Original Research

Using 3D Terrestial Laser Scanning (TLS) for Surveying Hydrotechnical Structures when Preparing Flood Hazard Maps

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Received: 30 August 2011
Accepted: 15 May 2012

Abstract

Directive 2007/60/WE of the European Parliament regarding flood risk assessment and management (The Floods Directive) obliges member states to achieve certain aims within given timeframes. The member states are to prepare planning policies, i.e. flood hazard and flood risk maps, by December 2013. The maps should be based on hydraulic models. Preparing the input data includes compiling hydraulic data (the shape of and material from which a river bed and a river valley are made) and data on the hydrotechnical infrastructure and communication. A detailed survey includes bridges and other hydrotechnical structures. The article presents possible use of 3D terrestrial laser scanning (TLS) in the survey of structures where measurement using classical methods may be hazardous. And also, where the level of the structure's complexity for some of the elements is so high, that the classical survey will not deliver eligible results. As an output, there appears to be an entirely measurable 3D model, ready to be used by experts in the field of hydrology and construction.

Keywords: laser scanning, hydrotechnical structures

Introduction

The overriding goal of The Floods Directive is to decrease flood risk and the flood consequences in EU countries. The state members' liabilities arising from the Floods Directive requires preparation of planning documents within a given timeframe. Poland is obliged to prepare the following planning documents and meet the following deadlines for implementation:

1. Preliminary flood risk assessment – due December 2011
2. Maps of flood hazards and risks – due December 2013
3. Plans for flood risk management – due December 2015.

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According to information published by the National Council of Water Management (www.kzgw.gov.pl), until December 2013 the state members are obliged to prepare flood hazard and risk maps for areas where flood risk (following the preliminary floods risk assessment) has been stated as high.

The maps have to indicate areas where the feasibility of the floods is:

(i) low likelihood of flooding (including the areas where the floods would be an extreme event)
(ii) medium likelihood of flooding (appearance of floods at least 1 in a 100-year event)
(iii) high likelihood of flooding. The flood hazard maps will include the extent of the floods according to flood sce-

narios, water depth or the level of water surface, and flow velocity or relevant water flow. The flood risk maps will fill up the flood hazard maps. It will comprise data on an indicative number of inhabitants potentially affected by the floods, type of economic activity, environmental damage potential, and information about major structures in the area.

The preparation of planning documents requires combining various data and hydraulic modeling with spatial analyses.

In this case, a common solution is to use spatial information systems (GIS). These systems are used for input, gathering, integration, storage and extraction, processing, and visualization of geographical data [2].

The system comprises:
- computer equipment
- computer software with molecular structure
- relational database (including spatial information)
- groups of operators.

Preparing the maps may be described in six stages:
(1) preparing the database
(2) constructing the hydraulic model
(3) defining flood scenarios
(4) hydraulic calculations according to the anticipated flood scenarios
(5) indicating flood hazard zones
(6) charting flood hazard maps

The basic component of the flood hazard maps are flood hazard zones, which according to the Floods Directive, can be divided into zones of the flood range with consideration of water depth (the SH type) and water flow velocity (the SV type). The SH type comes as a result of calculations conducted over one-dimensional (1D) or two-dimensional hydraulic models (2D) with the use of a digital terrain model (DTM). The SV type comes as a result of combining results of the hydraulic model and the digital terrain model (DTM) [1].

The 1D models that are sufficient to model flow processes in the channel are not detailed enough to model the flow in the floods areas, for which the 2D models are recommended. The production of the 2D hydraulic models requires the following input data:
- digital terrain model (DTM)
- DTM of a river bed
- orthophotomaps
- land use maps
- vectorized database of topographical objects (punctual, linear, polygon GIS objects). The topographical object database comprises the following data:

(i) drainage system
(ii) reservoirs
(iii) borders of a river basin
(iv) cross-section of the rivers
(v) river embankments
(vi) embankment sluice
(vii) engineering structures (bridges)
(viii) hydrotechnical structures (weirs, dams)

Our article presents the application of terrestrial laser scanning in surveying topographical objects, in particular surveying hydrotechnical structures as a part of the topographical object database.

