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In-sewer field-evaluation of an optical fibre-based condition monitoring system

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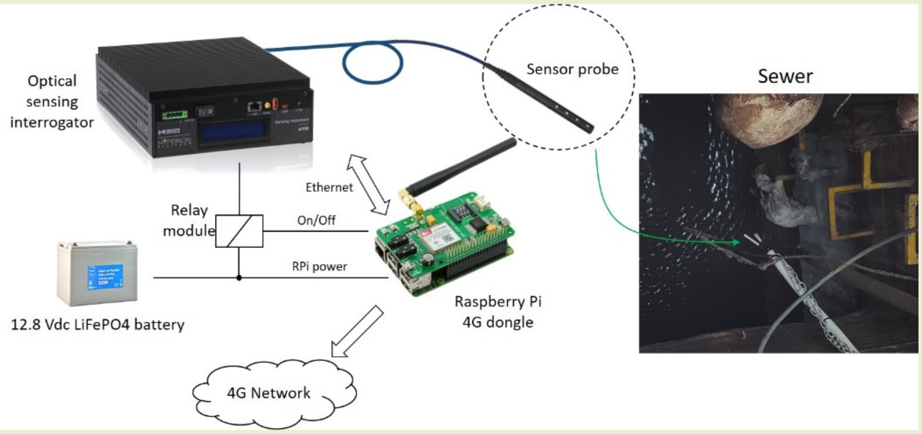
and Kenneth T. V. Grattan

Abstract— **A Fiber Bragg Grating (FBG) based monitoring system for continuous humidity and temperature measurement has been designed and evaluated experimentally in a sewer environment with high corrosion rates, humidity and the presence of gaseous hydrogen sulfide. The monitoring system has been designed specifically for field use, including packaging prepared for the harsh environment and the challenges of the operation. The system is battery powered and has hardware for controlling the interrogation equipment, power management, data logging and 4G connectivity. Results obtained show the long-term performance, over a 6-month period of non-stop monitoring of real-time data using the same probe. The data acquired was compared to the environmental data of temperature and precipitation for this period from the same location, which showed a good correlation between the expected and the measured data values. The data obtained point to the success of the optical fibre-based sensor system for monitoring in these harsh environments over long periods.**



***Index Terms*— Fibre Bragg Grating, humidity sensor, sewer corrosion.**

I. Introduction

THE AGEING of sewers, many of which were installed decades ago, is a major concern for the integrity of the wastewater infrastructure in developed countries. A significant cost of repair and refurbishment is related to the corrosion of concrete-based sewer structures, these being affected negatively by the natural biogenically generated sulfuric acid (H_2SO_4) from the oxidation of hydrogen sulphide (H_2S) on the concrete surface [1]. Previous research has found that humidity plays a fundamental role in the biogenic conversion of hydrogen sulphide into sulfuric acid and that potentially minor reductions in humidity can reduce corrosion rates [2].

Despite these well-established links between temperature and humidity and the rate of corrosion, the real-time monitoring of the corrosion occurring has not been systematically explored, as conventional electrical sensing methods often fail to deliver reliable long-term data due to the corrosive effect of the environment on conventional sensors. Usually tests performed in-the-field aim for the collection of data associated with corrosion (rather than the actual corrosion that is occurring) as a means to predict lifetime and maintenance issues. Sensors which are suitable to measure the corrosion itself directly are preferred but, in many cases, unavailable. Hence, access to durable and robust new sensors to monitor humidity would allow asset owners to optimize ventilation to reach humidity values where the formation of sulfuric acid is greatly reduced.

The main challenge for the development of a monitoring system that can be used reliably and long-term in such a harsh environment is that the acidic atmosphere causes corrosion of the electrical parts e.g. wiring, contacts and electronic materials, that are integral to conventionally-used devices. By contrast, optical fibre-based sensors being non-electrical and non-metallic in nature have the potential for superior performance in this kind of environment, compared to commercial electronic sensors [3].

Previous work has shown that optical fibre sensors were well suited to applications such as structural health monitoring, taking advantage of their light weight, robustness, chemical inertness and multiplexing capability. Fiber Bragg grating (FBG)-based sensors, as one major type of such sensors, have been used successfully for a wide range of industrial

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applications, including structural health monitoring and humidity sensing [4]. They are well established as a reliable, cost effective technology and have become more familiar to industry during the last decade. A prior proof-of-principle evaluation using FBG-based sensors [3] had been carried out in a sewer-like environment that existed in a small enclosed wastewater treatment plant, where the temperature of the gas phase varied in the region 20-23 °C, diurnally.

