Protecting Railway Transport: Advancements in Autonomous and Automated Geodetic Deformation Monitoring

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Key words: automated monitoring, autonomous, railway, innovation, safety, reliability, resilience

SUMMARY

The growing demand for fast and sustainable transportation within cities and across countries stimulates continuous modernisation in railway transportation to improve safety and security, achieve operational excellence, enhance the passenger experience and reduce carbon emissions. Employing faster trains at a higher traffic frequency, however, causes additional strain on the railway infrastructure. Age, geological instability and nearby construction work can also contribute to track geometry vulnerabilities, potentially endangering the safety of passengers and everyone in the rail vicinity, as well as creating economic losses for railway and metro-urban operators.

Surveying has always been crucial to railway construction and operation, including manual monitoring methods to calculate displacements. However, the path from raw total station measurements (i.e., angles and distances) to information about twist and alignment as parameters of track geometry is long and paved with configuration and computation parameters. Each of these can be a point of error, leading to incorrect or missing results and ultimately affecting the safety of railway transport. Therefore, the fewer manual steps are in that path, the higher the rate of accurate, successful measurements, and the more complete the data.

Transforming manual data acquisition into the autonomous collection and automating data processing is a significant advancement toward providing dependable data to stakeholders and decision makers. The latest innovations in Leica Geosystems' monitoring solution ensure highly resilient and autonomous data acquisition with continuous and uninterrupted dataflow. Automated measurements minimise the time surveyors need to be on the tracks and a recently released railway computation feature makes error-prone manual track geometry configuration and computation a thing of the past. Altogether, these advancements minimise errors and produce rich, comprehensive data used to maximise safety through timely and informed interventions.

Railway transportation has never been faster and more reliable, yet the stakes for its safety have never been higher. Utilising innovative deformation monitoring systems which continue to advance alongside railway technologies delivers crucial information that railway operators can rely on to keep high-speed, high traffic rail transport safe.

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1. INTRODUCTION

Technology trends in the rail sector span from autonomous train systems supporting efficient and reliable railway transportation, to modern railway mobile communications systems enhanced with 5G technologies, to high-speed rail and robotic systems for infrastructure maintenance. In China alone, the length of high-speed railways exceeded 40,000km in 2021 (Jie, et al., 2022). As railways expand, more freight is also transported by rail, reducing road congestion and auto emissions. The growing demand for fast and sustainable railway transportation within cities and across countries stimulates continuous modernisation to improve safety and security, achieve operational excellence, enhance the passenger experience and reduce carbon emissions.

Increasing the speed and frequency of trains puts additional strain on railway infrastructure, which may be further compromised by factors such as its age, geological instability, and nearby construction. Such vulnerabilities in the track geometry not only pose a threat to passenger safety and those in the rail vicinity but can also result in economic losses for railway and metro-urban operators. To mitigate these risks and improve safety, deformation monitoring of the railway and supporting structures and earthworks is essential.

This paper provides foundational contexts of railway monitoring and presents the latest technological advancements in Leica Geosystems' railway monitoring solution, including elements which ensure the quickest monitoring project configuration, continuous and uninterrupted dataflow, and standardisation in delivering railway information to the stakeholders.

2. RAILWAY MONITORING

Railway infrastructure is frequently exposed to major events that can compromise its operation and, in severe cases, result in accidents like train derailments, crashes, or breakdowns. Some of the most common challenges that significantly affect railway infrastructure include:

- excavation or construction works in the railway's vicinity
- natural hazard events such as landslides, rockfalls, flooding or other extreme environmental conditions
- variations in subsurface water levels which cause railway subsidence
- changes over time, which may affect the integrity of railway infrastructure, e.g. bridges and tunnels

To help ensure rail traffic safety, regular maintenance and monitoring of railway assets are essential. Deformation monitoring provides comprehensive information about movements, which enables infrastructure owners and operators to make prompt and well-informed decisions.

Depending on the environmental situation, identified risk factors and projects' safety requirements, various railway object types can be monitored. These can be grouped into three categories: earthworks, structures and railway tracks.

2.1 Earthworks

Railway earthworks shape the land adjacent to the track (Figure 1). If the land is lower than the track bed, the earthworks may slope down from the track creating an embankment. If the land is higher than the track bed, the earthworks may slope up from the track forming a cutting. Cuttings and embankments minimise the change in the vertical gradient or alignment along the track due to the ground profile.