Object Description

The Opatowice Sluice (Śluza Opatowice) has been chosen as a test object for the experiment. The object is in Wroclaw, in the Odra River Valley at 245.03 km. It is situated in the anthropogenically transformed meander of the Odra River, namely the Opatowicki Canal (Kanał Opatowicki), 1.0 km from the channel, between Opatowicka Island (Wyspa Opatowicka) and the Opatowice housing estate.

The sluice was built in 1913-17 as a part of the new waterway – the Wroclaw Water Junction (Wrocławski Węzel Wodny). The Opatowice Sluice is a part of the water dam complex called the Water Junction of Opatowice and Bartoszowice (Węzeł Wodny Opatowicko-Bartoszowicki). Due to its small size, the Opatowice Sluice is not an important part of the freight transport in the area. The sluice's size is as follows: length – 74.6 m; width – 9.6 m; water rise – 2.0 m. The Opatowice Sluice has two pairs of supportive gates. The sluice chambers are filled and unloaded through short circulation channels situated in the top and bottom heads. The circulation channels are locked with roll locks. The supportive gates and roll locks of the circulation channels are brought to operation with electrical engines. In case of emergency, there is also a manual transmission system. The gate's construction is riveted. The sealing of the gates is made of oak bars attached to the gates with screws.

Distances on the waterways running through the sluice are as follows:
(i) 5.6 km down the stream to the next sluice on Wrocławski Szlak Miejski (the Water Trail of Wroclaw) – the Szczytniki Sluice
(ii) 9.2 km down the stream, to the next sluice in Śródmiejski Węzeł Wodny (the Town Centre Water System) – the Piaskowa Sluice
(iii) 8.4 km up the stream to the Janowice Sluice.

Description of Laser Scanning Technology

Laser scanning is a high-tech development of measuring methods in surveying [3]. Reflectorless surveying with laser beam together with a precise angle measurement allows us to gather the XYZ coordinates of a given point with high accuracy. The technology also allows us to receive the data related to the intensity of the beam's reflection.

Modern laser scanners are able to scan any given area or object (Fig. 1). Laser scanning technology has been on the market for the last 10 years. As literature and market observation show, this segment of the surveying market has been developing rapidly. Laser scanning technology has changed today's way of analyzing surrounding reality: a transformation from geodetic surveys (at the discret point level) to analyses conducted on 3D models.

Laser scanners are used both for scientific research and for commercial services. Most often they are used for designing complex industrial installations. Classical survey methods may require long breaks in installation works that may cause large financial loses. Also, in the case of energetic and chemical installations, the classical survey may be impossible to conduct due to the risk of health damage. A significant number of laser scanning projects have been carried out to improve roads, highways, and other construction projects. The technology is widely used in mining industry. The developing trend can also be seen in architecture, where the quality of the structure survey is crucial for i.e. the extent and methods of renovation works. Laser scanning is also a very popular tool in archeology, where a tremendous amount of time can be saved on data recording as the analyses can be conducted on a virtual model. The technology is also used in the forestry industry.

From a scientific perspective, TLS is used in a variety of fields, for example building engineering and surveying [4]. Recently, laser scanning is more often used in environmental sciences [5]. In Poland, the major part of publications related to laser scanning are in the fields of archeology, monument conservation, and architecture. In this article, laser scanning is used for surveying hydrotechnical structures.

Surveying Opatowice Sluice Using Terrestial Laser Scanning (TLS) Technology

The terrestrial laser scanning survey basically relies on creating a virtual 3D model of an object and its surroundings. The works are conducted in two stages: the first stage includes fieldwork, which mean acquiring the database; the second stage includes labwork – processing the model and producing the output data. What is crucial is that an accurate database be acquired in the field.

