Advancing the digital railway with 4IR technologies

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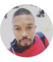

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Advancing the digital railway with 4IR technologies

The launch of Engineering 4.0 on 30 November 2020 at the University of Pretoria's Hillcrest campus marked the start of an ambitious endeavour to realise data-driven smart cities and transportation networks.

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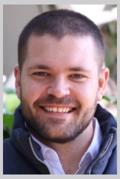

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Professor Tawana Kupe, Vice Chancellor and Principal of the University of Pretoria (UP), has a vision that Engineering 4.0, together with the Hatfield and Hillcrest campuses, the Innovation Hub, and the CSIR, would be established as "the most innovative square mile in Africa". Under the umbrella of smart transportation, the Chair in Railway Engineering is advancing the digital railway with Fourth Industrial Revolution (4IR) technologies. UP's team of post-graduate railway researchers lifts the curtain on six of these technologies and describes how their work will benefit the railway industry in the years to come:

1. Digital twinning for railways
2. High-tech instrumentation for climate change
3. The Internet of Railway Things (IoRT)
4. Train (defect) detectives
5. Mapping and hovering with drones and LiDAR
6. Smart diagnostics with clever track components.

DIGITAL TWINNING FOR RAILWAYS

The digital twin concept involves the development of a computer-aided model which is similar to a real-life structure. The twin model is capable of solving complex problems using 4IR technologies. The concept was originally coined and presented by Dr Michael Grieve in 2003 at the University of Michigan, with a focus on product lifecycle management. The digital twin combines engineering modelling with advanced analytics to create an intelligent model which responds to transient changes in governing parameters. The key feature is the ability of the model to continuously adapt to changes in its environment using input data from real-time sensors to predict future behaviour of the physical asset.

The operations of the railway industry rely heavily on various infrastructure components which would require a predictive and reliability-based approach for successful planned maintenance. The digital twin model therefore becomes a powerful tool for innovative asset management. However, the development of a robust digital twin model requires the combined use of elementary concepts of engineering and the following steps:

- Digitalisation of the physical geometry of the infrastructure
- Measurement of component behaviour using sensors
- Efficient data processing and analytics
- Intelligent models for predictive behaviour.

A study, which implements ideas of the digital twin concept, focusing on increased axle loading on railway foundations, will be used as an example. Although the study is still ongoing and elementary, it is the beginning of the development of a robust digital twin model. The study focuses on the effect of increased axle loading on the behaviour of saturated and unsaturated railway foundation materials. Axle loading starts with 20 tonnes per axle as a base case with increased axle loading of 26, 30, 32.5 and 40 tonnes per axle. A finite element model has been developed for digitalisation of the physical geometry of the track structure. The measurement of component behaviour, in this case of the subballast, involves the use of a cyclic triaxial apparatus instrumented with various sensors as shown in Figure 1. The constitutive behaviour of the subballast material is elasto-plastic for saturated soil conditions

