Dynamic Bridge Monitoring with Remote Sensing Techniques

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ABSTRACT

Dynamic monitoring of bridges is usually performed with mounted sensors on the structure. Typically used technologies are accelerometers, electric strain gauges or fibre bragg grating sensors. All of them have the drawback that access to the structures is needed. This usually results in bridge closures during installation or during the measurement campaign. Furthermore, every measurement position has to be equipped with a separate sensor.

We explore an alternative approach where the dynamic bridge behavior is determined with remote sensing techniques. Profile based terrestrial laser scanning as well as interferometric radar measurements enable the contactless measurement of bridge profiles with measurement rates of up to several hundred Hertz. Furthermore, dynamic 3D displacements can be determined with robotic total stations and GNSS receivers.

This article thus discusses the state-of-the art of dynamic remote sensing techniques and in addition investigates the spatial and frequency resolution in real world examples.

INTRODUCTION

Remote sensing techniques enable the monitoring of structures without the need of a physical access to the object. This brings many benefits, as structures can be kept in service during the monitoring period and instruments as well as observes can stay at a safe distance in case of a potential failure of a structure. Remote sensing is usually realized with geodetic instruments such as robotic total stations (RTS), GNSS (Global Navigation Satellite System) receivers, telescopic cameras, laser scanners or radar instruments as shown in Figure 1. Until recently these instruments were a valid tool to observe slow changes e.g. caused by temperature variations, or to monitor static load conditions, e.g. during a static bridge loading test.

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Figure 1. Remote sensors for dynamic monitoring: Robotic total station [1], GNSS receiver [2], telescopic camera [3], profile laser scanner [4], interferometric radar instrument [5]

However, within the last decade the measurement frequency of geodetic instruments increased considerably. Therefore, dynamic remote monitoring of bridge vibrations is nowadays possible with these instruments. This was already discussed conceptually in [6] and is demonstrated with real world examples in this article. Table I gives an overview of the performance of state-of-the-art equipment.

Complete 3D displacement data can be captured with total stations and GNSS receivers with up to 20 Hz, whereas if not the complete 3D movement has to be captured even higher measurement frequencies are possible.

Cameras and profile laser scanners allow the determination of 2D displacements with up to several hundred Hertz. Camera measurements are sensitive to movements orthogonal to the line of sight (LOS), while profile laser scanners are sensitive in a 2D profile.

Regarding profile laser scanning the spatial resolution on the object depends on the distance measurement rate (e.g. up to 1 million points/s) and the rotation rate of the scanner. A slower rotation rate e.g. 50 rotations/s instead of 200 rotations/s reduces the maximum detectable frequency by a factor of four, but improves the spatial resolution by the same amount.

Finally, radar measurements are sensitive only in LOS and therefore yield only 1D displacements. These LOS measurements must be converted into meaningful deformation directions, e.g., vertical settlements. This conversion requires knowledge of the orientation of the measurement signal with respect to the object and includes some assumptions. An exemplary assumption for dynamic load tests can be that the main deformation direction is vertical.

TABLE I. DYNAMIC MEASUREMENT CAPABILITIES OF REMOTE SENSING TECHNIQUES

Instrument type	**Meas. Frequency**	**Dimension**	**Sensitive direction.**
Robotic total station	20 Hz [1]	3D	3D
GNSS receiver	20 Hz [2]	3D	3D
Telescopic camera	500 Hz [3]	2D	orthogonal to LOS
Profile laser scanner	1 mill. points/s 200 profiles/s [4]	2D	in a profile
Interferometric radar	200 Hz [5]	1D	in LOS