This article presents the case study of the Opatowice Sluice (hydrotechnical structure) as an element of the topographical object database that has been surveyed using TLS . The survey of hydrotechnical and communication structures contains:

(i) field survey – plan, cross-sections
(ii) location of the main elements of the structure in relation to the median line of the riverbed and the valley
(iii) photographic survey
(iv) two cross-sections of the riverbed: down and up the stream from the structure

This case study is focused mainly on a site survey of the structure, production of the plan (Fig. 5), and cross-sections (Figs. 6 and 7).

The site survey has been conducted by two operators who used a Leica ScanStation2 terrestrial laser scanner. The field works were done in 1 day. The acquired data allowed for the preparation of a digital 3D model of the Opatowice Sluice (Fig. 2).

Leica ScanStation2 is equipped with a dual axis compensator that allows measuring with geodesic precision. The tool's scanning ranges up to 300 m and also has a very wide field of vision (vertically: 270º, horizontally 360º, with scanning speed up to 50,000 pt./sec.). Moreover, it has an independent density of scanning both vertically and horizontally, and finally, there also is a digital camera.

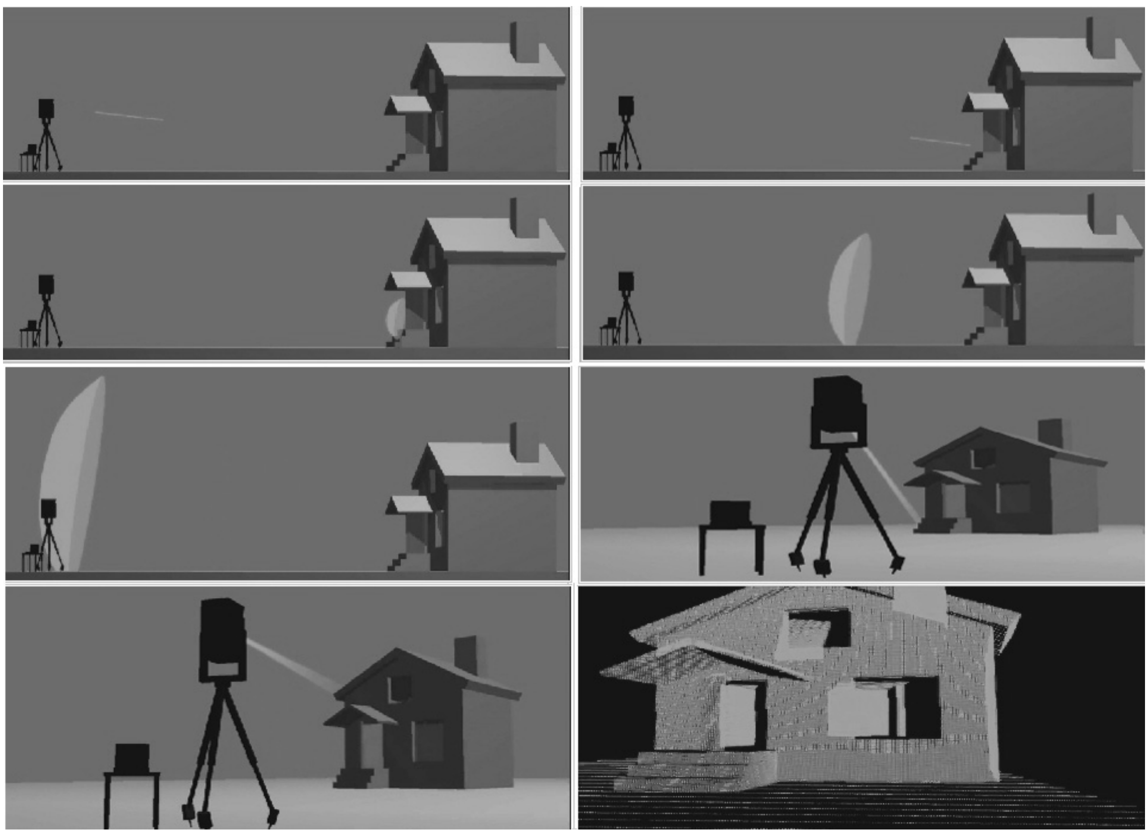

Fig. 1. Schematic drawing of the laser scanning technology [11].