This paper reports the extension of that prior work through the application of a full FBG-based optical fibre-based system for the monitoring of humidity and temperature changes, as a field application in a working sewer system in Sydney Australia, managed by Sydney Water. The system is installed in Manly, north of Sydney. The installation of the optical fibre-based sensor system has arisen due to the failure of conventional sensor systems due to hydrogen sulfide gas and high humidity (typically in the 95 – 100% region) and the need to be better able to control corrosion within the sewer. This paper reports on measurements taken over a continuous period of six months, thereby validating the reliability and robustness of the sensor system developed and used for this challenging application, typical of many sewer systems internationally.

II. SENSOR DESIGN AND INSTRUMENTATION

The combined fibre optic-based humidity and temperature sensor developed specifically for this work builds on prior research undertaken to develop such sensors [5]. Key here is enhancing the physical manifestation of the sensor – its ‘packaging’ – which has been tailor – designed to be suitable for the application in mind where the working principle of the sensor comprises of a pair of FBGs of 5 mm in length, inscribed into germanium-doped photosensitive fibre (Fiber Core SM1500(4.2/125)) using the familiar phase mask technique [6]. FBGs as the basis of sensor systems are well known, using optical fibres as strain or temperature sensors in a quasi-distributed topology. The sensor mechanism is based on using a hygroscopic material to coat the FBGs used, making them capable of inducing strain on the fibre (in a known and reproducible way relative to the humidity level to which it is exposed).

The arrangement used is shown in Fig. 1. Following the grating inscription, one of the FBGs (FBG2 in Fig. 1) was dip-coated using polyimide as the active element in the sensor (PI, HD Microsystems PI-2525). The number of layers will directly affect both the sensitivity and the time-response of the sensors and this tradeoff must be carefully engineered for each specific application. In this work a coating of up to a total of 20 layers of the hygroscopic material (each individually applied and dried before the next layer was applied), resulting in an overall coating thickness of approximately 22 μm was used. Our prior experience has helped us to create this specification for a stable and robust sensor. The dip-coating process is described in detail in prior work by some of the authors [5] for long period gratings (but is used in the same way for the coating of the FBGs used here). The hygroscopic material reacts to the humid environment (and thus changes in the relative humidity) by expanding or contracting, thus exerting strain on the coated section of fibre. As a consequence changing the characteristic wavelength of FBG2 in response to humidity. To facilitate the bonding of the PI to the bare fibre, the latter was first coated with one layer of 3-APTS (3-Aminopropyltrietoxysilane).

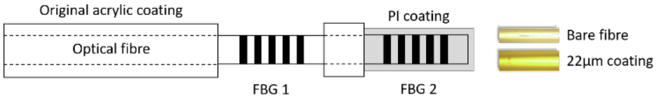

Fig. 1. Schematic of the proposed sensor comprising one bare FBG and one coated with a hygroscopic material of 22 micrometres.

As FBG2 responds to both humidity and temperature changes, FBG1 was left bare to allow effective temperature compensation to be applied. FBG1 (which is in a bare fibre) is not sensitive to humidity changes, while FBG2 is strained when exposed to different humidity levels. Therefore, if the wavelength signal from both FBGs is monitored, the relative humidity (RH) can be calculated, allowing accurate compensation for any temperature (T) changes, by the use of the following relationship:

$$\boldsymbol{T = \frac{1}{C_{T1}}\left(\lambda_1 - \lambda_{1(0)}\right)} \tag{1}$$

$$\boldsymbol{RH = \frac{1}{C_{RH2}}\left(\lambda_2 - \lambda_{2(0)} - C_{T2}\ T\right)} \tag{2}$$

where λ_i are the measured Bragg wavelengths (nm) of FBG1 and FBG2 (i = 1 or 2), $\lambda_{i(0)}$ their Bragg wavelengths at 0 °C, C_{Ti} the temperature coefficients or sensitivities (nm/°C), and C_{RHi} the moisture sensitivities (nm/%RH). In matrix form, the impact of changes in temperature and humidity on the FBG peak wavelengths can be described as:

$$\boldsymbol{\Lambda = CX}$$

with:

$$\boldsymbol{\Lambda = \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \end{bmatrix} C = \begin{bmatrix} C_{T1} & C_{RH1} \\ C_{T2} & C_{RH2} \end{bmatrix} \quad X = \begin{bmatrix} \Delta T \\ \Delta RH \end{bmatrix}}$$

where C_{RH1} equals zero as FBG1 does not respond to changes in relative humidity.

