Bridge Monitoring by Means of Video-Tacheometer – A Case Study

Überwachung von Brücken mit Video-Tachymetern – eine Fallstudie

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Built-in cameras are nowadays standard in modern total stations, but their possible potential of photogrammetric evaluation and analysis is not yet used. This article describes a research project for bridge monitoring using such an instrument at the Fatih Sultan Mehmet Bridge in Istanbul. By image processing algorithms an active LED target is detected and by using the exterior orientation of the total station brought directly into a suitable coordinate system. Thus, additional reference marks in the camera image become obsolete. After the description of the system the practical usability for detecting bridge motions is confirmed by two test measurements and a number of oscillation frequencies derived. So this article shows an example of additional measuring tasks for which video-tacheometer can be employed.

Keywords: Bridge monitoring, Fatih Sultan Mehmet Bridge, Image Assisted Total Station, LED targets, Structural Monitoring

Eingebaute Kameras gehören mittlerweile zum Standard moderner Totalstationen. Das volle Potenzial photogrammetrischer Auswerte- und Analysemethoden, die damit genutzt werden können, wird derzeit jedoch noch nicht ausgeschöpft. Dieser Artikel beschreibt ein Forschungsprojekt zur Überwachung von Brücken mit einem derartigen Sensor am Beispiel der Fatih-Sultan-Mehmet-Brücke in Istanbul. Ein aktives LED-Ziel wird mit Algorithmen der Bildverarbeitung detektiert und kann mit Hilfe der äußeren Orientierung des Tachymeters direkt in einem passenden Koordinatensystem ausgegeben werden, d.h. zusätzliche Passmarken im Kamerabild sind nicht mehr nötig. Neben der Beschreibung des Systems bestätigen zwei Testmessungen dessen Praxistauglichkeit zur Detektion unterschiedlicher Schwingungsfrequenzen an Brückenbauwerken. Dieser Artikel zeigt exemplarisch, welche zusätzlichen Messaufgaben mit bildgestützten Tachymetern lösbar sind.

Schlüsselwörter: Bildgestützte Totalstation, Brückenüberwachung, Fatih-Sultan-Mehmet-Brücke, LED Ziele, strukturelle Überwachung

1 INTRODUCTION

Since bridges are exposed to strong loads, varying load conditions, changing weather conditions as well as associated material stressing, regular control monitoring for the material fatigue as well as of pending damage is essential for early detection of damage. A too late assessment (of damage) does not only increase the general risk, but also raises the costs of structural reinforcement significantly.

Contactless measuring sensors like total stations and photogrammetric cameras are often used for bridge monitoring in which each approach has individual advantages. With photogrammetric measuring techniques it is e.g. possible to simultaneously measure (monitor) an almost infinite number of targets. Thereby signalised and non-signalised targets can be used and high sampling rates are possible. In order to gain 3D information usually two digital cameras are necessary. This can also be obtained by a single total station, however, with non-simultaneous targeting. Observations to stable points enable the relation to a superior coordinate system and the proof of the stability of the station. Recording the inclination values of the total station it is additional possible to detect vibrations of the station (within the sampling rate of the instrument). Through the quick installation and orientation the sensor is applicable in a permanent and discontinuous measurement system.

A video-tacheometer or Image Assisted Total Station (IATS) – an image capturing system in addition to a polar 3D point measurement system as described in section 2.1 – represents a combination of all advantages mentioned above. Thus, it is obvious to test the use of such a new system for bridge monitoring as described in this article. /Bürki et al. 2010/ already executed a similar test with a torch light attached to a bridge. Within a project granted by the Alexander von Humboldt Foundation, our realisation goes a step further by using solidly mounted LED (light-emitting diodes) clusters and a permanent station on a pillar with stability proof. A verification by a standard photogrammetric approach was planned as well.

The present paper describes a case study of a bridge monitoring at the Fatih Sultan Mehmet Bridge (Section 3.2) in Istanbul, which was performed in cooperation with the Division of Photogrammetry of the Istanbul Technical University (ITU). Our partners were in charge of the simultaneous measurements with classical photogrammetric methods.

As functional specification our system should be able to measure day and night, detect assumed displacements of the bridge deck of ± 30 cm in vertical and ± 15 cm in horizontal direction /Apaydin 1992/. To be comparable to the tests of ITU, we planned to record with a similar acquisition rate of 24 fps (frames per second). The main focus is to detect significant frequencies of the bridge movement and compare them with ITU results as well as previous theoretical and practical analyses. According to the approach of structural health monitoring e.g. /Wenzel 2009/ changing frequencies give a hint to structural damage of the object.

