Institution: City, University of London		
Unit of Assessment: 12. Engineering		
Title of case study: A new class of photonic humidity sensors for large system water supply and sanitation		
Period when the underpinning research was undertaken: 2008 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof Kenneth Grattan OBE FREng	Royal Academy of Engineering/George Daniels Professor of Scientific Instrumentation	1983 – current
Prof Tong Sun OBE FREng	Faiveley Brecknell Willis/Royal Academy of Engineering Research Chair	2001 – current
Period when the claimed impact occurred: 2012 – ongoing		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

This case study charts the success of a new class of photonic humidity sensors for use in so-called “extreme environments” such as are experienced by Sydney Water in its day-to-day operations. Developed in research at City, University of London, the sensors overcame weaknesses of existing technologies, to supply online, long-term, continuous humidity data resulting in reduced maintenance, reduced fines and regulation penalties, and greater stability of water supply. Further developments led to its deployment as a solution to problems Sydney Water experienced in 2018 with pumping stations and specifically with structural defects in some aged concrete structures. The project’s deliverables have created a new climate of thinking about the development and exploitation of photonics-based sensors to tackle a range of problems at Sydney Water, based on the project’s many successes.

2. Underpinning research (indicative maximum 500 words)

Over the past century, concrete has become the most widely used construction material in the built environment. One of the key challenges facing the industry is to design concrete structures that will stand the test of time, while retaining its integrity during its intended lifespan – and indeed beyond. One of the main pitfalls of concrete as a construction material is an inability to fully prevent its degradation and corrosion e.g., the reinforcing steel. While considerable advances have been made in terms of protecting against corrosion (from improvements in concrete durability), the risk of corrosion, and thus structural instability, is ever-present. As a result, the need for on-going, *in situ* corrosion monitoring is clear – in concrete structures it has now become a major component of the design process, and recognized from the late 1970s, after the negative impact of degradation of concrete structures by corrosion was seen as a reality and a threat.

The team at City, University of London is led by Professors Kenneth T V Grattan and Tong Sun (both Royal Academy of Engineering Research Chairs). They have long and wellestablished track records in developing sensor technology and tailoring it to address such industrial challenges. Here, the team's research has addressed the issue of humidity playing a fundamental role on the conversion of hydrogen sulphide into sulfuric acid causing corrosion of concrete in gravity sewers and that quantitative humidity data would allow action to create even the minor reductions in humidity which can reduce corrosion rates, as current high levels of hydrogen sulphide and the high relative humidity (typically > 98%) makes humidity measurement within such an environment with current electronic technology impossible in the long-term, due to sensor failure.

The research has tackled this by developing new photonics-based technology, enrobed in more durable packaging designed to withstand harsh environments: based on prior research into moisture-sensitive polymer-coated fibre grating technology (coupled in series with an uncoated grating for temperature compensation). To optimize the device for operational use in this hostile environment, several designs of the probe and its assembly were configured using different configurations and materials, targeting an overall design which created the needed long-term durability when used *in situ* in sewers.

The key achievement of the probe designs evaluated was achieving both the needed high sensitivity to humidity while protecting, at the same time, the sensing elements from the aggressive environment (and which had rendered ineffective the electrical sensors which previously had failed in sewer use). The packaged sensors were trialled *in situ* in sewers over a period of ~6 months, and biodigesters over ~20 months, while constantly subjected to the prevailing high, but varying levels of humidity, temperature and hydrogen sulphide gas.

The results demonstrated significant promise through the development of the underpinning design concepts and tailoring of the sensor packaging to allow a long, effective working life in these harsh environments, while retaining good sensitivity. These outcomes and successes have given confidence to create a new climate for the development and exploitation of photonics-based sensors to tackle a range of safety-critical monitoring problems at Sydney Water.

3. References to the research (indicative maximum of six references)

3.1 Yeo, T. L., **Sun, T.**, **Grattan, K. T. V.**, Parry, D., Lade, R., & Powell, B. D. (2005). "Polymer-coated fiber Bragg grating for relative humidity sensing". *IEEE Sensors Journal*, 5(5), 1082-1088.