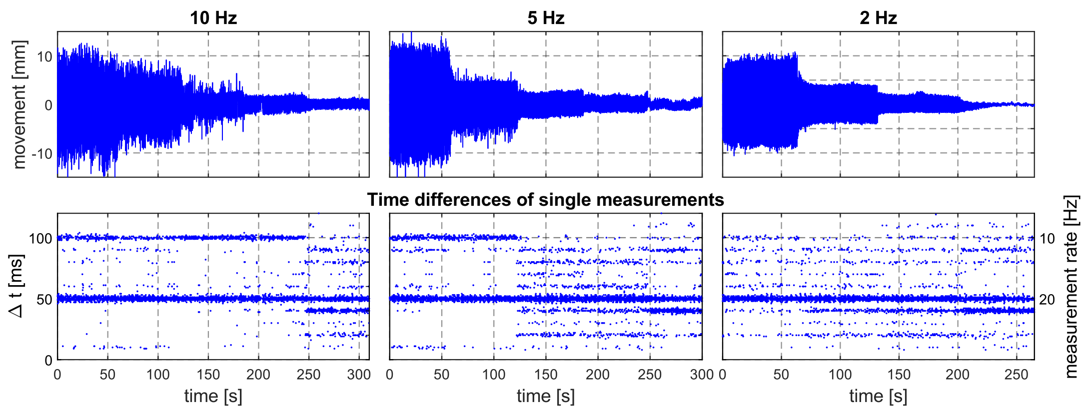

Figure 2. Height movement of shaker for 10, 5, and 2 Hz vibrations with different amplitudes (top) and corresponding time differences of single measurements (bottom)

ROBOTIC TOTAL STATIONS (RTS)

The usage of classical total stations focuses on the determination of static deformations, such as movement or rotation, of solid structures. But modern RTS are also capable of capturing dynamic point behavior. Considering a maximum measurement frequency of 20 Hz, vibration frequencies of less than 10 Hz can be determined according to the Nyquist theorem.

In reality, however, the measurement rate depends strongly on the local situation in which the RTS is used. With rising movement rate, and amplitude, the measurement rate drops significantly as seen in Figure 2, where a shaker was used to simulate different vibration frequencies and amplitudes.

While the dynamic movement in vertical direction could be derived by angle only measurements, the horizontal movement is only feasible with additional dynamic distance measurements. With these 3D measurements, also assertions about the horizontal behavior of structures with respect to different loading scenarios can be made. Such a test was performed on a multi-span highway bridge, where the structure was monitored under normal traffic conditions. Figure 3 shows the bridge combined with the movement of the prism in cross- and lengthwise direction, as well as the height changes when two trucks are crossing the bridge. A correlation between the horizontal and vertical displacements is clearly visible and can help to improve the understanding of the behavior of the bridge.

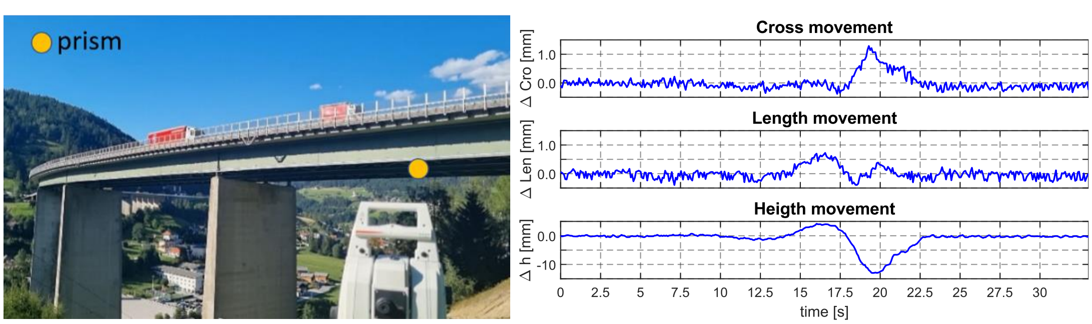

Figure 3. Highway bridge with observed prism (left), time series of position changes in all three directions while two trucks are passing the bridge (right)

GNSS RECEIVERS

High precision GNSS measurements require phase measurements and reference station data. The correction data can be provided either by a single reference station setup by the user or by a continuously operating reference stations (CORS) network. Although using a CORS network is very convenient, problems can occur when high dynamic measurements are performed. Usually CORS networks transmit correction data with a frequency of 1 Hz. If the receiver measures with 20 Hz, positions can still be determined with 20 Hz. However, in such a situation the correction data has to be extrapolated. This causes artefacts in the frequency domain of the 3D positions, which is highlighted in the following investigation. A GNSS rover and reference station were setup on pillars on a geodetic measurement roof. The native data rate of both instruments was set to 20 Hz. Both antennas were kept static and reference height position data was recorded with a laser triangulation sensor (LTS). Figure 4-left shows the frequency spectrum of the height component calculated with RTKLIB. It can be seen that after high pass filtering only white noise is present in the data. The same data was processed a second time where the reference station data was reduced to 1 Hz, see also [7]. As can be seen in Figure 4-right, spikes at the frequency of the reference station data and multiples of it occur. As a consequence, the frequency of the correction data has to be at least as high as the measurement frequency of the rover to avoid these artefacts.

