Using IATS and digital levelling staffs for the determination of dynamic displacements and natural oscillation frequencies of civil engineering structures

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Abstract

Image Assisted Total Stations (IATS) unify geodetic precision of total stations with image and video capturing. An appropriate system calibration provided, these images and video frames are accurately geo-referenced at any time. They are particularly suitable for deformation monitoring of civil engineering structures and geo-risk areas, which are very hard to approach. It is also possible to use the additional vision technology for levelling applications by reading and analysing digital levelling staff code patterns. This paper presents the use of IATS, i.e. IATS prototype which consists of RTS Leica TPS1201 and GoPro5 Hero camera. The focus of the paper is determination of simulated dynamic displacements and natural oscillation frequencies by the prototype. For the simulations, we used multi-purpose universal testing machine intended for static and dynamic testing of mechanical properties of building materials and construction in laboratory. The experiments will cover the dynamic displacements from 0.1 to 5.0 mm at the frequency of 2 Hz.

Key words: Image Assisted Total Station (IATS), digital levelling, barcode staff, dynamic shifts, natural oscillation frequencies, monitoring.

1 INTRODUCTION

Geodetic monitoring of engineering structures is usually done by GNSS in combination with Robotic Total Stations (RTS). GNSS offers great coverage and RTS offers high precision measurements. Today, modern total stations come with different integrated sensors. With the integration of cameras into total stations – so called Image Assisted Total Stations (IATS) – these different sensor classes are fusing to one single universal instrument (Wunderlich et al. 2014). This integration offers wide coverage of different geodetic tasks to be resolved much quicker, easier and more precise in comparison with classical geodetic methods and instruments. It even offers possibilities to solve some tasks that were not possible to be done in the past with the usage of classic total stations. An appropriate system calibration provided, these images and video frames are accurately geo-referenced at any time. They are particularly suitable for deformation monitoring of civil engineering structures and geo-risk areas, which are very hard to approach. It is also possible to use the additional vision technology for levelling applications by reading and analysing digital levelling staff code patterns.

2 DETERMINATION OF DYNAMIC DISPLACEMENTS AND NATURAL OSCILLATION FREQUENCIES BY IATS

Monitoring of civil engineering structures is one of the key tasks in engineering geodesy and the results of the monitoring represent an important parameter in assessing the condition and safety of the structures. Any kind of damage or significant deformation affects the safety of the constructions, e.g. bridges, and can result in their closure or even collapse which can then cause the collapse and disintegration of every traffic system (Paar, R. 2010). The aim of this research is to investigate the possibility to determine vertical dynamic displacements and natural oscillation frequencies caused by dynamic excitation using IATS to record the video of barcode pattern of digital levelling staff, i.e. to read and analyse it. The values of those dynamic displacements for most structures are in a range of few millimetres. Even for the modern total stations, it is a problem to precisely measure very fast and small movements with standard measurement approaches. Sampling frequency of older RTS instruments was 1 Hz which was insufficient for measurements of dynamic displacements (Cosser, E. et al. 2003). With constant improvements of GNSS and RTS instruments they are no longer limited merely for monitoring of static displacements of the structures, furthermore, they are used for monitoring of dynamic displacements (Marendić, A. et al. 2017). RTS can precisely measure the position of the moving point (reflector) with sampling frequency up to 20 Hz (Stempfhuber, W. 2003). Today, achievable level of precision with RTS instruments with classic prisms by automatic target recognition is on millimetre level.
For determining the high oscillation frequencies with different amplitudes, you need to have the instrument which can achieve high sampling rate of its measurements. E.g. if you want to determine the natural oscillation frequency of 3 Hz you need to have the instrument with sampling rate of 6 Hz or higher according to Nyquist rule (Leis W. J. 2011). IATS instruments offer that possibility with integrated cameras in the telescope, which have sampling rate i.e. frames per second (fps) while recording the video of 30 fps.