3.2 Yeo, T. L., **Sun, T**. & **Grattan, K. T. V**. (2008). Fibre-optic sensor technologies for humidity and moisture measurement." *Sensors and Actuators A: Physical*, 144(2), pp. 280-295.

3.3 McCague, C., Fabian, M., Karimi, M., Bravo, M., Jaroszewicz, L. R., Mergo, P., **Sun, T**. & **Grattan, K. T. V**. (2014). "Novel Sensor Design Using Photonic Crystal Fibres for Monitoring the Onset of Corrosion in Reinforced Concrete Structures". *Journal of Lightwave Technology*, 32(5), pp. 891-896.

3.4 Alwis, L. S. M., Bustamante, H., Roth, B., Bremer, K., **Sun, T**., & **Grattan, K. T. V.** (2017). "Evaluation of the Durability and Performance of FBG-Based Sensors for Monitoring Moisture in an Aggressive Gaseous Waste Sewer Environment". *Journal of Lightwave Technology*, 35(16), 3380-3386.

3.5 Alwis, L. S. M., Bustamante, H., Bremer, K., Roth, B., **Sun, T**., & **Grattan, K. T. V**. (2017). "A pilot study: Evaluation of sensor system design for optical fibre humidity sensors subjected to aggressive air sewer environment”. In *Proceedings of IEEE Sensors Conference*. ISBN:978-1-4799-8288-2

3.6 Rente, B., Fabian, M., Chen, Y., Vorreiter, L., Bustamante, H., **Sun, T**. & **Grattan, K. T. V.** (2020). “Extended Study of Fiber Optic-Based Humidity Sensing System Performance for Sewer Network Condition Monitoring”. *IEEE Sensors Journal*, 21(6), 7665 – 7671.

Indicators of quality for underpinning research:

Five out of six outputs were published in prestigious academic journals which apply a rigorous peer-review process prior to acceptance of papers (+ one in *IEEE Conference Proceedings*).

Research was supported by Royal Academy of Engineering Professorships for Professor Tong Sun OBE FREng, 2018-23 and Professor Kenneth Grattan OBE FREng, 2014-24.

Award of the Cornish Medal of the Institute of Measurement & Control/Worshipful Company of Scientific Instrument Makers of London to ‘individual, group or company that has excelled in some dimension of scientific instrument making within industry, academia and national or international laboratories’ for this work on for work done in ‘Humidity Monitoring in Wastewater Infrastructure’.

4. Details of the impact (indicative maximum 750 words)

The Sydney Water Corporation (SW), covering Greater Metropolitan Sydney, Illawarra and the Blue Mountains (serving 5 million people), spends ~A$60-80 million annually on management and rehabilitation of deteriorated concrete trunk sewers, corrosion and odour at treatment plants. Conventional humidity sensors for monitoring sewers were found to last for only a few weeks due to the key role of humidity in microbiologically-induced corrosion of concrete gravity sewers. Recognising the magnitude of the issue and the related expenditure, SW has partnered with City, University of London to use advanced sensor technology to combat the problems experienced and improve monitoring. [5.1]

In 2015, Professors Grattan and Sun (the City research team) began working with Sydney Water, carrying out a research project with staff there that demonstrated that, by adjusting the surface chemistry of the protective polymers, the photonics-based sensors that they developed could efficiently be used to monitor humidity in sewers, evaluated over an extended period of 6 months, and now beyond. [5.2] According to the Principal Scientist (Treatment), Sydney Water, the successful outcomes of this project “*has pioneered a new technological approach in our business: the use of photonics instrumentation in the Australian water industry*”. [5.3]

Sydney Water had invested approximately A$3 Million (£1.6M) in R&D with other parties and still had no effective way to consistently monitor humidity, prior to working with City. Given that even a slight reduction in humidity can reduce corrosion rates, the project was of paramount importance to Sydney Water, which spends around A$60-80 Million (£35 – 45M) annually on management and rehabilitation of deteriorated concrete trunk sewers due to microbiologically-formed sulfuric acid. [5.3]