The following section describes the system components: the prototype of an IATS, the LED targets and, the analysis software and strategy used. Section 3 presents and analyses the measurements in Istanbul including a first test at a pedestrian bridge at the TUM (Technische Universität München) campus area. A summary and outlook (Section 4) completes the paper.

2 SENSOR SYSTEM

2.1 IATS

The instrument used is a prototype manufactured by Leica Geosystems as a case study series in 2007. It is based on a standard TCRA1201+ with the eyepiece removed and replaced by a 5 Mpixel CMOS coloured camera (*Fig. 1*). The field-of-view of 1.56 x 1.17 gon corresponds to 2.5 x 1.8 m in a distance of 100 m. To allow remote-controlled focussing, the focus drive is also equipped with a step motor /Wasmeier 2009/. Although there are commercial tacheometers equipped with camera sensors already at the market, at the time of the project none of them was suitable for high-precision image analysis in real time. The respective Leica /Leica 2013/, Trimble /Trimble 2013/ and Pentax /Pentax 2013/ instruments only use a wide-angle overview camera which does not allow sub-mgon resolution, while the only instruments being equipped with an ocular camera, the Topcon Imaging Station family (IS, IS-3) /Topcon 2013/, unfortunately do not grant access to uncompressed images /Geiss 2013/. In addition, none of the instruments available would allow to process a real-time image with external devices (PC).

An essential step for high-quality image analysis (and target mapping to angular readings) is the system calibration consisting of a combined camera and tacheometer axis calibration. Due to the fact, that all calibration parameters are functionally linked to a given focus lens position, the calibration has to be done using a laboratory calibration device resulting in a tabulated parameter set. A brief description of the calibration, based on the continuation of work done by /Walser 2005/ and /Vogel 2006/, can be found in /Wasmeier 2012/. As a result oriented angular readings can be calculated for every pixel in an IATS image.

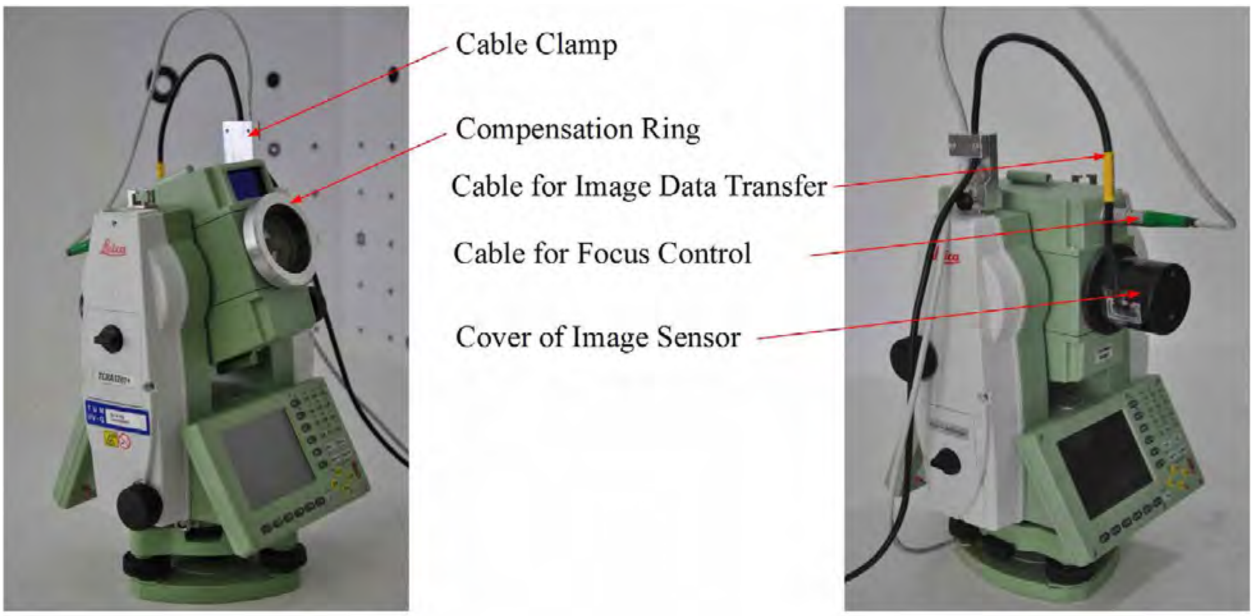

Fig. 1 | Prototype of an Image Assisted Total Station

A detailed overview on different image evaluation techniques and accuracy considerations can be found in /Reiterer, Wagner 2012/. Recently, this also led to thorough examinations of air turbulence effects on the use of IATS. /Reiterer 2012/ presented studies to turn the problem to an advantage: the IATS prototype shown above was used to derive the actual refraction and temperature gradient from the turbulences within the images acquired.