Apart from the two Bragg wavelengths, λ_i, measured, all other parameters have been obtained through the calibration of the sensors in a controlled temperature/humidity environment where these parameters can be carefully controlled (in a calibration chamber).

The coated fibre lies at the core of the moisture-sensitive instrument but it is important to develop a probe that is well suited to the often harsh environment thus it was carefully ‘packaged’ with the fibres carefully placed inside a perforated PEEK (polyether ether ketone) tube which has an outer diameter of 8 mm (Fig. 2). PEEK was chosen as it offers excellent mechanical and chemical resistance, characteristics that are resistent to high temperatures and which makes this material highly suitable for its intended use in a sewer environment. The sensor package consists of both an inner and outer tube with a PTFE (polytetrafluoroethylene) layer in-between to prevent solids from entering the tube and thus potentially damaging the key sensor element.

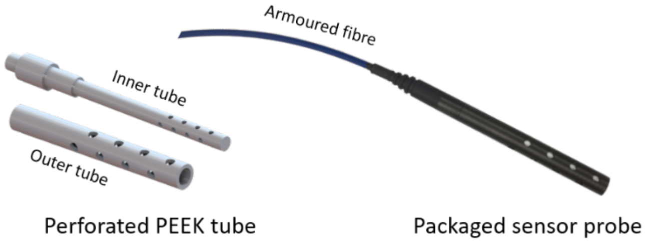

Fig. 2. Two-component perforated peek outer tube and smaller inner tube (left) design and the packaged sensor probe with armoured fibre (right).

The packaged sensor was then carefully calibrated in the environmental chamber (Binder KBF115), with the results obtained shown in Fig. 3. The peak wavelengths of both FBGs that form the sensor were recorded over a temperature range of 25-45 °C (the maximum temperature excursion expected in the sewer environment where the sensors would be used), in steps of 5 °C, as well as over a humidity range of 35-75 % RH, in steps of 10% RH. The wavelength readings were then fitted in order to obtain the calibration coefficients and reference peak wavelengths used in equations (1) and (2).

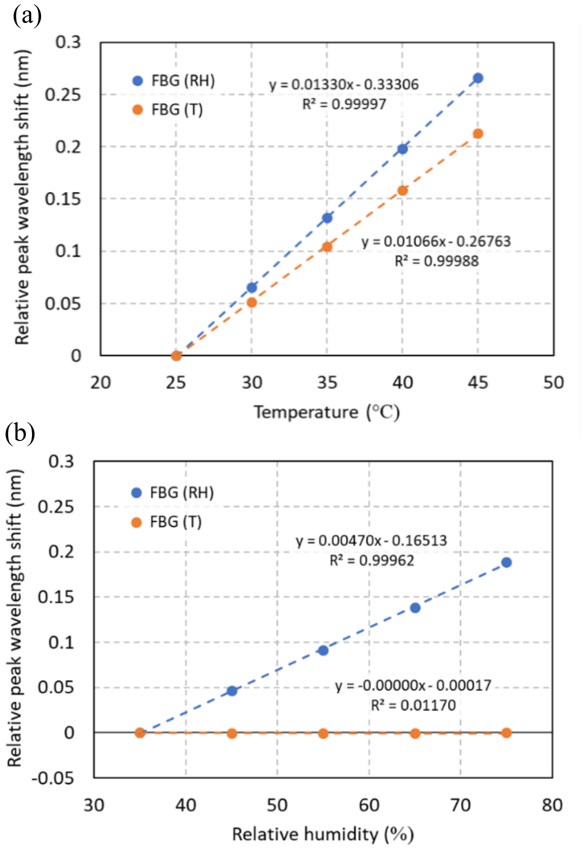

Fig. 3. Sensor calibration carried out in the Binder KBF115 environmental chamber. The temperature (a) and humidity (b) responses of both the FBGs used in the sensor probe are shown.

It is clear from Fig. 3 that, as expected, both FBGs are sensitive to temperature whereas only the coated FBG is responsive to changes in RH and thus will act as the core of the humidity sensor. Figure 3 shows that the responses of both sensors to T and RH are strongly linear (with R^2 values > 0.999).

