ENGINEERING4.0

Future-focused solutions

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Engineering, Built Environment and Information Technology

Fakulteit Ingenieurswese, Bou-omgewing en Inligtingtegnologie / Lefapha la Boetšenere, Tikologo ya Kago le Theknolotši ya Tshedimošo

ENGINEERING 4.0

Engineering 4.0 Road to a smart future

The University of Pretoria's Engineering 4.0 facility for smart transport, cities and infrastructure is a state-of-the-art facility that focuses on research for the future and the development of the critical skills needed for the transportation sector.

Situated on the Innovation Africa@UP Campus, it has its home in the University of Pretoria's Faculty of Engineering, Built Environment and Information Technology (EBIT). It is the first of its kind in Africa, developed in partnership with the South African National Roads Agency Limited (SANRAL), the Council for Scientific and Industrial Research (CSIR) and York Timbers.

The Engineering 4.0 facility forms part of the strategic research agenda of both the University of Pretoria and SANRAL. Its aim is to develop sustainable, optimised, smart, equitable transportation networks that support social and economic development in a disruptive and evolutionary society.

It forms part of SANRAL's thought leadership campaign stream related to the road infrastructure of the future, which aims to build SANRAL's position as a leading role player in the innovation of the road infrastructure space. This entails the following:

- Technology, innovation and the digital transformation: The role of the Fourth Industrial Revolution as an enabler for the optimisation of the infrastructure lifecycle, planning the infrastructure pipeline, and smart infrastructure and mobility
- Future talent and skills development: Using education to enable skills development and capacity building

In terms of the United Nations' 17 Sustainable Development Goals (SDGs), innovation, infrastructure, and sustainable cities and communities are critical for developing any economy. This new research hub, which will foster interdisciplinary research in the wake of the Fourth Industrial Revolution (4IR), will enable UP to make a distinct contribution to these goals through ongoing research into phenomena like data analytics, smart materials, artificial intelligence and the Internet of Things (IoT).

This unique world-class African facility is a place where novel ideas, scientific research, global expertise, students, academics, entrepreneurs and industry partners can converge to generate new thought leadership, innovation and training opportunities through collaborative partnerships.

Objectives and vision

Engineering 4.0 was developed to establish an integrated education, national certification, national reference and research laboratories facility. It would ensure maximum cooperation between the partners to create critical mass in laboratory facilities and human resources to efficiently address the prevailing skills shortage challenges in the sector. It would also avoid further erosion of the remaining skills in the country, enhance the quality and quantity of outputs, and avoid the costly duplication of laboratory facilities.

The vision of the facility was to provide an internationally renowned platform for academic and vocational training support in transportation infrastructure materials testing, a national transportation materials reference testing platform, and high-quality research facilities and skilled staff.

The result was a series of high-quality facilities that provide a platform for quality training, reference testing and research in transportation engineering:

- An education and certification laboratory for transportation materials
- A national transportation materials reference and proficiency scheme testing laboratory
- A research laboratory for transportation materials
- An accelerated pavement testing facility
- Optimal use of existing and new laboratories and testing facilities

The benefits of a unified partnership

The unified partnership between SANRAL, the CSIR and the University of Pretoria has the following benefits:

- High-quality facilities that provide a platform for quality training, reference testing and research in transportation engineering
- A combined effort to train engineers, technologists, technicians and materials testers for the transport engineering sector
- Research collaboration that will ensure a higher quality of research, and the development and implementation of new knowledge and technology that is locally relevant, as well as more research outputs in terms of publications, technology demonstrators and pilot projects
- Enhanced impact in the transport sector through the implementation of new and sustainable solutions that improve transportation performance, and reduce construction and maintenance costs
- Reduced impact on the environment through “green” solutions, the recycling of materials, the re-use of materials and energy saving.

South Africa’s skills shortage challenge

The current constraints faced in transportation engineering include the dire lack of civil engineers compared with other countries. In its Infrastructure Report Card, the South African Institution of Civil Engineering (SAICE) indicates that, in Europe, North America, India and China, there is one engineer for every 130 to 450 people in the population. In South Africa, this ratio is 3 200 to one – a ten-fold disadvantage. This applies equally to technologists, technicians and artisans, with the result that there is a lack of quality personnel throughout the transportation sector, which brings about a technical skills gap with regard to the quality control of projects and quality assurance.