2.1 IATS PROTOTYPE

At first, we wanted to conduct the tests using state of the art IATS, i.e. Leica MS50 and Leica MS60. But we realized that using these instruments we can transfer by GEOCOM the videos and images with resolution of 320 x 240 px by MS50, and 640 x 480 px by MS60. Those resolutions are not good enough for distanced objects, since the measuring points are represented by a very small number of pixels on images, regardless of high quality optics with 30x time magnification telescopes. Since the practical application of this approach for determining the dynamic displacements and natural frequencies must be considered we decided to make our own IATS prototype.
The IATS prototype consist of Leica TPS1201 and GoPro5 Hero camera (Fig. 1). Leica TPS1201 is a robotic total station with angle measurements accuracy of 1” (ISO 17123-3) and distance measurements accuracy of 2 mm + 2 ppm (ISO 17123-4) (Leica 2004). GoPro5 Hero camera is the latest model in the series of GoPro cameras. For the optics-lens the camera uses ultra-wide angle all-glass lens with reduced distortion. It offers wide variety of different

modes for recording the videos. User can record videos from WVGA resolution at max 240 fps, 720P resolution at max 240 fps, 960P at max 120 fps, 1080P at max 120 fps, 1440P at max 80 fps, 2.7K at max 60 fps to 4K at max 30 fps (URL 1). The camera also has different field of views (FOV) offered; narrow, linear, medium, wide and superview. The FOV and the video mode are directly correlated with the fps in a way that the wider FOV and higher video mode are the lower fps can be achieved.

For making the IATS prototype we made an adapter for fitting the GoPro5 camera on Leica TPS1201. The adapter was made with the 3D printer. It offers the possibility to directly attached the camera on the ocular of the telescope of Leica TPS1201. Before conducted experiments, we made the stability examination of the telescope of the instrument with fitted camera in vertical direction. The examination showed that there are no movements of the telescope. Also, IATS prototype offers the possibility to manage the camera by smartphone application. And we can manage the instrument via laptop computer. That way we do not have to touch the instrument or the camera, and we can ensure stability of the instrument or horizontal sight of the telescope if necessary during the experiments.

Fig. 1 IATS prototype: Leica TPS1201 & GoPro5 Hero camera

2.2 CONDUCTED TESTS

The simulations were carried out in the Structural Testing Laboratory of Civil Engineering Faculty, University of Zagreb. The dynamic displacements were simulated by a multi-purpose universal testing machine intended for static and dynamic testing of mechanical properties of building materials and constructions (Fig. 2 middle).

For signal marks on the testing machine we used digital levelling staff in the form of label invar with barcode stripe (Fig. 2 left). We also used another signal for making different comparisons in the form of photomark with four different circles. The circles radius and the distances between them are known in advance (Fig. 2 left). The experiments covered the dynamic displacements with oscillation amplitudes of 0.2, 0.5, 1.0, 2.0 and 5.0 mm at frequency of 2 Hz. Regarding the prototype, it was put at maximal distance from the testing machine that was possible in the laboratory, which was 13.709 m. The camera has been set to linear mode, 1080P with 30 fps.

