Development and Application of IATS for Structural Health Monitoring

Rinaldo PAAR, Ante MARENDIĆ, Ivan JAKOPEC, Miodrag ROIĆ and Hrvoje TOMIĆ, Croatia

Key words: IATS, SHM, displacement, natural frequency, accelerometer

SUMMARY

This paper describes the technological development of Image Assisted Total Stations (IATS) from early 2000s. The development enabled much wider integration of these types of geodetic instruments with their sensors for the purpose of structural health monitoring (SHM), i.e., for the displacement and deformation monitoring of structures. IATS can be used for periodic or continuous monitoring of structures, or during regular structure inspections. Also, they can be used for structural and geo-monitoring, i.e., for the determination of static and dynamic displacements and deformations, as well as for the determination of civil engineering structures' natural frequencies. This way we can collect essential data about the current condition of structures.

For this paper, we developed low-cost IATS prototype, which consists of an RTS Leica TPS1201 instrument and GoPro Hero5 camera. The application of IATS prototype is presented through experimental study that was performed for the purpose of later static and dynamic load testing of the bridges. The focus of the paper besides technological development of IATS is on the 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 amplitudes of 0.2, 1.0 and 5.0 mm at the frequency of 1 Hz. The procedure of conducting measurements with IATS, as well as the analysis of acquired data and achieved results, is presented. From the performed experiments, we manage to successfully determine simulated natural frequency and all dynamic displacements at different amplitudes with high level of overlap, accuracy and precision.

Development and Application of IATS for Structural Health Monitoring

Rinaldo PAAR, Ante MARENDIĆ, Ivan JAKOPEC, Miodrag ROIĆ and Hrvoje TOMIĆ, Croatia

1. INTRODUCTION

Structural health monitoring (SHM) of engineering structures besides physical sensors (accelerometers, LVDT, encoders) can be performed by geodetic instruments and 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 image sensors into total stations (TS) – so called Image Assisted Total Stations (IATS), due to the rapid technological development, these different sensor classes, each with their specific advantages, can be unified, utilized, and are fused as one single (nearly) 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 TS. 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, i.e., structural monitoring and geo-monitoring of hazardous areas, which are very hard to approach.

In this paper we will show our own developed IATS prototype which consists of an RTS Leica TPS1201 instrument and GoPro Hero5 camera, since modern state-of-the-art IATS instruments were not at our disposal, and they have some disadvantages that potentially could presented big factor for the purpose of determination of dynamic displacements and natural oscillation frequencies. The biggest disadvantage of these instruments is the fact that obtained images after their transfer to the computers have compressed resolutions which are not good enough for further image analysis. 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 of instruments with 30x time magnification telescopes. Developed IATS prototype is presented through experimental study in the laboratory where we used multi-purpose universal testing machine intended for static and dynamic testing of mechanical properties of building materials and construction for the simulation of dynamic displacements. The experiments covered the dynamic displacements of 0.2, 1.0 and 5.0 mm at the frequency of 1 Hz.

2. DEVELOPMENT AND APPLICATION OF IATS

Many different sensors and measurement methods are combined in total stations (TS), such as highly accurate angle reading, electronic distance measurements (EDM) to reflectors and to any other surface (reflectorless EDM), tilt correction by two-axis inclinometers, different types of motorization to drive both the horizontal and the vertical motion of the instruments, servo, piezo, and magnetic motors (robotic total station - RTS), image sensors (CCD or CMOS) for autofocus, automated aiming (i.e., automatic target recognition (ATR) and tracking of signal points), integration with global navigation satellite system (GNSS) positioning, wireless communication and operation using a controller, additional cameras for documentation (image-assisted total station - IATS), and IATS with a scanning function (image-assisted scanning total station - IASTS). Modern TS are multi-sensor systems which can determine the three-dimensional coordinates of target points by combining horizontal angle, vertical angle, and distance measurements (Lienhart et al. 2017).

Different types of motorizations developed to drive instruments in horizontal and vertical motion have been specially designed and implemented in RTS to automatically search for reflectors and, later, for reflector tracking. Most commonly, RTS are used for highly precise measurements such as displacements and deformation monitoring of civil engineering structures and the Earth's surface. RTS with additional integrated cameras on top of the telescope or in the telescope are commonly denoted as image-assisted total station (IATS) (Lienhart et al. 2017). IATS have possible applications in semiautomated object reconstruction systems (Walser 2004), fully automated deformation monitoring systems (Alexander et al. 2009), industrial measurement systems (Knoblach 2009), measurements of vibration amplitudes by means of high-frequency image measurements (Wasmeier 2009), capture of additional information such as high-frequency motions or intensity fluctuations of patterns using image sensor to derive the temperature gradient of the atmosphere as a decisive influence parameter for angular refraction effects and monitoring of cracks (Reiterer et al. 2012, Huep et al 2010).

2.1 Technological development from 2000s until today

The technological development of today IATS goes back to the past in the middle of 19th century, when first photo theodolites were developed for mapping projects. In the first half of 20th century the first commercial photo theodolite was manufactured by Wild company and named Wild P30. After the World War II the first video theodolites were developed for the purpose of tracking aircrafts and missiles. In the 1980s image sensors were integrated in video theodolites with the introduction of Kern E2-SE and Wild TM-3000V using motorization for the possibilities of automated aiming of signalized targets. Available prototypes of video theodolites in the 1990s encouraged intensive research on their application with high degrees of automation. Equipped with motors, video theodolites made it possible to increase the dynamism of computer-controlled measurements, turning a video theodolite into a robot. Electronic reading of directions and lengths was around for a long time, but the processing of data obtained using built-in cameras was still in its initial stages. The application of digital image processing methods and computer vision was investigated by the academic community. Initial research focused on detecting artificial targets and accurate aiming with the help of cameras. This research resulted with the development of the first motorized self-aiming surveying instrument Wild TCA1800. More on the development from the mild 19th century until the end of 20th century can be found in Paar et al 2021a. Below we will concentrate on the development of today state-of-the-art modern IATS which development started at the beginning of 21st century.

