Research Assessment Exercise 2020
Impact Case Study

University: The Hong Kong Polytechnic University
Unit of Assessment (UoA): Electrical & Electronic Engineering (12)

Title of case study: Optical fibre-based data-driven predictive maintenance system

(1) Summary of the impact

UoA12 developed the ***world's first optical fibre-based data-driven predictive maintenance system*** enabling the railway industry to shift from costly and inefficient scheduled maintenance regimes to predictive maintenance. The system identifies defects in rail tracks, overhead power lines, wheel flats, and cracks in bogies and carriages. Five systems were installed in MTR Hong Kong and two in SMRT lines in Singapore in 2014, and 2016, respectively. The system monitors developing faults and had successfully predicted broken power line along the *Amsterdam-Schiphol Airport Line* in 2015, several weeks in advance. The goal is to herald a safer railway industry with reduced maintenance cost, and high quality of service. The underpinning technology is also being pursued for lift and escalator monitoring in "Smart Buildings", leading to the formation of a startup company in 2018.

(2) Underpinning research

The underpinning research has been focused on ***optical fibre sensors*** (since 1993), ***sensing interrogation techniques*** (since 2000), and ***specialty optical fibres*** (since 2009).

Fibre sensor and specialty optical fibre underpinning research:

- Development of fibre Bragg grating (FBG)-based optical fibre sensors to measure a multitude of parameters. FBG is a short length of optical fibre, typically 5-mm long, with periodic variation in the fibre core's refractive index. It reflects a particular wavelength that is directly proportional to temperature and strain. Through the use of transducers, FBGs can measure many other parameters. FBG-based sensors to measure tilt [3.1], displacement, pressure, acceleration, etc., were developed for railway applications and successfully field-trialed [3.2, 3.3 and *US Patent Nos. 8,282,276 B2 & 8,861,973, B2 & European Patent No 2351680*].
- Development of specialty optical fibres (SOF) and SOF-based sensors to overcome the limitations of FBG-based sensors, by modifying the fibre' mechanical and optical properties to enhance the sensors' performance. This includes the development of a SOF-based accelerometer which was installed on an in-service train in Singapore in 2018. The results showed it performed considerably better than existing accelerometers [3.4].

Interrogation technique underpinning research:

- Wavelength-division multiplexing (WDM) is commonly used to multiplex FBG sensors but the sensor count using this technique is limited by the spectral width of the interrogation system. We invented a technique combining time-division multiplexing with WDM to vastly increase the number of FBG sensors in an optical fibre sensing network [*US Patent No. 7,505,642 B2*] [3.5].
- Development of a novel FBG sensor interrogation scheme that extended the maximum optical fibre measurement distance of about 25 km, which is limited by Rayleigh backscattering (RB) to over 75 km, by significantly reducing the RB [3.6].

Since 2000, HY Tam (UoA12) has been working with his research students and post-docs on FBG sensors. The capability of FBG sensors to measure different parameters ***provides important insights that sensory system can be constructed with FBG sensor networks to monitor the health condition of railway systems***.

In 2004, Tam started working with SL Ho, Mark Ho and SY Liu (UoA12) to study the use of FBG sensors to monitor wheel-rail interactions for axle counting and structural health condition of trains [3.2, 3.3]. In 2005, the UoA12 team in collaboration with Tony Lee, and KK Lee of MTR(HK), secured a HK$11 million research project "Smart Railway Sensing Network" to study the use of

FBGs on the 35-km long East Rail Line. The team gained invaluable experience and developed novel techniques to monitor rail and train defects. ***Chinese, European, and US patents on the use of FBG sensing network for railway monitoring were awarded*** in 2011, 2012, and 2014. In 2007, Tam and PK Wai and C Lu of (UoA12) secured about HK$15 million and built a facility to ***draw specialty optical fibres*** to fabricate novel sensors tailored for railway applications.