Developing skills for future smart cities

A unified effort by the partners to train engineers, technologists, technicians and materials testers for the transport engineering sector at Engineering 4.0 has the following outcomes:

- An independent national assessment and certification facility for material testers in South Africa, who will receive a certificate accredited by the Quality Council for Trades and Occupations (QCTO)
- An increased number of civil engineers, technologists and technicians who are skilled in transportation engineering, and who will contribute to improved designs and quality control on the South African road sector, which generates an expenditure of nearly R45 billion per annum
- An increased number of master's and PhD graduates in transportation engineering who will generate new knowledge in transportation engineering, and conduct research for the future, particularly to address capability that has been lost from research and academic institutions
- A pipeline of transportation engineers that have been exposed to the latest technologies and methods to be taken up in government, at SANRAL and in the industry.

Benefit to South Africa

The main benefits of the facilities at Engineering 4.0 to South Africa include the following:

- The increased availability of technical skills in transportation engineering
- The improved quality of skills of transportation engineers, technologists and technicians
- Cost savings due to improvements in the design, construction, maintenance and management of transportation infrastructure
- Better-performing transportation infrastructure due to improved quality control and the associated reduction in user operating costs
- Less impact on the environment from transport infrastructure construction and maintenance

Collaborative research

On 22 July 2020, the University signed a Memorandum of Agreement (MoA) with the CSIR to collaborate on smart transport, cities and environments. This cooperation means that UP can focus on creating a pipeline of potential researchers in these areas. According to Prof Wynand Steyn, Head of the Department of Civil Engineering, smart transport, cities and environments are part of an integrated system that encompasses digitised transportation systems, parking management, reduced traffic congestion and addressing environmental problems.

"In order to work towards smart cities, there is a need to develop researchers with advanced skills in robotics, AI, IoT and satellite technology. To this end, researchers will be trained through complementary skills at UP and the CSIR," said Prof Steyn. "This will further develop the skills required to design, construct, maintain and rehabilitate the extensive roads network in South Africa, a network that is vital for accessibility and the mobility of its communities, and in support of economic opportunities."

STUDENTS ARE EXPOSED TO HANDS-ON RESEARCH ACTIVITIES IN THE LABORATORIES, WHICH SUPPORT THEORETICAL TEACHING. THIS ENABLES A DEEPER UNDERSTANDING OF THE CIVIL ENGINEERING CURRICULUM IN PREPARATION FOR STUDENTS' WORKING LIVES AS CIVIL ENGINEERS.

Prof Wynand Steyn
Head of the Department of Civil Engineering and Chair of the School of Engineering

Engineering 4.0
Facilities

National Roads Reference Laboratory

This is the site for the independent reference testing of materials for the road construction industry. Standard testing is mostly conducted on road materials originating from SANRAL (for national roads projects), but also from the provinces and even neighbouring countries. It serves as the standard for the properties of such materials, to which field data can be compared. It thus characterises materials for appropriate construction. The National Laboratory Proficiency Scheme for Road Materials Laboratories is serviced from this laboratory, and it also participates in international proficiency schemes.

Training Laboratory

This is a 20-station facility that is used to train and certify road materials technicians employed by various testing laboratories. Once their skills are certified, laboratories can provide accurate test data to engineers. The objective is to ensure that materials testing in the field is up to standard and that the technicians who conduct the testing are capable and certified to do such tests with a high degree of accuracy. Engineering students are also trained and certified in this facility.

Concrete Laboratory

This laboratory consists of preparation areas, curing and humidity rooms, and a large test floor where various concrete and structural testing can be conducted.

It also has a 900 mm-deep 20 x 15 m strong floor, which provides possibilities for attaching presses and test members onto the floor, and a strong wall for testing.

York Wood Engineering Laboratory

This facility endeavours to cultivate, grow and expand the footprint of mass timber construction using advanced engineered wood products in South Africa and on the African continent in a collaborative effort between civil and chemical engineering, architecture, materials science, data science, genetics and other related bio-economy disciplines.

Accelerated Pavement Testing (APT) Track

The 100 x 6 m APT track allows for the construction of different pavement structures and their accelerated evaluation using a mobile APT device developed in South Africa. This enables engineers to monitor the expected behaviour of a pavement over a fraction of its full life.