At the beginning of this commercial period when IATS systems were brought to the geodetic scene, the first IATS instrument was presented by Sokkia (SET3110MV) at INTERGEO 2002. The instrument had two integrated cameras, an overview camera on the telescope and another camera integrated in the telescope. The curious aspect of this instrument was that it did not have an ocular; instead, the expert performed measurements using a remote controller displaying the live video obtained from the integrated cameras.

The forerunner of today's state-of-the-art commercial IATS systems was Topcon's model GPT-7000i from 2005**.** Topcon integrated the camera into a TS, which created a new generation of video theodolites, named IATS. The instrument was equipped with two different VGA cameras. One camera was wide-angle with an FOV of 28° × 22° and fixed focus, located on the telescope, allowing rotation to be synchronized and the field working area to be displayed. The second camera was coaxial, and it recorded the details of the terrain seen through the magnification of the telescope; thus, it included variable focus. It had an FOV that matched the telescope FOV (1°30′ × 1°30′). In 2007, Topcon introduced the successor of the first series model GPT-9000Ai. The greatest technological development compared to the GPT-7000i was manifested as the possibility of automatic focusing of signal points and remote guidance by the controller, which eliminated the need for an observer, making it a so-called "one-man station". It was also the first RTS that enabled the taking of photographs and the possibility of scanning as a unique function within the IATS system. The instrument could scan up 20 points per second. These types of IATS have been produced by Topcon for three generations and are known as Imaging Stations, with the latest model called IS3. Both cameras had an image sensor with a resolution of 1280 × 1024 pixels, and they could also record video at 10 frames per second (fps), which could be transmitted to the station control screen or to the controller screen (Topcon 2021a, b).

Trimble introduced its first IATS in 2007, the model VX Spatial Station. VX delivered images that were accurately georeferenced. The instrument was equipped with a 3 MPx colour camera, with fixed focus and an FOV of 16.5° × 12.3°. The camera was located on the telescope. This camera was later implemented in all total station models that Trimble released, including today's Trimble S9 series. The features of postprocessing photogrammetric analysis of calibrated images, 5 fps video recording, panoramic mosaic image, and overlap with measured data are known as "Trimble Vision". The VX Spatial Station was an RTS with MagDrive servo technology, involving an integrated servo/angle sensor electromagnetic direct drive in combination with added digital imaging and rudimentary scanning capabilities. The scanning function could scan 20 points per second with the ability to colorize scanned scenes based on recorded images (Trimble 2021).

In 2009, Pentax presented an RTS with integrated cameras into its instruments, known as Visio series model R-400VDN. The camera was placed on the telescope, and a screen displaying captured images and video from the camera was also placed on the telescope above the ocular (Figure 8). The FOV was 8.8° × 8.8°, and it could record video at 10 fps (Pentax 2021).

Leica introduced its IATS instrument in 2010 called Viva; two models with overview cameras placed on the telescope were presented: Leica TS11 and Leica TS15. Model TS15 was motorized using a servo focus drive with additional sensors for automatic and remote control, unlike TS11. The overview camera had an optical axis different from the optical axis of the telescope, which resulted in parallax; thus, the centre of the optical axis of the telescope did not coincide with the centre of the image sensor. The relative position of these two axes was determined by calibration at the time of its manufacturing. The effect of parallax could also be corrected by measuring the distance to the target. The integrated cameras in both models had a 5 MPx CMOS image sensor, with fixed focus and an FOV of 15.5° × 11.7°, with the possibility of recording video at 20 fps (Leica 2021a, b).

In 2013, Leica introduced the new series called Nova with two models TS50 and MS50. The instruments, in addition to an overview camera, had an integrated camera in the telescope with an FOV of 1.3° × 1.0°, an 8× digital zoom of the overview camera, and a 30× optical zoom of the telescope camera, as well as an 8× digital zoom. That way, the images from the telescope camera were magnified 30× (Figure 1). Leica MS50 also had a scanning function with the ability to scan 1000 points per second. Leica TS50 did not have a scanning function. Both models used the same motorization using a servo focus drive. Based on the scanning function with video and photo capture capabilities, a combined approach to image analysis and scanning was developed (Wagner et al. 2016, Wagner et al. 2017).