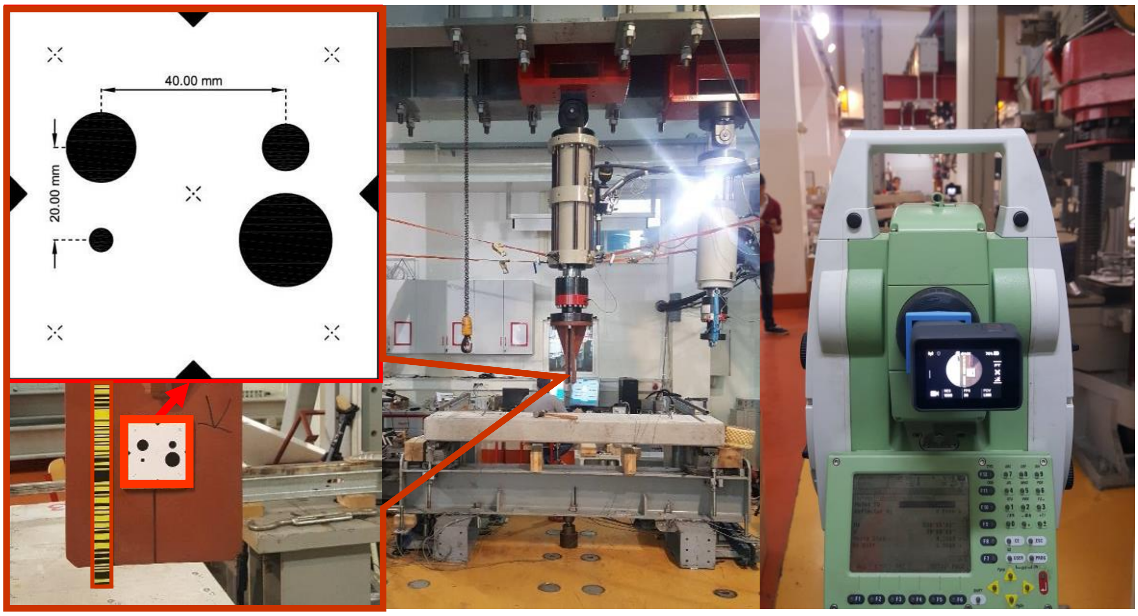

Fig. 2 Signal marks-barcode and photomark (red on the left), testing machine (middle) and IATS prototype (right)

3 IMAGE ANALYSIS

For the purpose of image analysis, we developed a software algorithm, which is able to read digital levelling staffs by IATS with high precision and which works with all currently used code patterns. The only requirement is that the reference code must be known in advance. However, this is not a limitation as enough information can be found in literature to reconstruct every digital levelling code pattern (Wiedemann, W. et al. 2017, Ingensand, H. 1999). Core part of the analysing strategy is the extraction of the barcode edges in each single video frame and the comparison with nominal heights of the known reference code. To extract the barcode edges in a recoded video file, the stream is split into single frames and subsequently analysed. First step of the image processing chain is an image rectification to correct a possible perspective-based distortion. This effect is caused by a non-horizontal view at the levelling staff and can be described and removed by a homography (projective transformation) based on the measured parameters: distance and vertical angle. For the further processing, the image part containing the barcode is transformed into two different signals: (1) a binary signal using an adaptive threshold and (2) a list of barcode edge positions using an edge detection algorithm. An approximation value for the height reading is calculated by a correlation of the binary signal with the reference signal, which is scaled to the image size using the measured distance as scale factor. The final height is determined by minimizing the distance between the measured barcode edges positions and the nominal heights at the levelling staff. Their functional relation can be solved by a least squares adjustment using the result of (1) as initial value. The pairwise assignment of the barcode edge positions is determined by a forward and backward search of nearest neighbours in both vectors. A distance filter and an outlier test removes these lines, which may be caused by failed edge detection or partial occlusion of the observed code pattern. Last step in the algorithm is to add a possible trigonometric height difference, based on the measured vertical angle and the slope distance. Further information to the image processing can be found in
Wagner, A. et al. (2016) or Wiedemann, W. et al. (2017).

3.1 DETERMINATION OF DYNAMIC DISPLACEMENTS FROM THE BARCODE

For each experiment, the video file was split into single video frames, which are separately analysed. A (manually defined) 40-pixel wide vertical band containing the barcode is cut out and used for the further processing by the above described approach. The result is a time series of (absolute) height readings at the levelling staff/stripe referred to the image centre. We subtracted the mean height reading of each experiment to get the relative displacements. Fig. 3 shows the first 4 seconds of a test with an amplitude of 5 mm. Clear visible is the regular discreet sampling with a rate of 30 Hz. The total displacement is slightly smaller than predefined amplitude of 5 mm on test machine. The reasons for that will be explained later in the paper.