(3) References to the research

[3.1] H. Y. Au, Sunil K. Khijwania, H. Y. Fu, W. H. Chung, and H. Y. Tam, "Temperature-insensitive fiber Bragg grating based tilt sensor with large dynamic range," *IEEE Journal of Lightwave Technol.,* Vol. 29, No. 11, pp. 1714 – 1720, 1 June, 2011

[3.2] Chu-liang Wei, Chun-cheung Lai, Sun-yee Liu, W. H. Chung, T. K. Ho, Hwa-yaw Tam, S. L. Ho, A. McCusker, J. Kam, and K. Y. Lee, "A fiber Bragg grating sensor system for train axle counting," *IEEE Sensors J.*, vol. 10, no. 12, pp. 1905–1912, Dec 2010.

[3.3] Chuliang Wei, Qin Xin, W. H. Chung, Shun-yee Liu, Hwa-yaw Tam, and S. L. Ho, "Real-Time Train Wheel Condition Monitoring by Fiber Bragg Grating Sensors," *International Journal of Distributed Sensor Networks*, Vol. 2012, Article ID 409048, Aug 2011

[3.4] Z Liu, L. Htein, D. S. Gunawardena, W. H. Chung, C. Lu, K.-K. Lee, H.-Y. Tam, "Novel accelerometer realized by a polarization-maintaining photonic crystal fiber for railway monitoring applications," *Opt. Express*, 27, 15, 21597-21607, July 2019

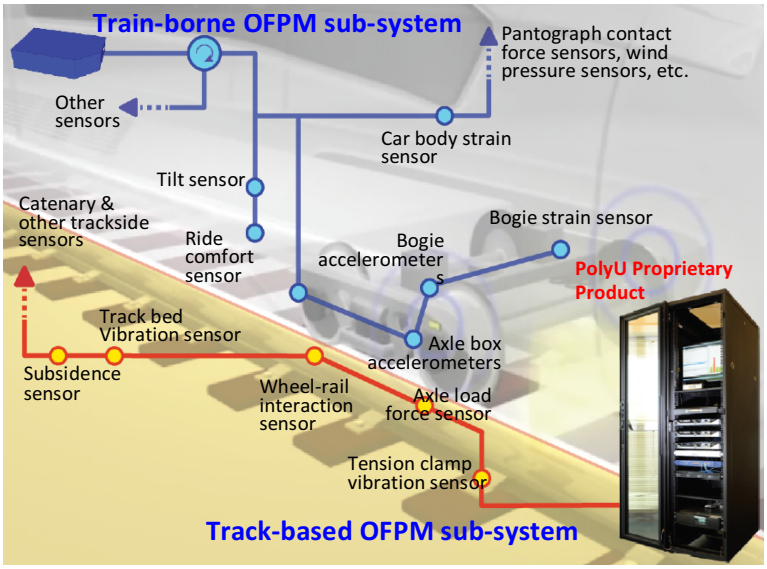
[3.5] W.H. Chung, H.Y. Tam, P.K.A. Wai, and A. Khandelwal, "Time- and Wavelength-Division Multiplexing of FBG Sensors Using a Semiconductor Optical Amplifier in Ring Cavity Configuration," *IEEE Photonics Technol. Letts*, Vol.17, No.12, pp 2709 – 2711, Dec 2005

[3.6] Hongyan FU, Heliang Liu, Wenghong Chung, and Hwa-Yaw Tam, "A Novel FBG Sensor Configuration for Long-distance Measurement," *IEEE Sensors J*, 8(9), pp. 1598, Sept 2008

(4) Details of the impact

Tremendous pressure is being imposed on railway operators to enhance service reliability and infrastructure maintenance to reduce disruption arising from train, track and overhead power line (OHL) failures. This requires condition-monitoring systems that can effectively and continuously monitor mission-critical components to produce big data in respect of railway asset maintenance for the development of advanced fault identification and prediction techniques. An all-optical fibre sensing system developed by UoA12 over the past 15 years is non-conductive, immune from electromagnetic interference, corrosion free, and has a long transmission distance, making it an excellent platform for the development of railway condition monitoring system [5.1].

The proprietary optical fibre-based predictive monitoring (**OFPM**) system developed by UoA12 consists of train-borne and track-based sub-systems is shown on the right.