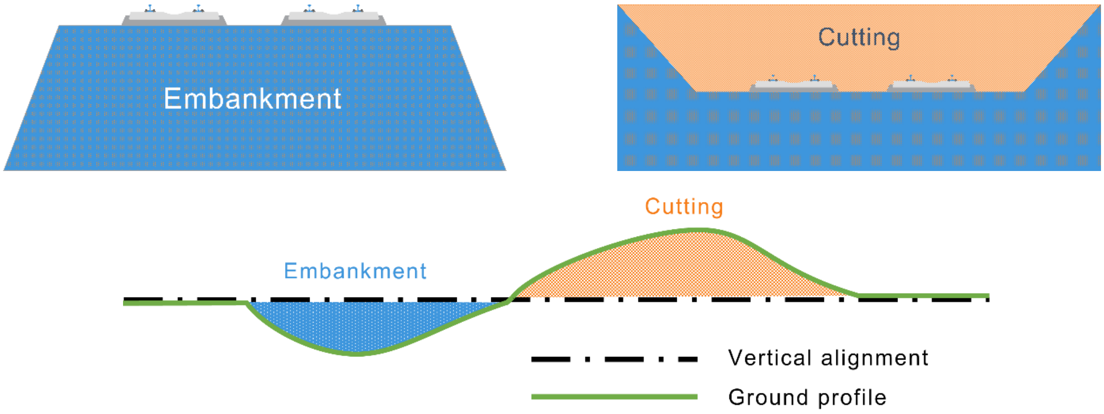


Figure 1 Railway earthworks

Both are susceptible to natural hazards, such as landslides or flooding, usually caused by severe weather conditions and changing water levels, and can result in earthworks failures (Figure 2). Additionally, adjacent construction sites create risk areas where sudden events are more likely to occur.

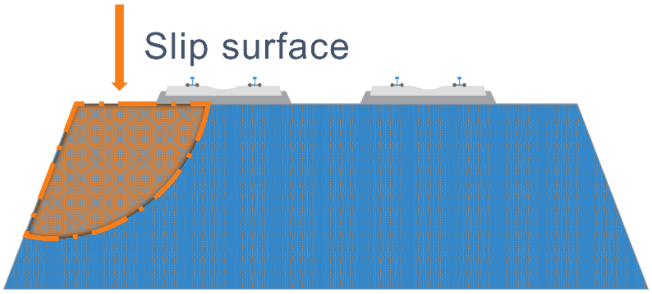


Figure 2 Failure in the earthworks

An unstable cutting slope that collapses and releases vast amounts of soil onto the railway can derail trains, damage the tracks, and harm the surrounding infrastructure. Therefore, monitoring earthworks stability is necessary to detect any deformation and provide timely information. Railway earthworks monitoring is utilised both underground and on the surface. Underground monitoring employs geotechnical sensors, like ShapeAccelArray (SAA), piezometers or extensometers as described in (Hendry, Barbour, & Martin, 2011). Surface monitoring includes geodetic and geotechnical methods, as well as traditional manual measurements.

2.2 Structures

Undertaking construction or excavation work in proximity to railways can result in movements that can affect the structures which facilitate train passage. This includes tunnels (Figure 3), bridges, retaining walls, masts, gantries, and even the track bed, all of which can become unstable and pose a threat to safe rail operation. Another common cause of movements is ageing infrastructure, i.e. the impact of changes over time on the structural health of the infrastructure.

