Investigating the precision of remote geodetic sensors for bridge monitoring: a large-scale field study

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Abstract

As infrastructure ages, monitoring is becoming increasingly important to ensure the safe operation of civil structures. Modern geodetic sensors can provide static and dynamic displacement data of these structures up to several hundred Hertz. As the measurements are made remotely, no direct access to the structure is required. While the precision of static geodetic measurements has been extensively studied, dynamic measurements have not been sufficiently investigated. To overcome this limitation, the dynamic capabilities of Robotic Total Stations (RTS) with respect to the precision of angle and distance measurements are investigated. The measurement systems were used in a large-scale load test on an Austrian motorway bridge. Several sensor systems such as RTS and Profile Laser Scanners (PLS) were used to monitor the structure and compare the capabilities of the sensors themselves. Controlled loading tests were carried out where two trucks, each weighing over 50 tonnes, passed the structure being monitored under controlled conditions. Additionally, static load tests were carried out. By comparing the two types of tests, it is possible to highlight the potential of dynamic tests. They offer advantages such as shorter closure times, which can increase the acceptance of load tests.

Keywords: structural health monitoring, sensor investigations, precision, dynamic bridge monitoring, load testing

1 Introduction

While geodetic sensors such as Robotic Total Stations (RTS) and Terrestrial Laser Scanners (TLS) are mostly used for static measurements only, the development of more advanced instruments or algorithms allows the possibility to capture dynamic phenomena of objects as well (Lienhart et al., 2023). Other sensors, such as accelerometers or inclinometers, could provide either static or dynamic information, but not both at the same time. These limitations could be overcome by modern remote geodetic sensors, which can measure static displacements as well as dynamic behaviour up to several hundred Hertz. However, geodetic sensors are not yet widely used for dynamic monitoring. One reason for this is the lack of reliable precision data that can be used in practice. This situation means that users of this technology are de facto unable to provide reliable evidence of the uncertainty they have achieved for the products they generate. In addition, in most cases, inaccurate uncertainty information from data sheets is passed directly to end users, who often continue to use this information without further verification. This paper presents a comparative study and investigates how different sensor technologies complement each other. Furthermore, the achievable precision difference between static and dynamic measurements is investigated. Geodetic sensors in the form of Profile Laser Scanners (PLS) and RTS are used to observe a multispan motorway bridge with different loading scenarios. The geometrical and temporal performance of capturing the bending of a bridge girder is examined. It can be shown, that with geodetic sensors not only static displacements, but as well dynamic movements of the object can be captured when used in kinematic mode.

2 Investigated Sensors

The focus of this study is on RTS and TLS, in their application as PLS (Schill and Eichhorn, 2019), which are very similar in their basic operating principle. All instruments collect polar coordinates consisting of angles in vertical and horizontal directions as well as distances to the observed object. A key difference between the instruments is that a RTS follows a single target and measures to that point at a nominal measurement rate of up to 20 Hz (Leica Geosystems AG, 2016), while a TLS or PLS measures in successive angles and to the surface itself, which is in line of sight. The TLS can measure up to 1 million points per second. The PLS combines this with up to 200 profiles per second (Zoller + Fröhlich, 2017). Due to its operating principle, the PLS can only detect 2D displacements in a profile, whereas the RTS and TLS measurements provide 3D information about the observed prism or object surface.

2.1 Robotic Total Station

The dynamic measurements of RTS are taken with the Leica Streaming App at a nominal measurement rate of 20 Hz. The result is a data entry for each measurement with information on horizontal and vertical angles, distance measurement, compensator and an internal time stamp. From this measurements, a 3D position for the target point can be derived. In order to bring together the different dynamic measurements, the RTS must be synchronised to each other.

2.2 Terrestrial Laser Scanner

TLS captures millions of points throughout the visible environment, creating a 360° panorama in the form of a point cloud, see e.g. Figure 1. The laser beam emitted and reflected by the target is analysed and non-contact distance measurements are performed. As the angles of the emitted laser beam are known, three-dimensional coordinates can be derived. Sequential acquisition is achieved by simultaneous rotation in two directions: the laser beam is deflected by a high-frequency rotating mirror and the TLS rotates around its standing axes.