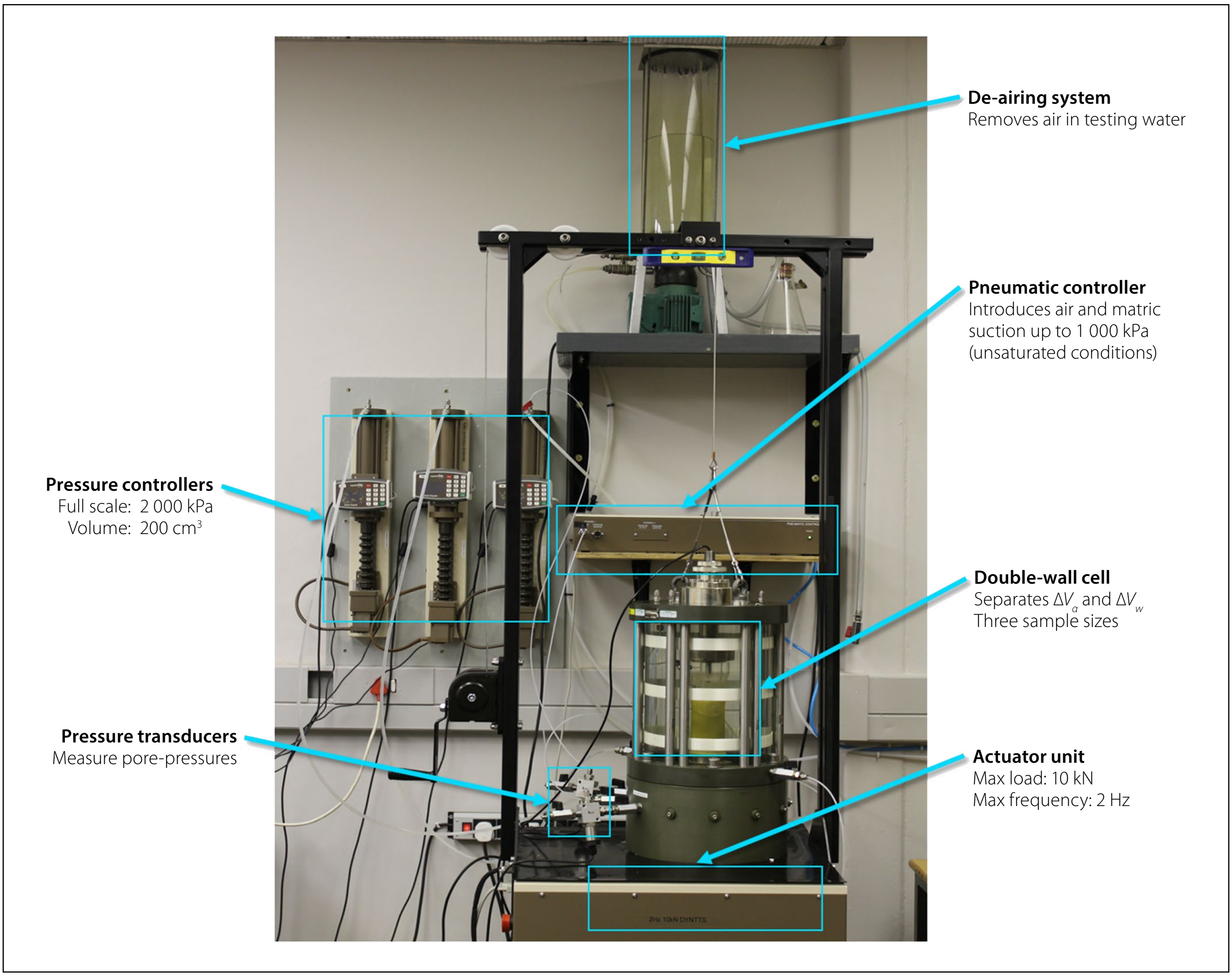

Figure 1 Cyclic triaxial apparatus for saturated and unsaturated soil testing

and elasto-hardening-softening for unsaturated soil conditions.

In the current form of the study, measurement of component behaviour is still laboratory based, and data processing and analytics, together with models for predictive behaviour, are manual. Moving forward, planned improvements include the installation of complimentary field sensors and automation of data processing and analytics using the Internet of Things (IoT) and machine learning to predict future behaviour.

HIGH-TECH INSTRUMENTATION FOR CLIMATE CHANGE

The scientific consensus is that climate change is a current problem requiring intervention. Changing climatic conditions will significantly influence the soil layers at the surface of the soil profile which remain in an unsaturated state most of the time. Much of our transportation infrastructure is constructed on or within this unsaturated layer. The formation layers of conventional railway tracks are no exception. This means that railway formations will be significantly affected by the extreme weather conditions predicted by climatologists. These extremes include heavier rainfall and longer drought periods.