Although the absolute accuracy of GNSS real time kinematic (RTK) solutions is in the centimeter range, vibrations with amplitudes in the millimeter range can be observed since long wavelength effects cancel out when deriving accelerations. This is shown in Figure 5, where the vibrations of a footbridge were measured during the crossing of a school class. The waterfall plot of the short time Fourier transform (STFT) shows that the amplitudes are only a few millimeters. From the measurement data the first eigenfrequency was determined to be 1.74 Hz which was confirmed with independent measurements performed with an inertial measurement unit (IMU).

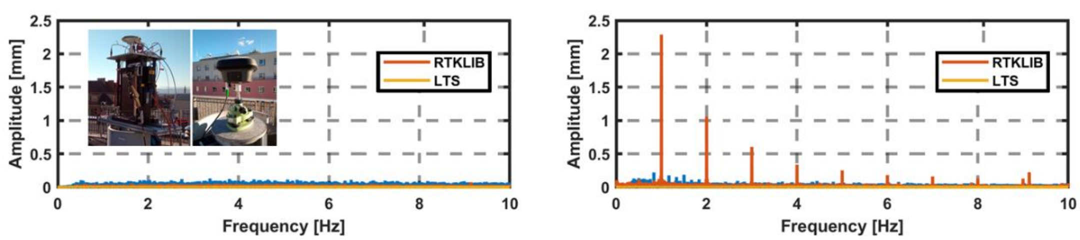

Figure 4. Frequency spectrum of the variations of the height at a static setup with 20 Hz reference data (left) and 1 Hz reference data (right)

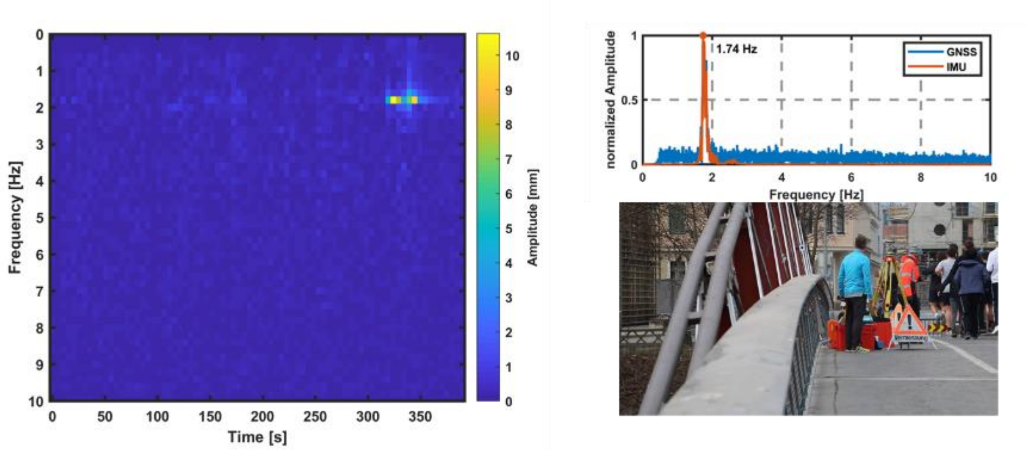

Figure 5. Waterfall plot of vibrations of footbridge measured with GNSS (left) during the crossing of a school class (bottom right) and frequency spectrum (top right)

TELESCOPIC CAMERAS

Telescopic cameras enable the acquisition of high-resolution images or videos from long distances. Common image processing methods to determine position changes of regions or objects within the camera's field of view (FoV) are digital image correlation (DIC), optical flow or feature matching. As a result, 2D deformations in pixel coordinates are gained. These have to be converted into metric units by knowing the camera parameters and the distance from the camera to the object. Alternatively, known distances in the camera image can be used. For high accurate measurements a camera calibration is mandatory. As can be seen in Figure 6, the vibration behavior and the first eigenfrequency can be reliable determined with a telescopic camera without the need to apply special markers on the bridge [8].