2.2 LED targets

Illuminated respectively active targets bring several advantages: The receiving sensor (IATS) does not need to focus emitted radiation on a single target and therefore may detect several targets simultaneously (as long as they are contained within the field of view) and the optical detection is even possible at night. For this reason, the choice fell to LEDs, which are low cost, have little power consumption and compact size. Furthermore, these are also available with infrared colour and therefore neither visible nor even disturbing for people. However, the camera system must be sensitive to the corresponding spectral range.

Single LEDs with different wavelengths from blue (~480 nm) up to infrared (~780 nm) were among the first targets tested when the IATS prototype was available. For high quality image analysis without the need of colour interpolation the camera should be used as a monochrome device and it could been shown that especially infrared diodes brought very good results.

Certainly a major disadvantage of illuminated targets is the need for power supply, even if it is considerable low. In preparation to the test at the Fatih Sultan Mehmet Bridge in Istanbul, see Section 3.2, the competent bridge authority, General Directorate of Highways (GDH), has not approved to install cable underneath the bridge. Therefore we had to investigate other ways to power the targets.

The first consideration was to use luminescent targets instead of active LEDs. When the (built-in) laser beam of the total station points to this kind of reflector it will glow autonomously for a certain period of time depending of the material used. This highly promising approach could be realised in practice but has the big disadvantage that a lot of time will be wasted to "recharge" the targets and during this period no measurements can be done. Using a second device doing this work could be helpful but it would increase the effort, complexity and costs inadequately compared to the benefit.

Therefore a second, more favourable way is to use high-performance batteries. We are using a very small power pack with limited weight which is originally designed for RC models. With a capacity of 4200 mAh it is able to energise the LED cluster for at least three days before the battery has to be recharged or replaced. This period of time will be enough for first practical tests. If our measurement approach will be used permanently we have to negotiate a solution with the GDH anyway.

The battery pack and the LED cluster is located in an insulated housing (*Fig. 2*). This protects the electronic system from extreme temperature and is splash-proof. Outside of the box a reflective target mark is attached, which enables a simple reference distance measurement. The additive constant between the reflective surface and the LED cluster must be noted however. Furthermore with this design an easy installing will be guaranteed (it is also not allowed to drill into the bridge) so we have to fix the target by gluing which is more stable using the large surface area of the housing.

Fig. 2 | LED target in self-made isolated housing. Detail of LED cluster top right

2.3 Software and Analysis

The initially round clustering of single LEDs does not necessarily lead to a circle-shaped blob structure. This may be because of divergent radiation performance, assembly and housing of the diode cluster. Of course, this effect intensifies the closer the LED cluster is situated to the observing camera and will lose impact with higher distances; but has to be taken into consideration anyway. Additionally, the outer shape of the blob might change due to meteorological conditions. In a pure geometric way, turbulent air density variations due to thermal and stochastic convection lead to an aggravation of the image representation of objects as apparent position variations of target points, deformations of target structures and blurring.

With that in mind, there are different possibilities to define the final target centre with respect to the illuminated area which can be extracted by using a simple threshold operator or gradient filter, e.g. /Gonzalez, Woods 1992/:

- Using the **gravity centre of blob area**: This would be favourable if the blob structure is strongly fragmented and/or divergent from geometrical primitives. Grey value based algorithms are robust with respect to random image deviations and prove to be computed fast and easy.
- Using a **best-fit geometrical primitive**: For initially round spots this, of course, maybe a circle or ellipsis structure incl. possible additional outlier tests. This would be favourable if some parts of the blob temporarily appear occluded or if there were variations in the illumination strength. Geometrical approaches may react sensitive if the spots are too divergent from the primitive structure and are expensive in computation time.

To attain a higher precision in our analysis we choose the second described method. In a first segmentation (threshold) step the image is pre-processed. The resulting regions are tested for their circularity – possible misdetections, e.g. reflections can thus be excluded from further analysis. We also tested to specify the area or radius of the regions but due to the infrared illumination of the target, a low exposure time and the resulting reliable detection there is no need for further restrictions /Wagner et al. 2012/. All remaining regions are approximated by ellipses and their centres are stored as (sub-)pixel coordinates. With appropriate calibration these centre points can be converted in angle values of the tacheometer coordinate system.

All image processing steps are implemented in a C#-software controlling the IATS device and use the HALCON[1] library. The segmentation of the image and the ellipse fitting following takes 13 ms on average – thus a maximum frame rate (MFR) of 77 Hz is possible. This run-time test was performed using full resolution images (2560 x 1920 pixel) and a common laptop (Intel Core 2Duo 2 x 2.7 GHz, 4 GB RAM). Using full-size images the MFR of our IATS is limited to 5 Hz due to the USB interface of the camera. By reducing the image size and/or resolution frame rates up to 200 Hz are possible. However, a reduction decreases the evaluation time of the algorithm as well. In contrast, the method mentioned above – using the gravity centre of the blob structure – takes only 8 ms and thus extends the (theoretical) MFR to 125 Hz.

