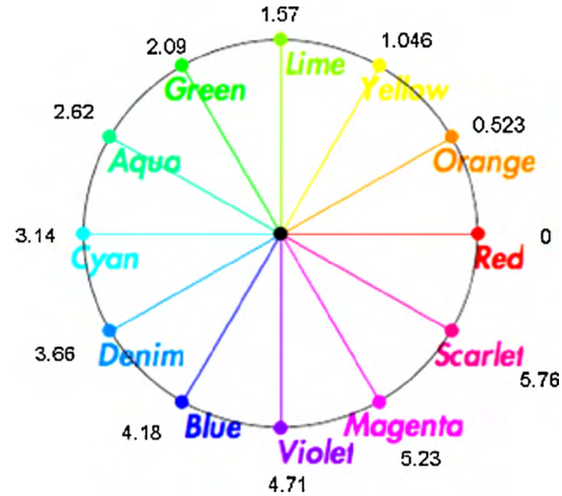

Fig. 7. Hue channel of the HSI colour space [34] normalised between 0 and 2π. Image shows quantitative values in relation to common colours at 30° (0.523 rad) intervals.

Fig. 5. Segmentation process to selectively extract the pH indicator region of the test station in the water container. (a) Single captured image of a pH sensing station from the wireless camera. (b) Generated binary mask image after applying region segmentation image processing algorithms. White pixels representing the pH sensing strip region. (c) Resulting image of the extracted pH indicator region after applying the binary mask image to the original captured image.

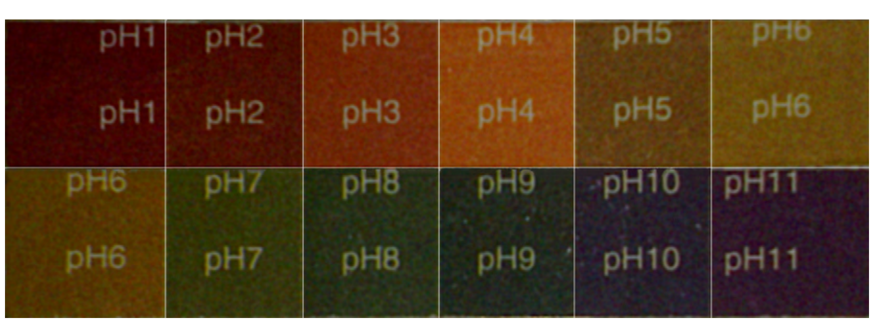

Fig. 6. Image showing the reference chart accompanying the pH indicator (Johnson Universal pH Indicator).

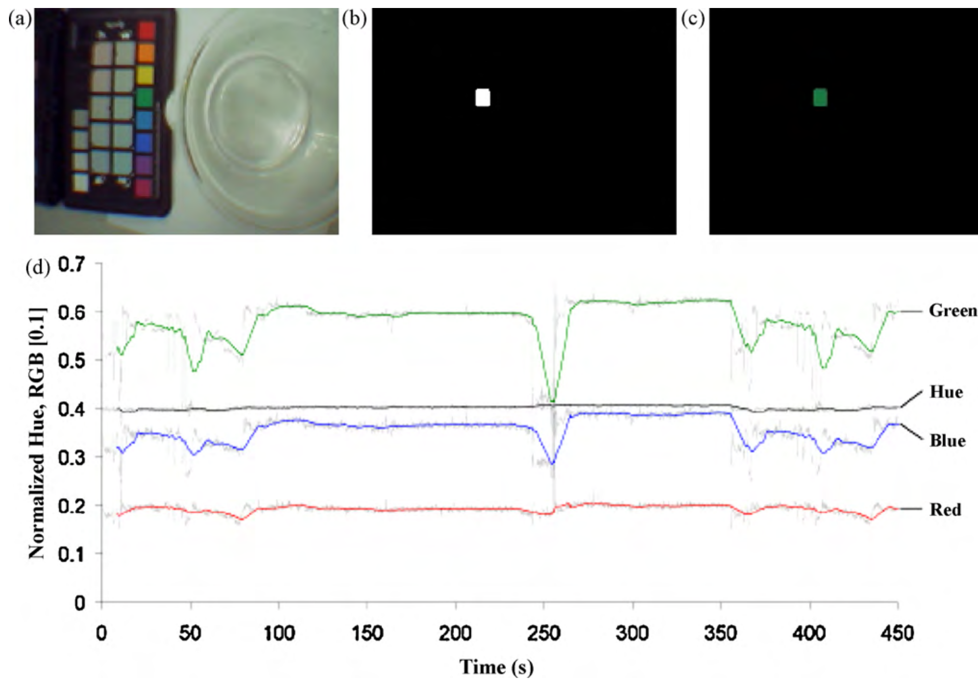

Fig. 8. Segmentation and evaluation process to selectively extract a reference colour patch, analyse it under induced light intensity variations and compare the RGB and HSI colour spaces. (a) Single captured image of the X-Rite colour reference chart from the wireless camera. (b) Generated binary mask image after applying region segmentation image processing algorithms. (c) Resulting image of the extracted green patch region after applying the binary mask image to the original captured image. (d) Real-time plot of the colour reference chart's green patch over a period of 450 s, showing the response of the red, green, blue and hue components. Smoothing (heavy lines) applied to raw captured data (grey lines) for visualisation purposes.

of the segmentation process once the mask was applied to the original image. The average of every identified pixel's hue component was taken to represent the pH at a given station.

3.3. Experimental procedure

First, a comparison was drawn between using the RGB and HSI colour spaces to investigate which model was more robust to light variation. To achieve this, the camera was maintained at a fixed location in an area of variable lighting intensities with the colour checker chart in view for reference (Fig. 8a), and a number of changes in the lighting were applied to investigate the robustness of the colour determination, see Section 4.1 and Fig. 8d.