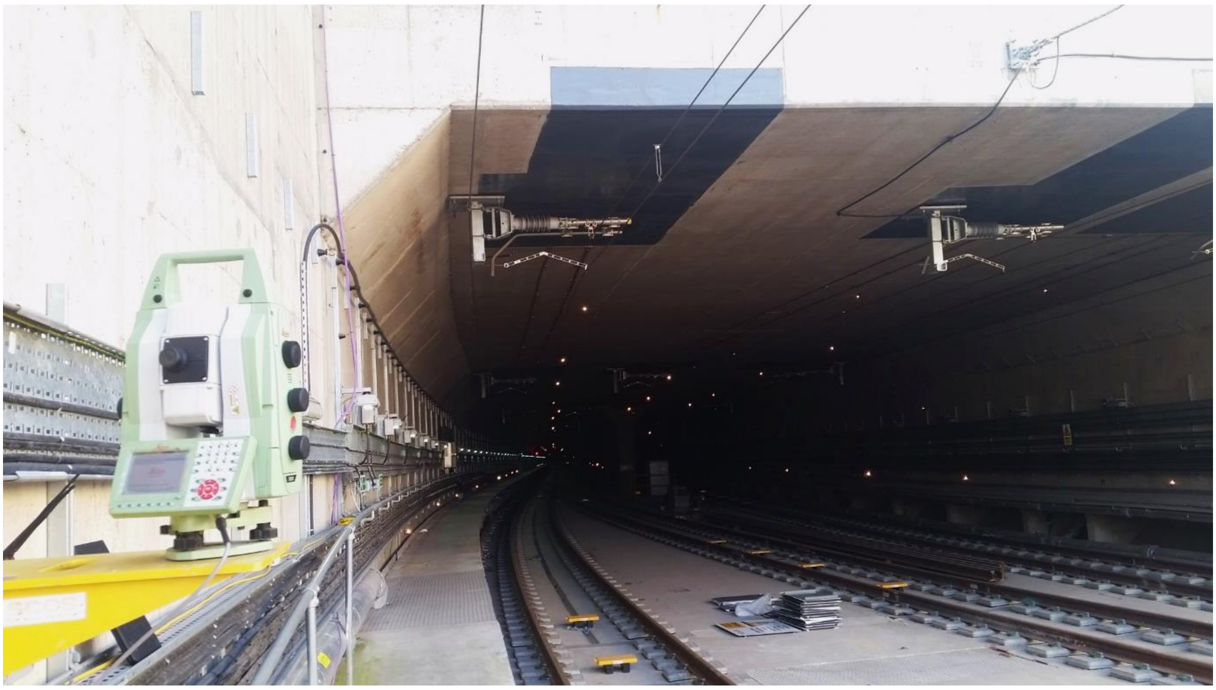


Figure 3 Prism monitoring of a railway tunnel in England

Apart from railway transport safety, monitoring is also required to observe the stability and reliability of the structures adjacent to the railway track to document changes and facilitate their maintenance and repair. For instance, damage to the railway tunnel or changes to its shape would affect the passage of trains, even though the tracks may be intact. Similarly to earthworks, structures are monitored on the surface and also underground, including foundations or the ground surrounding the structure.

2.3 Railway tracks

Railway track is a composition of different elements, including rails, sleepers, rail fasteners, ballast, or subgrade (Figure 4):

- **Rails** are the most important components of track structure, as they guide the train wheels forward and withstand the heavy pressure and wear of wheels
- **Sleepers** or railroad ties, not only support the rails but also maintain their position by transmitting the pressure to the ballast
- **Rail fasteners** fix rails to rail sleepers and therefore prevent their lateral and horizontal movements
- **Ballast** is a layer of broken stones or selected other granular material placed under the railway track. It fixes the position of the sleepers to maintain the correct line and slope of the track and provides drainage to the track area. Ballastless track or slab track, a continuous concrete slab under the rails and fasteners, can also be used for areas of heavy traffic or high-speed rail to reduce maintenance.
- **Subgrade (earthworks)** holds rails, sleepers and ballast, and supports the railway track from the bottom layer

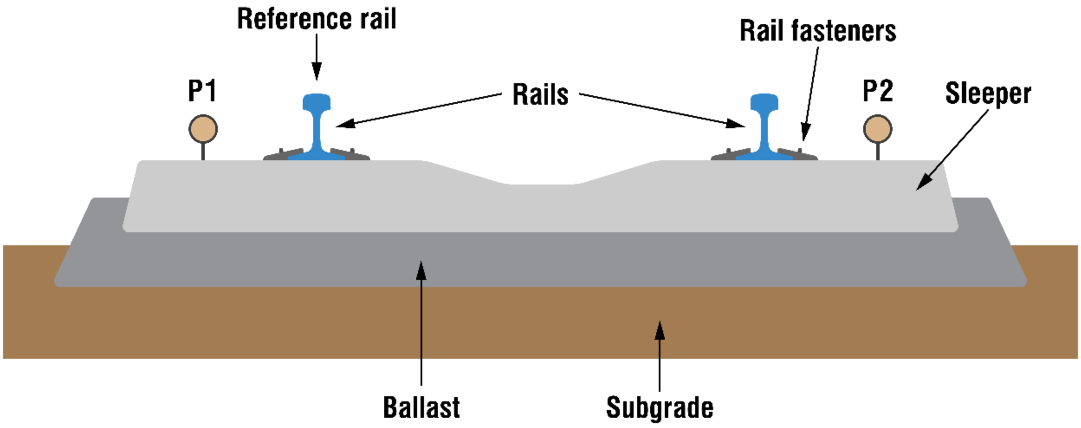


Figure 4 Components of a railway track

Deviations from the original geometric position of the track can pose severe risks to the safe passage of trains. The most common causes of track geometry changes include frequent heavy train transit over long periods of time putting strain on track geometry, high temperatures, and subsurface movements caused by natural hazards or changing water levels. Accurate measurements of the railway track geometry are therefore required to validate the track is operating per specification, ensuring safe and efficient use.

Changes in railway track geometry can be monitored by calculating changes in its parameters, including cant, twist, vertical and horizontal alignments, height displacement or difference in gauge. The most important geometry parameters are described in more detail in the following chapter.