III. IN-THE-FIELD SENSOR OPERATIONAL ISSUES

The sensor had been designed for use in-the-field in a remote location to measure humidity in a working sewer. Here high levels of humidity are present, combining to cause damage to conventional electronic humidity sensors which had been used previously and which had a service lifetime of merely days – clearly unsatisfactory for the long term monitoring needed by the owners of the asset.

The sensor performance, obtained through the monitoring of the wavelength characteristic of the FBGs used, was interrogated using a 'Micron Optics si155' unit. Due to the planned installation location, which is remote from access to mains electricity, battery-operation was required, necessitating a shut-down of the unit between measurements to conserve energy and extend the available measurement period between recharges of the battery. This low-power operation was achieved using a Raspberry Pi 3 (model B) module which at the same time provided 4G connectivity to allow remote data transfer. The Pi module itself was disconnected from the power supply between measurements, using a low-power extension board (Sleepy-Pi 2). The whole hardware setup (shown schematically in Figure 4) was then mounted in a suitable enclosure, type IP65 (ingress protection 65, dust tight and protected against water projected from a nozzle), to protect the system during the field tests, (as shown in the photograph in Figure 5).

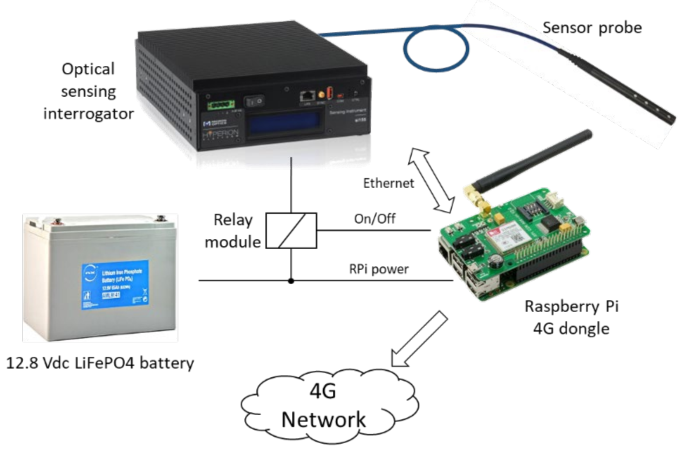

Fig. 4. Hardware setup for sensor interrogation and data transfer.

IV. RESULTS OF THE SENSOR EVALUATION

The full packaged and protected sensor system (as seen in Figure 5) was taken out to a location chosen by Sydney Water to allow measurements to be taken at a suitable site in Manly, Sydney, Australia. The probe was installed in the sewer through a protective tubing (as shown in the photograph in

Figure 6a) and aligned with the sewer flow, as is seen in Figure 6b.

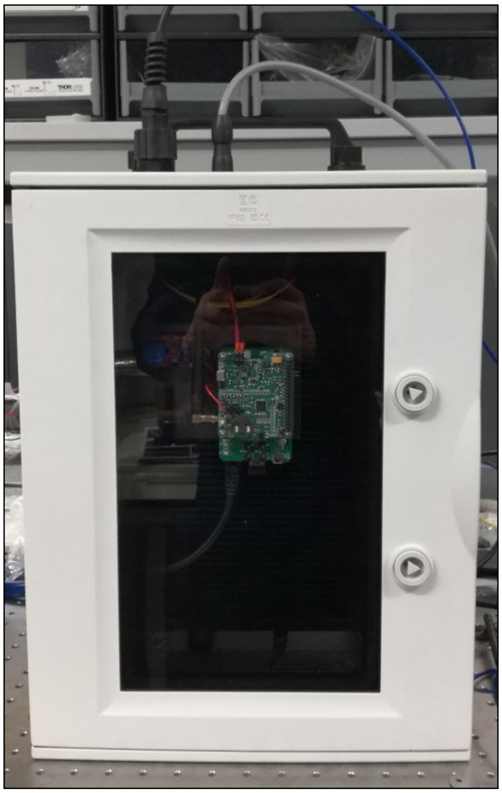

Fig. 5. Protective case with the whole system enclosed.

