Hybrid measurement techniques used to a study of historic cast iron suspension bridge

Wojciech Anigacz¹, Damian Beben¹ and Jacek Kwiatkowski²

¹Opole University of Technology, ul. Proszkowska 76, 45-758 Opole, Poland
²J&L Consulting, ul. Obroncow Stalingradu 29, 45-594 Opole, Poland

E-mail: w.anigacz@po.opole.pl

Abstract. Traditional measurement techniques consist of discrete measurements and they are time-consuming. Moreover, information obtained by means of these methods is limited to over a dozen points located on the examined bridge. The latest measurement methods such as laser scanning and digital photogrammetry enable to obtain quasi-continuous surface of the tested bridge. It consists of many millions of points with known spatial coordinates. The tested structure is a historic suspension bridge in the town of Ozimek in Poland. Nowadays the bridge is intended for pedestrian traffic across Mala Panew river. It was built in 1827 and it is the oldest cast iron suspension bridge in continental Europe. In the analyzed case, the measurements were performed with the use of terrestrial laser scanning (a FARO Focus 3DX130) and high-resolution photogrammetry (Canon 650D camera with the lens of fixed focus of 85 mm and the GigaPano turntable). The obtained results indicate that the differences between the two methods are within a few millimeters, which should be considered satisfactory. The advantage of the presented measurement methods is minimizing time of fieldwork and obtaining a 3D model of the bridge with millimeter accuracy.

1. Introduction

In most cases control measurements are held on bridge structures to confirm design basis or as diagnostic checks to ensure proper maintenance. Inspection results of bridges constitute basic source of information about their technical condition and existing damages. In majority of countries in the world they are obligatory and are held on the basis of a systematic condition check of transportation infrastructure. Typical measurements and tests are usually executed by bridge inspectors with the use of traditional methods. The majority of maintenance or inspection works require direct contact with the structure, which, in some conditions, can cause problems with structure accessibility for tests and often requires using scaffolding or lifts. In many cases, especially historic bridges, design documents do not exist. This causes a major problem at renovation and/or maintenance works. Maintenance or inspection works are very time-consuming, especially when complex and complicated structures are concerned. Most of researchers [1,7,9] have a classic approach to the structure examinations, which means that they put a reference measurement grid outside the tested object and on the object itself. They mark or signalize points that are measured. Such approach is fully correct in the case of conducting long-term tests. The reference points outside the tested structure allow to determine changes of the bridge structure geometry in the absolute frame of reference comprised of the reference points, with coordinates determined, for instance, using the GPS method.
The method of laser scanning allows to obtain a cloud of points [4], and as a result, it can be used with success for survey checks of various structures, especially ones with difficult access. Yu et al. [9] reported a very interesting comparison of the measurement methods, measurement accuracy, measurement type, bridge type and measurements costs. However, the presented information, e.g. with regards to the laser scanning, turned out to be too optimistic because obtaining accuracy below 1 mm is in practice limited to small bridges only (where the distance between the scanner and the bridge is small). While Tang et al. [8] compared potential of the tachymetry method and laser scanning in the measurements of bridges. They reported values of the measurement errors on real objects. This article verifies the method of laser scanning on the example of a historic suspension bridge. Measuring capabilities of this method have been analyzed, i.e. the quality of inventory works was checked with use of a laser scanner on the historic cast iron bridge. Fast developing measurement techniques, especially geodetic, and in particular the mass measurements, in theory and practice, enable to obtain full information on the structure and changes in the bridge geometry [1]. The authors of the article have such technology, the latest equipment (often prototype-pre-production), the latest software, and adequate knowledge and experience [6]. Similar measuring techniques used for dynamic measurements of a technological suspension bridge are presented in papers [2,3]. It was found that one of the most important factors affecting the accuracy of the measurement is the distance of the scanner, camera or total station from the object being tested. This paper presents continuously modified measuring methods, equipment and software on the example of a relatively small bridge, but it is very interesting structurally and architecturally.

2. Description of bridge structure
The object is a historic bridge on Mala Panew river in the town of Ozimek, district Opole, in Opole Voivodship in Poland (Fig. 1). The parameters of the bridge are as follows: span – 27.7 m, axial spacing of pylons – 31.5 m, width of the bridge deck – 6.6 m (Fig.2).