We need to formulate our models using unsaturated soil mechanics in order to understand the behaviour of in-service railway formations and to determine the impact that these predicted climate changes will have on our railway infrastructure. Unsaturated soil mechanics relies heavily on the determination of a soil function called the soil water retention curve (SWRC). The SWRC is the relationship between the suction in the soil and the soil's water content. The effective stress state which governs all soil behaviour can be directly linked to the SWRC.

Measurement of the SWRC has typically been a time consuming and costly exercise reserved solely for the most patient of researchers. However, recent developments in low-cost suction sensors, coupled with wireless apparatuses, have enabled the rapid, cost effective, and accurate determination of the SWRC. A new apparatus for the determination of the SWRC was developed at UP incorporating low cost tensiometers, wireless data loggers, and laser displacement transducers (Figure 2). This new apparatus allows for automated testing whereby the drying path can be stopped at a predetermined level of suction and a wetting path started without the presence of an operator. This is important as tensiometers can cavitate if the suction becomes too high, which regularly occurs if not continuously monitored.

The sample mass must be monitored to the nearest 0.01 g during SWRC testing to accurately trace the soil moisture behaviour. This means that no cables should be allowed to run from sensors located on the mass balance to logging equipment located off the mass balance. This was completely mitigated in the current setup using non-contact displacement measurement systems, Wi-Fi enabled data logging, and light-dependant resistors to trigger wetting and drying cycles.

This novel apparatus has allowed for the characterisation of the SWRC of unsaturated railway formations. This enables the implementation of unsaturated soil mechanics to address the issue of climate change and its impact on heavy haul railway formations and transportation infrastructure.

THE INTERNET OF RAILWAY THINGS (IoRT)

A dedicated Data House has been constructed adjacent to the N4 highway, serving as a centralised data acquisition and transmission platform for transdisciplinary research projects in and around UP's Innovation Africa campus. The potential of an edge intelligence solution was successfully demonstrated in 2020, whereby a low-cost, low-power computer hardware platform detects and classifies passing vehicles in real-time along the freeway with an accuracy of 96%. These statistics are aggregated alongside environmental data (ambient air temperature, pavement surfacing temperature, soil moisture, air quality, CO_2 concentration, and weather station data) measured by a wide range of LoRaWAN (long-range wide area network) sensors.

The LoRaWAN provides the capacity to serve hundreds of these devices with coverage extending across the entirety of the Hillcrest campus. To date, more than 40 of these low-cost, battery powered sensors have been installed across the Innovation Africa campus, with customised sensor platforms located as far away as Port Alfred due to join the network in 2021. Data from this distributed sensor network is aggregated within the centralised Innovation Africa IoT Data Platform. This scalable sensor network serves as the next evolution in real-time condition monitoring of infrastructure, in particular railway environments; characterised by remote, distributed assets of significant economic importance where continuous measurement and identification of temperature, rail breaks, impact loads, and permeant settlement effects are crucial for safe railway operations.