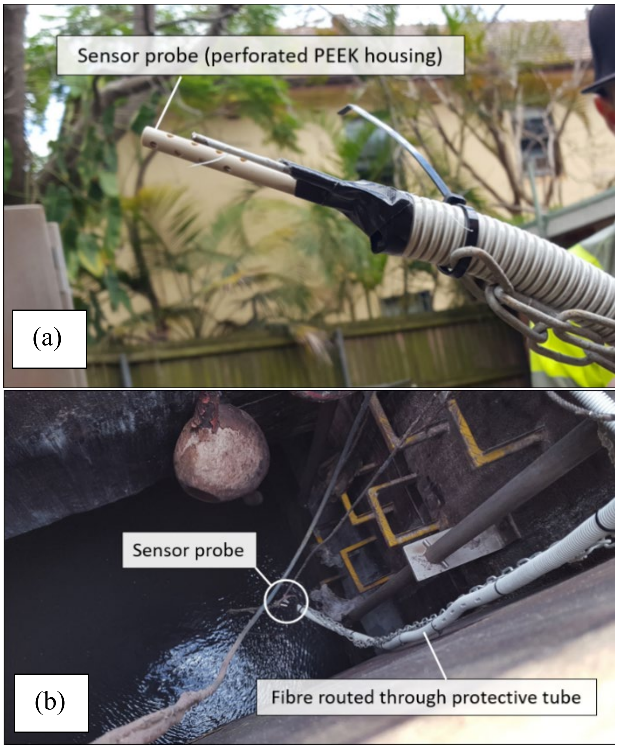

Fig. 6. Sensor packaged with the PEEK housing, mounted through the protective tubing (a) and placed into the chosen sewer in Manly, Sydney, Australia.

The sensors were placed such that they were in the same environment as the air flow of the sewer. The placement of the sensors is critical in that regard to make the optimum measurements as the space above the sewer ledge forms a low pressure chamber that must be avoided (to allow reliable measurements to be taken).

A long term evaluation was designed and thus data were acquired from 6 months of measurement (from 18th December 2018 to 18th June 2019). The results show that both temperature and humidity levels are more stable than the external weather conditions which varied considerably from high summer (December) to mid-winter (June) [7]. Over that period there were major one-off weather events such as high levels of precipitation and the data recorded show that this indeed affects the environment monitored inside the sewers (despite the sensor being installed inside a rubber sealed lid in the sewer).

Figure 7 shows the results of the measurement of relative humidity as acquired by the monitoring system, with data for the precipitation recorded over the same period. During the whole measurement period, the humidity level of the sewer is constantly above 95% (as can be seen from the top (blue) curve). Meterological data consulted showed that whilst the average humidity externally was 66% (full data set not shown), with very high precipitation levels experienced particularly between the months of March and April, as shown in the precipitation plot in orange.

Figure 8 shows the 'zoomed in' data obtained over a short period of measurement over approximately one month during March/April, during which an event where ~200 mm of precipitation fell between the days of 17th and 18th March [8] (interestingly this is more than the amount of rain expected for a whole month in Sydney in March). This extreme event was very interesting for the monitoring cycle used, as it is indicative of the peaks in humidity measured by the sensor, (importantly with subsequent recovery during the following dryer days to allow the measurement cycle to continue essentially unaffected by this 'freak'event).

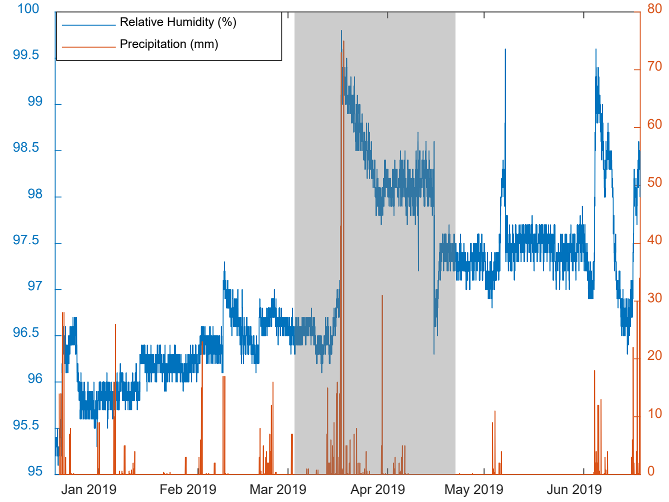

Fig. 7. Relative humidity data from sensors installed in Manly and precipitation for the same period. Data refer to six months of measurement.