The density of a scanning net and the size of an object are crucial for producing a good quality 3D model. A complete test survey of the Opatowice Sluice has been prepared in a few different resolutions for different elements, varying from 1×1 (points) mm to 10×10 (points) mm.

Scans produced at the density of 1×1 mm allow us to prepare a precise 3D model that looks photorealistic when overlaid with colors sampled from photographs taken with the scanner (Fig. 3). The time necessary to acquire the data from the full view of 360º (for one stand) approaches 5 hours. The same area in a resolution of 10×10 mm, takes a little more than 12 minutes.

The time extent necessary for the scan and for further data processing is related to the amount of the collected data. An area of 10 m^2 scanned at the density of 1×1 mm, produces a model containing 10,000,000 points. A model produced at the density of 10×10 mm for the same area is made of 100,000 points. In the course of processing the data in a 3D model, the computer is calculating the data. Tests show that a laptop equipped with 4GB RAM and a 2.1 GHz dual-core processor with Windows 7 32-bit can work smoothly with a point cloud of 6-10 million points. This depends strongly on the software, which brings us to the proprietary firmware from Leica. More complex point clouds are prone to skipping over between views during model rotation, or result in software shutdown, which greatly influences work efficiency with the model. High-density scans also need more storage space as volumes of acquired data are in tens of gigabytes when scanned with fine resolution. Therefore, the choice of scanning density depends on the aim and required quality of the output data.

Good practice is to adjust the quality of measurements for all the objects separately – at the field survey stage.

A scan of 1×1 mm density is a good tool for i.e. registering the data of surfaces that may be subject to deformations, and also for other construction elements where even a few millimeters dislocation may cause problems.

Optimizing the time and quality of the survey of hydrotechnical structures, it is agreed that scanning at the 10×10 mm resolution is sufficient for hydraulic modeling. A model acquired at this point density is fully measurable with sufficient precision for the hydrotechnical structures. Time gained due to resolution reduction may be partly used for extension of the scanning area. It is useful for the mod-

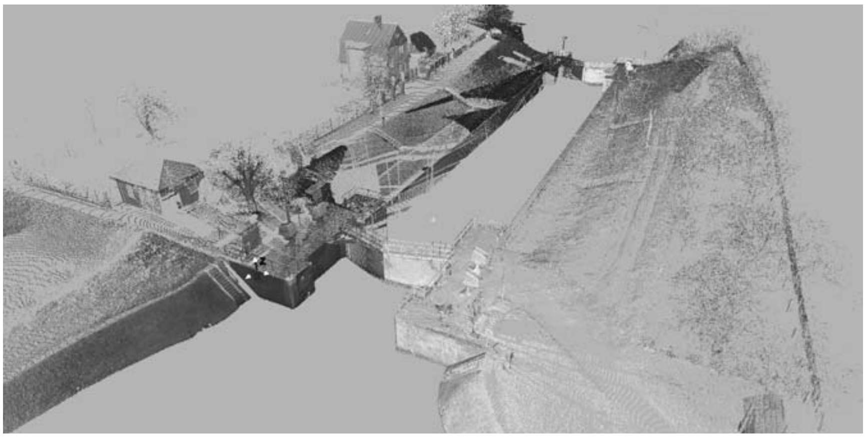

Fig. 2. Perspective view over a “raw” point cloud collected at the Opatowice Sluice. Left side of the point cloud in real colors sampled from pictures. Right side of the point cloud in colors related to the strength of the reflected laser beam.