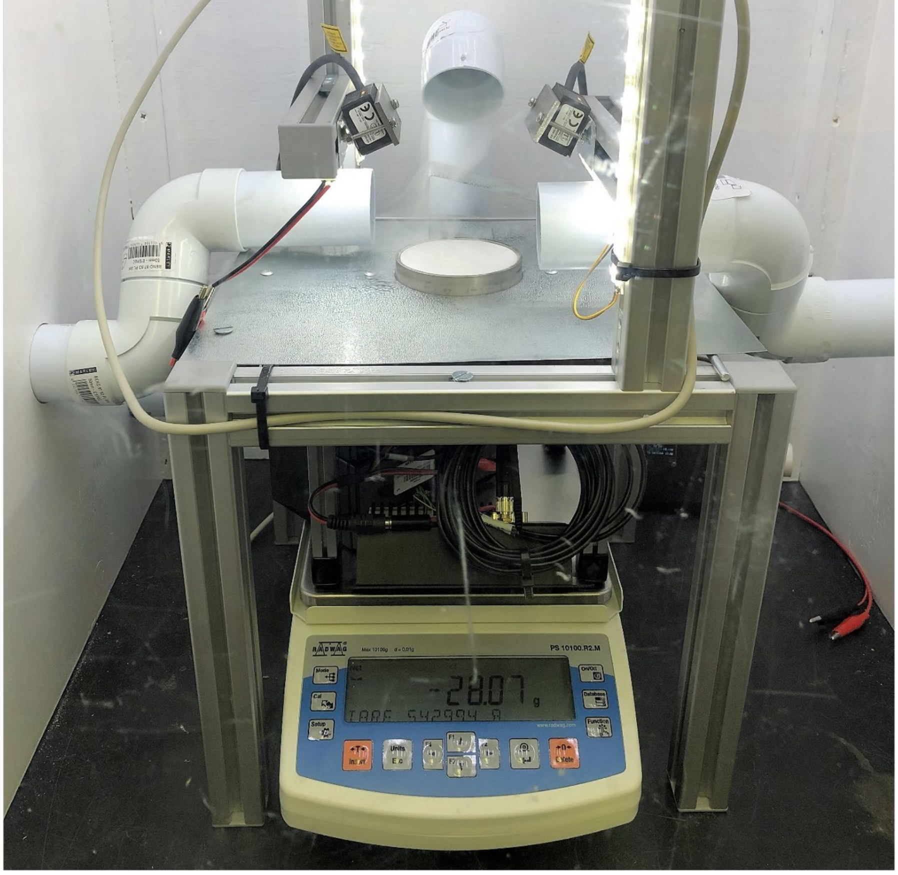

Figure 2 The newly developed SWRC apparatus incorporating wireless technologies for the accurate measurement of soil sample mass