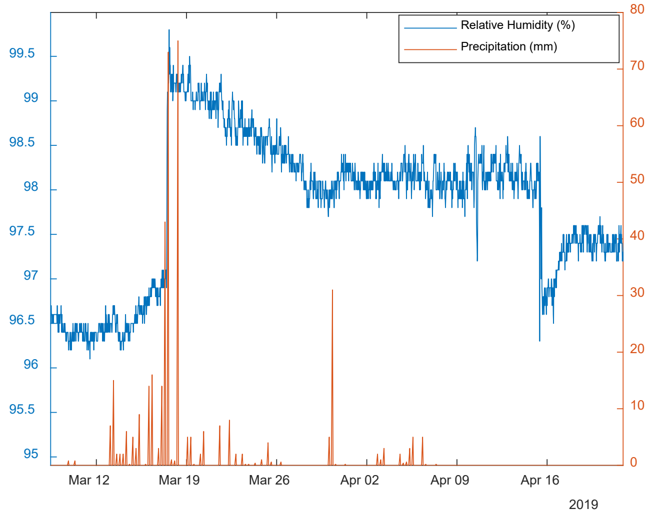

Fig. 8. ‘Zoom in’: highlighting the extreme, high precipitation event of 17th - 18th March (seen in Figure 7).

Figure 9 shows a comparison between the outside temperature and precipitation from meteorological data for Sydney and the sewer temperature measurements for the same period – the weather conditions create larger variations than do the diurnal changes. Here the sensor curve (in black) shows a more smooth response compared to that for weather conditions for the same period (in green). This artises as is expected due to the closed environment of the sewer, which is shielded from the outside weather. However, even with this degree of insulation from the outside weather conditions, the sewer environment still reflects the changes in temperature, specially when the precipitation levels rise.

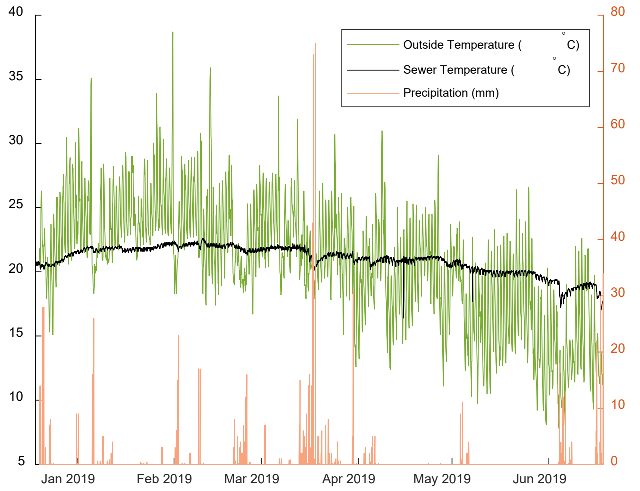

Fig. 9. Comparison between the outside temperature and precipitation from meteorological data for Sydney and the sewer temperature measurements for the same period.

In order to maximize the battery-life of the sensor system, without compromising the resolution and reflecting the expected rate of change of the measured conditions, data were collected every 20 minutes. Then once in every 24 hour period, the system connects to the 4G network to send the data acquired throughout the day, via a SMS message. The hardware designed to interface the interrogation equipment to the 4G network and datalogging is also responsible for the battery management and its operation is critical for the system to be sucessful for long-term use. The Sleepy Pi board totally shuts off the system, so the power consumption is almost zero during the idle time. Using this configuration, the 100 Ah $LiFePO_4$ battery being used lasted for an average of two months for a single charge (data not shown) before intervention to charge it again. Plans for the use of solar cells installed with the battery to charge it during daylight and taking advanatge of the long sunny days in the Sydney area are being developed.

V. DISCUSSION

The work undertaken has been a successful follow-up to the previous limited proof-of-principle study [3] undertaken with Sydney Water and has successfully extended the measurements to gravity sewers, where the ventilation could then be controlled. The research successfully demonstrated that data obtained from the optical sensors installed in that harsh environment seen could be used to address the corrosion problem that arise due to high humidity and H_2S, by controlleing fresh air intake and ventilation rates. Reliable performance of the field based FBG- humidity monitoring system developed was seen, with the system operating in a harsh sewer environment and battery powered. The calibration procedure had been designed to fit well with the requirement of this specific application, creating a sensor response which is sufficiently stable over a long, continuous period of use of 6 months, without the need for further recalibration. The system was proved to need no maintenance or human interference and had no offline events during the whole period of operation other than recharging of the battery every 2 months. The sensors also responded well to large temperature changes (which had not been possible to determine in the previous study carried out in Sydney Water). As a result, the data obtained by the system have been designed to support maintenance operations at Sydney Water, to allow them to develop more effective action plans for maintenance, as well as helping to develop more reliable models to predict the state and health of the structures used.