2.4 Accuracy consideration

The precision detecting the ellipse centre depends on the size of the target on the camera chip. To determinate the ellipse parameter five unknowns have to be solved. A target size of 100 x 100 pixel leads to a high level of redundancy and therefore to a small standard deviation. Similar subpixel operators are specified with a precision higher than 1/10 pixel, e.g. /Sookman 2006/, which corresponds to 0.06 mgon for the IATS system. Due to the fact that the telescope is not moving during LED tracking and the precision of relative angle measurements of the TPS1201+ achieves 0.1 mgon /Wasmeier 2009b/, the precision of the complete system can be specified with 0.12 mgon (according to the Gaussian error propagation law). For a distance of 100 m this is equivalent to a standard deviation of 0.2 mm. For absolute measurements the angle accuracy of the tacheometer will be the limiting factor /Wasmeier 2009b/. It is specified with 0.3 mgon which corresponds to 0.5 mm at 100 m /Leica 2009/.

However, contactless measuring methods are affected by the influence of the atmosphere between the object and the recording device. Under outdoor conditions air turbulences and refraction effects overlay the image acquisition and degrade single measurement accuracy to 1 - 2 mgon (1.6 - 3.1 mm / 100 m).

3 EXPERIMENTS AND RESULTS

The following section will describe two experiments performed with the system: The first one was taken at a pedestrian bridge at the TUM campus area (Section 3.1) to test preparatory the whole system locally. Section 3.2 describes the work done at the 2nd Bosporus Bridge (Fatih Sultan Mehmet Bridge) in Istanbul.

[1] MVTec Software GmbH: http://www.mvtec.com/halcon/

3.1 Pedestrian bridge

At the TUM campus area two infrared LED targets – as described in Section 2.2 – had been attached to a steel construction pedestrian bridge of approx. 25 m span. The IATS instrument was mounted at a pillar at the top of the institute building in an object distance of approx. 80 m, see *Fig. 3*. In full resolution (2560 x 1920 pixel) the field of view would be therefore 2.0 x 1.5 m but it was reduced to 1280 x 960 pixel (1.0 x 0.75 m) to achieve a frame rate of 20 Hz. According to Section 2.4 this leads to an accuracy of 0.4 mm, disregarding the influence of refraction.

The aim of this measurement was to track multiple targets simultaneously within one image. Therefore two LED targets were mounted on each side of the bridge which allows to detect possible torsions of the bridge deck. *Fig. 3* top right shows a screenshot of the recording software. With low exposure time the IR targets are clearly visible in the camera image and easy to detect.

During the measuring period of several hours the targets could be tracked with only sporadic data gaps when the line of site was temporarily interrupted by people passing by. Before and after the recording time measurements to surrounding control points were used to prove the stability of the station. Through the relative stable construction of the bridge and its sheltered position – the bridge is located in the courtyard and protected from wind – no significant movement or frequencies could be detected during the measurement period and so a comparison of both targets was not meaningful. Therefore we stimulated the construction by a jumping person and imposed an oscillation. *Fig. 4* displays the frequency spectrum – generated by a Fast Fourier Transformation (FFT) – of the observing period. Even though the displacement was still in the range of a

Fig. 3 | Test measurement at TUM campus with screenshot (top right) and used LED target (bottom right)