Figure 5 Prisms along the railway track

Deformation monitoring of track geometry can be carried out using a variety of measurement techniques and methods providing different data, measurement frequencies, automation levels and required human presence on the tracks. The most accurate 3D technique, however, is robotic total station measurements of prisms installed on sleepers along the railway track (Figure 5Figure 1).

2.4 Railway track geometry parameters

Track geometry pertains to the characteristics and interconnections of points, lines, curves, and surfaces in the 3D positioning of railroad tracks. It determines regulations, speed limits and standards, usually observed in horizontal and vertical layouts that dictate the track's gauge, alignment, elevation, curvature, and surface. Track geometry also includes the measurements utilised in the design, construction and maintenance of the track. The reference rail (Figure 4) serves as the base rail and reference point for these measurements. While definitions vary across countries, usually one of the rails is commonly designated as the reference rail, e.g., the left rail in the direction of the chainage. Track geometry parameters are calculated with respect to the reference rail.

2.4.1 Cant

Cant, track crosslevel or superelevation is a parameter that describes the level difference between the two rail heads. In the case of geodetic monitoring (Figure 6), calculation of the cant depends on the position of the monitoring prisms and the distance between measured points needs to be scaled to the track gauge to be correct. For high accuracy results, monitoring prisms should be installed outside the two rails where practical, e.g. on the sleepers, so that the distance between the prisms is greater than the gauge. The gauge is the stretch between the inner sides of the heads of the two rails, which for standard rails lays at the value of 1485mm. Cant is often computed as the height difference over the base of 1500mm for a standard gauge railway of 1435mm.

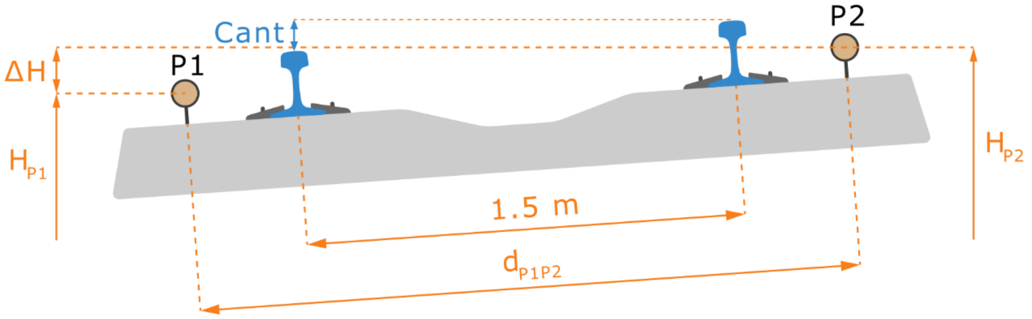


Figure 6 Geodetic monitoring of cant

2.4.2 Twist

Twist or torsion is the relative variation of cants over a given distance along the track. Cants for the twist calculation are usually measured over a defined distance, e.g. 3-5m depending on project requirements. As the most common deformation type and cause of train derailments, twist is the most important parameter of the track and is generally reported as a gradient (‰ or mm/m). If any deviation beyond track operation limits is detected in the twist calculation, it is important to take immediate action for remedial works to restore the correct track geometry. In geodetic monitoring, twist calculation always includes four prisms (Figure 7) from two consecutive or distant sections (long twist).