Future work will focus on the monitoring of multiple locations across Sydney Water’s sewer network creating a map of the conditions which most facilitate corrosion. This will allow a more efficient control of ventilation and preventive actions throughout the whole sewer. Additional parameters such a the pH of the environment or the presence of other gases can be included for the same purpose, thus better to understand the corrosion issues and preventative actions.

ACKNOWLEDGMENT

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Dr Bruno Rente has a degree on Electronic Engineering from Federal Centre for Technological Education, Rio de Janeiro, Brazil, in 2010. He got his master degree in the Brazilian Center for Research in Physics where he gained experience with instrumentation and photonics. He worked as laboratory engineer for the Metallurgy and Material Department of the same university he was awarded a PhD degree, from the Federal University of Rio de Janeiro, in 2017. In that occasion, his work was focused in photonics and materials for chemistry, optics and tribological applications. He was lecturer for the Federal Centre for Technological Education, Rio de Janeiro in the field of Instrumentation and Electronics. His research interests are material science applications on photonic devices, fibre optic sensors applications and instrumentation. He is currently a post-doctoral research fellow at City University of London working with fibre sensor for harsh environment applications.

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Dr Heriberto Bustamante is Principal Research Scientist, Treatment at the water utility Sydney Water (Australia). One of his roles is to identify knowledge gaps in Sydney Water's operations and convert them in to research projects to be carried out by local and international Universities. Heri pioneered the introduction of photonic sensors in collaboration with City, University of London to manage corrosion in concrete sewers. In collaboration with the University of New South Wales (UNSW) and the manufacturer Instruments Works he has developed the Floc Strength Instrument that will help maximise water production in water treatment plants. Heri is also researching with UNSW the development and scaling up of graphene oxide membranes for water treatment.

Professor Tong Sun was awarded the degrees of Bachelor of Engineering, Master of Engineering and Doctor of Engineering from the Department of Precision Instrumentation of Harbin Institute of Technology, Harbin, China in 1990, 1993 and 1998 respectively. She was awarded the degree of Doctor of Philosophy at City University in applied physics in 1999 and was an Assistant Professor at Nanyang Technological University in Singapore from year 2000 to 2001 before she re-joined City University in 2001 as a Lecturer. Subsequently she was promoted to a Senior Lecturer in 2003, a Reader in 2006 and a Professor in 2008 at City University, London. Prof. Sun is currently the Director of Research Centre of Sensors and Instrumentation and is leading a research team focused on developing a range of optical fibre sensors for a variety of industrial applications, including structural condition monitoring, early fire detection, homeland security, process monitoring, food quality and environmental monitoring. She has been working closely with partners across disciplines from academia and industry, both in the UK and overseas. Prof. Sun is a member of the Institute of Physics and a Fellow of the Institution of Engineering and Technology and a Chartered Physicist and a Chartered Engineer in the United Kingdom. She has authored or co-authored some 230 scientific and technical papers.

Professor Grattan graduated in Physics from Queens University Belfast with a BSc (First Class Honours) in 1974, followed by a PhD in Laser Physics in the use of laser-probe techniques for measurements on potential new dye laser systems. In 1978 he became a Research Fellow at the Imperial College of Science and Technology, to work on advanced photolytic drivers for novel laser systems. In 1983 he joined City University as a new blood Lecturer in Physics, being appointed Professor of Measurement and Instrumentation and Head of the Department of Electrical, Electronic and Information Engineering in 1991. His research interests have expanded to include the use of fibre optic and optical systems in the measurement of a range of physical and chemical parameters for industrial applications. He obtained a DSc from City University in 1992 for his work in sensor systems was President of the Institute of Measurement and Control during the year 2000. He was awarded the Calendar Medal and the Honeywell Prize of the Institute of Measurement and Control and was Dean of the School of Engineering & Mathematical Sciences and the School of Informatics at City University from 2008-12. He was appointed Dean of the City Graduate School in 2012. He was elected a Fellow of the Royal Academy of Engineering in 2008. He is the author of over seven hundred publications in major international journals and conferences and is the co-editor of a five-volume topical series on Optical Fibre Sensor Technology.