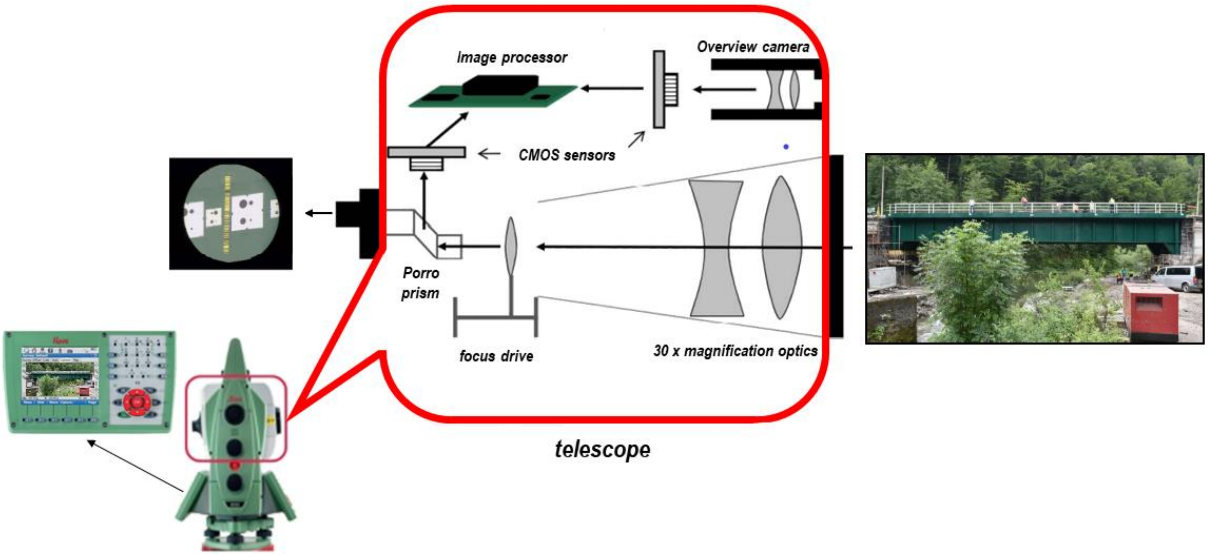

Figure 1. Leica MS50 schematic cross-sectional view of the telescope with image sensors and processor integration, as well as motorization for autofocus modified for this paper from Paar et al 2021a.

In 2015, Trimble introduced its IATS model S9 which used the same camera and image sensor as Trimble VX Spatial Station introduced in 2007. The S9 replaced the VX and S8 for both precise and long-range applications. It offered higher angular and distance accuracy than the

VX Spatial Station. The predecessor of today's state-of-the-art IATS and IASTS company, Topcon, unfortunately abandoned its original design with two integrated cameras in the instrument; in 2014, it offered IATS model DS-200i with one camera, an overview ultra-wide camera on the telescope with a 5 MPx image sensor, which was mainly integrated for providing imaging documentation and a live video stream on the remote controller (Topcon 2021c).

Today, Leica offers the models TS60 and MS60 from the Nova series introduced for the first time in 2015 with improved functions of ATR (ATR plus), reflector self-search us-ing the PowerSearch function, dynamic look function, motorized direct drives based on Piezo technology, improved scanning function with 3D laser scanning of 30,000 points per second, image-assisted surveying, and documentation using advanced artificial intelligence; it is called the first self-learning multi-station (Maar and Zogg 2021). Trimble introduced its new generation of IATS instruments in 2016, model SX10. This is the first commercial TS, i.e., IATS without an ocular. Three 5 MPx cameras (overview, primary, and general) are integrated in the telescope, offering a maximum total FOV of 360° × 300° with 84× zoom. The general camera enables an FOV of 57.5° × 43.0°. An expert controls the instrument using a remote controller via live video at 15 fps. SX10 combines high-density 3D scan data, enhanced imaging called Trimble Vision, and high-accuracy total station data. It uses MagDrive servo technology, and it can measure dense 3D scan data at up to 26,600 points per second with high precision over the full measurement range of up to 600 m (Trimble 2021b). In 2021 Trimble introduced its successor SX12 with the following upgrades: 8.1 MPx image sensors, 107× zoom of the main camera, and a new laser pointer, while the remaining features regarding angle and distance measurements and scanning function are at the same level as SX10 (Trimble 2021c). Topcon presented its GTL-1000 in 2019, and it is the world's first RTS and laser scanner with an inbuilt camera, which is primarily used for colorizing the scanned scenes. The camera has a 5 MPx image sensor which is also used for live video. A 3D laser scanner is installed in place of the RTS handle, resulting in a solution that it is both a geodetic measuring station and a geodetic 3D laser scanner. The instrument uses direct drive via an ultrasonic motor. The main advantage of this IASTS compared to other commercially available IASTS is the scan rate, which is on the level of today's terrestrial laser scanners and is specified as 100,000 points per second. It is the first such instrument in the world (Topcon 2021d).

Table 1. Main specifications of currently available IASTS.

Specifications	**Leica MS60**	**Trimble SX 12**	**Topcon GTL-1000**
Camera/sensor	2×/CMOS	3×/CMOS	1×/CMOS
Resolution	5 MPx	8.1 MPx	5 MPx
Fps	20 Hz	15 Hz	Live video
FOV overview/telescope	15.5° × 11.7°/1.3° × 1.0°	[2] Total 360° × 300°	270° × 360°/✗
Zoom overview/telescope	8×/30×	107× [3]	[1]
Accuracy distance (prism)	1 mm + 1.5 ppm	1 mm + 1.5 ppm	1 mm + 2 ppm
Accuracy distance (non-prism)	2 mm + 2 ppm	2 mm + 1.5 ppm	2 mm + 2 ppm
Accuracy Hz and V	1″	1″	1″
Scan rate	30,000 Hz	26,600 Hz	100,000 Hz
Year released	2020	2021	2019

Leica MS60, Trimble SX12 and Topcon GTL-1000 combine imaging with scanning on a level that is not rudimentary, so we can call them image-assisted scanning total stations (IASTS). In Table 1 Leica MS60, Trimble SX12, and Topcon GTL-1000 are compared with their main specifications and characteristics. All instruments have a scanning function, and they are classified as multi-stations, so-called IASTS. These three instruments, at the moment, represent the state-of-the-art geodetic instruments in the world.