Next it was necessary to investigate the camera's response to pH induced colour changes. WANDA was kept stationary in the water container allowing for a continuous view of one pH station, see Fig. 9 for setup. Next, ca. 5 ml of the HCl solution was injected using a standard 5 ml pipette around the sensing station causing a colorimetric change of the pH sensor. After that, the indicator was encouraged to return to its original state i.e. prior to the addition of the acid solution by manually mixing the water in the vicinity of the station to disperse the acid plume. The resulting video stream was processed and analysed as explained previously in Section 3.2 and a plot of the changing state of the colorimetric sensor from a neutral (green) to an acidic (yellow) state was generated, see Section 4.2 and Fig. 10. This process was repeated three times to investigate reproducibility.

To determine if WANDA can detect a chemical event during a patrol, three pH indicator stations, designated as L1, L2 and L3, were placed at three different locations within the water container as shown in Fig. 11. Software was implemented to achieve an autonomous circular patrol route within the water container with a diameter of ca. 0.7 m. The starting point 'S' was defined to be the starting point and the finishing point WANDA reaches on its circular patrol route when viewed from above. Each station was positioned to be in the camera's field of view as WANDA swims past. Next, a pH plume was injected at station L2 causing a colorimetric change in the pH sensor. Three images of each pH station were processed and analysed as explained in Section 3.2. Finally, the hue value of each sensor station against time was plotted, see Section 4.3, Figs. 12 and 13.

4. Results and discussion

4.1. Using a video camera as a chemical detector

Previous studies, as mentioned in Section 2.2, have successfully used a video camera as a pH colorimetric detector. However, these studies have been performed under controlled lighting conditions

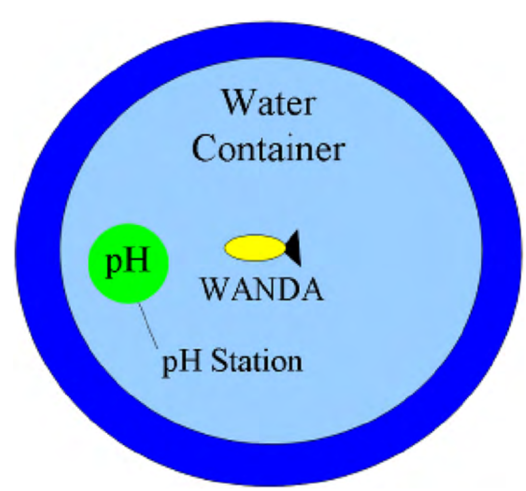

Fig. 9. Layout of pH station and WANDA within the water container for profiling the response of the camera to induced pH changes of the water surrounding a sensing station. See Fig. 5a for a similar captured view of the sensing station.

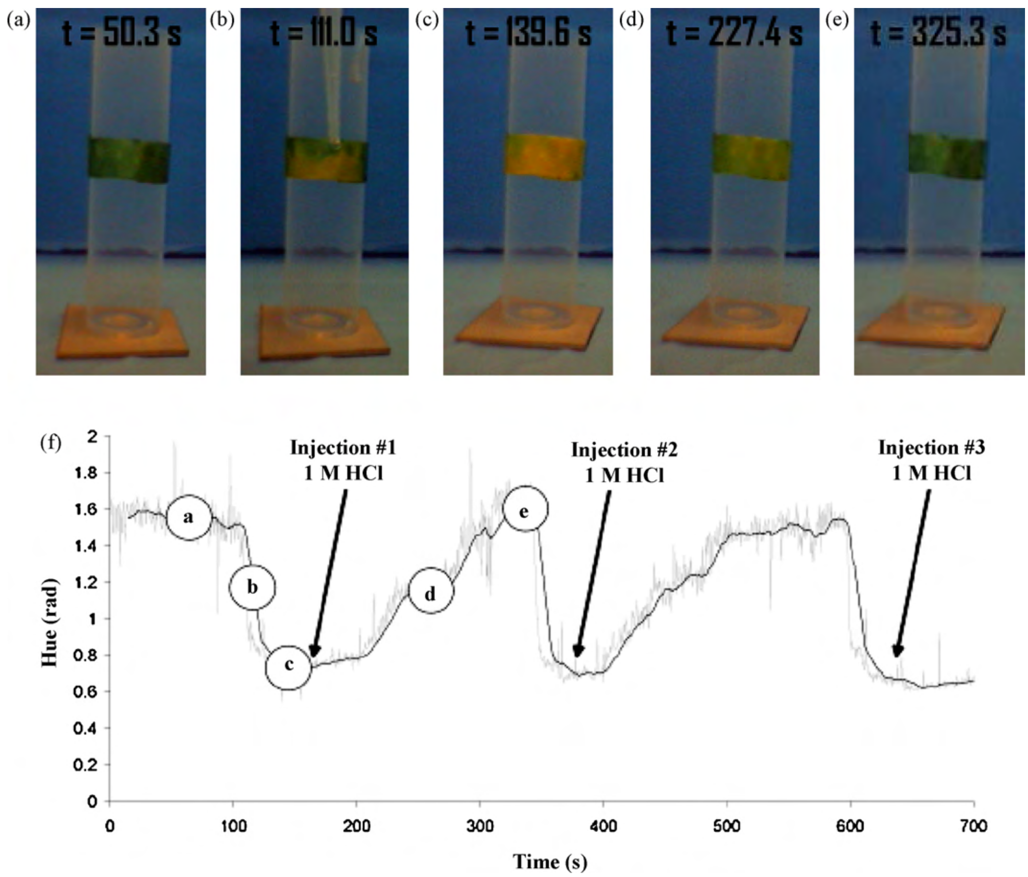

Fig. 10. Image sequence and response plot showing reaction to addition of acid near a sensor station. (a) Before acidification. (b) During acidification. (c) Acidified. (d) Recovering. (e) Recovered. (f) Real-time response plot of the camera's hue analysis of the sensing station to 3 induced pH changes over time. Labels 'a'–'e' correspond to figure elements 'a–e', respectively. Smoothing (black line) applied to raw captured data (grey line) for visualisation purposes.

and using the RGB colour model. A key requirement in this study was for the system to be capable of performing under variable ambient lighting conditions. The RGB colour space is inherently sensitive to variations in lighting, and cannot meet this requirement; thus a more robust method was needed. For this reason the HSI colour space technique was adopted. The transformation from RGB to HSI separates the light intensity 'I' (intensity), colour intensity 'S' (saturation) and colour 'H' (hue) into separate components. By separating the light intensity from the colour, the Hue component is more robust than RGB to variable lighting conditions. To illustrate this, Fig. 8a–c shows segmentation steps of the colour chart's green patch (chosen as it was the nearest colour to the neutral state of the pH indicator, seen in Fig. 5a).