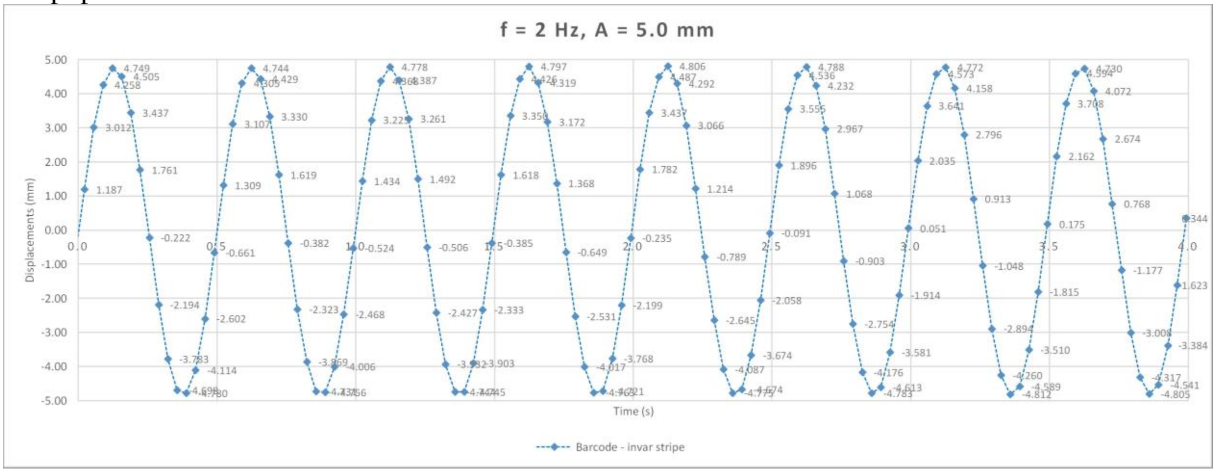

Fig. 3 Detail (first 4 seconds) of one analysed video stream; every dot represents the vertical displacement of one video frame

To calculate metric displacements from image data it is necessary to determine a scale factor between the dimensions of the pixel coordinate system and the object space. As described above, we were calculating a last squares adjustment of measured and reference barcode edge positions in our data processing. Both data are correlated by a constant offset – the searched height reading – and a scale factor, which is functionally related to the object distance and the angular resolution of the camera system. We were estimating the scale factor in each image, which should be constant if the acquisition geometry is not changing. However, we found in our data a slightly varying scale factor, which is caused by (1) an optical distortion of the camera and (2) by a motion blur of the barcode of invar stripe. The first effect could be minimized by an appropriate camera calibration, which was not available at the time of the data evaluation. We tried to reduce this influence by analysing only the centre part of the image. The second effect depends on the exposure time of the camera and the lighting conditions. The effect enlarges the bars of the levelling code and depends on the speed of the target sign, which is varying in our case. The motion blur has its minimum in frames at the turning point and its maximum between. To get the final displacements, the scale factor for each experiment was fixed to the mean value of a first evaluation with variable scales. A slight modification of this value is changing the final amplitude already. It would be easy to find a scale factor that results in the expected amplitude and is still in accordance with the measured distance and camera resolution. We found, however, that using the mean value of all estimated scales is the correct way of evaluating the data.

3.2 DETERMINATION OF DYNAMIC DISPLACEMENTS FROM THE PHOTOMARK

The results of the barcode invar stripe evaluation were compared with a second, different approach. For that reason, a target sign was installed next to the barcode, photomark showing four circles in a known fixed spacing (Fig. 2). The circles are detected in the same images as the barcode invar stripe by a blob analysis, filtering all found blobs by size and roundness. For the remaining objects – the four circles – the centroids are estimated. This enables to track the movement induced by the testing machine in the image space (pixel coordinate system). With the known spacing between the circle centres, it is possible to calculate the scale factor to transform these values in the metric units. A frequency analysis of the movement detected by the circle targets, shows nearly the same results as the barcode approach. The difference between the two approaches is from -0.04 to 0.04 mm for A = 0.2 mm, -0.04 to 0.05 mm for A = 0.5 mm, -0.05 to 0.07 mm for A = 1.0 mm, -0.09 to 0.11 mm for A = 2.0 mm, and -0.18 to 0.12 mm for A = 5.0 mm. Comparing the absolute values (amplitudes) of the movement, we see slightly differences between both evaluations. The reason is that the scale factor, calculated by the known metric spacing of the circle centres and their measured pixel value only, is not constant over the image sequence. This effect may be caused by the influence of the uncalibrated camera (radial distortion) and the fact that only a very small image section is evaluated. Here, the barcode approach has the advantage that the entire (vertical) image section is used and the scale factor is determined using the reference code over the entire visible bar code. In general, the mean of many individual edge measurements is calculated, leading to more stable results with very high precision. An additional advantage of evaluating the levelling barcode is that we can derive a metric, absolute value for the object’s equilibrium position. With the higher expansion of the barcode pattern, it is also possible to gain height information with partial occlusion in the image. If using a target sign (like one circle) only, it must be guaranteed that the entire sign is visible at any object movement.