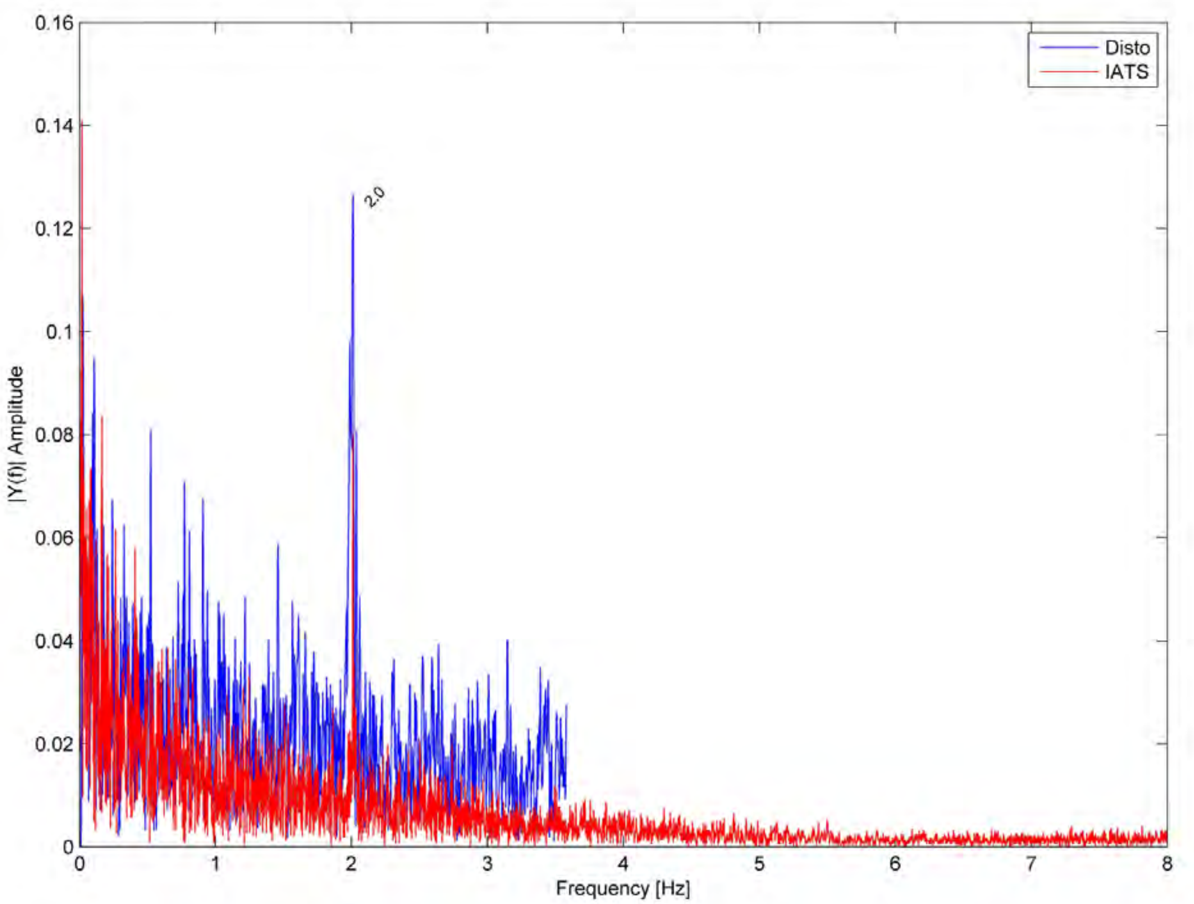

Fig. 4 | Frequency spectrum of the IATS observations incl. comparative measurement by a distance meter few millimetres a dominant frequency of 2.0 Hz, which most probably is the resonance frequency of the bridge is clearly visible.

As reference an additional experiment at the bridge was done using a laser distancemeter (Leica DISTO™ OEM module 3.0 WH15) as independent measuring method. The device has a typical measuring accuracy of +/- 1.5 mm /Leica 2001/. A precision of approx. a half a millimetre is possible by averaging the data. The instrument was positioned directly beneath the bridge on a tripod targeting in zenith direction to the underside of the bridge. As in the above described experiment a jumping person stimulated the construction. The determined displacement rates and the detected frequency (*Fig. 4*), are both consistent with those of the IATS test.

3.2 Fatih Sultan Mehmet Bridge

The Bosporus is considered as one of the most important water ways, because of its role as the connection between the Mediterranean and the Black Sea. The Fatih Sultan Mehmet Bridge is one of two bridges in Istanbul, which span the Bosporus and connect the European and the Asiatic part of the mega city. The bridge had been the 6th longest suspension bridge span in the world when it was completed and released for motor vehicles in 1988. The bridge connects Edirne with Ankara. For this reason an immense importance comes to the bridge, since it is part of the "arteries of the Turkish transportation net" and essential in the transportation of Istanbul. The structure is designed as suspension bridge as shown in *Fig. 5*. It spans 1,510 m from bank to bank and 1,090 m between the sus-