The nature of the impact is that the OFPM system ***improves train availability, service quality*** and ***safety.*** It provides operators with real-time train, track, and catenary condition information so that they can ***act promptly in case of a fault*** and ***reduce maintenance cost***.

In 2014, the OFPM system won the third prize of the ***prestigious Berthold Leibinger Innovationspreis*** in Germany. The jury of Berthold Leibinger Innovationspreis commended "***The beauty of the technology is manifold: it delivers clear signals, it is electrically robust, the sensor network requires no local electric energy and many sensors can be integrated into a single fibre along many kilometers of length. All it requires is a laser and a spectroscope at the end of the fibre***" [5.2].

In 2014-2018, UoA12 secured ***HK$3 million*** from MTR to install five track-based OFPM sub-systems in MTR ***monitoring about 80% of all the trains*** in Hong Kong. The systems identify wheel condition via wheel-rail interaction of in-service trains, which is more effective than any existing approaches. MTR plans to install the train-borne and track-based OFPM systems in all their railway networks in the next few years. This is the result of a productive and long-term collaboration between UoA12 and MTR. During the reporting period, UoA12 has secured more than ***HK$9 million*** in technology transfer to MTR [5.3].

In 2016, UoA12 secured a project worth ***SGD 1.54 million*** to build two train-borne and two track-based OFPM systems to monitor the train and track conditions of two of the busiest lines in the ***Singapore SMRT*** metro network [5.4]. The train-borne sub-systems installed on two in-service trains assess the track condition of SMRT's East-West and North-South Lines to identify and locate corrugations and rail cracks continuously for over 18 hours, every day between 5:30 am to midnight. This is in contrast to traditional inspection conducted in the field that provides sparse and discrete condition data, which is insufficient to realize health projection and prognostic maintenance.

"[We are] the first in the world to have adopted this preventive monitoring system, enabled by the cutting-edge technologies, pioneered by PolyU. I am sure this optical fibre sensing network installed in both the tracks and running trains will enhance the operation of our metro lines" said Dr. Tan Chee Keong, deputy director of SMRT, Singapore [5.5].

The OFPM System ensures safer and more reliable metro services to commuters travelling on the Hong Kong's MTR and Singapore's SMRT metro lines. The two companies carry a combined total of **8.8 million passengers** per day. In addition, the diagnostic capability of the OFPM system assisted railway operators to identify faults for remediation. In early 2016, the installed system in Hong Kong was able to pick up structural defects due to cracks developing on the under-frame and a broken headstock, and derailment could happen if the operator was not informed in advance.

In 2015, UoA12 collaborated with Ricardo Nederland B.V. to develop an overhead line inspection system using passenger trains to monitor the position and contact force of power lines. The instrumented train operated in the Netherlands for 3 months covering about 80% of the country. The measurement results shown that the system could *detect broken power lines 5 weeks in advance*. Ricardo and PolyU are jointly developing the products for the European markets [5.6]. The results led to the award of a ***HK$1.65 million contract*** to investigate the technical issues with the pantograph and overhead wiring of the Sydney Metro Northwest Rail Line using the OFPM to monitor overhead power lines [5.7]. The daily ridership of the line is about 80,000. To support the efforts in the railway monitoring technologies, currently 6 staff members and their research teams from the UoA12 are involved with developing the underlying technologies. Additionally, there have been 1 former colleague and about 10 former researchers from the department who have gone to affiliated companies and agencies involved with the deployment of the railway monitoring systems. For example, recent activities during the assessment period include training of Singapore SMRT and Hong Kong MTR staff on optical fibre technologies and on the operation of the proprietary OFPM system developed by UoA12.