3.3 FREQUENCY ANALYSIS

A common approach for vibration monitoring, i.e. the analysis of the measured natural oscillation frequencies, is to compute the discrete Fourier transform of the signal using a Fast Fourier Transform (FFT) algorithm. No camera calibration is necessary when using image data for this task, as the raw image coordinates (pixel values) can be used directly (Cosser, E. - Roberts, G.W. - Meng, X. - Dodson, A. H. 2003. Measuring the dynamic deformation of bridges using a total station. In Proceedings of the 11th FIG Symposium on Deformation Measurements, Santorini, Greece. pp. 605–612.
Ehrhart, M. et al., 2015). Fig. 4 shows the frequency spectrum of the analysed experiments with varying amplitudes between 0.2 mm and 5.0 mm. Clearly visible is the dominant frequency 2.01 Hz in all experiments evaluations. This proves on the one hand the stable excitation frequency of the test facility and on the other hand the correct determination of our image processing.

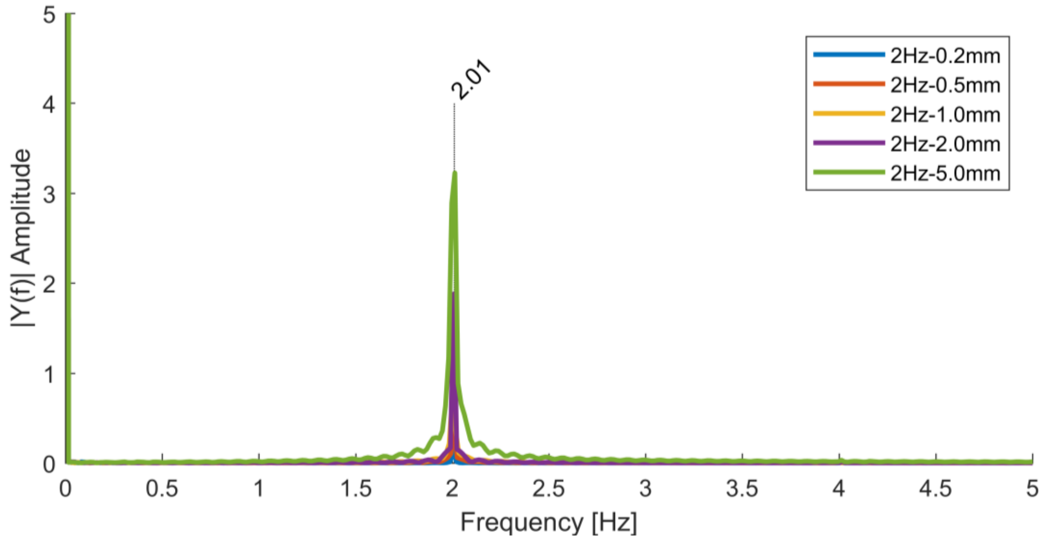

Fig. 4 Frequency spectrum of analysed experiments with varying amplitudes

4 ACHIVED RESULTS

After conducted experiments, gathered data was analysed. The analysis was done in way to firstly determine the dynamic displacements, and afterwards to determine the natural oscillation frequencies. Also, since we were determining the displacements from two different signals, i.e. the barcode invar stripe and the photomark with the circles, we analysed the differences between the obtained results.

4.1 ACHIEVED ACCURACY AND PRECISION

Fig. 5 shows achieved and determined amplitudes during five different experiments. In all experiments predefined frequency was 2 Hz with different amplitudes of 0.2, 0.5, 1.0, 2.0 and 5.0 mm. All experiments had duration of 60 sec. The deviations from predefined amplitudes exists in every experiment, but in a very small amount. What can be seen from the Fig. 5 is that there is excellent overlap between different approaches with the barcode and with the photomark. Also, the accuracy of the testing machine, i.e. the achieved predefined amplitudes, must be considered. They were not accomplished 100% precisely. These can be seen from the Fig. 5 and from the Tables 1 to 5.