Further developments of this technology have led to its deployment as a solution to problems Sydney Water experienced in 2018 with pumping stations and specifically with structural defects in some concrete structures. The City research team successfully assembled a multidisciplinary team which has involved both experts in sensing and in civil engineering to address it. This has allowed the research team to develop a feasible, highly deployable experimental design, to maximize the opportunities for success. The experimental design in this project has recently been done successfully under highly restrictive conditions due to the pandemic that even while preventing the visit of the London-based researchers to the pumping stations in Sydney in the last twelve months, in spite of that the program is continuing 'on-track'. [5.3]

The technology again has proved very versatile and the project has been successful in the tailored-design and manufacture of strain and vibration sensors of the required sensitivity, creation of monitoring, measurement and testing methodology and thus a predictive failure tool that Sydney Water is aiming to employ to monitor sensitive structures across its entire network. The urgency of the situation is seen in Sydney Water recently having pleaded guilty to two counts of water pollution in the Land and Environment Court and been fined A$175,000 (£100,000) with costs of a further A$22,000 (£15,000) for the release of nearly 3 million litres of raw sewage into the Parramatta River in 2018, not to mention the serious impact on our reputation. [5.4] [5.3]

Sydney Water is further utilizing the research innovations and successful project developments using fibre optic technology from City to measure the presence of the ubiquitous Natural Organic Matter (NOM) in the water entering its ten water treatment plants and to predict its impact on their performance. There have been occasions where the increase in NOM has reduced plant capacity by 40%. Sydney Water has done a desk-top study to assess 35 technology options and has estimated that retrofitting commercially available technologies would cost hundreds of millions of dollars in the next decade. Given the difficult conditions for such measurements in a live water dam environment has highlighted the unique capability of the City research team to tackle this monitoring problem in a realistic and timely way. In response, Sydney Water has opted to use City research team's expertise in sensor technology, especially in challenging environments, to develop a new ultra violet (UV-)transmitting fibre optic flexible fluorimeter which operates where conventional devices cannot. [5.3]

As in the case of the humidity sensors developed by the City team, Sydney Water have realized a new means of modifying technology in the development and in field testing of the sensor which is assisting in NOM monitoring *in situ* and which has eliminated problems associated with laboratory monitoring such as storage, transportation, and sample spoilage – as well as eliminating associated costs. These fibre optic sensors developed have enabled deeper-UV optical analysis of the samples and created a flexibility in their use due to the inclusion of optical fibre, rather than the use of rigid optics. All of this offers greater potential for wider use in monitoring natural organic matter, *in situ.* [5.3]

The impact of the successful work done and collaboration was evidenced in Australia by the New South Wales Branch of the Australian Water Association making the Research Innovation Award in 2017 to the City/Sydney Water team and in the UK by the Worshipful Company of Scientific instrument Makers and Institute of Measurement & Control awarding the team its Dr Derek Cornish Medal for excellence in the field of scientific instrument making, this year. [5.5]

Finally, this photonics research has played an important role in the successful application for a A$21 million a Cooperative Research Centre (CRC) 'SmartCrete' from the Australian Federal Government. The Asset Management Program of the CRC SmartCrete will be mainly dedicated to research on concrete and advanced monitoring with photonic sensors. This would not have happened without the 2015 collaborative project between City University and Sydney Water. [5.3]

5. Sources to corroborate the impact (indicative maximum of 10 references)

5.1 Nelson, Nicola, 2019 "Technologies that are changing the way Sydney Water manages its networks", *Utility Magazine: Engineering, Construction, Maintenance*, January 25, 2019

5.2 H Bustamante, et al, 2017 Innovation in corrosion monitoring in sewers. Use of novel photonic sensors for humidity measurements in gravity sewers, *Water e-Journal of the Australian Water Association*, vol 2 (4), pp 1-6

5.3 Letter of Support, Principal Scientist, Treatment, Research & Innovation Team, Sydney Water Corporation.

5.4 Media Statement: Sydney Water begins recovery after pumping station failure https://www.sydneywater.com.au/SW/about-us/our-publications/Media/recovery-after-pumping-station-failure/index.htm

5.5 Australian Water Association – 2017 New South Wales Water Awards, Honour Roll: Research Innovation Award 2017 - Winner – **City, University of London** for Exploiting Photonics Sensors Research through to its Introduction to the Water Industry, Sydney Water, City University of London.