Fig. 8d shows the real-time plot of the colour reference chart's green path over a period of 450 s. During this time deliberate light variation effects were implemented such as shadows at the beginning (0–100 s) and end (350–450 s) and switching on and off the laboratory light at ca. 250 s. This figure (where all component values are normalised between 0 and 1) shows the effects of light intensity variations on the individual green, blue, red and hue components, ordered from most to least effected. It can be seen that the RGB components do not respond uniformly to the induced lighting effects. The non-uniformity results from a combination of two factors; the light source and the response of the red, green and blue photo sensors within the camera. However, the hue component remains less sensitive to the camera calibration and light source and, as such,

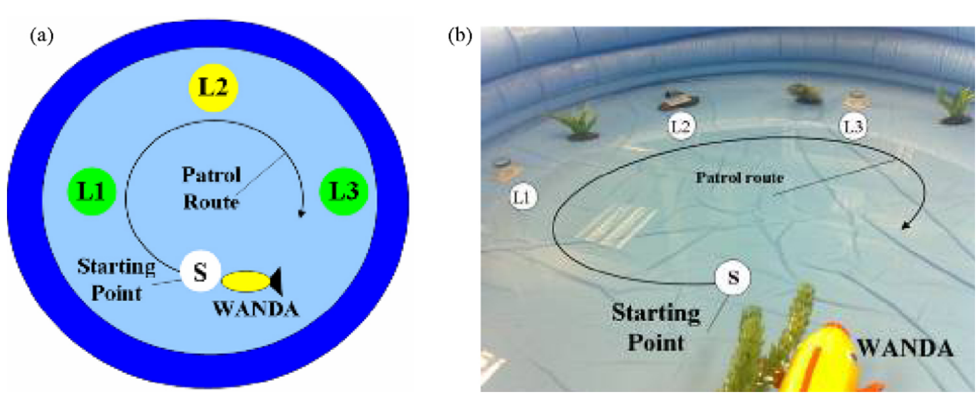

Fig. 11. Layout of pH stations and patrol route within the water container. 'S' starting and ending point of the patrol route, 'L1' pH station 1, 'L2' pH station 2, 'L3' pH station 3. (a) Plan view diagram of patrol route of sensing platform. (b) Corresponding photographic image for reference.