Figure 1. Extract from the 3D point cloud of span 7 of the motorway bridge. Intensity values are shown as grey scales.

In principle, the measurement method is characterised by a very high spatial resolution, but in turn only allows a low temporal resolution. In addition, the single-point accuracy is in the millimetre range and is therefore not sufficiently accurate for most monitoring applications.

2.3 Profile Laser Scanner

When TLS are used in profile mode (Schill et al., 2019), the instrument only uses the high-frequency rotating mirror, but unlike 3D TLS, it does not rotate around its standing axis, so the laser beam is repeatedly deflected into the same profile. By reducing the spatial resolution to such a single profile, the temporal resolution can be significantly increased. In this way, PLS can be used either to record dynamic and spatially distributed motion behaviour, such as displacements of objects of interest. Or to capture static surface geometry within a profile with increased accuracy by time averaging measurements taken when the structure is stationary. With more than one epoch of statically recorded surface profiles, static displacements can be derived with high spatial resolution and high precision. Both applications involve a spatial approximation of the profiles measured on the object surface. In the simplest case, this is achieved by spatially averaging the closely spaced profile points. In this way the system precision can be significantly increased for both application scenarios.

3 Load testing at a motorway bridge

The Austrian Brenner motorway is part of the E45 European route and crosses Europe in a north-south direction from the north of Finland to the south of Italy. The crossing of the Austrian Alps is a crucial part of the route and is also crucial for the European transnational movement of goods. The motorway crossing of the Alps was mainly built in the 1960s, when the Gschnitztal bridge was also constructed. The structure itself is a steel-concrete composite and is designed as a 7-span continuous beam, with the two outer spans being 70 m long and all others being 84 m long, giving a total length of 560 m. The monitoring of the load test focused on the last two spans adjacent to the southern abutment of the bridge. In this paper we will analyse the measurements at span 7 only, as shown in Figure 2.

3.1 Test Procedure

As part of this monitoring, a load test was carried out in May 2023. One direction of the motorway bridge was temporarily closed so that two trucks, each weighing more than 50 tonnes, could be placed on it to create different load scenarios. The trucks were placed statically in the middle of span 6 and span 7, giving 2 load scenarios. In addition, four dynamic tests were carried out where the trucks crossed the bridge at speeds of 5 or 30 km/h on the first and second lane.

3.2 Test Setup

Six Leica MS60 RTS were set up next to each other to follow the movement of six monitoring prisms mounted directly on the steel girder at span 6 and 7, see Figure 2. A PLS was located under each of the two observed spans, enabling both dynamic and static observations. At span 7 a Z+F Imager 5016 3D laser scanner is used in profile mode, and a Z+F Profiler 9012 is used at span 6.

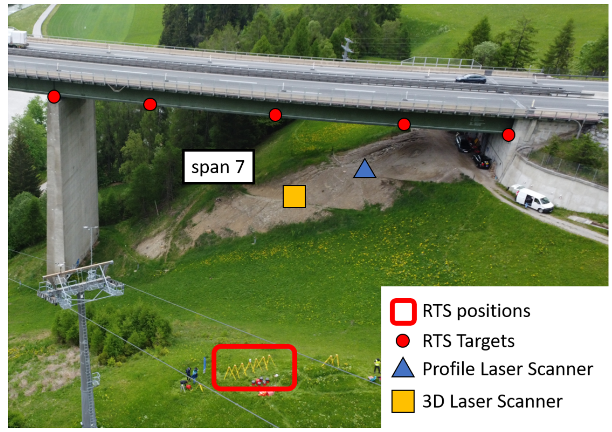

Figure 2. Overview of the observed span of the bridge with the position of the remote sensors.

4 Investigation of the measurement precision

The measurement precision of geodetic sensors is crucial for the reliable detection of both static and dynamic displacements. In this context, both temporal integrity and geometric accuracy are relevant considerations. Particularly in high-frequency measurements, temporal deviations can significantly impact data quality.