2.2 Application of IATS

All currently available commercial IATS and IASTS instruments use recorded images and videos for additional attributes of the measured point, i.e., primarily for documentation and colorizing the scanned scenes. Standard measurement methods in the field have been largely developed and improved by technological developments of TS. Manual focusing has been replaced by auto-focusing; moreover, using remote control, an expert can select the point of interest defined by a pixel from a live video/image on a display, thereby pointing the instrument to a signalized or unsignalized point. For pointing the instrument to the point of interest and for tracking the reflector in the field, instruments use motorization, which is currently realized by piezo, magnetic, or ultrasonic drives depending on the manufacturer. The recorded images can be automatically downloaded for each point or for a set of points for documentation purposes. This way, it is possible to visualize these points. More importantly, we can perform photogrammetric processing of collected georeferenced images afterward and, e.g., use them for structural and geo-monitoring, levelling, and fusion of laser scan and image data for deformation monitoring. Commercial IATS and IASTS instruments still do not use the full potential and functions of these instruments (Wagner 2017).

Monitoring of artificial or natural structures is one of the key tasks in engineering geodesy, next to site surveying and setting out. Geodetic monitoring is one aspect of monitoring systems in general. There are two subtypes of geodetic monitoring (Wagner 2017):

1. **Structural monitoring** refers to the measurement and evaluation of civil engineering structures such as bridges, tunnels, dams, railways, towers, or skyscrapers, i.e., generally manmade objects.
2. **Geo-monitoring** in contrast, is used as a term for the determination of changes, movements, or deformation of natural structures, such as landslides and slopes.

The main aim of geodetic monitoring is to determine statistically significant geometric changes in size, shape, and position between two or more measuring epochs. According to the monitoring data, action can be taken on the construction to prevent material and nonmaterial damages. Vibration-based monitoring, i.e., structural monitoring, has become common recently. Vibration-based monitoring consists of determining the dynamic displacements and natural frequencies of objects from different epochs of measurements. Any changes from the designed frequencies can be a sign of structural damage and a cause for alarm.

Dynamic displacements and natural frequencies of objects can be determined by RTS and GNSS instruments, although their use in these projects has certain limitations. The limitation of the first RTS models was their instrument measurement frequency of 1 Hz, which was lower than the fundamental frequency of the bridge, as demonstrated in. Possibilities of newer RTS models with measuring frequencies of 5–7 Hz were presented in, where RTS instruments were used for the measurement of simulated dynamic displacements to analyse the accuracy of dynamic measurements by RTS, as well as for the determination of dynamic displacements and natural frequencies of bridges in exploitation. The accuracy of an RTS instrument with 20 Hz measuring frequencies for recording changing 3D coordinates of a moving target was tested in and for measuring dynamic displacements and natural frequencies of railway bridges where the RTS determined dynamic displacements of the bridge in vertical and lateral directions and the first five natural frequencies of the bridge (Paar et al. 2021).

Precise 3D point measurement is either automated using an RTS with reflectors or using a GNSS. However, reflectors and GNSS cannot be used in every situation because they cannot be placed on every point or object of interest. Furthermore, in the case of GNSS, a power supply must be ensured in sometimes hazardous and inaccessible places. These issues mean that we must use IATS with image sensors to collect spatial, spectral, and radio metrical information of the target point of interest and its environment, whereby, with the use of image analysis methods, RTS and GNSS methods can be replaced for determining precise 3D-point measurements of signalized points and unsignalized points (Walser 2004). One of the first applications of IATS for structural monitoring was conducted by the Chair of Geodesy, TU Munich, for the measurement of dynamic displacements and natural frequencies of the Fatih Sultan Mehmet Bridge over the Bosporus waterway in Istanbul, Turkey. Using a self-developed low-cost IATS prototype consisting of a Leica TPS1201 RTS with an ocular replaced by a 5 MPx CMOS colour camera, they managed to determine vertical displacements of up to 50 cm and the first six natural frequencies of the bridge. Research conducted at the Institute of Engineering Geodesy and Measurement Systems, TU Graz, covered a variety of experimental studies and in situ measurements using IATS Leica MS50 and MS60. They were aimed at determining the natural frequencies of the Augarten and Pongratz-Moore-Steg footbridges over the river Mur in Graz, Austria (Paar et all 2021). In the next section, the potential for application of the IATS is presented through the developed and tested low-cost IATS prototype in the laboratory.

3. EXPERIMENTAL TESTING IN THE LABORATORY

Experimental testing was performed in the Structural Testing Laboratory of the Faculty of Civil Engineering, University of Zagreb. The tests were performed to see if the determination of dynamic vertical displacements and natural frequencies is possible in ideal controlled laboratory conditions. The dynamic vertical displacements were simulated by a multi-purpose universal testing machine intended for static and dynamic testing of mechanical properties of building materials and constructions and were measured by the IATS prototype, while a signal photomark was used for measuring with four predefined known circles' radius and distance between the circles' centres (Figure 2).

The test consisted of simulated displacements with the amplitudes of A = 0.2, 1.0, and 5.0 mm at the frequency of F = 1.0 Hz. We managed to determine all displacements and frequency. Some of the similar previous experiments conducted in the laboratory and in the field were presented in (Paar et all 2017, 2021a, 2021b]. The low-cost IATS prototype was set up at the distance from the testing machine d = 13.709 m. The IATS prototype GoPro Hero5 camera was set to narrow mode, 1080P with 30 fps for video recording. Measurements and results obtained by the IATS prototype and testing machine for all three experiments are shown separately in Figures 3, 4 and 5. For each experiment, top part of figure shows 60 s of obtained measurements by the IATS prototype, bottom left part of the figure shows the comparison between simulated (TM - testing machine) and measured displacements (IATS prototype) with the difference between them for a time interval of 3 s, and third, bottom right part of the figure shows the determined frequency from IATS prototype measurements.