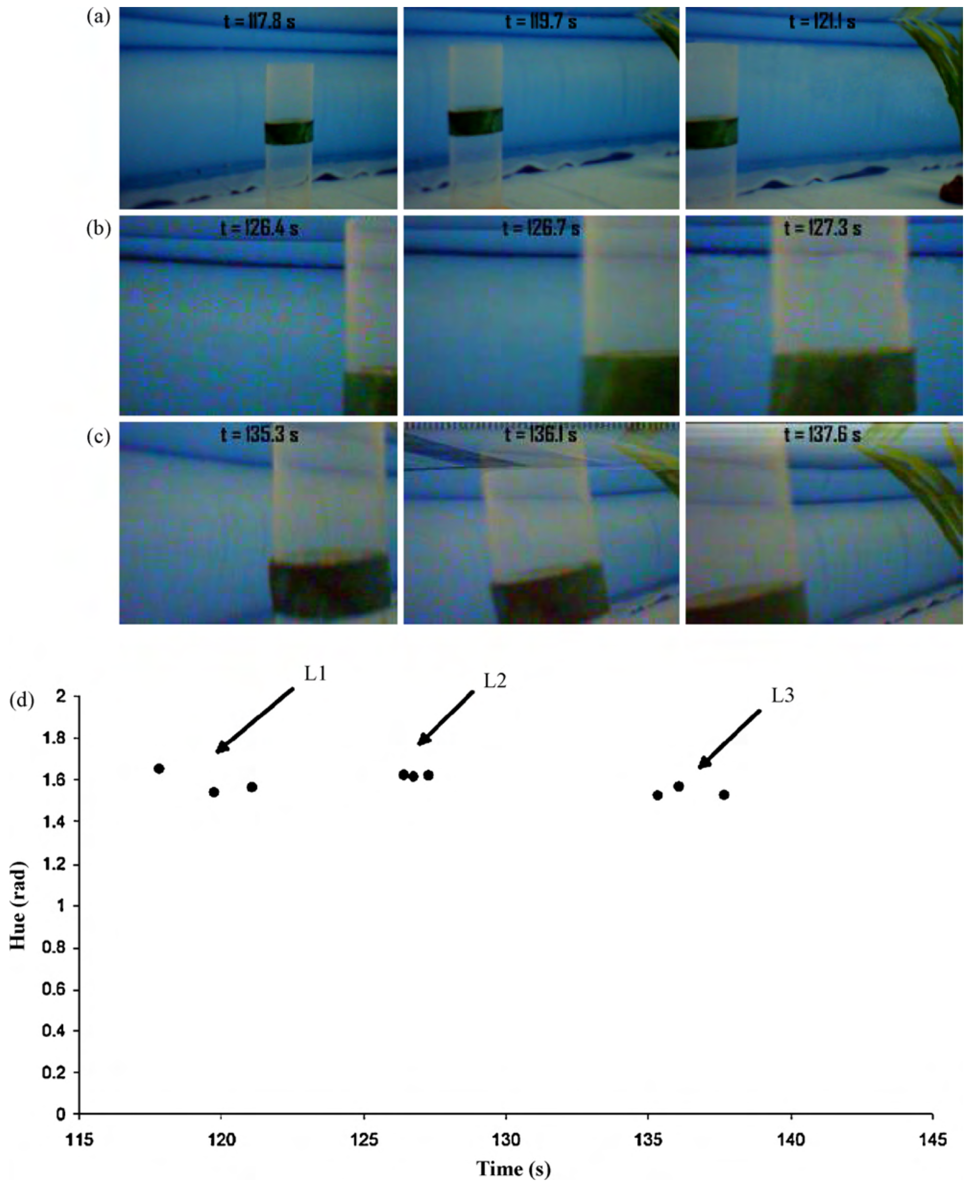

Fig. 12. Image sequence and response plot showing the response of the camera to all three pH sensing stations during Patrol # 1 'normal conditions' in the water container. (a) Three captured video frames of pH station L1 as WANDA swims past. (b) Three captured video frames of pH station L2 as WANDA swims past. (c) Three captured video frames of pH station L3 as WANDA swims past. (d) Response plot of the camera's hue analysis of sensing stations L1, L2 and L3 corresponding to figure elements (a)–(c).

is our preferred choice for our analysis during subsequent patrols, see Section 4.3.

4.2. Camera evaluation

For proving the overall concept hypothesised in this paper we are only interested in two clearly detectable states; neutral 'pH 7' and an identifiable acidic 'pH < 5' while keeping the detection system robust to variations in lighting. Fig. 6 shows the reference chart accompanying the pH indicator. In its neutral state, i.e. pH 7, the indicator is green in colour, however, when an acid is introduced the colour will shift towards a colour between green and red depending on the concentration of acid and its dispersion in the water.

The camera's response was profiled by analysing the pH strip in its neutral and acidic states. WANDA was kept stationary in the water container with a pH station directly in the camera's field of view (Fig. 9). An acidic plume was introduced near the pH station by injecting ca. 5 ml 1 M hydrochloric acid, triggering a colour change of the pH indicator material. The indicator pixels in the captured image were extracted using the image processing approach outlined previously and the colour change was represented numerically according to the hue angle.

Fig. 10 shows the analysis of the dominant Hue colour value of the pH station in the two identifiable states; green in neutral state and yellow when the acidic plume was introduced (a pH change from 7 to ca. 5, see Figs. 6 and 7). Fig. 10f shows a plot of this change occurring three times. Labels a–e in Fig. 10f show a correlation to Fig. 10 elements (a)–(e), numerically and visually, of the change and recovery at specified times. From Fig. 10f it can be seen that this process is clearly reproducible and that the colour/Hue is proportional to the level of chemical contaminant. The response is sufficiently clear to enable the two states to be identified. For more accurate analysis we could consider employing noise reduction algorithms such as dropping frames with identifiable noise during image processing.