![Figure 1. Location of the bridge: a) on a map, b) on aerial photograph (www.maps.google.pl).](image-url)

Nowadays the bridge is intended for pedestrian traffic across the Mala Panew river. It was built in 1827 and it is the oldest cast iron suspension bridge in continental Europe. It is a suspension chain bridge completely made of cast iron. Following this parameter it should be acknowledged to be the oldest bridge of this type in the world existing till today. An older existing iron suspension bridge was built between 1819 and 1826 over the Menai Strait in Wales, however this one is suspended on stone pylons. Complete renovation of the bridge was carried out between 2009 and 2010. It was disassembled, renovated and reassembled. The bridge structure was strengthened with steel ropes. In the FOOTBRIDGE AWARD 2014 world competition the bridge won in the category of historic renovation/reuse of existing footbridges as the best renovated structure [5].
3. Methodology of research

The presented historic bridge on Mała Panew river in Ozimek is characterized not only by historical, technical and technological originality, but also by its design and cultural values. Due to the above conditions, it is desirable to use a wide range of measuring techniques to show not only the key structural elements, but also the aspects of aesthetics.

The method of bulk measurement, i.e. laser scanning and digital photogrammetry was used for survey check of the structure. In the presented case, it was intended to minimize preparatory works. A decision was made to use well-visible details of the bridge structure as measurement points. Vertical verification of selected points on the bridge was executed by means of spirit leveling with use of the patent [1]. To verify distance measurement of characteristic points of the structure by means of scanning and photogrammetric methods, total station TC2002 Leica was used.

3.1. Laser scanning method

Laser scanning method is a relatively new measurement method allowing to obtain a quasi-constant, spatial representation of the area of the examined structure seen in central view. The accuracy of the results depends mainly on distance between the scanner and the examined structure. In the last several years, fast development of laser scanning has been observed [2, 4]. A scanner uses a laser beam which, after being reflected from the measured structure, returns to the scanner. The distance is determined on the basis of the difference of phases of the generated and the reflected beam. During the measurement, scanner can be turned by 360 degrees horizontally. Horizontal and vertical angle of the scanner mirror set, information on the measured distance and quality of the reflected signal are calculated in real time into the coordinates.
The measurements were using a TLS (Terrestrial Laser Scanning) method by FARO Focus 3DX130 scanner. Scanning was executed in 13 positions (Fig. 3). Density of the registered cloud of points allowed for fully satisfactory identification of elements and even details of the bridge.

![Figure 3. Distribution of scanner positions: a) a view from above, b) a side view.](image)

In the case of the bridge the results clearly indicate that the distance to the bridge about 40 m allows to obtain satisfactory results, i.e. a full inventory of the bridge elements. For the bridge experimental examinations a FARO Focus 3D X130 scanner was used which measures up to 1 million of points per second and allows to create clouds of over a billion of points. The accuracy, declared by the accuracy of the measurement of the distance was ±2 mm, and angle resolution amounted at 0.009° (0.16 billion). The standard unit of resolution is dpi, i.e. a dot per inch of length. In technical applications where most frequently elements of the examined structure are located in different distances from the scanner, it is more convenient to use the angle resolution, and not the dpi which constantly changes as the distance changes. Data obtained by means of the scanner were then analyzed with help of a functionally advanced software Trimble Real Works Advanced Plant version 10.3.

3.2. Photogrammetric method
The second used method was a high-resolution photogrammetry. A Canon 650D camera with the lens of fixed focus of 85 mm and a GigaPano turntable were used to take photos (Fig. 4a). Nine 360°

![Figure 4. Positions of the measuring equipment used: a) GigaPano turntable with Canon 650D camera, b) FARO Focus 3D X130 scanner.](image)
panoramic photographs of high resolution were taken (Fig. 5). The aim was to ensure that the photos are taken from the exact scanning positions. (Fig. 4b).

**Figure 5.** The 360° panoramic image taken with use of Canon 650D camera from a position located within the half of the bridge span.