4.1 Robotic Total Station

This study analyses the RTS Leica MS60 in terms of measurement precision at varying distances and measurement configurations, as well as the consistency of its timestamps and potential data gaps. Our investigations have shown that on average 17 % of the measurements are missing, resulting in irregular time intervals. Most data points are captured at an effective sampling rate of approximately 23 Hz, but occasional gaps of up to 256 ms reduce the average sampling rate to approximately 21 Hz. In order to maintain a consistent data sequence, these irregularities are corrected by interpolation, ensuring a consistent sampling rate.

The bridge measurements described in Section 3 serve as a baseline for assessing the RTS's geometric precision under real-world conditions. These tests allow for an evaluation of the measurement precision during static load phases, where deviations from zero movement indicate a loss of precision.
Although static analysis do not fully represent dy-

namic behavior, it provides a reference for verifying fundamental measurement precision before analysing more complex dynamic scenarios.

As shown in Figure 2, the RTS targets in the form of monitoring prisms are positioned at varying distances from the RTS station. This setup allows a distance-dependent evaluation of precision. Since the primary motion of the bridge occurs in the vertical direction, the analysis focuses on the z-coordinate. From Figure 3, it can be observed that the precision in the examined range of approximately 50 to 115 metres increases from 0.14 mm to 0.28 mm.

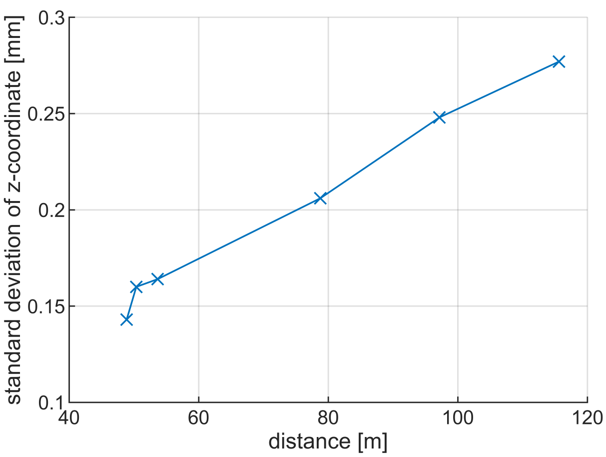

Figure 3. Geometric precision of the six RTS in various distances during static load phases.

Since static observations alone cannot accurately predict sensor behaviour under dynamic conditions, the evaluation of dynamic precision requires a moving target, ideally with a controlled reference motion. To achieve this, additional experiments are conducted using a motion simulator, shown in Figure 4 that generates a sinusoidal oscillation as a reference motion (Schill and Eichhorn, 2016). The measurement precision is evaluated by determining the difference between the measured and generated motion at each time step, followed by calculating the standard deviation of these differences. For the investigations with the motion simulator, the same measuring range of up to 100 m was analysed as for the measurements at the bridge.

The dynamic precision is analysed separately in measurement direction and perpendicular to it to identify the various influencing factors of the distance and angle measurement sensors. As shown

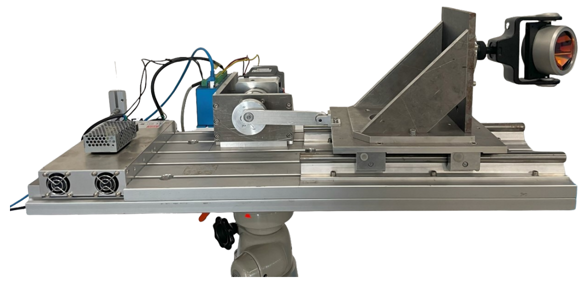

Figure 4. Motion simulator to generate sinusoidal oscillations as a reference motion.

in Figure 5, the data for a 1 Hz and 3 Hz oscillation indicates that the standard deviation of the motion in the measurement direction, which depends mainly on the electro-optical distance measurement, increases only slightly from 0.08 mm to 0.15 mm as the distance increases.

The actual angle measurement is performed through a combination of optical reading of the horizontal and vertical encoder and the Automatic Target Recognition (ATR). The latter is a vision-based method that plays a key role in precision for limited movement amplitudes (Lienhart et al., 2017). The results in Figure 5 show that the angular measurement loses precision with increasing distance; for oscillations perpendicular to the measurement direction, the standard deviation increases from 0.09 mm at a distance of 17 m to 1.03 mm at 103 m. No significant difference occurs between 1 Hz and 3 Hz. This indicates a causal relationship between the geometric measurement configuration, the influence of the different sensors of the RTS and the achievable precision.