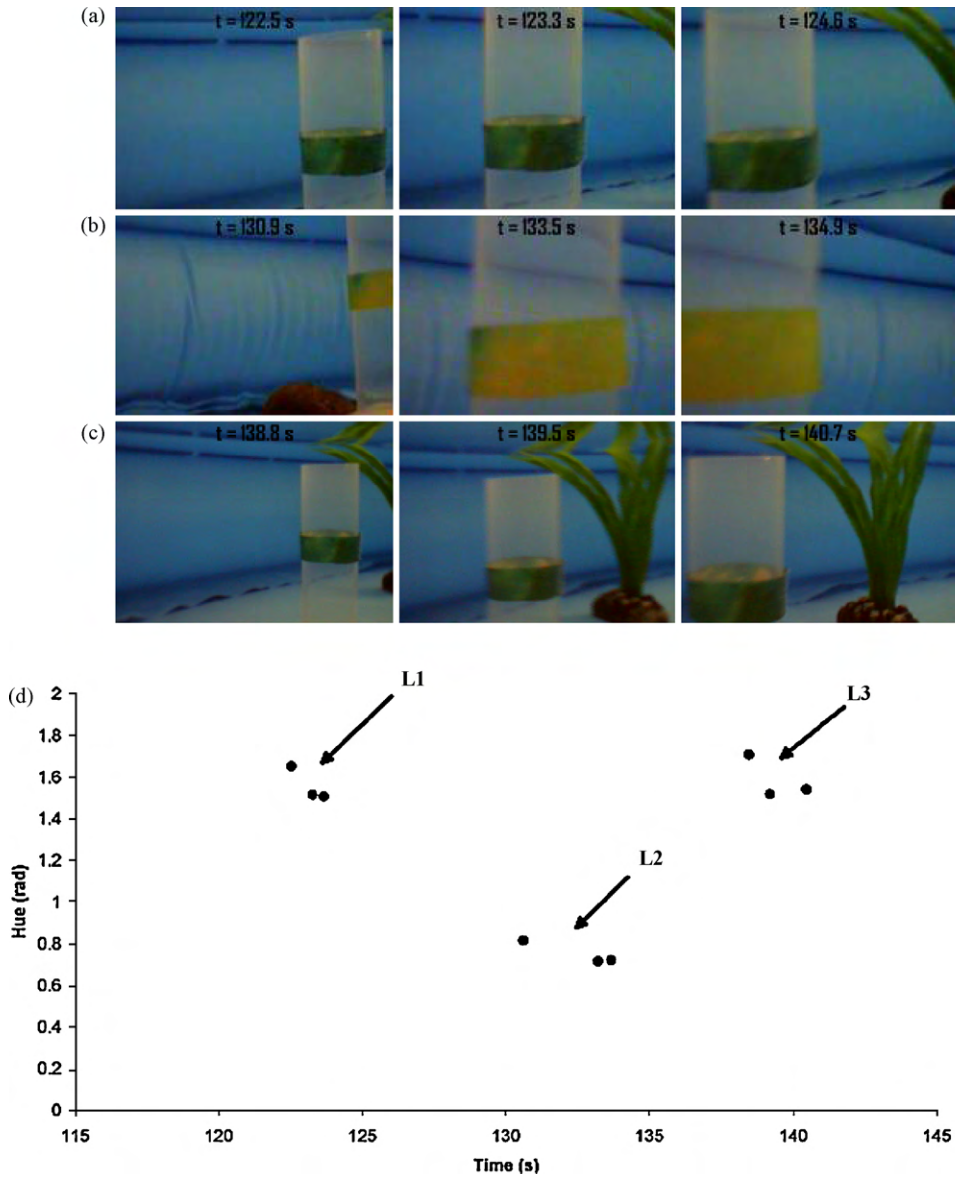

Fig. 13. Image sequence and response plot showing the response of camera to all three pH sensing stations during Patrol # 2 'change in local pH conditions' in the water container. (a) Three captured video frames of pH station L1 as WANDA swims past. (b) Three captured video frames of pH station L2 as WANDA swims past. (c) Three captured video frames of pH station L3 as WANDA swims past. (d) Response plot of the camera's hue analysis of sensing stations L1, L2 and L3 corresponding to figure elements (a)–(c).

4.3. Environmental monitoring—WANDA on patrol

Once it had been established that the camera can be used to detect the presence of an acid plume in the immediate environment surrounding the pH sensor station, the approach was extended to the use of WANDA in a 'patrol' mode, where WANDA would follow a set path to check the pH status of the water container by monitoring the colour of several land mark stations.

The three pH stations, labelled (L1, L2 and L3), were placed in different areas of the water container and a fixed patrol route was defined; starting from point S, passing station 1, 2 and 3 en route and finishing up back at the starting point. Video images were recorded and transmitted wirelessly in real-time to a PC. Image analysis was performed off-line for these experiments, but it is our intention to develop a fully autonomous procedure that will be implemented on the WANDA platform. Three video frames per station were manually selected to investigate reproducibility. These frames were chosen to offer the best quality for analysis, i.e. those without any noise obscuring the colorimetric sensor pixel area.

Two separate patrol operations were performed to demonstrate the principle.

- Patrol # 1: Normal condition; all landmark stations were green in colour.
- Patrol # 2: Event occurred; the environment surrounding station L2 was acidified and the station indicated a yellow colour. The other two stations (L1 and L3) remained unchanged to simulate a locally occurring event.

The results from Patrol # 1 were analysed and used as reference for normal conditions. Any change in colour on each of the landmark station would therefore be indicative of a change in their respective local chemical environment.

During operation, the individual landmark identity was signified by its specific shape and feature (cylindrical with colour strip) from its surroundings and the time taken to reach it. A specifically shaped colour code could be used for each location if preferred; here we adopted the simplest format to reduce the amount of image analysis for site recognition in this first trial.

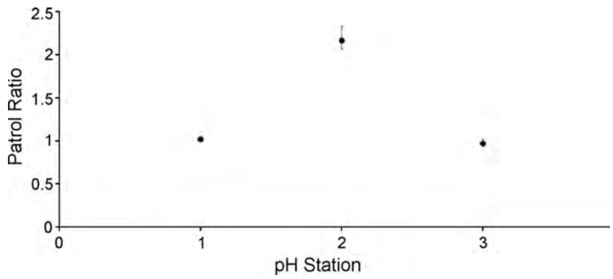

Fig. 14. Comparison of Patrol # 1 and Patrol # 2. A single hue value is taken to represent each sensing station. Points represent the average hue ratio of station's L1, L2 and L3. Upper and lower error bars represent the max and min hue ratio, respectively.

Fig. 12(a–c) displays an extracted image sequence from the video stream showing that the three indicator stations are green for visual reference. The result of the image analysis (Fig. 12d) indicates that the three stations gave a similar green hue output with values of ca. 1.6 rad, in agreement with the initial camera response experiments (see Fig. 10f). This data has shown that WANDA – in conjunction with the image analysis technique – was successful in determining the correct status of the colorimetric sensors, i.e. that the environmental status of all sensor stations was 'normal'. This information was stored and used as reference for future monitoring operations.

By comparing the colour/hue state of the indicator stations in future patrols with the reference data; one can therefore provide information about changes in the local pH. This is demonstrated here in the case of Patrol # 2. The exact same method for Patrol # 1 was employed to produce video images and colour information for Patrol # 2, shown in Figs. 12 and 13, respectively. The captured images (Figs. 12a, 12c, 13a and 13c) show that stations L1 and L3 remain unchanged, whereas station L2 (Figs. 12b and 13b) has changed from green to yellow, visually indicating that the sensor has responded to a change in pH of the environment immediately surrounding station L2 and that this contaminant was localised because it did not affect stations L1 or L3. The results of the image analysis (Figs. 12d and 13d) indicates that the two stations L1 and L3 gave similar green hue outputs (ca. 1.6 rad) as previously recorded, whereas L2 has changed its reported hue output from ca. 1.6 rad to ca. 0.7 rad. Hence the change in sensor colour was successfully captured by WANDA.

A more robust and simple technique has also been developed to determine if an event has occurred. It is based on comparing the hue value of each respective sensor stations between different patrols through the comparison of the ratio of the sensor hue values between runs. For comparison, a single hue value is taken to represent each sensing station; i.e. the hue average of the 3 captured images of a single sensing station is calculated and is representative of the station's pH state. Next, the hue ratio of each respective sensing station is calculated, e.g. ratio of L1 (Patrol # 1) to that of L1 (Patrol # 2). Fig. 14 shows the plot of the hue ratio of respective sensors between Patrol # 1 and Patrol # 2. The results clearly show that when there was no change in the pH environment, the colour ratio of the sensor stations (L1 and L3) were very close to 1. Meanwhile a ratio value of >2 was obtained for L2 when a pH change in the surrounding environment was induced. This demonstrates that WANDA has successfully reported a chemical change in the local environment.