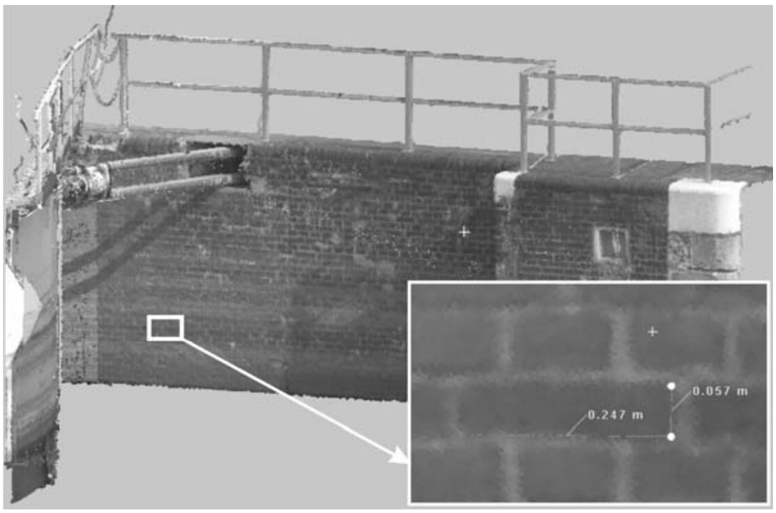

Fig. 3. Point cloud at the 1×1 mm density.

eler to know the setting of the hydrotechnical object. Usually for this purpose photographs are taken on site, but it is helpful to have a fully measurable spatial point cloud of river embankments or dikes, for example, instead of a flat image. The time of the fieldwork should not exceed 1 day. Scanning works can be detailed as follows: during the site visit an analysis of the scale and complexity level of the object was done. It has been decided that a complete model should be made of 6 scanning stations (standpoints) from different locations. The aim was to achieve a model without or with only a small portion of "shadows." The shadows are the areas that are invisible for the scanner. Also, well recognized standpoints minimize the measurement error occurrence and ensure even distribution of the potential error over the scanned object [6].

The tool's parameters have been set up individually for every scanning station. The parameters are: the extent of a scanned area and the resolution of the scan – separately horizontal and vertical. The acquired point cloud contains "raw" unprocessed data with a variety of noises. However, this database is already a rich source of spatial data. Lengths, angles, azimuths, surfaces, volumes, cross-sections, and plans can be easily extracted from the received point cloud.

A "raw" point cloud contains noises that need to be removed. Further post processing of the point cloud depends on the requirement of the modelers. In its most basic form, information that has to be delivered to the modeler is point cloud cleaned of noise. Cleaning and registering to the geographical system for an object of the size of the Opatowice Sluice takes one working day in the lab. The Opatowice Sluice took 2 days due to technical constraints. When more complex information is needed, as modeled 3D geometries and CAD drawings (plan, sections) for objects of the size and spatial alignment of the Opatowice Sluice, the lab works will require the next 7 working days. Postprocessing of the cloud requires dedicated software. A firmware program for Leica laser scanners is Cyclon (we used Cyclon 7.0). Cyclon works with a scanner when acquiring the data and it is also used in further processing of the point cloud. For users who do not have access to Cyclon, Leica has prepared the Cloudworx plug-in for

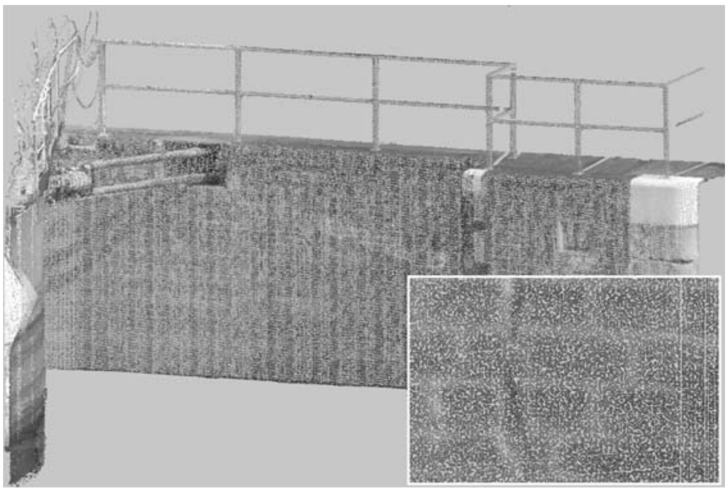

Fig. 4. Point cloud at the 10×10 mm density.