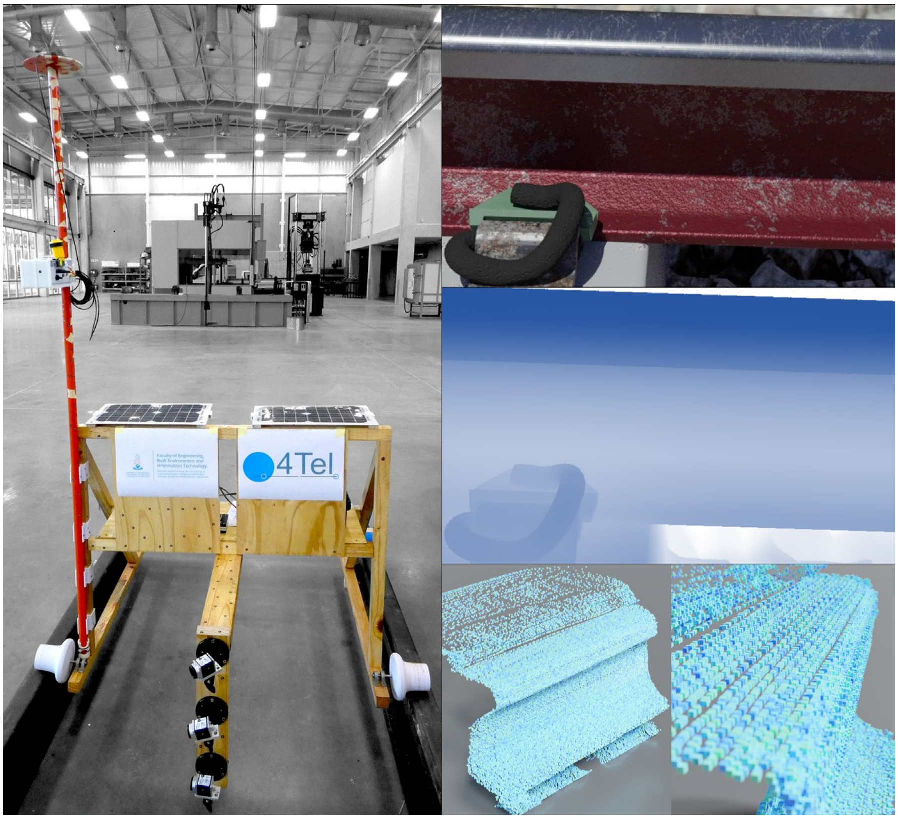

Figure 3 Camera frame (left) with GPS antenna installed and on the righthand side the synthetically rendered rail, a depth map and finally a point cloud of the railway profile

To address the disparity between state-of-the-art advancements in deep learning and efficient condition monitoring of the digital railway, the Chair in Railway Engineering established a collaborative research project with 4Tel, based in Australia, in 2019. Neural network-based multi-view stereopsis (MVS) reconstruction pipelines are incorporated with millimetre-accurate geolocation services to measure the condition of railway assets (track geometry). A low-cost, mobile, real-time kinematic (RTK) geolocation service was developed at UP which provides 14 mm accurate geolocation capabilities up to 13 km away from the stationary reference antenna installed at the Data House.

Figure 4 UP's RRV with vehicle-track response monitoring

The corrections associated with the base station are transmitted over the internet for increased accessibility in the Pretoria region. The mobility provided by the hardware enables diverse application ranging from MVS techniques which require an absolute reference frame for successful reconstruction (see Figure 3) to direct antenna surface mapping (RTK-ASM) techniques for more intricate applications such as preservation of historical structures. Research activities associated with advancements in sensory capabilities and alternative geolocation services serve as the catalyst for realising robust digital twins in the 4IR era.

TRAIN (DEFECT) DETECTIVES

With the increased reliance on rail as a form of public and freight transport, the rate of degradation of railway tracks and the resulting decrease in passenger comfort (for passenger trains) have become important aspects for further research. This forces researchers to develop faster, cheaper methods of detecting track defects – a task that is of high importance within the spectrum of predictive maintenance. One such method is analysing vibration data from the accelerometers installed on asset tracking terminals (commonly known as tags) installed on railway vehicles.

Asset tracking terminals are installed on railway vehicles for organisations to track their movements with the GPS that is installed as part of the terminal. An accelerometer is installed to power up the terminal whenever a large enough vibration is detected so that the terminal can record a time and location. The magnitude of the induced vibration is also recorded. This data can easily be accessed and downloaded from online dashboards to which the recorded data is uploaded. With hundreds of terminals on a single train passing over a particular defect, the analysed data will indicate that there may be a defect present at a specific location. Maintenance engineers can then send professionals to assess the defect.

Using this inexpensive equipment installed on railway vehicles to detect the presence of track defects alleviates the need to send out expensive and time-consuming geometry cars on a regular basis. The added benefit of these terminals is that other occurrences may be detected, such as railway vehicle coupling dislocations or vehicle speed.

The flexibility of the uses of the asset tracking terminals, together with their low cost and ease of data acquisition, enables organisations to effectively and efficiently detect the presence and locations of track defects from their workstations, at low cost, using revenue-earning trains to do so.

To test this novel track defect detection method, accelerometers and terminals have been installed on UP's Road/Rail Vehicle (RRV) (see Figure 4) and preliminary results have been obtained. The expectation is that much will be learnt from

Using this inexpensive equipment installed on railway vehicles to detect the presence of track defects alleviates the need to send out expensive and time-consuming geometry cars

Figure 5 DJI Matrice M300 drone with Hovermap LiDAR system and GoPro colourisation

the trial installation and that the next step of developing an autonomous track defect detector is now much closer.

MAPPING AND HOVERING WITH DRONES AND LIDAR

Recent additions to state-of-the-art monitoring and mapping equipment in UP's Department of Civil Engineering include that of the Emesent Hovermap LiDAR system, infrared thermoIMAGER camera and the DJI Matrice M300 UAV, all of which have opened a realm of opportunities for application in the railway sector.