This simple analysis technique can be made useful for detecting minor changes in a pH environment by setting a threshold value of how far the ratio deviates from normal conditions (e.g. 5% deviation from ratio = 1), resulting in a semi quantitative mobile warning system for detecting localised events in target areas.

4.4. Significance and future developments

The significance of the approach demonstrated in this paper to the realisation of water quality monitoring sensing networks is that it potentially allows for a significant cost reduction of infrastructure and maintenance. The need for power, communications, and processing units is no longer necessary for individual sensor stations. As a result, this model is inherently more scalable than traditional techniques and as such allows for wider areas to be sensed meeting the needs of future legislation. Other areas where this type of technology may be useful include; port monitoring for oil spillages, air quality in hazardous workplaces, food preparation surroundings, detection of threats (e.g. detection of release of chem/bio-warfare agents) using mobile or fixed cameras. For example, low cost colorimetric sensors could be deployed within water catchments areas or aquariums where ammonia levels increases with biological waste. If the continuously operating filtration system breaks down without a monitoring technique in place, such as the approach offered in this paper, it can result in heavy cost and loss of fish life.

As this concept is in its early stage, numerous improvements can be introduced. Since the patrol route was fixed; the order/time at which the stations were encountered was used for identification purposes. Although it is not required for the simplified conditions in this lab experiment, deployments in real situations will rely more significantly on a shape and/or a colour coded pattern design as a discriminating factor. The chemical indicator stations can be designed with a unique 3D shape/colour id with a high contrast to anything in its environment for location/identification purposes.

Noise is an unavoidable problem for any analytical measurement. For the approach used in this study, i.e. using a wireless camera for chemical analysis, image quality is paramount. Limitations of using wireless cameras have been outlined by Byrne et al. [37], where one faces challenges such as range, chromatic noise, horizontal scan line noise and visible vertical blanking due to vertical sync loss. Such challenges have been encountered in this study, i.e. visible in plots Figs. 8d and 10f shown as grey lines. Methods to overcome these problems can include noise identification in video frames (mentioned in Section 4.2) and/or to perform image and video processing on the device itself (mentioned in Section 4.3) whereby an autonomous regime can be implemented on WANDA allowing for flexibility towards true autonomy without range limitations.

Improvements to the platform itself are also foreseen. At present, WANDA is limited to low flow rate areas in its current implementation. Enhancements may include; the development of a more streamlined casing to accommodate higher flow rates, investigation into new PPy arrangements for greater efficiency or even replacement of the propulsion method with a more conventional system. However, replacing the propulsion may impact on deployment life-time due to a higher power draw, e.g. a motor with directional control.

Multiple dye-based sensors immobilised on a single station will enable the status of multiple components and numerous locations to be monitored. Establishing colour references on stations in conjunction with adaptive training techniques will help with any potential biological fouling or medium discolouration encountered in long term real deployments. Further research into how this detector will behave with drastically changing lighting conditions in a real environment, e.g. night time, is clearly necessary. In addition, generating more robust quantitative data will be necessary before one can expect real deployments to be productive.

5. Conclusions

This work reports the successful demonstration of a novel approach to chemical sensing networks. A low cost, biomimetic robotic fish was used to patrol a water container in a laboratory and inspect static chemical sensor stations en route. A first patrol was used as a reference for normal conditions. During a second patrol, a contaminant was added in the vicinity of one of the stations. By applying a sequence of image processing techniques to the captured video stream, the presence of the pH plume was successfully identified. While this study comprised of three stations, each with one colorimetric sensor, the approach is potentially scalable to numerous stations fitted with multiple sensors for a range of possible contaminants. Moreover with evolving CCD technology, power efficiency and processing power; it is feasible that the entire detection-processing algorithm will be integrated onto the autonomous vehicle in the near future.

Acknowledgement

This work was supported by Science Foundation Ireland under the CLARITY: Centre for Sensor Web Technologies (grant 07/CE/I1147) and the Australian Research Council.