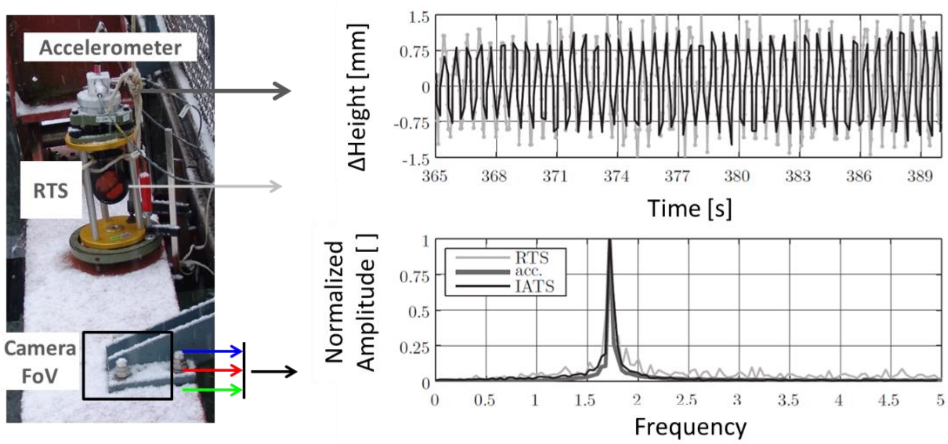

Figure 6. Comparison of bridge vibrations derived from camera streams, RTS measurements and accelerometer measurements

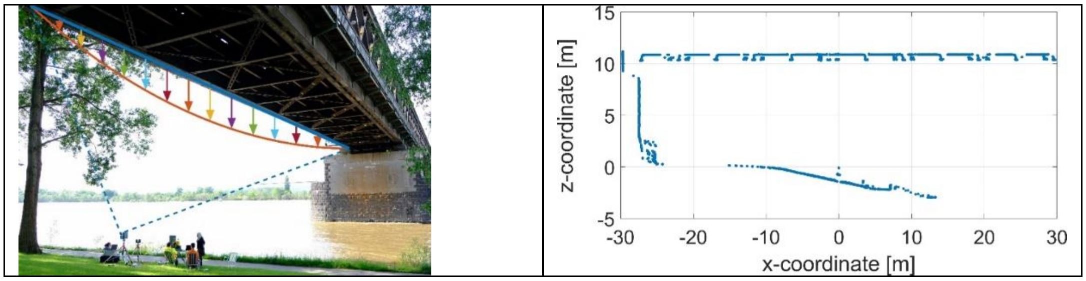

Figure 7. Measurement configuration and point cloud for monitoring applications with a profile scanner.

PROFILE LASERSCANNER

Terrestrial laser scanners (TLS), enable the digitisation of the entire environment in a 360° panorama in the form of a 3D point cloud. In contrast to 3D-TLS a profile scanner (TLS in profile mode, see Figure 7) only uses the high-frequency rotating deflection mirror, but there is no rotation around the standing axis. By reducing the spatial resolution to a single profile (with up to 80.000 points), a significantly higher temporal resolution up to 200 Hz is possible.

The profile scanner determines a spatial and temporal component for every measured point, which corresponds to a spatio temporal acquisition of the structure. The measurements must then be analyzed in the context of the structural surface and local conditions [9, 10]. Based on the algorithms presented there, spatially distributed deformations can thus be derived, see Figure 8.

Due to their high spatial resolution, profile scanners are suitable for the dynamic detection of large building structures and can be used particularly efficiently and cost-effectively. Furthermore, it is even possible to record the horizontal and vertical deformation simultaneously. In addition to the time series shown in Figure 8 about 100 spatially distributed time series can be derived for a single crossing. Thus, it is also possible to display the whole dataset as a spatial animation of the bridge deformation.

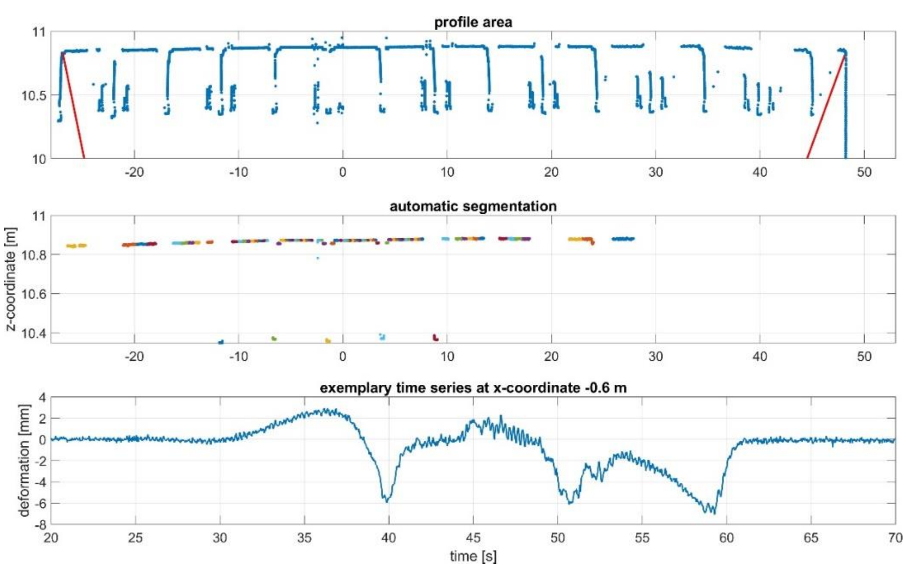

Figure 8. Automatic segmentation of the measurement profile and exemplary time series.