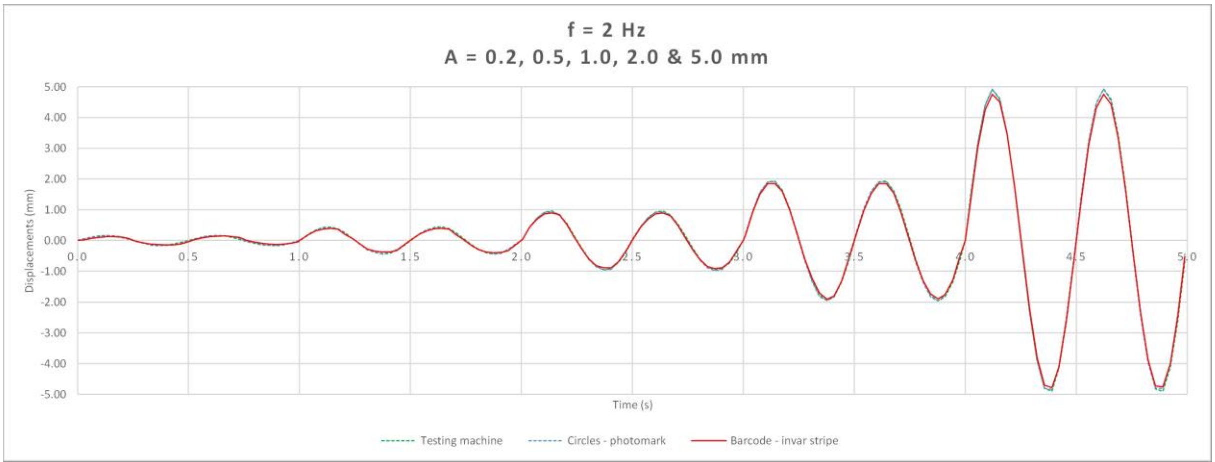

Fig. 5 Resulting amplitudes of five different experiments (1 sec period each experiment)

Tables 1 to 5 shows the predefined frequency (2 Hz in all experiments) and predefined amplitudes (0.2 to 5.0 mm) that had to be achieved with the testing machine. Tables also shows determined amplitudes with the testing machine, and with the usage of barcode invar stripe and photomark with the circles. Mean differences and standard deviations are also shown in the tables. What can be seen from the results is that testing machine didn't achieved predefined amplitudes in each test, which means that determined results from the barcode invar stripe and photomark with the circles are even better that we firstly thought, because we are comparing them with the achieved amplitudes and not with the predefined. So, we decided to use the data from the testing machine as the reference data.
Deviations for the photomark with the circles (PM-circles) are in the range from 0.03 to 0.12 mm (except in experiment with A = 5.0 mm the deviation is 0.23 mm), with the standard deviation in the range from 0.017 to 0.088 mm depending on the predefined amplitudes.
Deviations for the barcode invar stripe (IS-barcode) are in the range from 0.05 to 0.18 mm, with the standard deviation in the range from 0.033 to 0.113 mm depending on the predefined amplitudes. The data showed in the Tables 1 to 5 confirms excellent overlap between the different approaches which can also be seen on the Fig. 5, and achieved excellent level of precision shown by standard deviations.

Table 1 Achieved min, max & mean amplitudes with standard deviations for test f = 2 Hz, A = 0.2 mm

	f=2 Hz, A = 0.2 mm				
	TM (mm)	PM-circles (mm)	Δ_{PMC-TM} (mm)	IS-barcode (mm)	Δ_{BIS-TM} (mm)
Min	-0.161	-0.169	-0.030	-0.150	-0.048
Max	0.169	0.156	0.029	0.146	0.057
Mean			-0.001		-0.003
St. dev.			0.017		0.033