The motion simulator represents exactly the opposite case to the static evaluation, continuous motion with large amplitudes. Since the main motion of the bridge is perpendicular to the measurement direction, the precision is best estimated from the results of the motion simulator experiments for perpendicular motion. As the evaluated frequencies make no significant difference to the precision, it can be assumed that these values are generally valid for the used measurement mode. In contrast to the measurements on the motion simulator, the measurements on the bridge took place at night, so the atmospheric influences are presumably lower than in daylight. In addition, the experiments with the

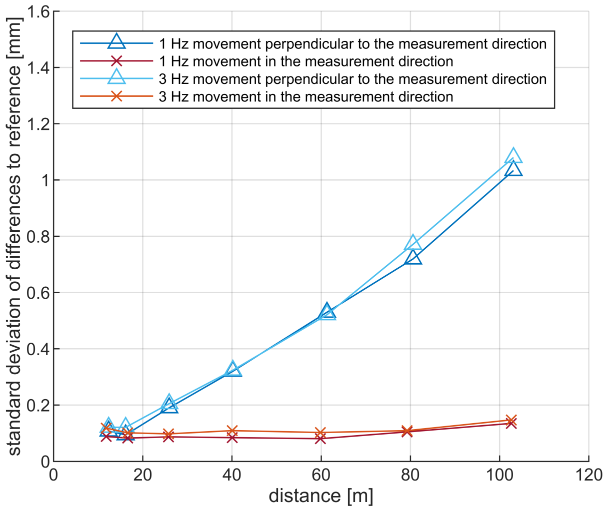

Figure 5. Resulting precision for different distances, geometric measuring set-ups and movement frequencies.

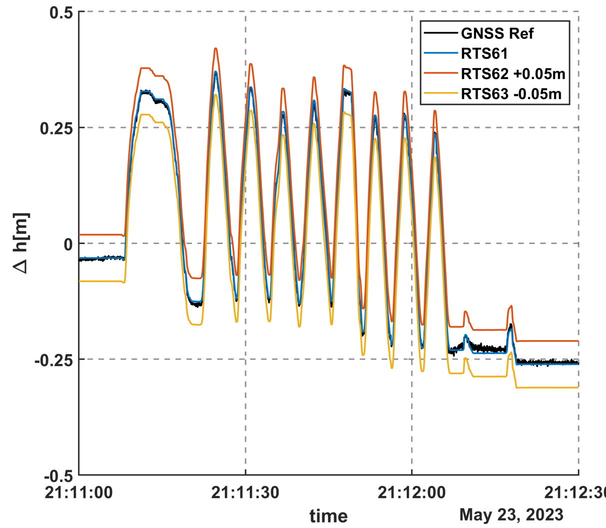

Figure 6. Height component of correlation event of 3 RTS with GNSS Reference, whereby two RTS timeseries are shifted by 0.05m. Mean values are subtracted of the data.

motion simulator are probably more strongly influenced by refraction effects, as the target was positioned closer to the ground than in the bridge tests. Accordingly, the actual dynamic precision at the bridge is probably slightly lower than the precision determined with the motion simulator.

4.1.1 In situ time correlation

To capture the dynamic movement of the bridge at multiple locations, all instruments must share the same time system. The received internal time stamp of the RTS consists of a continuous counter in milliseconds from the moment the instrument is switched on. This means, that all instruments record their measurements in their own time system. To overcome this problem, a synchronisation routine (Gojcic et al., 2018) is performed whereas a 360° prism is put on a pole.

A significant and unique vertical movement is performed while the RTS track the prism. In addition, a GNSS receiver is mounted above the prism to capture the motion using dynamic GNSS measurements which are also performed at 20 Hz. These captured movements are used as a correlation pattern not only to synchronise the different RTS with each other, but also to set the measurements into the global time system provided by GNSS. Figure 6 shows the correlation time series for 3 of the 6 RTS used together with the GNSS motion used as reference. Two RTS time series are shifted by 0.05 m for better visibility.