Active Traffic Lane

This active traffic test track is a lane on the N4 into Pretoria that is dedicated to research. It allows for the installation of sensors inside, next to and over the lane that can be monitored from a dedicated data house situated next to the N4. The datahouse is also the location of a traffic counter and classifier that has been developed in-house and uses artificial intelligence (AI) to monitor traffic on the N4. This unique facility allows one to characterise pavement design and construction, while using data obtained from the active traffic lane to model many aspects in transportation systems. Such data and models support the planning and design of future transportation systems, and support cost-effective and innovative pavement engineering for Africa's infrastructure development.

A living laboratory for Civil Engineering

An important component of the training of civil engineers entails ensuring that graduates have superior knowledge of the development and maintenance of civil engineering infrastructure. The design and construction of the Engineering 4.0 Building therefore includes elements that function as a living laboratory for civil engineering.

A living laboratory is a user-centred, open innovation ecosystem that is based on a systematic user co-creation approach that integrates research and innovation processes in real-life communities and settings. It was first incorporated in the architecture of the University of Pretoria's revamped Boukunde Building in 2018.

As an element in the architecture of the Engineering 4.0 Building, components are included that form part of the construction of the building that are left exposed and encased in glass to enable students to experience first-hand what these structures look like and how they are used.

Such components include a section of the ablution services corridor, a section of the 900-mm deep strong floor in the Concrete Laboratory with its reinforced steel members, open roof structures that display trusses and insulation, and a section of the innovative heating, ventilation and air-conditioning (HVAC) installation with its unique intricacies and coordination.

The tilt-up design of the building's external concrete walls, which involved the casting of wall elements in stacks and lifting them into position on pad foundations, provided another educational opportunity for students to see the result of such a construction approach at close range.

Finally, the building's surrounding natural environment was positioned as a unique outdoor laboratory to investigate the impact of transportation systems and human activity on the natural environment.

Engineering 4.0

Flagship projects for digital transformation

The heartbeat of the Faculty is innovation. EBIT researchers are rising to the challenge of ensuring that they can make a significant contribution to society at large by focusing their research on topics that lead to real-world change.

EBIT is one of the few academic faculties in Africa to feature among the top 550 in the world in five subject areas in the 2022 QS World University Rankings by Subject in the field of engineering and technology, as well as in the subject area of Architecture and Built Environment, featuring in the top 200 in the world.

Technology has launched a digital transformation process that extends beyond tools and processes. It impacts on individuals and organisations, resulting in the improved wellbeing of both people and the planet. It also enhances globalisation by removing physical barriers and making it possible to work anywhere, anytime, on any device. Future-focused and transdisciplinary research is imperative to make sense of this new digitalised world.

Engineering 4.0 shares its vast resources in technology and data science with all the University's faculties via Future Africa, which is a platform for developing interdisciplinary and transdisciplinary research networks within the University and the global research community.

Man's best friend:
Enabling data-collection in high-risk environments

With the help of artificial intelligence, robotics and Big Data, the University, through the Department of Civil Engineering, is making use of its four-legged terrestrial robot. SmWoef is used to facilitate data collection in high-risk environments that are difficult or unsafe to access for human, or that require repetitive data collection. This is an excellent example of how robots and humans can co-exist and work together to innovate our tomorrow.

EBIT is the first faculty in South Africa to apply the quadrupedal robot for data collection specifically in such areas. Prof Wynand Steyn, Head of the Department of Civil Engineering, together with a team that includes interns and postgraduate students, is training smWoef to assist with multiple research projects at the University's state-of-the-art Engineering 4.0 facility. It will be used primarily as a platform for a diversity of research.

With the help of this smart alternative transportation platform, infrastructure such as buildings and bridges can be inspected more regularly, and weak and unsafe points identified; thus avoiding failure of the infrastructure.

Smart alternative transportation platforms can help researchers to accumulate more accurate data to design more innovative solutions to everyday situations. Some areas previously restricted or cpnsidered too dangerous for humans to inspect for data collection – such as restricted airspaces, crime scenes, condemned buildings and upstream dam wall evaluations – will become more accessible.

Not only can this technology be used to transport sensors into unsafe, high-risk areas and those that are inaccessible to humans, it can also be used to perform repetitive tasks in a safe and managed way to allow for the collection of useful data. An example of this is its application in the agriculture sector, where smWoef can collect routine data among crops for future use and to improve farming techniques.