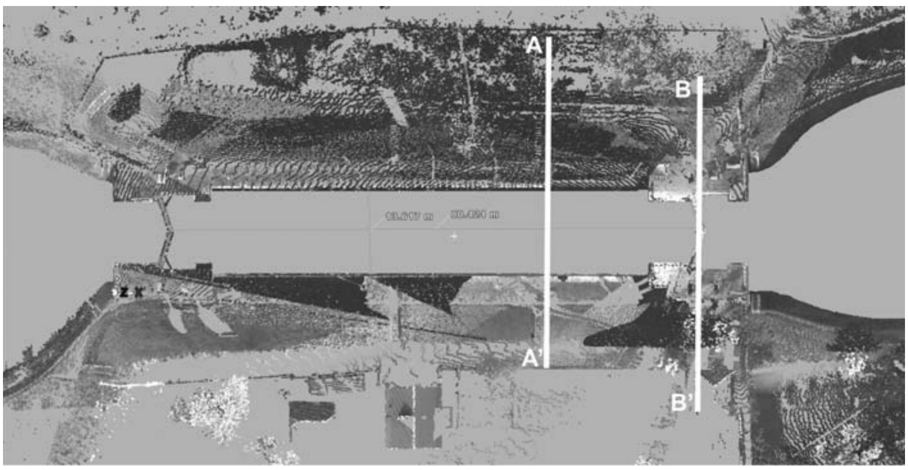

Fig. 5. The plan of the Opatowice Sluice point cloud.

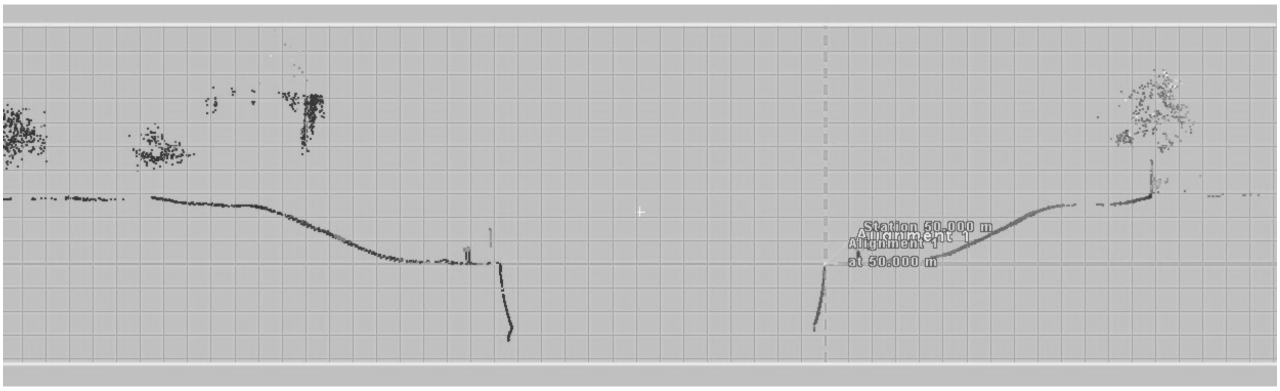

Fig. 6. Cross-section A-A'.