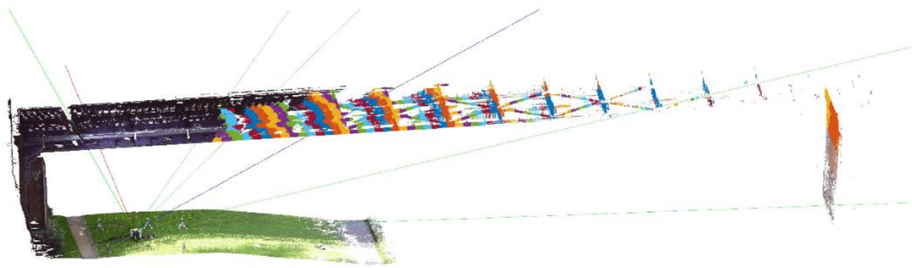

Figure 9. Perspective view of a 3D bridge scan with color-coded radar resolution cells.

INTERFEROMETRIC RADAR

Microwave interferometry systems enable the detection of 1D line-of-sight (LOS) displacements based on amplitude and phase measurements. For this purpose, the instrument emits electromagnetic waves in the microwave spectrum (e.g. Ku band, 17.4 mm wavelength). Due to a stable phase reference of successive measurements, it is possible to evaluate not only the amplitude (intensity) but also the phase in particular. Specifically, from the phase, the relative movement of objects in the sensor's line of sight can be derived by means of interferometry, i.e., the difference of the phase of two measurements, also known as the interferometric phase. By modulating the frequency of the emitted signal, multiple objects can be differentiated by their LOS range to the sensor, as seen as a color code in Figure 9.

Microwave interferometers offer a coarse spatial resolution when the radar head is tilted. However, the size of the resolution cells can be problematic and projection errors can occur. In Figure 10 two time series are compared to profile scanner measurement.

This graph shows two different effects. In the left time series deviations occur due to a scale factor caused by a distorted projection and in the right graph the radar measurements are strongly distorted due to multiple reflectors in a single resolution cell. Overall, it is evident that deformation measurements with interferometric radar pose great challenges to the user and should ideally be controlled by independent measurements [10].

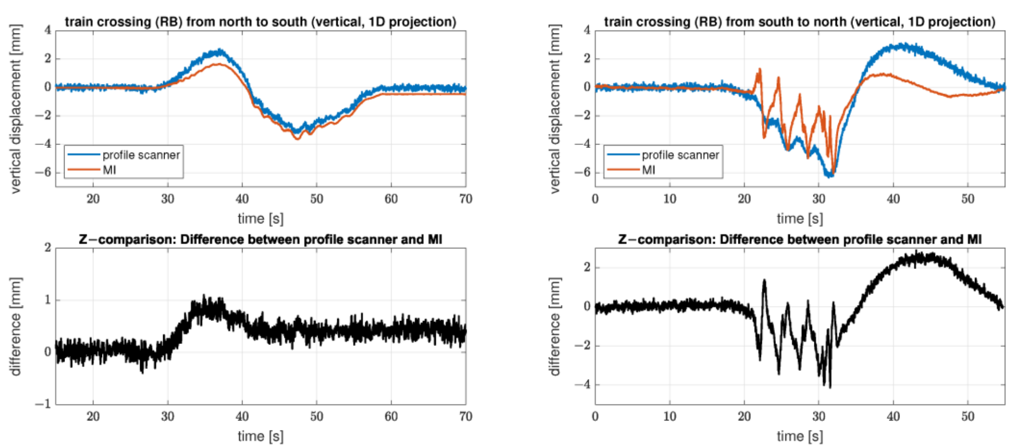

Figure 10. Comparison of two different time series from radar with profile scanner measurements.

SUMMARY

This article has shown with many real-world examples that modern geodetic instruments are a valuable tool for the remote monitoring of dynamic bridge deformations. Contrary, to conventional methods e.g. based on accelerometer data, the geodetic measurements provide absolute deformations without the need of double integration to derive position changes. However, a sound understanding of the measurement properties (e.g. 3D vs. 2D vs. LOS sensitivity) and correct instrument settings (e.g. same measurement rate of GNSS reference and rover) are crucial to obtain reliable and interpretable results.

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