The digital repository that can be built based on the data that is gathered through smWoef can be used for several transdisciplinary projects, including those conducted by the University's Forestry and Agricultural Biotechnology Unstitute (FABI). Further potential interactions with departments in the School of Medicine and School for the Built Environment are being pursued; where access to unsafe, inaccessible environments may aid in novel data collection and research support. This enables people to focus on safe tasks where human capabilities are essential, and leave technology to tackle those tasks deemed unsafe or repetitive for humans.

In addition, smWoef can gather data to help build a digital twin of an area, which will enable engineers to plan, understand and manage infrastructure more optimally. It will play a vital role in collecting data for the University's ambitious Hatfield Precinct Digital Twin City project.

Why is this research important?

A smart alternative research platform such as smWoef is a perfect example of how man and machine can work together for the betterment of humankind. By combining an autonomous robot platform with sensor networks, an infrastructure data collection methodology can be developed that provides for a safe, sustainable, continuous process of collection current digital infrastructure data (including ambient environmental conditions and images at a range of wavelengths). This can form the basis of infrastructure maintenance, rehabilitation and risk management decisions.

SmWoef can fetch, roll over and act as an early-warning system – just like a dog. It has quite a pedigree:

- It is an agile quadrupedal robot that can navigate inaccessible terrain with unparalleled mobility.
- It can carry a payload of up to 5 kg at speeds of up to 12 km/h, depending on terrain conditions.
- Payloads can be self-sustained – linked with GPS and long-range wide area network (LoraWAN) stations – or integrated with the robot.
- Operational modes include a manual follow-me and simultaneous localisation and mapping (SLAM) mode, meaning the user can select the option best suited to the specific application and terrain.

The Hatfield Precinct Digital Twin City project

The University of Pretoria is leading the charge in the future of African cities, particularly the exciting world of "digital twinning" – where reality and simulation meet in real time – on the Hatfield Digital Twin City. This long-term initiative will be a living laboratory that provides a fully simulated, mirrored image of Hatfield and its surroundings. By establishing thousands of real-time feedback loops between nature, environments, cities, people and processes, researchers can ask new kinds of curious and innovative questions.

The Hatfield Digital Twin City is leading a large-scale transdisciplinary initiative that includes themes in city simulation modelling, artificial intelligence, machine learning, scenario and prediction design, urban systems, city-making, Society 5.0 and many other exciting topics.

Future cities – our greatest and shared wicked problem[1]

The problem of urbanisation, city-making and our concerns for sustainable development places our planetary system under extreme pressure.

1 A "wicked problem" is a social or cultural problem that is often difficult or impossible to solve. It is a systems problem that is complex and interconnected in nature.

The great majority of the world's population lives in cities, which consume two-thirds of the world's energy, while being responsible for over 75% of global CO_2 emissions.

Cities drive the forces of the world economy, and are directly responsible for our nested resource feedback loops, as well as national and global economic performance. Since 2007, the world has moved far beyond the global urbanisation tipping point. According to the United Nations Human Settlement Programme (UN-Habitat), mankind will continue to add three million inhabitants to cities every week for the next 40 years. By 2030, the world's largest cities will be in Asia and Africa, which is where 90% of global urbanisation will occur. Vast, interconnected and complex megacities become increasingly harder to manage or maintain. Meanwhile, most cities are not resilient to system shocks such as climate events or public health threats.

Both the ecological and economic prosperity of cities will continue to shape countries' contributions to long-term planetary sustainability. According to the World Economic Forum, city systems, the climate crisis and climate action failure pose the greatest, most likely and highest risk to humanity's future. Thriving cities are imperative to ensure planetary ecological survival. In the future of cities, we have our greatest and most shared wicked problem at hand. What tools do we have at our disposal to get to work on this?

Future-ready African cities

In fighting the climate crisis, complex megacity concerns and technological disruption, new ideas are emerging in city-making tools: the Smart City, and its big brother, the Digital Twin City.

A Smart City utilises digital sensors and communication technologies to improve the services, environments, infrastructure, performance, and social and health objectives of cities. Proponents offer "smart solutions" as the means to achieve resilient, socially equitable and climate-smart cities. System shocks (such as Covid-19 or climate events) expose the vulnerabilities of cities, which further accelerate the application of smart or digital solutions[2].

A common starting block to make cities "smarter" is to create instruments that improvise city performance efficiency. One such instrument is the digital twin – a smart 3D or digital mirror of an object, process or complex system. In city applications, a digital twin provides a real-time virtual model of the urban fabric (streets, buildings and infrastructure), along with real-time resource flows or feedback loops of the physical city.