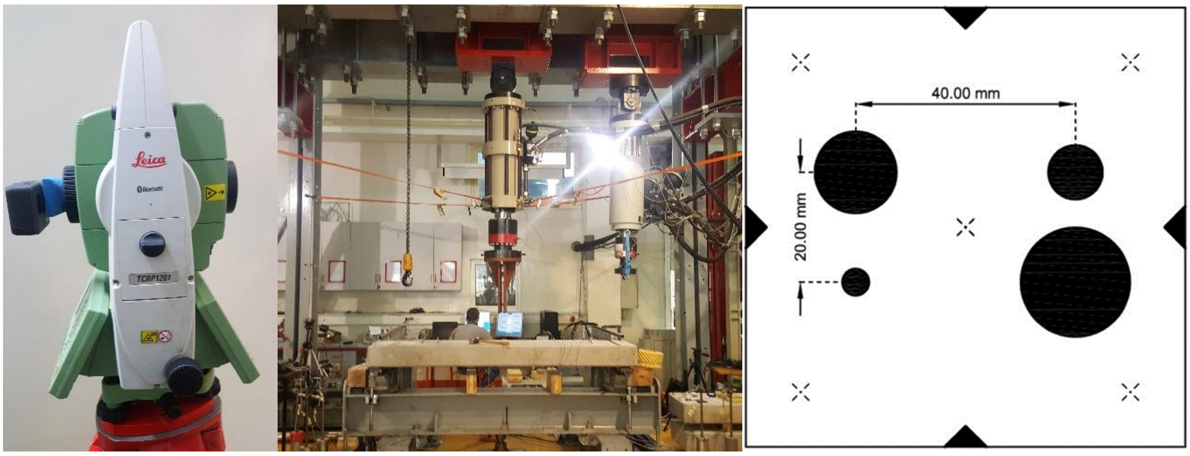

Figure 2. IATS prototype: Leica TPS1201 plus GoPro Hero5 camera (left), multi-purpose universal testing machine in the laboratory (middle) and photomark measuring signal (left).

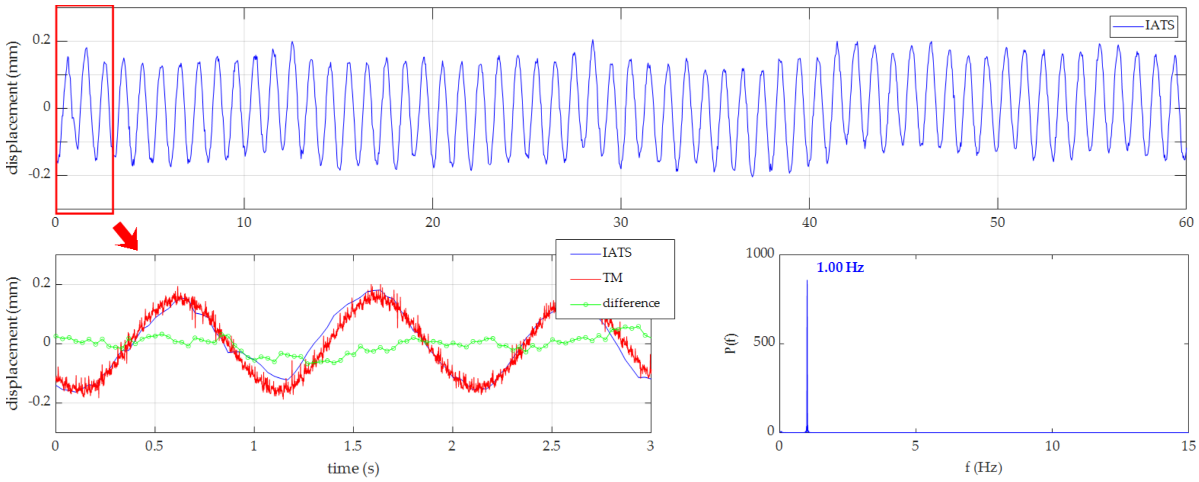

Figure 3. The measurements and results obtained by means of IATS prototype for the test A = 0.2 mm and F = 1.0 Hz.

The second aim of the experiment was to test the ability of the IATS prototype to determine the oscillation frequency of the simulated dynamic displacements with oscillation amplitudes of less than 0.2, 1.0 and 5.0 mm at F = 1 Hz oscillation frequency. Dominant frequencies of oscillations in all tests were calculated using the Fast Fourier Transform (FFT) analysis. The results of determined frequencies from measurement data obtained by means of IATS prototype are shown in figures 3, 4 and 5. Based on the comparison with simulated oscillating frequency, we can conclude that the IATS prototype was able to determine simulated frequency in all three tests with a 100 % overlap.