The correlation of the individual RTS is carried out more frequently so that a device-dependent time drift can be derived from the differences in the correlation. Therefore, correlation events are performed before and after the load tests. The elapsed time between start and end is approximately 5 hours. With 2 RTS, no second correlation could take place because the devices were not switched on all the time, so no time drift could be calculated. The time drift of the instruments can be seen in Table 1 and is given in ppm, which corresponds to 1 μs/s.

Table 1. Time drifts of all used RTS, whereas the RTS numbered for span 6 (61-63) and span 7 (71-73). The RTS 63 and 73 had to be switched off in between, so no time drift could be derived, as the time base of the RTS restarts.

RTS	Serial No.	time drift [ppm]
61	892327	-36.2
62	890300	-34.4
71	890315	-39.9
72	882001	-60.3

4.2 Profile Laser Scanner

The decision as to whether a measuring instrument is sufficient or suitable for a given task in terms of uncertainty is usually made on the basis of data

sheets. In tacheometry, for example, uncertainty information is specified in data sheets by standards such as ISO (2001) 17123-3. This allows direct comparison of different sensors and also allows estimation of the uncertainty that can be achieved in the field by variance-covariance propagation.
By comparison, the situation is unclear even for static terrestrial laser scanners (TLS). All manufacturers relate sensor-specific uncertainty specifications for reflectorless rangefinders, a key component of TLS, to individual and very specific survey configurations, such as different target distances or varying surface characteristics. As a result, neither comparisons between sensors nor reliable estimates for scenarios that deviate from the data sheet are possible (Wujanz, 2023), (Wujanz and Gielsdorf, 2022).

However, to solve this problem, information that TLS records as standard can be used. In addition to the 3D coordinates, an intensity value is recorded for each measurement point, which is the ratio of the transmitted and received signal strength of the signal reflected from the object. As the uncertainty of the phase measurement is directly related to the signal-to-noise ratio (SNR) of the reflected signal (Wujanz et al., 2017), the intensity value includes all effects that influence the measurement process (surface reflection, measurement geometry, atmosphere, etc.).

In Schill et al. (2025) such an intensity-based stochastic model was established for the Z+F Imager 5016 series. Since absolute accuracy is usually not important for monitoring measurements, but rather a relative evaluation, the precision of the distance measurement covers the largest part of the error sources. In the profiles at the Gschnitztal bridge 90 % of the intensity values in the analysed area are between 100,000 and 650,000 Inc, which means that the distance measurements of the individual points have a precision between 1 mm at the periphery of the span and 0.4 mm in the middle.
As described in section 2.3, a spatial approximation of the profiles in so called classes is performed to further increase precision, e.g. by spatially averaging closely spaced profile points.

According to the theory, averaging improves the precision by $\sqrt{n}$, where n = number of measurements. However, the individual laser measurements are not independent of each other, e.g. they overlap and therefore partly contain the same measurement information. Accordingly, the information about the effective number of measurements that contribute independent measurement information is still missing (Schmitz et al., 2020).

Since terrestrial laser scanners always work with a high scanning frequency, even when they are used statically, the measurement modes do not differ in contrast to total stations. This means that a difference in precision between static and dynamic use as a profile laser scanner can be discounted. Accordingly, the corresponding standard deviation of the measurement time series can be easily derived from static time periods of the structure and these also apply to time periods in which the structure is in motion (Schill, 2018). For a bridge crossing of the two trucks at 5 km/h, for which the outcome is shown in Figure 7, this results in standard deviations of just under 0.2 mm at the edge of the span and up to 0.05 mm in the centre.

5 Comparison

As described in Section 3.1, both static and dynamic analyses of the bridge were carried out. The static tests required load holding periods of up to 10 minutes due to the large number of sensors used. The blocking of traffic is correspondingly problematic, with a single test lasting up to 30 minutes. On the other hand, the results of the static tests are more accurate and are used as a reference in the following. By comparison, the dynamic tests only take a few minutes, as the trucks only have to maintain the specified speed on a short section of the bridge. The higher the speed, the faster the test can be carried out, but then dynamic effects can distort the results and the challenge for the sensors increases, especially with regard to the necessary temporal resolution.