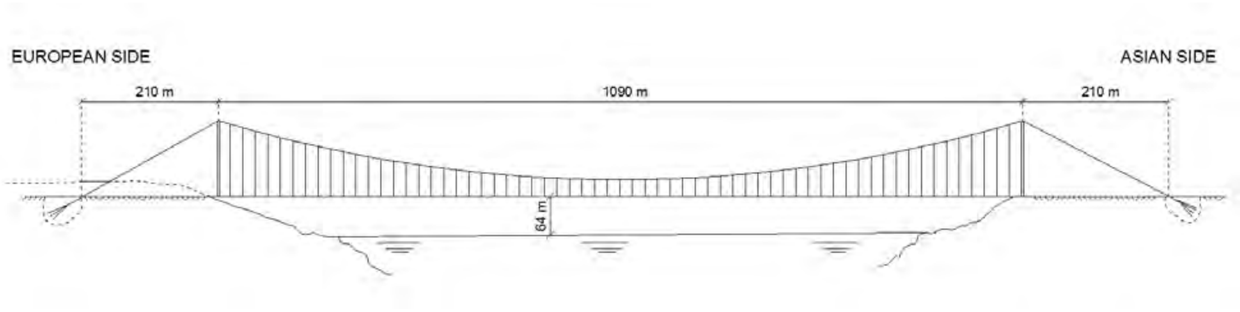

Fig. 5 | General arrangement of Fatih Sultan Mehmet Bridge (modified from /Apaydin 2002/)

Fig. 6 | Fatih Sultan Mehmet Bridge seen from observation pillar with highlighted LED targets. The red circle indicates the IATS observed target.

pension pylons which tower 105 m above the roadway. The clearance of the bridge from the sea level is 64 m.

At the lower side of the bridge 16 LED targets, as described in Section 2.2, have been installed. The targets were arranged in four rows with four units across the deck. Access to the underside of the bridge was possible using a service crane as shown in *Fig. 6*. Most of the targets have been used by our partner ITU which observed them with two wide angle cameras simultaneously.

With the IATS only one of the LED targets in a distance of ca. 128 m from the abutment has been observed (*Fig. 6*). The IATS was positioned on a pillar which is approx. 20 m beside the abutment of the European side and located about 8 m below the deck. The camera field of view corresponds to an area of 3.1 m x 2.4 m in object distance. Around the station several fix points have been monumented to define a local coordinate system.

Due to security reasons we could only dispose of two half observation days. On the 12th of December 2012 measurements were taken for one hour and on the following day for five hours.

The meteorological data of both measurement periods was similar as shown in *Tab. 1*. At the first day the measurement was taken between 3 pm and 4 pm. Because of the beginning rush hour period the number of vehicles is higher as during the second measurement which was performed between 10 am and 3 pm.

Date	Wind speed	Wind direction	Temperature	Vehicles per hour
12.12.	18 km/h	NW	7 °C	7.400
13.12	23 - 25 km/h	NW	4 - 5 °C	5.900 - 6.700

Tab. 1 | Meteorological data of measurement periods

Fig. 7 shows a total vertical displacement of 50 cm (blue line) and a lateral one of 3 cm at the first measurement day. These ranges are also representative for the measurement at the second day. In both cases the acquisition rate was set to 25 Hz by reducing the field of view to 800 x 900 pixels (1.0 x 1.1 m in object distance). As described in Section 2.3 only 5 Hz would be possible in full resolution.

Fig. 8 displays the frequency spectrum of the two measurement series (vertical displacement) of December 12 and 13. Equal fundamental vibration frequencies can be detected in both days clearly. The amplitudes of day one are larger than those of day two which is probably caused by different traffic loads.

Frequency analyses and finite element models of the Fatih Sultan Mehmet bridge were already presented, e.g. from /Apaydin 2002/ or /Dumanoglu 1992/. In contrary to this study accelerometers, seismometers or GPS were used as measurement sensors. For more details about the finite element analysis and theoretical derived quantities it is referred to the specified literature. *Tab. 2* compares the results of the previously mentioned studies to our investigation in vertical direction. The detected frequencies correspond to the known determined values in essence. However three frequencies (0.132, 0.176 and 0.272) are slightly higher than the range of the previous tests. Following the approach of structural health monitoring, e.g. /Wenzel 2009/, this could be a hint to some structural damage and further investigation should be carried out.

Dumanoglu et al. (1992)	Apaydin (2002)	IATS
Hz	Hz	Hz
0,108	0,102	0,106
0,125	0,118	0,132
0,145	0,154	0,176
0,159	0,205	0,209
0,232	0,255	0,272
0,317	0,374	0,333

Tab. 2 | Comparison between resonance frequencies of experimental studies (vertical)

It is still pending that these results can be confirmed by the photogrammetric evaluations of our partners from the ITU.

4 SUMMARY AND OUTLOOK

The paper at hand presented a case study for bridge monitoring with video-tacheometry in two examples using active LED targets to determine absolute displacements directly – as in contrast to relative measurement methods, like acceleration or inclination sensors. The system is mobile, quick to deploy and can be used permanent and/or discontinuous for only a couple of hours or days. The use of a video-tacheometer allows photogrammetric image measurement methods to detect signalised and non-signalised points in combination with total station methods, such as precise angle and distance measurement (to prisms or reflectorless) to acquire the exterior orientation or to control the stability of the station point incl. inclination values of the instrument. Using non-signalised targets would require neither access to the target area nor energy supply, but measurements at night are no longer possible.