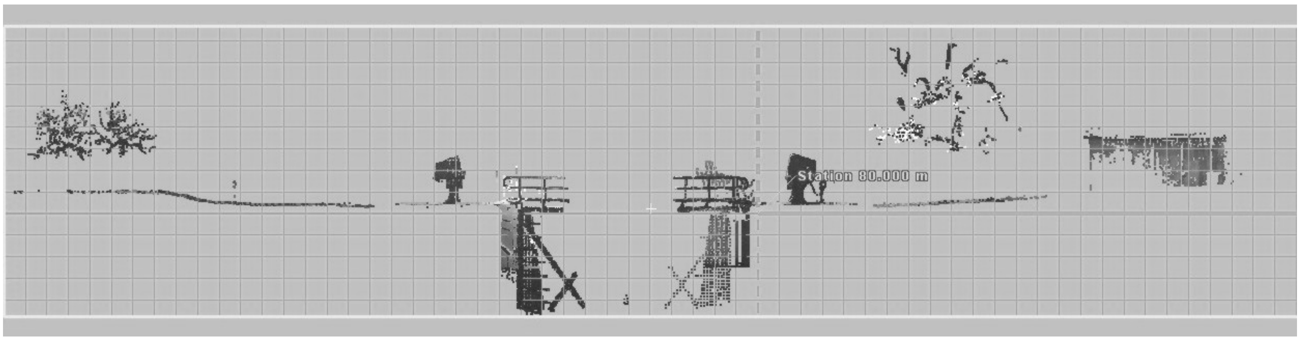

Fig. 7. Cross-section B-B'.

CAD platforms (Autocad and Microstation). With both Cyclon and Cloudworx software the user is able to read all of the parameters of the scanned object. In cases when the user does not own a registered version of Cyclon or Cloudworx, it is possible to use Cyclon without licencing in a viewer mode. In this option, editing tools are disabled, but viewing and measuring tools are available. Also, open source tools may be used for point cloud handling, i.e. Meshlab or PCL (Point Cloud Library). All of the mentioned tools are available and useful for modelers. Modelers receive point cloud and, if required, modeled geometries as lines, surfaces, CAD plans, and sections. All of the data is digital. The modeled geometries may be passed on in a variety of formats (GIS, CAD, TXT) depending on the platform and software used by modelers. Additionally, the supplied point cloud can be used for the purpose of geometry verification while modeling and performing additional measurements.

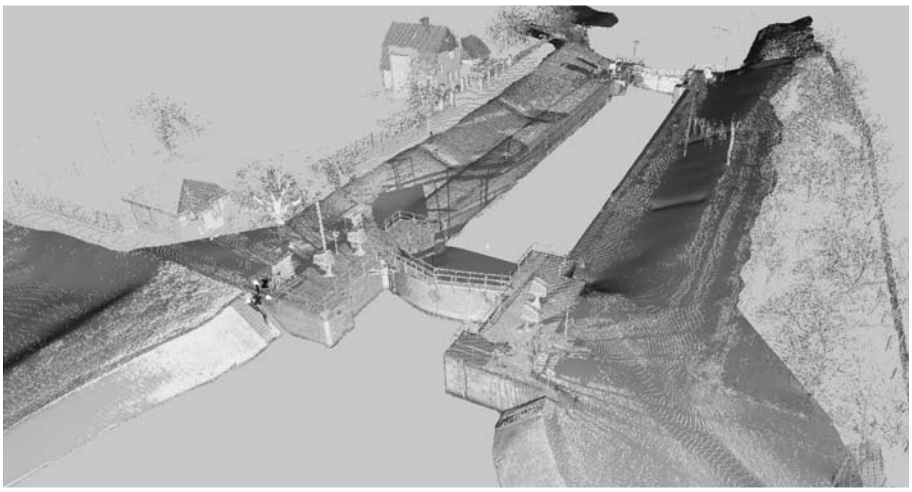

Fig. 8. The point cloud with an underlying mesh.

In this case study, the most essential data is the measurement of all the hydrotechnical structure elements, the hydrotechnical structure's cross-sections, and plans. The acquired 3D model supplies all of this type of data.

One additional asset of the point cloud is the possibility of vectorization [7]. The point cloud can be transformed into 2D (line, circle, etc.) and 3D (cone, box, mesh, etc.) vector objects, which allow for volume calculations or generations of contours (Fig. 9). In Cyclon 7.0, it is also possible to create geo-referenced raster maps, generated from the point cloud, that can be used as GIS maps (Fig. 10).