5.1 Dynamic vs. static load tests

Figure 7 shows an exemplary evaluation of a dynamic test at 5 km/h. The upper graph displays the time series measured with the PLS approximately at the position of the centre prism in span 7. The rise and fall of the bridge deck can be identified, starting when the two trucks are in span 4, leading to a slight increase in height for span 7. Then

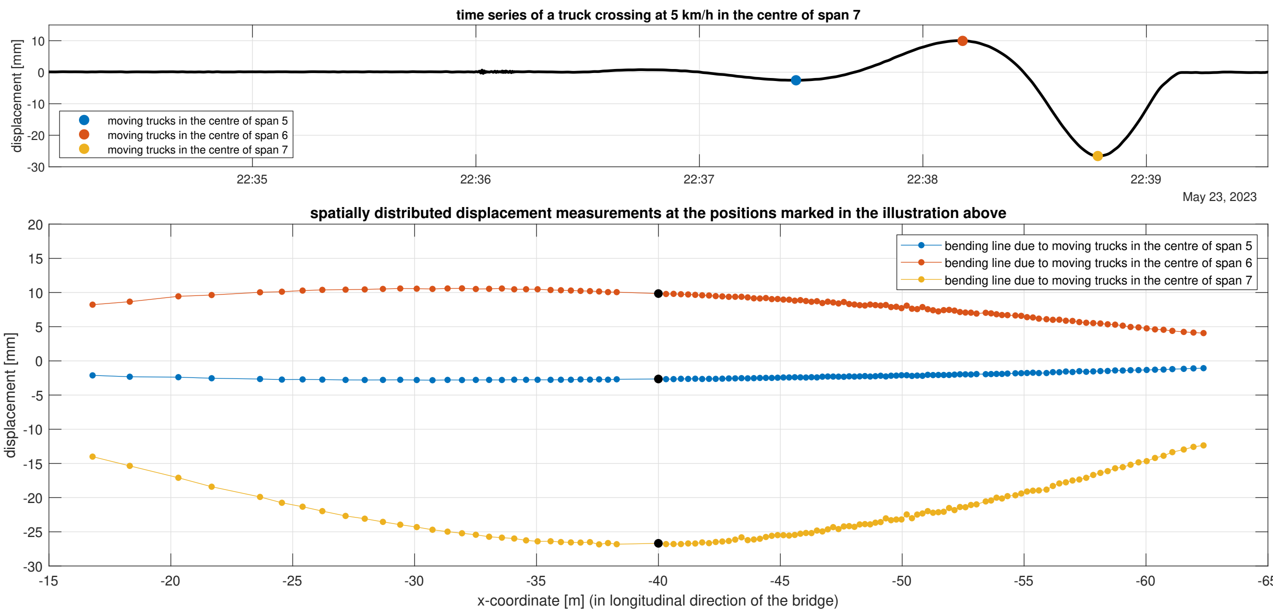

Figure 7. Exemplary results of the evaluation of a quasi-static load test: The upper diagram shows a pure point-by-point time-displacement representation, while the lower diagram shows the potential of profile scanning, as a bending line can be analysed over the entire visible range at any time.

the times when the trucks are in span 5 (lowering), span 6 (blue, maximum rise) and span 7 (red, maximum lowering) can be clearly seen. The lower graph shows the spatially distributed displacement measurements of the profile scanner for the latter three times, which are also marked in corresponding colours in the upper graph. These three exemplary time points are intended to illustrate the potential of a single PLS. In this example, up to 117 spatially distributed displacement time series can be derived with sub-millimetre accuracy and a high temporal resolution. To get an idea of the achievable spatial resolution, two examples are given below:

1. At a measurement frequency of 55 Hz, 20,000 points are measured per profile, which corresponds to a theoretical angular increment of 0.018 degree. If 75 neighbouring measurement points are combined , the actual available angular increment is reduced to 1.35 degree, which corresponds to a spatial resolution of 0.24 m at a distance of 10 m.