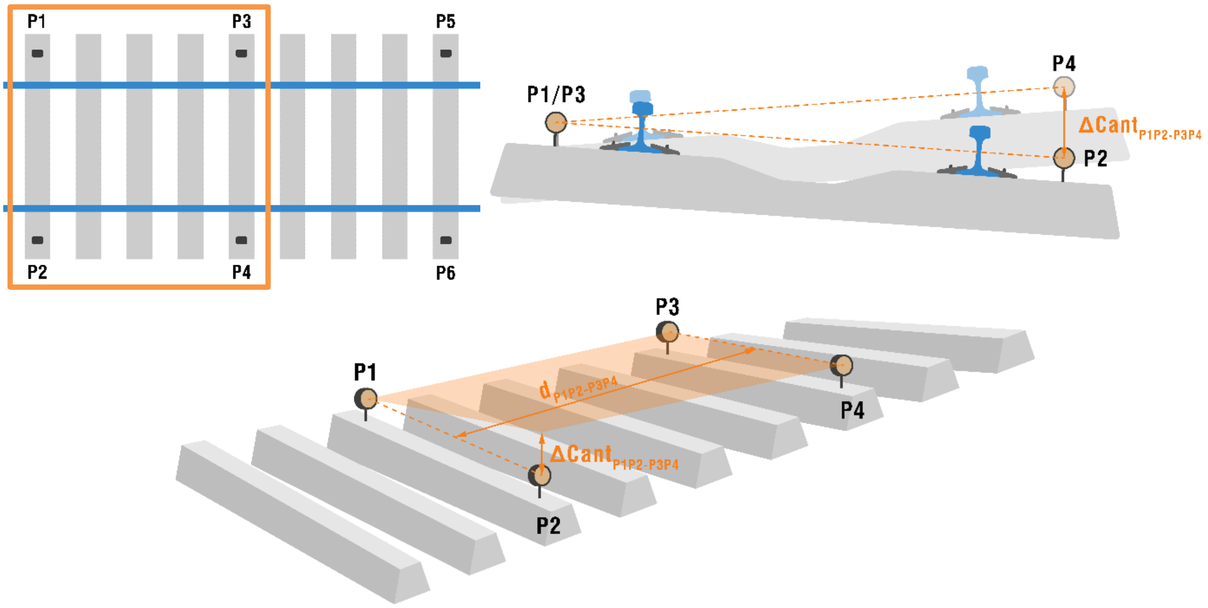


Figure 7 Geodetic monitoring of twist shown in 2D and 3D

2.4.3 Alignments

3D positioning of the tracks is, as mentioned above, observed in horizontal and vertical layouts. Horizontal layout is the track layout on the horizontal plane, i.e. the plan view of a track from the position above the track. Vertical layout, on the other hand, is the track layout on the vertical plane. The term **alignment** is used in both horizontal and vertical layouts to describe the directional axis of the railway track and therefore railways have both **horizontal** and **vertical** alignments.

Horizontal alignment is the geometry of the track centreline projected onto the longitudinal horizontal plane. It is used to determine deviations in the horizontal direction along the rail. Vertical alignment is the geometry of the track centreline projected onto the longitudinal vertical plane. It is used to determine deviations in the vertical direction (height) along the rail. Alignment tolerances for deviations from design depend on maximum allowed speed of the train for defined rail sections.

In geodetic monitoring, alignment calculation always includes six prisms (Figure 8) from three sequential sections along the track.

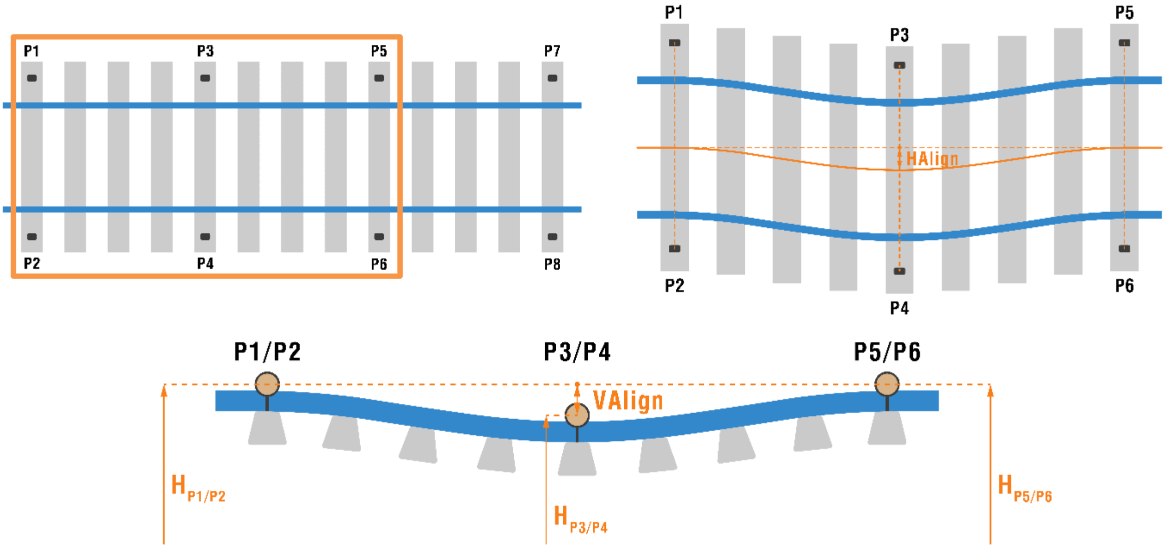


Figure 8 Geodetic monitoring of horizontal and vertical alignments

3. MONITORING TECHNIQUES

Railway tracks require regular examination to evaluate the track quality and ensure their efficient operation. This can be achieved through various measurement techniques and methods, each providing different types of data, measurement frequencies, levels of automation, and human presence required on the tracks.