Table 2 Achieved min, max & mean amplitudes with standard deviations for test f = 2 Hz, A = 0.5 mm

	f=2 Hz, A = 0.5 mm				
	TM (mm)	PM-circles (mm)	Δ_{PMC-TM} (mm)	IS-barcode (mm)	Δ_{BIS-TM} (mm)
Min	-0.436	-0.423	-0.050	-0.395	-0.067
Max	0.443	0.415	0.045	0.394	0.064
Mean			-0.004		-0.004
St. dev.			0.024		0.033

Table 3 Achieved min, max & mean amplitudes with standard deviations for test f = 2 Hz, A = 1.0 mm

	f=2 Hz, A = 1.0 mm				
	TM (mm)	PM-circles (mm)	Δ_{PMC-TM} (mm)	IS-barcode (mm)	Δ_{BIS-TM} (mm)
Min	-0.955	-0.980	-0.052	-0.914	-0.066
Max	0.956	0.930	0.042	0.896	0.067
Mean			-0.010		-0.008
St. dev.			0.028		0.039

Table 4 Achieved min, max & mean amplitudes with standard deviations for test f = 2 Hz, A = 2.0 mm

	f=2 Hz, A = 2.0 mm				
	TM (mm)	PM-circles (mm)	Δ_{PMC-TM} (mm)	IS-barcode (mm)	Δ_{BIS-TM} (mm)
Min	-1.959	-1.960	-0.121	-1.912	-0.088
Max	1.939	1.918	0.120	1.857	0.119
Mean			-0.004		-0.003
St. dev.			0.058		0.059

Table 5 Achieved min, max & mean amplitudes with standard deviations for test f = 2 Hz, A = 5.0 mm

	f=2 Hz, A = 5.0 mm				
	TM (mm)	PM-circles (mm)	Δ_{PMC-TM} (mm)	IS-barcode (mm)	Δ_{BIS-TM} (mm)
Min	-4.903	-4.835	-0.115	-4.780	-0.186
Max	4.919	4.921	0.228	4.749	0.147
Mean			0.016		-0.012
St. dev.			0.088		0.113

From conducted experiments and showed results we can highlight some advantages, differences and similarities between the two approaches; the reading of the barcode invar stripe and the photomark with the circles. Advantages of using the levelling barcode invar stripes are:

- The analysis is based on the entire (vertical) image size.
- Parts of the barcode pattern may be hidden.
- The calculation is in general sense a mean of many individual edge measurements.
- The scale factor is determined using the reference code over the entire visible bar code.

In difference, when using other signalisation e.g. photomark with the circles:

- Only a small image region is used.
- It must be guaranteed that the entire sign is visible, at any object movement.
- The scale factor must be known or a scale must be printed at the object.

Both methods offer high level of precision and accuracy. But, in the future what must be tested is the determination of dynamic displacements and natural oscillation frequencies with higher amplitudes and longer distances between the IATS prototype and the moving object.

5 CONCLUSION

The paper shows the application of IATS, i.e. IATS prototype for the determination of the dynamic displacements and natural oscillation frequencies. These instruments have the possibilities to collect the videos and the images with high resolution and fps. For the marking of measuring points on the testing machine, we used the barcode invar stripe and the photomark with the circles. The end results are collected video frames and extracted images from them. For that purpose, a software algorithm for the image analysis was developed, which can read digital levelling staffs, i.e. barcode invar stripe, obtained as an image by IATS with high precision and which works with all currently used code patterns.

The achieved results showed high level of precision, i.e. the lowest achieved standard deviation is 0.113 mm and the highest achieved standard deviation is 0.024 mm, which is to our opinion excellent result.

The on-axis camera of a modern IATS offers a comparable high magnification of the telescope as built in a digital level, or as in our way added camera for video and image collection. The differences between both instrument types are an additional rotation axis in the vertical plane and an electronic inclinometer instead of the mechanical compensator. This means, if the accuracy of the vertical angle reading is high enough, it is possible to level with a total station in the same way as with a levelling instrument. This way we get the best from the two instruments in one. The presented innovative approach enables the monitoring of civil engineering structures in static as well as in dynamic mode using IATS for measuring the dynamic displacements and natural oscillation frequencies. These way surveyors get an additional monitoring method and more flexibility in the realisation strategy.

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