The level of spherical aberrations of the camera was confirmed in the laboratory on the test rectangle (Graph paper 420×297 mm), it did not exceed 3 columns of the matrix pixels, to be exact 5184×3456 pixels. To process the pictures Kolor AutoPano Giga 4.0 software was used. To calibrate the generated panorama through rescaling for defining the “size” of individual pixel, the Photoshop CC computer software was used. The Photoshop CC software enables linear rescaling of the pixel size. To scale the panorama of the bridge to the set pixel size, characteristic distances were used, which in the studied case were the distances between subsequent segments of the span (Fig. 6) that previously were measured with the tachymetry method. The photogrammetric method has the following advantages, among others: short time of making measurements for taking a picture and their sequences, possibility of visualization with the elements of spatialization, and possibility of multiple interpretations of the measurement. It is a relatively cheap method, and commonly available.

4. Analysis of the results
Figures 6 and 7 show location of control sections on photos and scans. Table 1 presents lengths of test sections together with differences in length.

**Figure 6a.** The photogrammetric rescaled image of the bridge in Ozimek.
Table 1. Tabular summary of lengths of control sections measured by means of the photogrammetry and scanning methods.

| Bridge element                      | Dimensions obtained by means of: | Difference [m] |
|-------------------------------------|----------------------------------|----------------|
|                                     | photogrammetric method [m]       | (2)            |
|                                     | laser scanning method [m]        | (3)            |
| Distance in abutments clearing      | (1)                              | (2)-(3)        |
| Spacing of pylons                   | 21.214                           | 21.208         |
| Height of the right-bank abutment   | 31.470                           | 31.477         |
| Height of the left-bank abutment    | 3.020                            | 3.012          |
| Distance between the middle hangers (at the top) | 2.922                           | 2.914          |
| Distance between the middle hangers (at the bottom) | 2.924                           | 2.916          |
| Length of the 4th hanger from the left bank | 1.674                           | 1.680          |
| Length of the 4th hanger from the right bank | 1.672                           | 1.678          |

Figure 6b. Scan of suspension bridge in Ozimek made with use of FARO Focus 3D X130 scanner.
Figure 7a. Control sections shown on a section of 360° panoramic view.

Figure 7b. Control sections shown on a section of the scan.

All the differences fall within the range of -7 to +10 mm. Laser scanning should be considered a more precise method. Individual images were recorded on a 24 Mpix matrix. Resolution is a function of the distance of the camera from the structure. The analyzed control sections were verified with rescaled resolution of the panorama to 1 pixel = 1 mm.

Such a resolution of a 360° panoramic image predisposes it to a highly photorealistic visual evaluation of the bridge and the surroundings. Differences in section length result from accuracy of binding the panorama by software and faithfulness of the parallel projection used i.e. projection of a sphere onto a plane. Measurement of distance on a photograph is made within the plane of the image, counting pixels and multiplying the result by pixel size in accordance with rescaled resolution.

5. Conclusions
As a result of measurements of historic cast iron suspension bridge conducted with use of two methods, i.e. photogrammetric and laser scanning, the following conclusions can be drawn:
1. The measurements unequivocally indicate that for conditions where distance to the bridge is up to about 40 m, the two methods allow to obtain fully satisfactory inventory results. The scans present structure details with sufficient resolution and accuracy.
2. In the photogrammetric method the camera’s focus needs to be chosen in such a way as to ensure that the value of a pixel would amount at, for example, 1 mm. A higher scale of the photograms will allow to obtain additional information on the surroundings of the measured point, e.g. permanent deformations, cracks, etc.
3. The results of measurement of various bridge elements with use of two discussed methods confirm that both of them are appropriate for survey checks of bridge structure of complex geometry. The differences in results obtained with use of the respective methods fall within the range of a couple of millimeters.
4. The final analytical data illustrating the effects of the measurement session depend on three main factors:
   - resolution of the matrix of the digital camera,
   - quality of the optics (resolution, reduction of the spherical aberration),
   - quality of parallel projection.
5. Hybrid measurement techniques used to study the bridge are methods which allow to get external object topology and a high quality photorealistic image of the structure. It is of special importance when the object is a structure of historic value with no existing design documentation.

From the presented measurement methods, the equipment and software connected to the laser scanning is the most expensive. It would be ideal to use three methods at the same time for examination of bridges. Then the information about the bridge structure geometry would be a synthesis of all the methods used.

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