References

[1] M.V. Hoyer, et al., Fish kills in Florida's canals, creeks/rivers, and ponds/lakes, J. Aquat. Plant Manage. 47 (2009) 53–56.
[2] S.N. Al-Bahry, et al., Coastal sewage discharge and its impact on fish with reference to antibiotic resistant enteric bacteria and enteric pathogens as bio-indicators of pollution, Chemosphere 77 (11) (2009) 1534–1539.
[3] B. Austin, The involvement of pollution with fish health, in: Anonymous, 2007, pp. 13–30.
[4] Z. Palacio, Fish Kills Linked to Water Pollutants, 2009, 2009-19-10;2010(March/08), p. 1.
[5] J. Hayden, Fisheries officials investigate Tipperary fish kill, The Irish Times (2009), Thursday, July 2, 2009.
[6] M. Wainwright, Pollution kills fish in waterways, The Guardian UK (2003), Wednesday 4 June, 2003, Environment.
[7] EU Water Framework Directive, [online], http://www.wfdireland.ie/.
[8] Office of Ground Water and Drinking Water (OGWDW), [online], http://www.epa.gov/OGWDW/.
[9] Water Quality Association, [online], http://www.wqa.org/.
[10] EPA, Water Quality in Ireland 2007–2008: Key Indicators of the Aquatic Environment, 2009, ISBN 978-1-84095-319-0, pp. 1–52.
[11] D. Diamond, Internet-scale sensing, Anal. Chem. 76 (15) (2004) 278A–286A.
[12] D. Diamond, et al., Integration of analytical measurements and wireless communications—current issues and future strategies, Talanta 75 (3) (2008) 606–612.
[13] C.M. McGraw, et al., Autonomous microfluidic system for phosphate detection, Talanta 71 (3) (2007) 1180–1185.
[14] J. Hayes, et al., Intelligent environmental sensing with a phosphate monitoring system and online resources, in: Computation in Modern Science and Engineering: Proceedings of the International Conference on Computational Methods in Science and Engineering 2007 (ICCMSE 2007), vol. 963, 12/2007, American Institute of Physics, 2007, pp. 1216–1219.
[15] J. Cleary, et al., An autonomous microfluidic sensor for phosphate: on-site analysis of treated wastewater, IEEE Sens. J. 8 (5–6) (2008) 508–515.
[16] S. McGovern, et al., Finding NEMO (novel electromaterial muscle oscillator): a polypyrrole powered robotic fish with real-time wireless speed and directional control, Smart Mater. Struct. 18 (9) (2009) 095009.
[17] D.S. Zhang, G.J. Lu, Review of shape representation and description techniques, Pattern Recogn. 37 (1) (2004) 1–19.
[18] E. Smela, O. Inganas, I. Lundstrom, Conducting polymers as artificial muscles: challenges and possibilities, J. Micromech. Microeng. 3 (4) (1993) 203.
[19] H. Durrant-Whyte, T. Bailey, Simultaneous localization and mapping. Part I, IEEE Robot. Autom. Mag. 13 (2) (2006) 99–108.
[20] T. Bailey, H. Durrant-Whyte, Simultaneous localization and mapping (SLAM). Part II, IEEE Robot. Autom. Mag. 13 (3) (2006) 108–117.
[21] L. Byrne, et al., Digital imaging as a detector for quantitative colorimetric analyses, in: ETATS-UNIS (Ed.), Proceedings of SPIE, the International Society for Optical Engineering, vol. 4205, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, SPIE INIST-CNRS, Cote INIST: 21760, 35400013481602.0330, 2001, pp. 267–277.
[22] K.T. Lau, S. Edwards, D. Diamond, Solid-state ammonia sensor based on Berthelot's reaction, Sens. Actuators B: Chem. 98 (1) (2004) 12–17.
[23] A. Safavi, et al., CCD camera full range pH sensor array, Talanta 71 (1) (2007) 498–501.
[24] M.I.J. Stich, et al., Read-out of multiple optical chemical sensors by means of digital color cameras, Sens. Actuators B: Chem. 139 (1) (2009) 204–207.
[25] J. Hayes, et al., Web-based colorimetric sensing for food quality monitoring, in: Sensors, 2006, 5th IEEE Conference, IEEE, Daegu, October 22–25, 2006, pp. 855–858.
[26] Wireless camera ZT-830T product page, [online], http://www.rapserv.com.au/prod4944.htm (Accessed 31/03/2010).
[27] EZ Radio ER900TRS Datasheet (available as a downloadable document), [online], http://www.datasheetarchive.com/datasheet-pdf/078/DSAE0066545.html (Accessed 31/03/2010).
[28] Sun Microsystems, Java Runtime Edition.
[29] Sun Microsystems, Java Communications Package.
[30] Humatic Media Tools, DirectShow Java Wrapper.
[31] Sun Microsystems, Java Advanced Imaging (JAI), 2010 (10/03/2010), p. 1.
[32] J.J. Bardyn, et al., Une architecture VLSI pour un operateur de filtrage median, in: Congres Reconnaissance des Formes et Intelligence Artificielle, vol. 1, Paris, January 25–27, 1984, pp. 557–566.
[33] SUN Microsystems, Programming in Java Advanced Imaging, 1st ed., SUN Microsystems, 1999.
[34] A.R. Smith, Color gamut transform pairs, in: SIGGRAPH '78: Proceedings of the 5th Annual Conference on Computer Graphics and Interactive Techniques, ACM New York, NY, USA, 1978, pp. 12–19.
[35] B. Fortner, T.E. Meyer, Number by Colors: A Guide to Using Color to Understand Technical Data, 1st ed., TELOS, Electronic Library of Science, Santa Clara, CA, 1997.
[36] R.C. Gonzalez, R.E. Woods, Digital Image Processing, 2nd ed., International ed., Prentice Hall, Upper Saddle River, NJ, 2002.
[37] J. Byrne, R. Mehra, Wireless video noise classification for micro air vehicles, in: Proceedings of the 2008 Association for Unmanned Vehicle Systems International (AUVSI) Conference, AUVSI, June 10–12, 2008.

Biographies

Cormac Fay graduated from Dublin City University (DCU) with a BEng in mechatronic engineering (2005) and a MEng telecommunications (2007). He subsequently pursued a an internship within the Adaptive Information Cluster (AIC) in 2007 within Prof. Dermot Diamond's group before progressing towards a research assistant position in the AIC and soon afterwards with CLARITY. His research area includes a range of disciplines including; novel environmental monitoring techniques, ultra low-power low cost environmental chemical sensing platforms, end to end system architectures, wearable sensors, robotics, etc. His position continuously demands realising the transition from chemical sensing to information retrieval on the world wide web.

King-Tong Lau received his MSc in 1997 and PhD in 2001 from Birkbeck College, University of London. He is an associate lecture in the Department of Chemical Sciences, Dublin City University (DCU) since 2005 and is an adjunct professor of chemistry department, Northeastern University of China, Liaonin, China. He is also the research manager of Adaptive Sensors Group (ASG), a member group of CLARITY, in the National Centre for Sensor Research (NCSR), Dublin City University. He received the DCU Research Fellowship Award in 2007. He is the founding director of The China-Ireland Research Centre for Advanced Materials and Sensor Development, established in Northeastern University of China. His research area includes new material research, molecular recognition, deployable low cost optical sensors, biosensors, electrochemical sensors & actuators and wearable sensors. Application areas include environmental, food quality and personal health monitoring.

Stephen Beirne received his PhD (Development of a Low Power reactive Wireless Chemical Sensing Network) from Dublin City University in 2008. Since 2003 he has worked with the Adaptive Sensors Group (ASG) as part of the Adaptive Information Cluster and CLARITY: Centre for Sensor Web Technologies, Dublin City University, on projects concerning wireless sensor devices. His research interests include wireless sensing devices, environmental sensors, and field deployable sensing systems.