A digital twin creates a data-driven platform for use and application by a wide range of stakeholders, serving as an armature into which other digital data can be plugged. These environments lead to rich, virtual, interactive models, simulations and visualisations.

Digital twin city environments allow for a multitude of real-time research and experimentation opportunities to occur, such as real-time urban service monitoring tools and processes, scenario and prediction design, risk and performance management, maintenance planning and operations, or design simulations of development interventions.

The Hatfield Digital Twin City

The Hatfield Digital Twin City is the 10 km^2 urban area surrounding the University's main campus. It includes a multitude of university-owned residential assets, natural systems, the UP Experimental Farm, the University's Sports Campus, the Innovation Africa @UP Campus and other unique asset and environmental classes. The University is the dominant permanent asset and infrastructure owner in this territory, managing and owning approximately 65% of the land, communities,

2 Allam, Z. and Jones, DS., 2021. Future (post-COVID) digital, smart and sustainable cities in the wake of 6G: Digital twins, immersive realities and new urban economies. Land Use Policy, 101, pp. 105201.

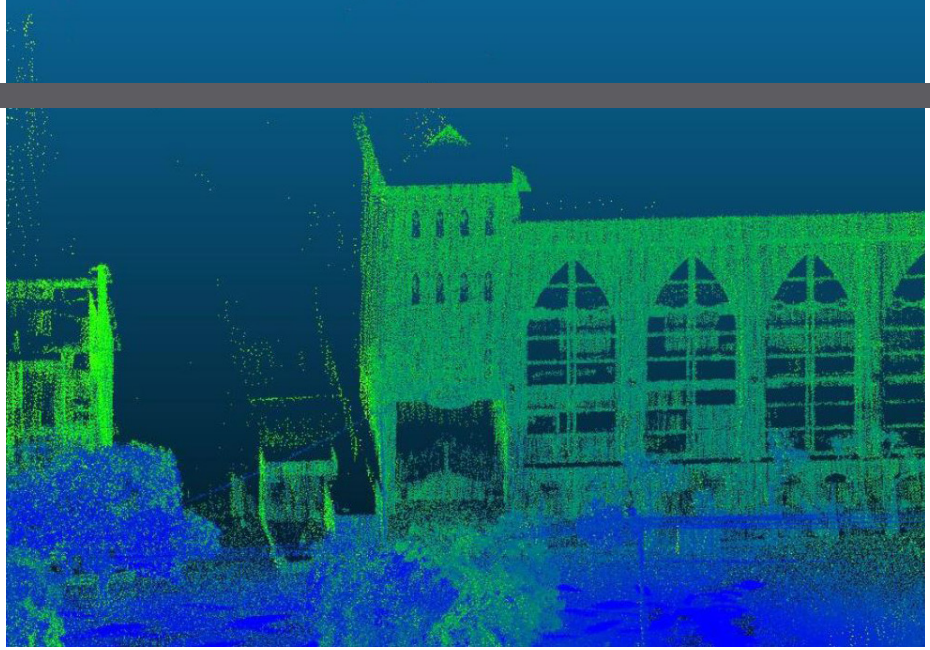
systems or stakeholder relations in this space. This puts the territory at a unique advantage to develop a world-leading comprehensive digital twin city: a living laboratory that can generate value in education, research, innovation and development trajectories in Africa.

The Hatfield Digital Twin City is transdisciplinary and non-exclusionary, allowing for direct vertical and horizontal collaboration between all academic disciplines, while inviting direct engagement with the public sector, industries and markets. It is already aligned with several key local city stakeholders' objectives, including the Hatfield CID, the City of Tshwane and the CSIR.

Future African city-makers – solving wicked problems together

The contemporary and future uncertainties are growing exponentially and are shifting more rapidly than the prevailing regulations, standards, guidelines and best practices in African city-making can accommodate.

Our historic and customary urban practices usually take a deterministic approach. This approach was useful in helping to reduce degrees of uncertainty. However, uncertainties are very high today and are increasing at alarming rates. Along with impacts of current and future scenarios, a deterministic approach simply cannot deliver the results we need.



The urgency of action necessary to improve complex systems, like cities, requires us to produce practitioners who are really good at operating in complexity and uncertainty. If we want to solve the wicked problems of the future of cities, we need complex critical thinkers who can think on their feet, work well with others, and leverage technology quickly to achieve their goals.