Advantages and Weaknesses of the Technology

The 3D model received as a product of TLS offers considerably better data of object geometry than any other flat survey. It is particularly noticeable in the case of complex structures. TLS allows, in a short timeframe [8] and in comparison to classical survey costs, us to receive a dense point cloud of a tested object, which aids control over designing, modernization, and realization works. The acquired 3D model ensures an objective record of the structure displacement in time [9].

Measurements are taken remotely and do not rely on the operator [10].

The use of TLS gives not only time savings during the surveying works, but it also saves time devoted to data preparation for the presentations. The data is presented in a precise, realistic, and measurable 3D model (it can be either a point cloud alone or with additionally extracted geometries). Despite the fact that a "raw" point cloud is a very first step in the whole TLS process, it is already possible to obtain all of the necessary measurements at this stage. Further steps allow us to perform such advanced works as vector object or contours generation. Digital form of the database allows us to work efficiently with the model – the views may be easily zoomed, rotated, etc. Digital point cloud and extracted geometry (vectorized) objects also allow the modeler to take the measurements that were not specified for the survey. In order to conduct the classical survey of an object, the surveyor is told which dimensions and at what precision should be taken. Sometimes it is the case that in the course of modeling some more exact data is needed. For example, surveyed object geometry is complex or there are associated objects in the vicinity that may be omitted with classical survey, but are likely to be captured using TLS due to the nature of the data acquirement.

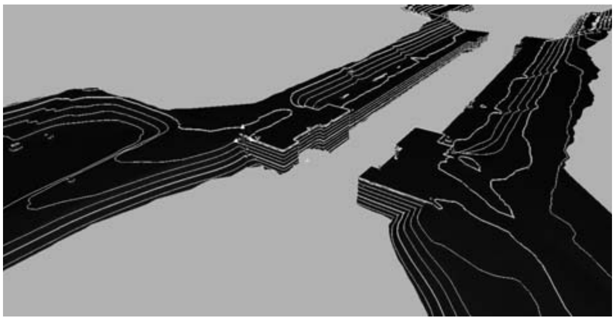

Fig. 9. Mesh with the contours. Mesh allows to generate the contours and calculations of the volumes.

Fig. 10. Orthophotomap produced in Cyclon 7.0 used as a database in Quantum GIS 'Mimas'.

The surveyed objects are referenced by the tool's coordination system, which is located in the rotation axis of the scanner device, or to the coordinates in a chosen geographic system. It is also possible to extend the area of the survey without loosing the quality of measurements. It is also a very fast and easy technique to record slopes gradient, embankments, or plantings. The cost of the TLS technique is comparable to that of a classical survey.

Disadvantages of the TLS technology are: the survey cannot be conducted in winter when there is a snow cover and during all falls (rain, snow etc.), as the tool is not water resistant, and also there is a problem with increased noises in the model.

In the case of the tested hydrotechnical structures, a major limitation is an inability to measure underwater surfaces. In order to do such measurements, it is required to combine survey techniques.

TLS decreases the risk of data interpretation. The high precision of the ScanStation 2 allows us to acquire a realistic 3D model even of a very small element, which could not be measured using a traditional tachimetric survey.

Conclusions

The survey conducted in the Opatowice Sluice using terrestrial laser scanning (TLS) technology resulted in the following conclusions:

- point cloud received as a product of the TLS scanning has an advantage over classical survey products due to the vast amount of data acquired during the measurement
- TLS allows us to prepare a precise 3D model of the structure, which can easily be measured
- the applied conditions in the test (acquiring the data at 1×1 mm and 10×10 mm densities) provides an opportunity to assess time required to survey the test object and further process the database

The model acquired at 10×10 mm density is fully measurable with sufficient precision for the hydrotechnical structures in relation to the topographical objects database.

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