An ocular camera like the one of the used prototype is currently only available in just one commercial device. As long as other manufacturers will not incorporate this additional camera in their devices, the available overview cameras can be used instead as described above. This would also have the advantage that multiple targets can be detected and tracked simultaneously using the larger field of view. However, since the magnification of the telescope is missing, the achievable resolution is lower which affects the detection accuracy. As example one pixel of a Leica Viva wide-angle camera corresponds to 6.8 mgon, cf. /Leica 2013/. The observed LED target (Ø 5.5 cm) at Fatih Sultan Mehmet Bridge would be mapped to 5 x 5 pixels at the camera chip – in contrast to 45 x 45 pixels at the IATS camera chip. A reliable ellipse fit will be therefore problematic and a subpixel accuracy unlikely, which means the angle accuracy of the tacheometer is underachieved.

If a full 3D motion, i.e. also in the viewing direction, is needed, the distance measuring module of the total station or a forward intersection (FI) with two devices could be used. For the first method the

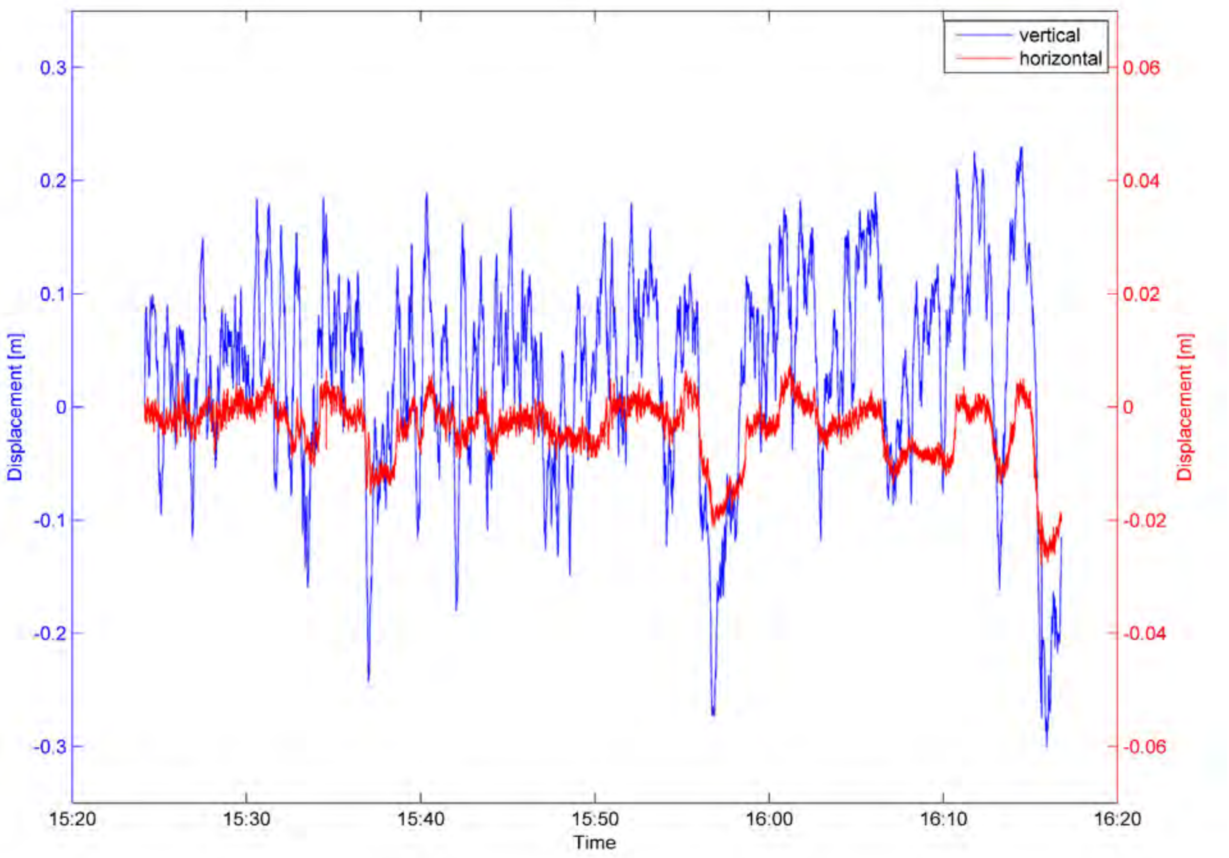

Fig. 7 | Vertical (blue) and horizontal displacement of the bridge at first observation day (please note different scales on the vertical axes)