With the Hatfield Digital Twin City, we aim to create both high-end and low-data, and low-cost and real-time virtual labs for research, innovation, education and training. We hope to maximise our laboratory to greatly expand our remote and distributed learning capabilities, allowing anyone from anywhere to participate.

The digital twin city can integrate much of the baseline learning in our current education practices.

Much of the baseline data necessary to construct such twins includes the production of maps, 3D buildings, engineering instruments, measurements, community engagement, interviews or observations. These are all standard practices and discipline agnostic. Furthermore, the upkeep of datasets, experiments and learning within comprehensive virtual cities is vital to the health of virtual laboratories.

To solve the great wicked problem of cities and the crisis of our climate future, we need novel practices that produce vertical and horizontal integration among built environment practitioners. The future is indeed in city-making, but we urgently need another playbook, better tools and improved skills. To develop these, we need a laboratory: a comprehensive complex system that imitates the real world - as seen in the digital twin city.

Engineered solutions enhance agricultural exports

Ensuring that agricultural products intended for the export market arrive at their destination unblemished and suitable for further distribution and sale is a challenge experienced by producers in South Africa.

Researchers in the Department of Civil Engineering accepted this challenge to find an innovative solution. This entailed the combination of traditional civil engineering with electronics, the internet of things (IoT), programming, computer science and additive manufacturing (3D printing).

This flagship project involved monitoring the transportation by cargo ship of a consignment of avocados destined for Rotterdam in The Netherlands, from where it would be further distributed throughout the European Union. The research team made use of the Department's unique smAvo sensor platform, which is used to monitor the entire value chain, from farm to fork.

To optimise the data recorded during the transportation of the avocados, the team developed a measuring instrument with microsensors embedded in a number of 3D-printed avocados with a soft water-resistant outer covering that would be exposed to the same conditions as the real produce surrounding them. This instrument was developed from "off-the-shelf" components and microcontrollers. It was programmed and customised for the objectives of this particular project so that live, real-time data could be collected and stored for analysis.

Real-time data on the ship's location in the Atlantic Ocean, as well as weather conditions throughout the trip, was sent to the University's researchers at Engineering 4.0 in Pretoria, where the data was captured on a central platform for analysis, interpretation and recommendations for future action.

The microsensors with which the "smart avos" were fitted measured variables such as accelerations in speed, rotational movements of the ship and temperature, as well as other elements of the ship's behaviour, to determine whether this impacted on the produce itself and the condition in which it arrived at its destination.

It also determined whether the cold chain was preserved along the route.

This data will later be linked to maritime data such as the height of the waves, wind speed and the direction in which the ship is travelling, which were obtained from satellite data. This information is not just of value to producers to ensure that they can obtain top prices for South Africa's best products, but also to avoid additional costs related to transporting products that have been damaged or are no longer suitable for trade in the export market back to South Africa.

Reimagining transportation networks for a digital future

The development of digital technologies for the country's rail networks forms part of the University of Pretoria's endeavour to realise data-driven smart cities and transportation networks for the future. This forms part of research conducted in the Chair in Railway Engineering.

One of the initiatives that is already making an impact in the fast-developing world of the digital railway is that of condition monitoring. This is a technique that makes use of Big Data, Artificial Intelligence (AI) and the Internet of Railway Things (IoRT) to monitor the condition of railway assets. A test track that has been established at Engineering 4.0, together with a special road/rail vehicle that has been developed for sophisticated infrastructure condition monitoring, is utilised for the real-world testing of the data obtained via digital monitoring.

Condition monitoring traditionally utilises a dedicated instrumentation vehicle that periodically measures the track geometry, quantifying parameters such as the gauge, profile, alignment, twist and cant. These vehicles are specialised and are frequently unavailable for the entire network of track that carries regular traffic.

This limitation gave rise to the development of an innovative system that makes use of 4IR technology to replace the relatively slow traditional methods of obtaining geometric measurements. These include techniques such as simultaneous localisation and mapping (SLAM) and photogrammetry, which produces high-resolution three-dimensional (3D) reconstructions that incorporate and combine state-of-the-art neural network architectures.

By fusing AI approaches with traditional research methods, a new type of condition monitoring allows the rail industry to improve the safety, efficiency and cost-effectiveness of its rail and train control systems.

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