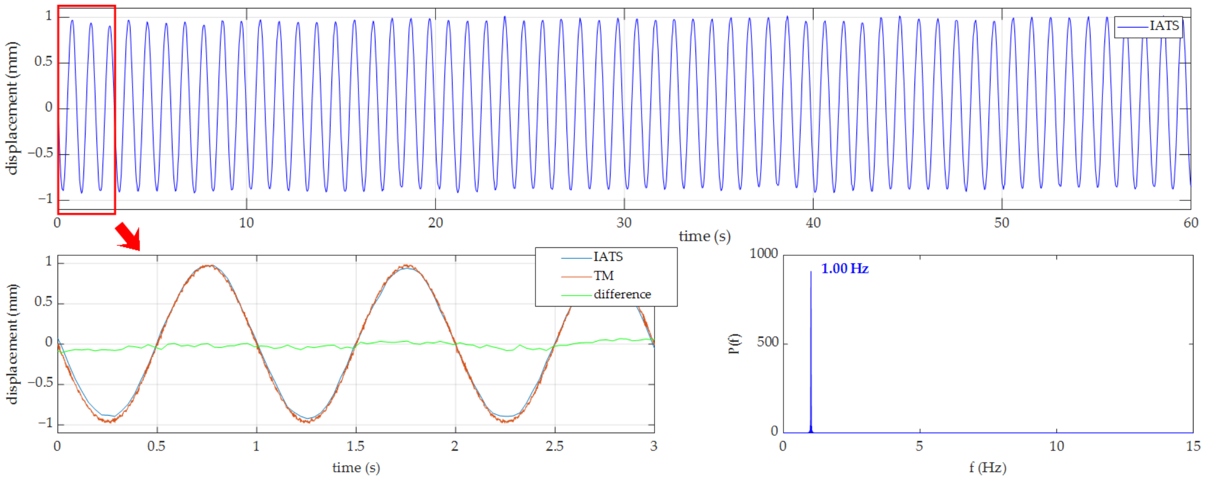

Figure 4. The measurements and results obtained by means of IATS prototype for the test A = 1.0 mm and F = 1.0 Hz.

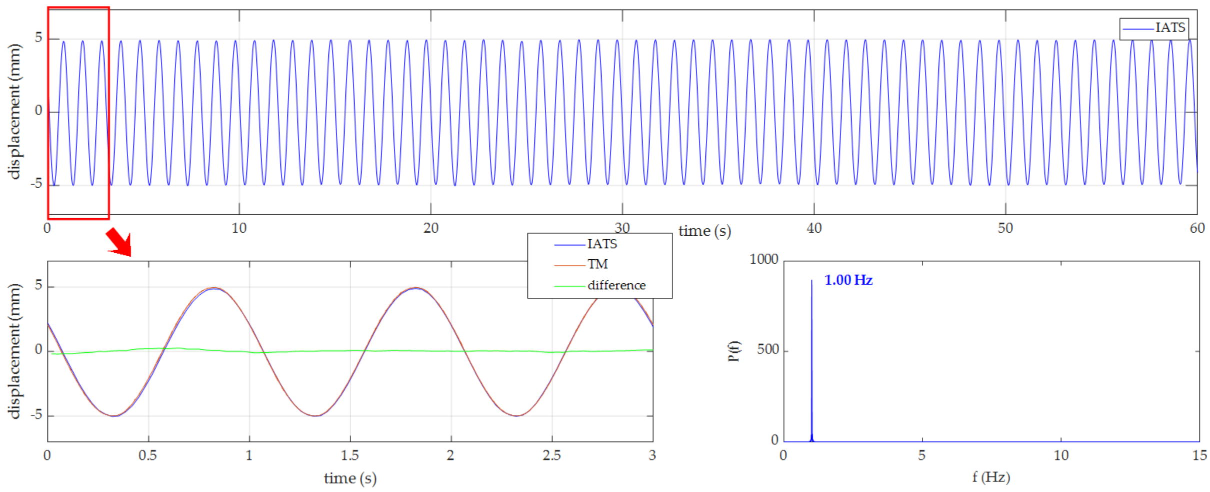

Figure 5. The measurements and results obtained by means of IATS prototype for the test A = 5.0 mm and F = 1.0 Hz.

Table 1 shows minimal, maximal, and average oscillation amplitudes with their standard deviations determined by the low-cost IATS prototype and TM, as well as its RMS. The average amplitudes in all tests determined by IATS differ from the average amplitudes simulated by TM up to maximally 0.04 mm. Due to the IATS prototype measurement frequency of 30 Hz (GoPro Hero5 camera was set up to 30 fps for video recording), some amplitudes of the simulated displacements at F = 1.0 Hz were not determined equally as simulated because maximal amplitude was achieved between two IATS measurements (between two frames of recorded video). This can be noticed on the lower left part of figures 3, 4 and 5 (the differences between TM and IATS prototype are presented by the green line) and from Table 1 (differences between TM and IATS min and max values of determined amplitude). The calculated differences between TM and IATS with their standard deviations of σ = 0.029 mm, 0.045 mm and 0.111 mm can be characterized as very precise. Also, their accuracy, i.e., the accuracy measure RMS was 0.029, 0.052 and 0.122 mm. Furthermore, the IATS prototype sampling rate of 30 Hz does not influence the accuracy in determining the frequency of simulated vertical displacements, since according to the Nyquist theorem, the minimum sampling rate condition (two times higher) for determining the oscillation frequency is met, i.e., it is actually 15 times higher since we very recording video with 30 fps for determination of frequency of 1 Hz.

Table 1. Achieved min, max, and average amplitudes with standard deviations for test F = 1 Hz, A = 0.2, 0.5, and 1.0 mm.

Test	**A = 0.2 mm**		**A = 1.0 mm**		**A = 5.0 mm**	
F = 1.0 Hz	**TM**	**IATS**	**TM**	**IATS**	**TM**	**IATS**
Min (mm)	0.170	0.172	0.980	0.923	4.977	4.923
Max (mm)	0.170	0.182	0.994	0.970	4.989	5.025
Average (mm)	0.170	0.177	0.987	0.947	4.983	4.974
St. dev. (mm)		0.029		0.045		0.111
RMS (mm)		0.029		0.052		0.122

4. DISCUSSION AND CONCLUSIONS

The paper deals with the technological development of IATS from the early 2000s and with the determination of dynamic displacements and natural oscillations frequencies in the laboratory with developed low-cost IATS prototype. Main milestones in the development of IATS and its predecessors have been presented with the focus on the development period from the 2000s until today. Basic principle of the IATS prototype is elaborated with a focus on the analysis of data obtained from measurements.