Hovermap is a mobile LiDAR scanning system where data capture can take the form of handheld, vehicle- or drone-mounted scans. An onboard computer encased within the Hovermap allows simultaneous localisation and mapping (SLAM) algorithms to generate point clouds of the scanned environment. The real-time processing of this data has changed the way one operates drones, with autonomous functions now available that enable programmable flights in GPS-denied environments, collision avoidance and position hold.

The Hovermap, initially intended for underground mining, is easy to use and comes with 480 GB onboard storage, allowing a full day of scanning to be recorded and downloaded at the end of the day. The final product is a high-resolution, data-rich point cloud that can be exported in non-proprietary, open-source formats (.las .laz .ply .dxf) for post-processing in third party software.

Work currently underway aims to conduct a full performance evaluation of the Hovermap system in terms of its accuracy, data density, and object detection capabilities. This evaluation will prompt future railway research and assist in understanding the capabilities of the Hovermap system. This will allow users to further exploit its advantages in the space of railways. Emesent's recent release of the GoPro attachment enables colourisation of point clouds, increasing the possibilities of data capture and analysis.

The thermoIMAGER infrared camera, another recently acquired item in the rail department, provides high resolution non-contact temperature measurements. The compact size of this high-resolution camera makes it an ideal attachment for drones. It can perform both static and in-motion scans of different object surfaces, with the ability to measure temperatures accurately at millisecond intervals (80 Hz).

The integration of thermal and colourisation information into 3D point clouds obtained from the Matrice M300 drone and Hovermap system (see Figure 5), will be used to conduct bridge and tunnel inspections in difficult to reach places or areas that are too dangerous for personnel to access.

The study forms part of a bigger end goal which is to combine various tools, scanners, and sensors to achieve a complete condition monitoring system that will form part of or be fitted to the RRV for both road and rail infrastructure inspections and condition monitoring.

SMART DIAGNOSTICS WITH CLEVER TRACK COMPONENTS

Structural health monitoring in railway infrastructure is not a new concept, but the application of fibre optic sensors (FOS), for the purpose of monitoring,