2. If the measuring frequency is reduced to 14 Hz, 80,000 points per profile are measured and a spatial resolution of 0.06 m at a distance of 10 m is achieved.

In addition the PLS was also used to analyse the static load tests, further increasing precision and spatial resolution through additional time averaging during the load holding phases. With a load holding phase of 10 minutes, approx. 8400 profiles are measured. This means that in the previously defined example with 75 points per class and profile, 630,000 individual measurements can be used for the further derivation of the measured values, which enables a significant increase in precision.

In the upper and lower graph in Figure 8 the results of the static load tests (in black) are presented together with the profiles of the dynamic load test (red and yellow, see also Figure 7) at 5 km/h. Two aspects are initially noticeable: a significantly higher spatial resolution of about 600 classes in the static analysis compared to 117 classes in the dynamic analysis and there are deviations between the different datasets, as shown in the middle figure. For this purpose, the 600 static classes were interpolated to the positions of the 117 dynamic classes.

The upper and lower figures, and thus also the differences, show different systematic effects, which have a magnitude of up to 0.8 mm. The deformations assigned to a load in span 7 show a systematic that occurs symmetrically to the centre of the span. The maximum deviation occurs in the centre of the field and has a magnitude of approximately 0.5 mm. In contrast, with a load in span 6, an asymmetrical

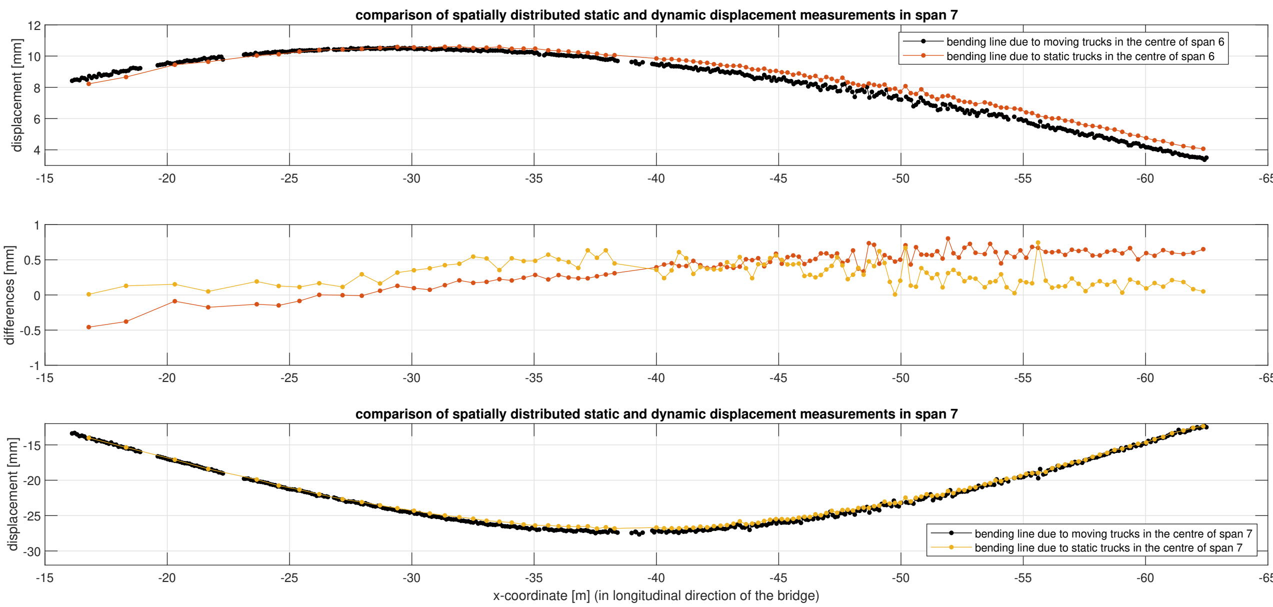

Figure 8. Comparison of the static and dynamic load tests. The upper and lower diagram shows the bending lines of span 7 for two different load positions. The middle diagram shows the differences between the respective load tests.

deviation occurs in span 7.