The results from the experimental testing conducted in the laboratory showed that with IATS prototype amplitudes of A = 0.2 mm, 1.0 mm, and 5.0 mm at F = 1.0 Hz, were successfully determined by standard deviation of σ = 0.029 mm, 0.045 mm and 0.111 mm, i.e., mm and sub mm displacements can be detected with a high level of precision. The displacement errors that occurred and the differences between simulated displacements by the TM and those detected by the IATS prototype are in a range from $\Delta = -0.057$ mm to 0.12 mm depending on the simulated amplitude but were detected with a high level of precision. The accuracy measure RMS was 0.029, 0.052 and 0.122 mm for corresponding amplitudes. The simulated frequency by the TM of F = 1.00 Hz was detected by the IATS prototype in every test as F = 1.00 Hz, i.e., with 100 % overlap. The successful application of IATS prototype for measuring dynamic displacements and natural oscillation frequencies of the bridge have been presented in Paar et al 2021b.

The achieved precision and accuracy of measured displacements are at a high level because contactless vision-based measurements are performed by the GoPro camera, which uses 30× optical magnification of RTS Leica TPS1201. Contactless methods have distinct advantages over contact methods since they generally measure visible light, can be easily set up, and measure a large scene of interest as every pixel collects a time series. Further, IATS prototype does not need to be placed on the monitored object, and thus access to it is not necessary like contact methods. However, the trade-off is less precise data compared to contact techniques (Maar and Zogg 2021). Nevertheless, in our case, we managed to overcome this lack of precision by combining the video camera with the high-quality optics of the Leica TPS1201 RTS, which resulted in the developed IATS prototype. The conducted study showed that our low-cost IATS prototype can be used for vibration monitoring, confirming the previous studies performed for commercial high-cost IATS (Wagner et al. 2013).

REFERENCES

Alexander, R.; Lehmann, M.; Kahmen, H.; Paar, G.; Miljanovic, M.; Ali, H.; Egly, U.; Eiter, T. A 3D optical deformation measurement system supported by knowledge-based and learning techniques. J. Appl. Geod. 2009, 3, 1–13, doi:10.1515/JAG.2009.001.

Huep, W. Scannen mit der trimble VX spatial station. Z. Vermess. 2010, 135, 330–336.

Knoblach, S. Entwicklung , Kalibrierung und Erprobung eines kameraunterstützten Hängetachymeters. Ph.D. Thesis, Technische Universität Dresden, Dresden, Germany, 2009.

Leica Geosystems, A. Leica Viva TS11 Datasheet. Available online: https://leica-geosystems.com/-/media/files/leicageosystems/products/brochures/tender-flexline-plus/leica-viva-ts11-ds-lr.ashx?la=en&hash=8467ACC4E2E31C6DFF7C1497091D3692 (accessed on 25 March 2021a).

Leica Geosystems, A. Leica Viva TS15 Datasheet. Available online: http://kumonos.info/downloads/datasheet_ts15.pdf (accessed on 25 March 2021b).

Lienhart, W.; Ehrhart, M.; Grick, M. High frequent total station measurements for the monitoring of bridge vibrations. J. Appl. Geod. 2017, 11, 1–8, doi:10.1515/jag-2016-0028.

Maar, H.; Zogg, H.-M. Leica Nova MS60 White Paper. Available online: http://leica-geosystems.com/products/total-stations/multistation/leica-nova-ms60 (accessed on 25 March 2021).

Paar, R.; Marendić, A.; Jakopec, I.; Grgac, I. Vibration Monitoring of Civil Engineering Structures Using Contactless Vision-Based Low-Cost IATS Prototype. Sensors 2021b, 21, 7952. https://doi.org/10.3390/s21237952

Paar, R.; Marendić, A.; Wagner, A.; Wiedemann, W.; Wunderlich, T.; Roić, M.; Damjanović, D. Using IATS and digital levelling staffs for the determination of dynamic displacements and natural oscillation frequencies of civil engineering structures. In Proceedings of the INGEO 2017—7th International Conference on Engineering Surveying, Lisbon, Portugal, 18–20 October 2017.

Paar, R.; Roić, M.; Marendić, A.; Miletić, S. Technological Development and Application of Photo and Video Theodolites. Appl. Sci. 2021a, 11, 3893. https://doi.org/10.3390/app11093893

Pentax R-400VDN Series. Available online: https://pdf.archiexpo.com/pdf/pentax-precision/r-400vdn-series/151417-284341.html (accessed on 25 March 2021).

Reiterer, A.; Wagner, A. System Considerations of an Image Assisted Total Station - Evaluation and Assessment. AVN Allg. Vermess.-Nachr. 2012, 119, 83–94.

Topcon GPT-7000i Specifications. Available online: http://www.topcon.si/zares4/dokumenti/gpt-7000i.pdf (accessed on 25 March 2021a).

Topcon GPT-9000Ai Specifications. Available online: https://totalstations.co/wp-content/uploads/2017/07/Topcon-GPT-9001A-Edited-1.pdf (accessed on 11 March 2021b).

Topcon Topcon GTL-1000 Laser Scanner Total Station. Available online: https://www.topcon.co.jp/en/positioning/products/pdf/GTL-1000_E.pdf (accessed on 25 March 2021d).

Topocon DS-200i Series Imaging Robotic Total Station. Available online: https://www.topconpositioning.com/sites/default/files/product_files/ds-200i_series_broch_7010_2160_revc_sm.pdf (accessed on 25 March 2021c).

Trimble Trimble SX10|Scanning Total Station. Available online: https://geospatial.trimble.com/products-and-solutions/trimble-sx10 (accessed on 25 March 2021b).