Ciarán Ó Conaire received his BEng in telecommunications in 2003 and his PhD in computer vision in 2007, both from Dublin City University. He has authored more than 20 peer-reviewed papers in international conferences and journals and is currently a post-doctoral researcher in CLARITY. His research interests include: adaptive object detection and tracking, large-scale image search, multi-modal analysis, data fusion and human body pose estimation using wearable sensors. Currently, he is a deliverable coordinator within the TennisSense demonstrator, investigating tennis stroke identification using IMUs. He has also developed computer vision algorithms for tracking tennis players and the tennis ball, as well as investigating the quality of automatic summary generation of tennis matches for coaches, using randomised user studies. He has been a reviewer for many international conferences and journals, including IEEE Transactions on Multimedia, IEEE Transactions on Circuits and Systems for Video Technology, Machine Vision and Applications Journal, International Conference on Image Processing (ICIP) and IEEE International Conference on Multimedia & Expo (ICME).

Kevin McGuinness graduated from Dublin City University in 2005 with a BSc (Hons) in computer applications and software engineering. He subsequently joined the Center for Digital Video Processing group in DCU, and was awarded a PhD from the School of Electronic Engineering in 2009. He has since been employed as a post-doctoratoral researcher in CLARITY: Centre for Sensor Web Technologies in Dublin City University. His research interests include image and video segmentation, segmentation evaluation, content-based multimedia information retrieval, human–computer interaction, and software systems development. He is currently involved in research on computer vision, image and video processing, medical image analysis, embedded systems development, and HCI.

Brian Corcoran received his doctorate degree in mechanical engineering in 2003 from Dublin City University, Ireland. Since then he has supervised research in high purity water systems, wireless sensor networks, CFD and microfluidics. He is currently a lecturer in mechanical and manufacturing engineering at DCU.

Noel E. O'Connor received his PhD from Dublin City University in 1999, where he is currently an associate professor in the School of Electronic Engineering. He has published over 160 peer-reviewed publications, filed 5 patents and spun off a campus company. He has edited 6 journal special issues, including Signal Processing: Image Communication, Multimedia Tools and Applications, the Journal of Web Semantics and the Journal of Embedded Systems. He has acted as programme co-chair for 4 international conferences, CIVR 2009, SAMT 2006, WIAMIS 2007 and CIVR 2004. He is a member of the Academic Steering Committee of the ACM Multimedia Grand Challenge series. In 2010 he received the DCU President's Award for research excellence in ICT. He is a member of IEEE and IET.

Dermot Diamond received his PhD and DSc from Queen's University Belfast (Chemical Sensors, 1987, Internet Scale Sensing, 2002), and was VP for Research at Dublin City University (2002–2004). He has published over 240 peer-reviewed papers in international journals, is a named inventor in 13 patents, and is co-author and editor of three books. He is currently director of the National Centre for Sensor Research (www.ncsr.ie) at Dublin City University, and a principle investigator in CLARITY (www.clarity-centre.com/), a major research initiative focused on wireless sensor networks. In 2002, he was awarded the inaugural silver medal for Sensor Research by the Royal Society of Chemistry, London and in 2006 he received the DCU President's Award for research excellence. Details of his research can be found at www.dcu.ie/chemistry/asg.

Scott McGovern received his PhD from the University of Wollongong in 2007. His PhD studies related to the use of conducting polymers as embedded moisture sensors for composites and adhesives. Since graduating he has worked as a research fellow at the University of Wollongong, principally involved in the development and modelling of conducting polymer actuators.

Greg Coleman is an undergraduate student of mechatronics at the University of Wollongong. He has also worked as a research assistant with the Intelligent Polymer Research Institute at the University of Wollongong.

Rod Shepherd received his BEnvSc (Hons) and PhD from the University of Wollongong, Australia in 1997 and 2002, respectively. He is currently a research fellow at the Intelligent Polymer Research Institute, University of Wollongong, Australia. His research interests include chemical sensors, inherently conducting polymers, colorimetric optical sensors, robotics, electrochromics and wireless sensor networking.

Gursel Alici received the PhD degree in robotics from the Department of Engineering Science, Oxford University, UK, in 1994. He is currently a professor at the University of Wollongong, NSW, Australia, where he is the discipline leader of mechatronic engineering. His current research interests include intelligent mechatronic systems involving mechanisms/serial/parallel robot manipulators, micro/nano robotic systems for medical applications, and conducting polymers as macro/micro/nano sized-actuators and sensors for robotic and bio-inspired applications. He is currently a technical editor of IEEE/ASME Transactions on Mechatronics, a member of the Mechatronics National Panel formed by the Institution of Engineers, Australia. He is one of the chief investigators of the ARC Center of Excellence for Electromaterials Science (ACES) in the Energy conversion and Bionics programs. He has published more than 150 refereed publications in his areas of research.

Geoffrey Spinks obtained his PhD from the University of Melbourne in 1990 for his work on the fracture behaviour of thermosetting polyesters. He has since worked at the University of Wollongong and is currently a professor in materials engineering. He maintains a research interest in mechanical properties of polymers and, in particular, in polymer actuators. He has published over 120 peer-reviewed papers and co-authored one book that is now in its third edition. He has received several awards from the Royal Australian Chemical Institute for research excellence.

Gordon Wallace obtained his PhD from Deakin University, Geelong, Australia, in 1983. He joined the University of Wollongong in 1986 and is currently Director of the Intelligent Polymer Research Institute (http://ipri.uow.edu.au/aboutipri/index.html) and Executive Research Director of the ARC Centre of Excellence for Electromaterials Science (http://www.electromaterials.edu.au/). He is a fellow of the Australian Academy of Science and the Australian Academy of Technological Sciences and Engineering. He has published over 500 papers and numerous patents in the areas of organic conductors, nanomaterials, the development of intelligent polymer systems, and their exploitation in medical bionics and energy production and storage.