Depending on the spatial context, monitoring methods can be categorised in the following way:

- **Relative** monitoring, which provides information about rotation and relative individual measurements, like cant and gauge measurements, but without global reference
- **Quasi-absolute** monitoring, which is absolute within the system, but unrelated to an external reference
- **Absolute** monitoring, which provides absolute X/Y/Z measurements, referenced to an external datum


Figure 9 Examples of hybrid monitoring techniques

Railway monitoring projects are often similar, yet they typically entail distinct measurement requirements that vary depending on the type of railway line, its location, speed or use. Although optical 3D measurements can typically fulfil the most demanding requirements and deliver data with millimetre-level accuracy, in certain scenarios optical measurements alone aren't sufficient to provide the full picture of movements in the railway environment.

Therefore, using hybrid monitoring systems (Figure 9) comprised of complementary and independent measurement systems and techniques provides data redundancy by observing different parameters and enhances the understanding of deformation. For example, hybrid systems can include various combinations of manual, semi-automated and automated data acquisition methods using geodetic and geotechnical sensors, such as manual levelling or total station monitoring combined with automated tilt measurements. The biggest advantages of hybrid systems are realised when the acquired data is processed and analysed within a single monitoring software, such as Leica GeoMoS, so that all information is available within one platform.

3.1 Geodetic monitoring

Geodetic deformation monitoring, in its essence, is an application of surveying methods by measuring the same object repeatedly and analysing the displacements (Figure 1010). This can be done with manual, semi-automated and automated data acquisition methods. Geodetic railway monitoring techniques include total station measurements and precise levelling.

However, GNSS is rarer and typically only used for reference network measurements or cutting slope monitoring. Another geodetic method is patch scanning of sleepers or other infrastructure near the track using the Leica MultiStation laser scanning total stations (Leica Geosystems AG, 2019), applied when monitoring sensors like prisms cannot be physically mounted on the track. The results of geodetic measurements are displacements in 3D or 1D (height).

Surveying has always been crucial to railway construction and operation, including manual monitoring methods to calculate displacements. However, the path from raw total station measurements (i.e., angles and distances) to information about twist and alignment as parameters of track geometry is long and paved with configuration and computation parameters. Each of these can be a point of error, leading to incorrect or missing results and ultimately affecting the safety of railway transport. Therefore, the fewer manual steps are in that path, the higher the rate of accurate, successful measurements, and the more complete the data.

Automation of error-prone tasks within surveying and monitoring is the key to delivering reliable and dependable information to stakeholders. While the latest surveying automation innovations from Leica Geosystems are described in (Maar, 2022), automation in monitoring is the topic of chapter 4.

Figure 10 Surveying and monitoring of a railway platform construction in Switzerland and Australia

3.2 Other techniques

A comprehensive range of other measurement techniques can be used to measure and monitor track geometry using different sensors, such as IoT geotechnical sensors, cant and gauge sticks, railway geometry trains, dynamic void meters, rail trolleys and others. Their data acquisition methods range from manual to fully automated. Manual techniques, e.g., rail trolley, cant and gauge stick or railway geometry train, require safe track access at each measurement, which also means that train operation must be stopped while tracks are measured. On the other hand, modern IoT sensors, such as WiSenMeshWAN®, support automated data acquisition delivering real-time displacement information while train traffic remains operational. Vibration monitoring is a particular automated monitoring technique that involves taking high-frequency measurements while a train passes to analyse soil damping and comprehend the transmission of vibrations from the tracks to the surrounding foundations.

4. AUTOMATION AND AUTONOMY IN GEODETIC MONITORING

Automated geodetic monitoring systems have been in use for more than three decades (Brown, Kaloustian, & Roeckle, 2007). However, automating data acquisition and processing is just a first step towards autonomous monitoring systems, which provide additional intelligence and adapt to environmental conditions automatically. This brings resilience to monitoring systems, facilitating data completeness and ultimately providing dependable data to stakeholders and decision-makers.

Each automated monitoring system consists of four components (Špiranec & Niel, 2021):

- **monitoring sensors**, which collect raw measurements at defined intervals
- **power supply**, which is essentially a 24/7 power source for the on-site equipment
- **communication device**, which enables near-instantaneous data transfer between the field and the office
- **monitoring software**, which processes measured data from the field sensors and provides near real-time information about movements

The latest innovations in Leica Geosystems’ monitoring solution ensure highly resilient and autonomous data acquisition with continuous and uninterrupted data flow. These innovations focus on the **instrumentation setup** to minimise “time to monitor”, **autonomous data acquisition** to ensure data completeness, and the standardised **configuration of railway geometry computations**, which provides railway operators and stakeholders with instant, reliable information about movements. Altogether, these advancements minimise errors and produce rich, comprehensive data used to maximise safety through timely and informed interventions.

4.1 Instrumentation setup

Instrumentation setup entails the process between the physical installation of sensors and other equipment on-site and the moment when data collection starts. It is, in fact, the process of configuring the monitoring system within the software, from adding the sensors to the project to triggering the automated measurement cycle. The bigger the project, the more equipment is required and the longer the setup procedure.