There are two possible reasons for these deviations between the dynamic and static deformation figures. In the static case, the distance between the two trucks is approx. 1 m smaller than in the dynamic case, and the speed and distance are also variable to a certain extent. In addition, the supporting structure has more time to adapt to the load in a static load test, which could explain why the static deformation is more pronounced than the dynamic deformation in the lower graph.

5.2 Robotic Total Station vs. Profile Laser Scanning

To compare the detection of the bridge movement of both the RTS and PLS sensors during the dynamic load tests, Figure 9 shows two time series for the time span in which the two trucks pass the bridge in direct succession. The RTS data is the recorded centre prism of span 7, the PLS data consists of the corresponding point recorded by PLS. The mean value of the first 100 data points is subtracted from both time series.

The detected movement corresponds to the description in Section 5.1. The lower diagram in Figure 9 shows the differences between the sensors. The first period consists only of the measurement noise of the two sensors and has a size of about 0.2 mm. When the bridge starts to move due to the dynamic load from the trucks, the differences increase and are mostly in a range of about 0.5 mm. However, there is a larger outlier of approx. 1 mm.

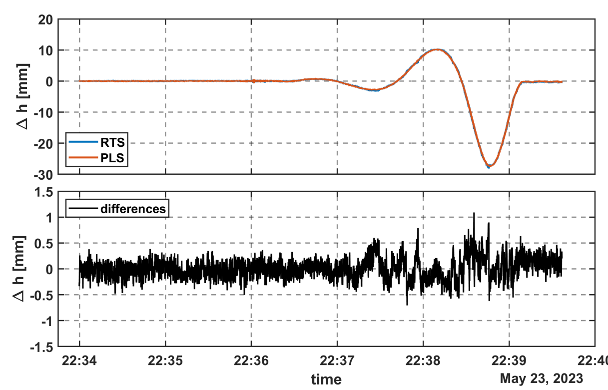

Figure 9. The upper timeseries shows the center prism at span 7 captured by RTS and the same location captured by the PLS. The lower timeseries shows the differences of the sensors.

6 Conclusion

It could be shown, that both RTS and PLS are highly capable of detecting static and dynamic displacements of bridges. If both, static and dynamic results are compared, the performance of the sensors are promising in both applications.

However, the two systems have different strengths that complement each other. While the potential of PLS lies in the recording of deflection curves with a very high temporal and spatial resolution, the advantage of RTS lies in the recording of the same reproducible point. This makes it possible to track the absolute deflection of the bridge in height, but also in the longitudinal and transverse directions. This requires a prism to be mounted on the bridge. The RTS can be set up in any position as long as there is a direct line of sight between the RTS and the prism.

RTS are therefore able to detect real 3D deviations of a single point, ranging from sub-millimetres to one millimetre, depending on the distance and positioning of the RTS to the measurement object. However, a fundamental problem is that there is no direct possibility of synchronisation with other sensors, as it is not possible to couple a GNSS receiver directly with the total station. In addition, the time drift of each individual sensor must also be taken into account, especially if it is used over a longer period of time, as the drift can accumulate to up to 1 s after 5 hours.

These time-related problems do not exist with PLS, as direct integration of the GNSS time into the measurement data stream has been implemented. The reduction to one measurement profile can significantly increase the temporal resolution, up to several hundred Hertz depending on the scanner model. With a temporal and/or spatial averaging, the precision of the recorded profile increases to the low sub-millimetre range. In addition, a large number of spatially distributed displacement values can be derived.

The comparison between the dynamic and static load test shows differences in the sub-millimetre range, which can be explained by the movement of the trucks and other varying parameters. In principle, both measuring systems are able to deliver reliable displacement values for dynamic and quasi-static tests. In terms of timing, dynamic load tests have a clear advantage, but static tests are likely to provide more accurate results. A consideration of each individual case is therefore important.

Overall, a comprehensive understanding of bridge displacements under static and dynamic load scenarios can be achieved with relatively little effort. The use of geodetic remote sensors can therefore address the challenges of an ageing infrastructure by providing more actually measured information. The next step should be a comprehensive integration of these remote measurements into digital twins to enable an integrated analysis accompanying the life cycle of infrastructure buildings.

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