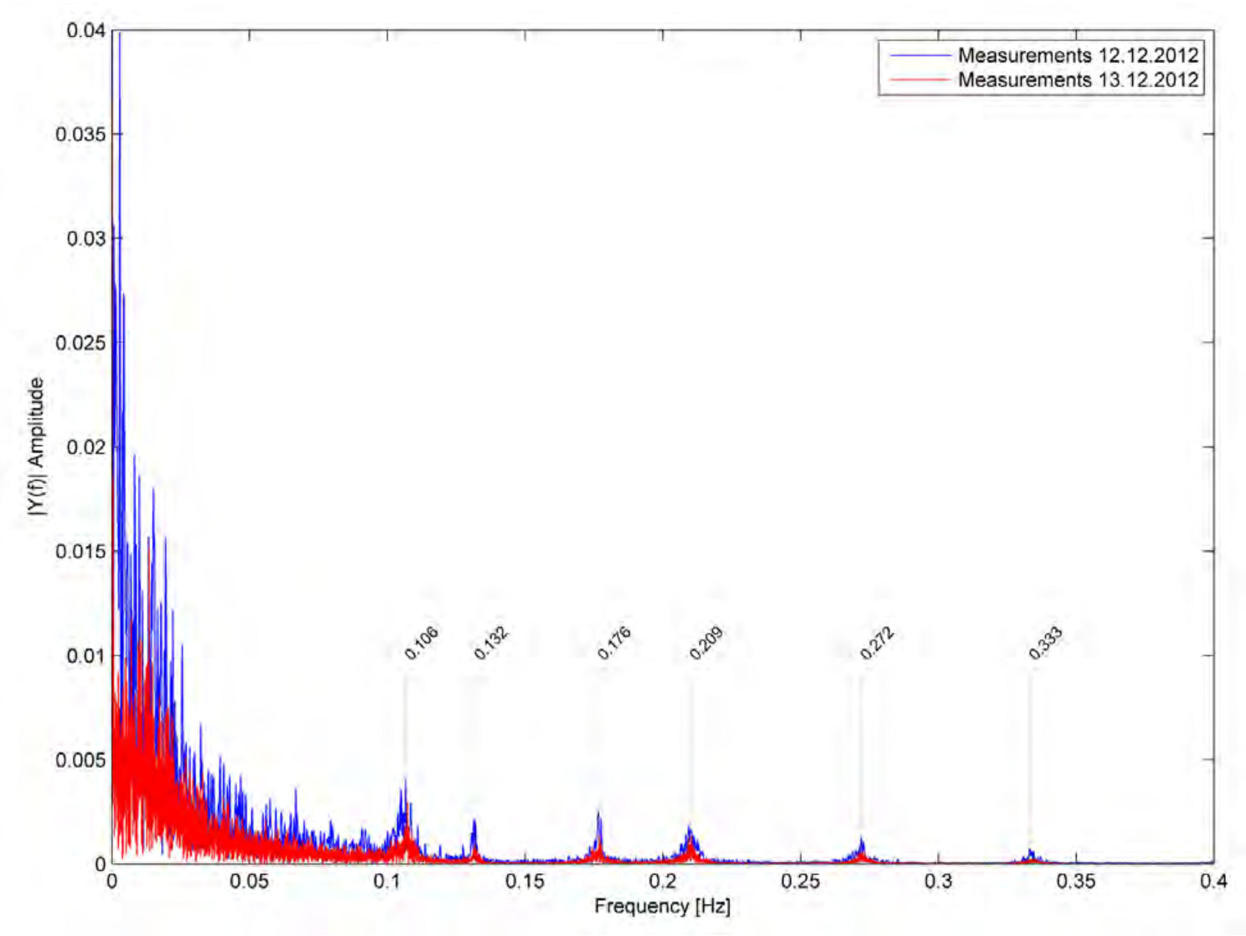

Fig. 8 | Amplitude spectrum of y-component (vertical) incl. detected frequencies

available hardware currently allows repetition rates of a few Hertz only. It is therefore necessary to check whether this is sufficient for the measurement task. In addition, with increasing distance, prisms must be used to ensure reliable distance measurements. Using a FI on the other side needs a precise synchronisation of both video-tacheometer which can be done e.g. as described in /Bürki et al. 2010/: The group made tests for refraction monitoring by simultaneous reciprocal vertical angle measurements using UTC time given by small GPS receivers to synchronise their devices.

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REMARK

During the review process of this article Leica Geosystems released the Leica Nova (series) – a total station with integrated telescope camera. As far as known a direct access to the video stream is not possible but the on-board saved images can be downloaded in full resolution. Thus a trend to the combination of total station and photogrammetric methods is visible and will find its way into surveyors' workaday life.

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