A significant advantage of the Leica GeoMoS software suite is that it allows for the centralised configuration of all communication devices and sensors. From a single interface, the user can pair all Leica ComBox60 devices via EdgeConnect technology and simply add sensors connected to them. The most time-consuming process is adding or learning (measuring for the first time) the prisms. One method requires measuring prism positions manually, e.g. with GNSS rovers, one by one with a total station on-site or using a total station's cameras via software interface. Alternately, robotic total stations provide a way to automate prism learning. For example, the Leica TM60, the total station built specifically for monitoring, in combination with GeoMoS provides an automatic detection and learning of prisms within a defined area. The GeoMoS AutoLearn feature (Špiranec & Niel, 2021) is especially valuable and time-saving in railway monitoring, as prisms are usually very densely positioned along the track and each total station measures dozens of them.

Automation in instrumentation setup is also a considerable safety benefit, as it eliminates the need for surveyors' presence on tracks once the instrumentation is installed on-site. Simultaneously, it is a cost-effective measure for the railway company as transportation can remain operational during monitoring project configuration.

4.2 Autonomous data acquisition

Autonomous data acquisition is the step that comes after instrumentation setup and starts with the moment of triggering the automated measurement cycle. Automated measurements are driven and operated by software, unlike manual ones which are carried out by a surveyor on-site. Automation in data acquisition, therefore, supports the same safety and economic measures as mentioned above. The innovation of the Leica Geosystems monitoring solution lies in multiple aspects, which support autonomous operation.

Figure 11 Leica TM60 with ComBox60

The first innovation is the **Leica TM60**, the only self-learning monitoring total station in the world. ATRplus technology enables the TM60 to adapt to changing environmental conditions by automatically setting the correct measurement parameters for the best automatic target recognition performance (Grimm, Kleemaier, & Zogg, ATRplus, 2015). In an automated monitoring context, this means higher measurement frequency and data completeness. The Leica TM60 is also equipped with a Piezo-Drive system. This ensures smooth long-term operation, reliability and stability independent of the surrounding conditions (Grimm & Zogg, 2013), which translates into longer maintenance intervals. Another important TM60 feature for railway monitoring is the small field of view – its ability to distinguish densely placed prisms at longer distances provides the precision needed to capture all data. The Leica TM60 can also measure prisms with an angular accuracy of 0.5” with automatic target recognition up to 3000m.

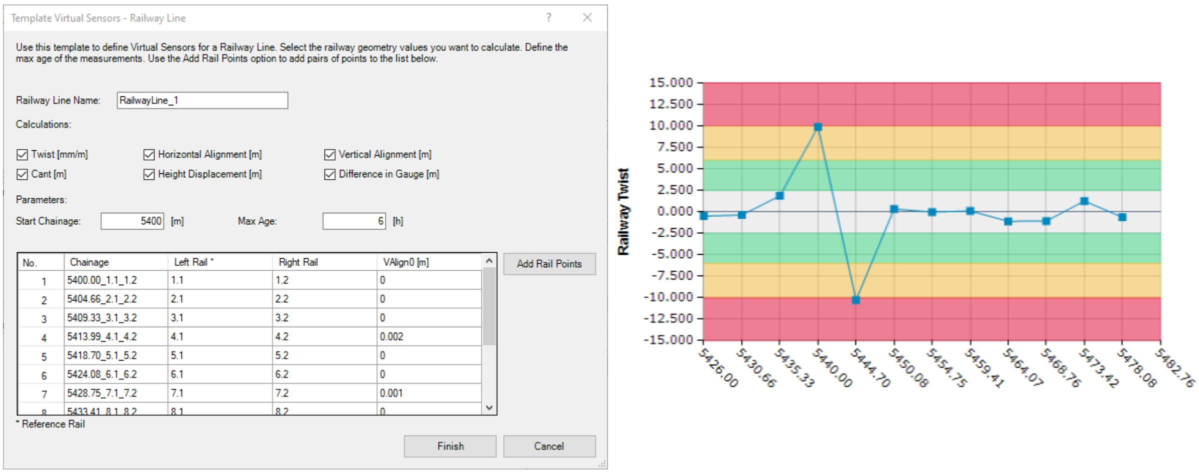
Another very important autonomous aspect of data acquisition is the **Leica ComBox60** (Figure 11), the monitoring communication and power management device, with an embedded **GeoMoS Edge** software component. The hardware part of the solution offers an IP66-rated weather-resistant enclosure with cellular and ethernet communication interfaces and a battery as a temporary fallback power solution in case of malfunction or outage of the primary power source. The onboard software allows for secure connection to the office software via EdgeConnect, which the device receives the measurement cycle configuration from and sends raw measurements to. GeoMoS Edge is the edge computing technology responsible for the autonomous execution of the measurement cycles. It controls the sensors, checks and validates the quality of raw data, automatically triggers repeated measurements in case of unsuccessful or low-quality initial measurements and stores the data locally on the ComBox60 in case of communication failure. ComBox60 is the key element enabling the monitoring system’s autonomy, ensuring the full operability of sensors and continued data acquisition in case of power failure or lost communication with the office software, or both. It represents the resilience of the monitoring system and, in combination with the TM60 and Leica GeoMoS, offers the most intelligent monitoring solution on the market.