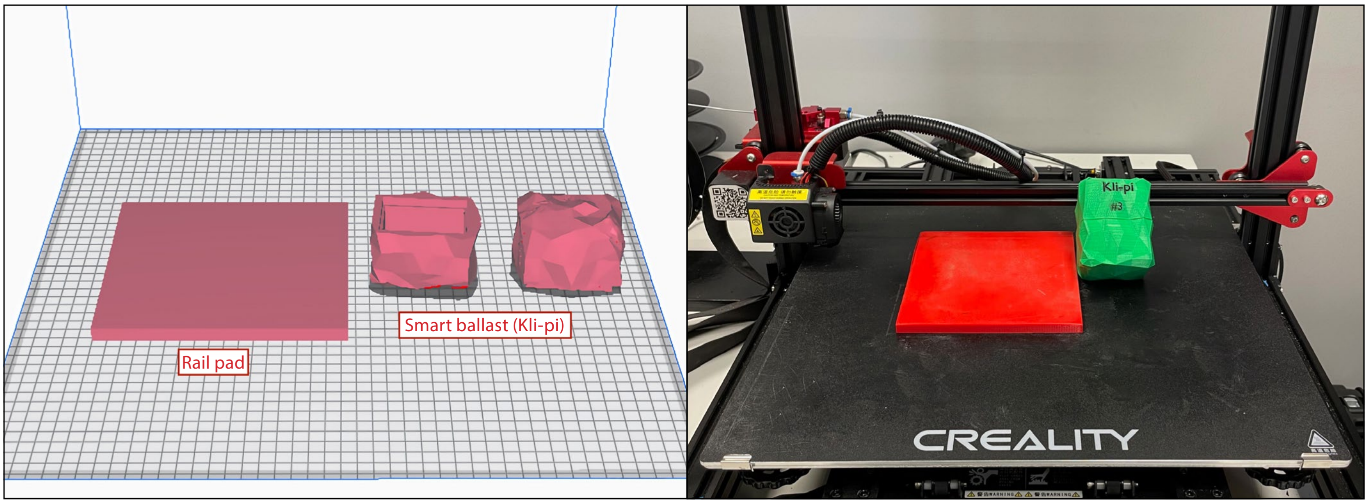

Figure 6 3D models of a rail pad and smart ballast (Kli-pi) (left) and 3D printed versions of these track components (right)

is considered a new technology. Conventional sensors including accelerometers, strain gauges and inclinometers, among others, are prone to durability and stability failures under specific conditions. To overcome these limitations, FOS provide various advantages in comparison with conventional sensors. These advantages include being lightweight, being immune to electromagnetic interference, and having the ability to operate under harsh conditions. These advantages make FOS an attractive solution for condition monitoring in the railway space.

A specific type of FOS, called Fibre Bragg Grating (FBG) sensors, can be used to measure strain and temperature within the rail pad. In grating sensors, the light moves through the optical fibre and the grating serves as a narrow band filter to modulate the range of wavelengths, known as Bragg wavelengths. The variation in the grating period and refractive index corresponds to the deformation of the FBG sensor by strain or temperature.

Elastic rail pads are made with rubber or plastics which provide resiliency for the track structure and damping of wheel-induced vibrations and noise. Rail pads are most commonly made from HDPE (high–density polyethylene), EVA (ethylene-vinyl acetate) and TPE (thermopolymer polyester elastomer). 3D printing technology can introduce a new and interesting method of creating rail pads. There are various 3D printing filaments ranging from flexible to hard and brittle plastics. TPU (thermoplastic polyurethane) is a flexible and abrasion resistant thermoplastic that can withstand impacts and serve as an alternative to common rail pad materials.

Instrumenting rail pads with smart sensing technology such as FOS is a new and exciting condition monitoring avenue. Rail pads can provide useful information such as load transmission to the substructure when instrumented with load sensing capabilities. An instrumented rail pad can provide a window into the stresses and strains experienced by a rail pad. Similarly, the South African version of smart rock or smart ballast, namely Kli-pi, uses a miniature battery-powered micro-processor inside a 3D printed ballast stone to measure the deflections, rotations, and vibrations experienced by ballasts during train loading. By combining 3D printed rail pads with smart sensing technology, a cost-effective, small, and lightweight alternative to most conventional condition monitoring systems can be provided.

CONCLUSIONS

The digital railway is all about creating value at new frontiers and creating value in the core business of the railway operator. The following acronym, DIGITAL, summarises the main characteristics of the digital railway as touched upon in this paper:

- Proactive **D**ecision making
- Contextual **I**nteractivity
- **G**lobal connectivity
- Journey-focused **I**nnovation
- **T**echnology
- Real-time **A**utomation
- **L**inking people, ideas and things.

The technologies of the 4IR are all about people: building foundational digital capabilities, mindsets, and system and data architecture. The digital railway will not be shaped by the binary digits 0 and 1, but will be shaped by people. The investment in technology should be complemented by empowering people who will embrace technology, connectivity, and automation.

It is here that our institutions of higher learning can and should play a much more significant role. The more digital our railways become, the greater the importance of people skills that cannot be performed by machines. The digital railway has the ability to capture the imagination of a new generation – it is engaging, exciting and transforming our world. The Chair in Railway Engineering at UP invites industry and railway operators into partnerships that will empower these companies to become digitally enabled and 4IR ready. Our world-class facilities and equipment at Engineering 4.0 are there to serve and advance the railway industry in the Southern African region.

ACKNOWLEDGMENTS

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