Trimble Trimble SX12|Scanning Total Station. Available online: https://geospatial.trimble.com/SX12 (accessed on 25 March 2021c).

Trimble Trimble VX Spatial Station. Available online: http://trl.trimble.com/docushare/dsweb/Get/Document-348124/022543-261F_TrimbleVX_DS_0110_lr.pdf (accessed on 25 March 2021).

Wagner, A. New Geodetic Monitoring Approaches using Image Assisted Total Stations. Ph.D. Thesis, Technische Universität München, München, Germany, 2017.

Wagner, A.; Wasmeier, P.; Reith, C.; Wunderlich, T. Bridge Monitoring by Means of Video-Tacheometer - A Case Study. AVN Allg. Vermess.-Nachr. 2013, 120, 283–292.

Walser, B.H. Development and calibration of an image assisted total station. Ph.D. Thesis, ETH Zürich, Zürich, Switzerland, 2004.

Wasmeier, P. Grundlagen der Deformationsbestimmung mit Messdaten bildgebender Tachymeter. Ph.D. Thesis, Technische Universität München, München, Germany, 2009.

Wunderlich, T.; Wasmeier, P.; Wagner, A. Auf dem Weg zum geodätischen Universalinstrument - Wie nahe am Ziel sind IATS und MS50? In Proceedings of the Terrestrisches Laserscanning 2014 (TLS 2014), Fulda, Germany, 11–12 December 2014; pp. 177–192.

BIOGRAPHICAL NOTES

Rinaldo Paar works as an Associate Professor at Department of Applied Geodesy, Faculty of Geodesy, University of Zagreb, Croatia. In 2010 he received his Ph.D. from University of Zagreb for the thesis: “Geospatial data bases of objects in the highway management system of the Republic of Croatia”. His main research interests are engineering geodesy, deformation analysis, SHM. cadastre and LLL. He has participated on several scientific and professional projects and has published several papers. He is a member of Croatian Chamber of Charted Engineers. From 2017 he is the president of Croatian Geodetic Society.

Ante Marendić works as an Associate Professor at Department of Applied Geodesy, Faculty of Geodesy, University of Zagreb, Croatia. In 2011 he received his Ph.D. from University of Zagreb for the thesis: "The application of geodetic measuring systems for deformation monitoring of engineering structures with an emphasis on monitoring dynamic movements". His main research interests are engineering geodesy, deformation analysis and SHM. He has participated on several scientific and professional projects and has published several papers. He is a member of Croatian Chamber of Charted Engineers and Croatian Geodetic Society.

Ivan Jakopec works as an assistant at Department of Applied Geodesy, Faculty of Geodesy, University of Zagreb, Croatia. In 2013 he graduated at the Faculty of Geodesy. His main research interests are engineering geodesy, deformation analysis, SHM and UAVs. He has participated on several scientific and professional projects and has published several papers.

Miodrag Roić graduated with a degree in Geodesy from the University of Zagreb, Faculty of Geodesy. In 1994 he received a PhD from the Technical University Vienna. Since 1996, he has been a professor at the University of Zagreb, Faculty of Geodesy. He was Dean of the Faculty during the period spanning 2011-2015. The topics in which he specializes are Cadastre, Land Administration Systems, Engineering Geodesy and Geoinformatics. He is a corresponding member of the German Geodetic Commission (DGK) and many other national and international scientific and professional institutions.

Hrvoje Tomić works as an Associate Professor at Department of Applied Geodesy, Faculty of Geodesy, University of Zagreb, Croatia. In 2010 he received his Ph.D. from University of Zagreb for the thesis: "Geospatial Data Analysis in Purpose of Real Estate Valuation in Urban Areas". His main research interests are GIS and DBMS technology in spatial data handling. Hrvoje Tomić has participated on several projects and has published several papers.

CONTACTS

Assoc. Prof. PhD. Rinaldo Paar
University of Zagreb, Faculty of Geodesy
Fra Andrije Kačića Miošića 26
HR-10105 Zagreb
CROATIA
Tel. +385 (1) 4639 371
Email: rinaldo.paar@geof.unizg.hr
Web site: https://www.geof.unizg.hr/en/djelatnici/rinaldo-paar/

Assoc. Prof. PhD. Ante Marendić
University of Zagreb, Faculty of Geodesy
Fra Andrije Kačića Miošića 26

HR-10105 Zagreb
CROATIA
Tel. +385 (1) 4639 186
Email: ante.marendic@geof.unizg.hr
Web site: https://www.geof.unizg.hr/en/djelatnici/ass-prof-ante-marendic-phd/

Assistant Ivan Jakopec, mag. ing. geod. et geoinf.
University of Zagreb, Faculty of Geodesy
Fra Andrije Kačića Miošića 26
HR-10105 Zagreb
CROATIA
Tel. +385 (1) 4639 192
Email: ivan.jakopec@geof.unizg.hr
Web site: https://www.geof.unizg.hr/en/djelatnici/ivan-jakopec/

Full Prof. PhD. Miodrag Roić
University of Zagreb, Faculty of Geodesy
Fra Andrije Kačića Miošića 26
HR-10105 Zagreb
CROATIA
Tel. +385 (1) 4639 229
Email: miodrag.roic@geof.unizg.hr
Web site: https://www.geof.unizg.hr/en/djelatnici/miodrag-roic/

Assoc. Prof. PhD. Hrvoje Tomić
University of Zagreb, Faculty of Geodesy
Fra Andrije Kačića Miošića 26
HR-10105 Zagreb
CROATIA
Tel. +385 (1) 4639 522
Email: hrvoje.tomic@geof.unizg.hr
Web site: https://www.geof.unizg.hr/en/djelatnici/hrvoje-tomic/