The nature of the impact and beneficiaries: The railway operators of MTR, Singapore SMRT and Sydney Metro have access to real-time train, track, or catenary condition information so that they can provide more effective maintenance as well as act promptly in case of a fault. The approximately 9 million passengers riding daily on these metro networks are enjoying better train availability, service quality and safety. The OFPM system is helping the railway industry to move away from inefficient and costly traditional scheduled maintenance regimes to predictive and condition-based maintenance. The availability of novel optical fibre sensors and new types of condition data enriches the railway database, thereby aiding the development of pristine fault detection capabilities and prognostic functions through advanced data analysis and machine learning. UoA12 is world leader in optical fibre railway monitoring and its recent work in optical railway sensor has reached millions of audience due to the various press activities undertaken by the Optical Society of America [5.8]

Lifts and Escalators Predictive Maintenance Systems: The underpinning technology is also being pursued for lifts and escalators (L&E) monitoring in Smart Buildings. L&Es are essential vertical transportation systems that are indispensable to Hongkongers. Hong Kong has about 70,000 lifts and 10,000 escalators. Any breakdown of these appliances will induce waste of time to the users or even fatal injuries in some severe cases. In Hong Kong, preventive maintenance of L&E follows regular routine inspection methodology. Inspections are carried out by registered personnel at least once a month for 1.5 hours. Undoubtedly, hidden defects or premature aging of the mechanical parts can be easily overlooked with this maintenance methodology. Therefore, condition monitoring system that relies less on human factors and capable of providing real-time continuous operation and diagnostic information of L&E is very important for passenger safety and system reliability.

HY Tam and SY Liu from UoA12 are working closely with the L&E industry as well as with the Electrical & Mechanical Service Department of the Hong Kong Gov. and developed a smart L&E predictive maintenance system. The system is able to measure the tension of individual suspension robes, and monitor the braking mechanism, motors, door opening/closing, and count the number of passenger going in and out of lifts. The same system can also monitor the condition of the step chain sprockets, handrail tensioning mechanism, comb plates at landing platform, step chain guide rail at turnaround and step chain and step wheel guide rails of escalators.

A startup company, ***Avaron*** (https://avarontechs.com) from UoA12 was created by HY Tam and his formers students in June 2018 to market the L&E predictive maintenance system [5.9]. The core business of Avaron is to offer ***innovative and disruptive technologies, and complete solutions with AI-based analytics to address the underlying needs on condition based and predictive maintenance for smart and green buildings*** to enhance asset's operation and maintenance efficiency, service quality, reliability, and availability. Avaron employs the latest cloud-based predictive maintenance solutions – capable of effective monitoring the condition of the mission critical components in lift, escalator, HVAC and fire detection systems with an integrated optical sensing system.

Currently, Avaron has 6 employees, including 3 PhD graduates (all previously worked at UoA12) and 1 MSc. graduate. The startup secured about ***HK$5 million of financial support from the Hong Kong Science and Technology Park's Incu-Tech Programme***. As of September 2019, ***Avaron secured four projects, worth about HK$ 7 million***, to monitor air-conditioning systems, lifts and escalators in HK. The Electrical & Mechanical Service Department is in discussion with Avaron to install the system to monitor their 3,000 lifts in hospitals, public housing & government buildings.

The nature of the impact of the L&E predictive monitoring system: provide complete one-stop monitoring solutions for smart buildings to attain greater efficiency, safety and better service, as well as helping the property owners realize cost saving in manpower and lifecycle extension of critical components. ***Beneficiaries*** to the L&E operators and manufacturers include improvement of manpower constraint; effective performance checking after maintenance or repairing; improvement in asset management; and elimination of L&E incidents due to operation malfunctioning.

(5) Sources to corroborate the impact

[5.1] "Optical fibre networks facilitate shift to predictive maintenance," *International Railway Journal*, Vol.57, Issue 8, pp. 38 – 40, August 2017

[5.2] https://www.leibinger-stiftung.de/en/innovationspreis-zukunftspreis/winner-award-ceremony-2014/

[5.3] Consultancy projects for MTR Corporation

[5.4] Consultancy projects for Singapore SMRT Trains Ltd. (overseas)

[5.5] https://www.smartcitiesworld.net/news/news/worlds-first-onboard-train-track-monitoring-system-in-singapore-1026

[5.6] NDA between Ricardo Nederland B.V. and UoA12, signed on 3rd December 2015

[5.7] Mr. Ivan Lai, former CEO, Metrotrains Sydney, Australia

[5.8] OSA Letter

[5.9] Dr. Cheng Kei Chun, CEO of Avaron Technologies Limited, Hong Kong