4.3 Railway geometry computation configuration

The step of configuring railway track geometry calculations usually comes directly after the instrumentation setup, but from the monitoring system’s perspective, it is the process that defines which collected data will be utilised for the calculation of the railway geometry parameters. The **Railway Template feature within Leica GeoMoS** automates the configuration and computation of track geometry parameters, significantly reducing setup time and, correspondingly, the time needed until results are delivered to the stakeholders.

Manual definition of input data and formulas and exporting data to third-party software for computations increases the chances for errors, especially in bigger projects, and can create delays in delivering important information. Additionally, faulty calculations can lead to undesirable outcomes such as failing to report relevant movements or falsely reporting non-existing or irrelevant movements, both of which can have serious consequences.

By using Leica GeoMoS for railway monitoring, the need for manual inputs or as-built surveys is removed, configuration and calculation of track geometry parameters, such as cant, twist or alignments are automated and synchronised with total station measurements, ensuring standardised output. Additionally, GeoMoS generates reports and provides automated notifications if user-defined thresholds are exceeded. The Railway Template feature completes Leica Geosystems’ solution for high-quality railway monitoring (Figure 12).



Template Virtual Sensors - Railway Line

Use this template to define Virtual Sensors for a Railway Line. Select the railway geometry values you want to calculate. Define the max age of the measurements. Use the Add Rail Points option to add pairs of points to the list below.

Railway Line Name: RailwayLine_1

Calculations:

☑ Twist [mm/m]
☑ Horizontal Alignment [m]
☑ Vertical Alignment [m]
☑ Cant [m]
☑ Height Displacement [m]
☑ Difference in Gauge [m]

Parameters:

Start Chainage: 5400 [m]
Max Age: 6 [h]

No.	Chainage	Left Rail *	Right Rail	VAlign0 [m]
1	5400.00_1.1_1.2	1.1	1.2	0
2	5404.66_2.1_2.2	2.1	2.2	0
3	5409.33_3.1_3.2	3.1	3.2	0
4	5413.99_4.1_4.2	4.1	4.2	0.002
5	5418.70_5.1_5.2	5.1	5.2	0
6	5424.08_6.1_6.2	6.1	6.2	0
7	5428.75_7.1_7.2	7.1	7.2	0.001
8	5433.41_8.1_8.2	8.1	8.2	0

* Reference Rail

Figure 12 Configuration of railway template and visualisation of results in GeoMoS

5. CONCLUSION

Railway transportation has never been faster and more reliable, yet the stakes for its safety have never been higher. The safe operation of trains and railway infrastructure can be jeopardized by undetected rail track deformations. Therefore, monitoring of railways, including the track geometry, adjacent structures and earthworks, is crucial to identify infrastructure vulnerabilities.

The purpose of deformation monitoring systems is to inform about movements in the monitored area. Independent from the monitoring technique itself, higher automation in monitoring requires less human presence on the tracks, increasing safety and reducing operational costs. Monitoring systems that operate autonomously represent a further enhancement in which on-site equipment holds its own intelligence. This enables automatic reaction and adaptation to environmental conditions, making the monitoring system highly resilient to external effects.

Leica Geosystems monitoring solution offers a broad and scalable hardware and software portfolio, which fulfils even the most demanding project requirements. This includes geodetic monitoring and gathering and processing data from hybrid monitoring systems in a single interface to provide a complete understanding of deformation. In the railway monitoring context, using high-end equipment and software, including the TM60 monitoring total station, ComBox60 communication and power management device, and Leica GeoMoS, ensures the highest level of monitoring automation and autonomy. From quick and self-acting instrumentation setup to intelligent data acquisition management and, finally, to template-style configuration of rail track geometry calculations, the workflow is tailored for the highest quality deliverables and reliable information about movements.

Utilising innovative deformation monitoring systems which continue to advance alongside railway technologies delivers crucial information that supports progress towards fast and sustainable passenger and freight railway transportation whilst mitigating economic and safety risks.

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BIOGRAPHICAL NOTES

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