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Comprehensive 3D measurements of tram tracks in the tunnel using the combination of laser scanning technology and traditional TPS/GPS surveying

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Abstract

Urban Transport systems in big cities face many challenges because of continuous growth of the urban population, amount of cars and general overload of the public transportation. Challenges which the urban transport is facing have consequences for households, businesses and the whole urban community. Urban transportation takes a special part in linking economic growth and collective development as well as extensive negative impact on citizens' health and surrounding environment. Many financial institutions and governments support cities and countries in their endeavor to build and improve transport infrastructure and systems to solve above issues.

Within the other modern cities also Kraków with its almost 800 thousand people population is being challenged also in this regards. During the recent decades there has been done a major change in its urban transportation network. Trams rails network with a modern tram machines was defined as the one of the most important for the system. In Kraków the project is called "Krakow's Fast Tram". Along with this extraordinary development there needs to be adopted and efficiently used a way to verify and maintain transportation infrastructure. Among the others the laser scanning with its incredible functionality and speed is becoming an answer for this demand. In the lane with data capturing the proper data management and access is coming. The authors used and underlined a big benefit of the combination of available metrology techniques including accurate total station measurements, laser scanning and GPS positioning. The project was started by measuring the Fast Tram Tunnel in Kraków with techniques mentioned above. The next step was to post process the data and assure proper quality so it can be used in all disciplines. To illustrate this innovative combination of techniques and possible use for various disciplines there has been

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prepared verification of transition curve, circulation curve, track gauge, cant and other parameters which are standard deliverables for tram track geometry studies. On the other hand the scan data management portal has been created with scan data available through the web site regardless the location.

Finally with regards to the rapid development of the city infrastructure and community it is extremely important to use all currently available measuring techniques in an efficient and modern way which has to be fast and flexible enough to cope current demands. In this particular study laser scanning together with other surveying and analytics techniques helps to verify and maintenance tram infrastructure in urban transportation today and very likely will be the best method as well in the future.

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Keywords: laser scanner; tunnel; tram track surveying; diagnostics of track geometry; clearance

Nomenclature

W3C	The World Wide Web Consortium (W3C) is an international community that develops open standards to ensure the long-term growth of the Web. Read about the W3C mission.
XML	The Extensible Markup Language (short XML) is a computer language. It is a markup language like HTML but is extensible. It's created by the World Wide Web Consortium (W3C).
SOAP	Originally an acronym for Simple Object Access Protocol, is a protocol specification for exchanging structured information in the implementation of web services in computer networks
WSDL	The Web Services Description Language is an XML-based interface definition language that is used for describing the functionality offered by a web service.
UDDI	Universal Description, Discovery and Integration is a platform-independent, Extensible Markup Language (XML)-based registry by which businesses worldwide can list themselves on the Internet, and a mechanism to register and locate web service applications.
FLASH	Formerly Macromedia Flash, is a rich internet application distributed by Adobe Systems
JAVA	is a general-purpose computer programming language that is concurrent, class-based, object-oriented and specifically designed to have as few implementation dependencies as possible
WWW	is an information space where documents and other web resources are identified by URLs, interlinked by hypertext links, and can be accessed via the Internet. It has become known simply as the Web.
LASER SCANNING	– in functional terms can be defined as system that produces digital surface models. The system comprises an assemblage of various sensors, recording devices, and software. The core component is the laser instrument
RMS	The root mean square also known as the quadratic mean, in statistics is a statistical measure defined as the square root of the mean of the squares of a sample
ASG-EUPOS	– Active Surveying Network is an all country polish network of reference stations started in 2008 and managed by Main National Surveying and Cartography Office.

1. Introduction

Project execution, properly planned and organized work on site as well as final facility reception, have an influence on railways and surrounding construction quality and durability. There were made verification measurements in the lane with progress on the construction site which needs to give an answer if building tolerances are being fulfilled. Moreover, during normal facility maintenance similar control of its technical condition is also needed (Jong-Suk at al., 2009, Hoult and Soga, 2014). According to the standards such measurements are being made individually for each factor individually. Such workflow leads to inefficient and long surveys and issues with complex data collection. Development of the transport infrastructure management system requires to create a specialized databases. Those databases will be created from surveying and diagnostic measures. Described conditions forced us to search modern detection techniques which would be suitable for fast and rich enough data collection about surveyed facilities. Development of the technology in regards to the surveying hardware functionality, especially about terrestrial laser scanners has become an occasion to test laser scanning technology in detailed and complex measurements of the tunnel and tram tracks. There have been done studies on the usage of terrestrial laser scanning and mobile scanning in tunnel surveys (Gikas, 2012, Pejić, 2013, Weixing at al., 2014). Usually, it has been limited to gauge verification (Novaković at al., 2010). These article extend the usage of the laser scanning by the tram track diagnostic. It has also potential capabilities in the process of tram track regulation. Point cloud data handling from the capturing process, through post processing until the data exchange and online usage was also covered by this publication.

2. Data capture

2.1. General

Onsite activities were divided into two major parts. The first one was to stabilize reference points and measure them in accordance to the National Coordinate System. The second part directly related to the subject of the measurement was to capture 3D facility environment by the use of terrestrial laser scanners. 3D laser scanners are surveying instruments which are recording in a nondestructive manner surrounding surfaces with a significant speed and accuracy. Laser scanners transmit and register an electromagnetic beam to calculate the distance to the object, additional sensors measure the vertical and horizontal angles which are being constantly modified by rotating mirrors and motorized body head. As a result special coordinates are collected.

There are many hardware providers on the marked. The most popular are: Leica Geosystems, Faro, Zooler+Frohlich and Riegl. All of these producers are providing scanners which are suitable for close and medium range data capturing. They have individual characteristics and different quality parameters presented in the Table 1.

Table 1. Laser scanner parameters.

Example of a column heading	Range	Max measurement speed	Field of view (vertical / horizontal)	Ranging error	Position error
Leica C10	1–500 m	50 000 points/sec	270/360	4 mm	6 mm (1–50 m)
Faro Focus X130	0.6–130 m	976 000 points/sec	300/360	4 mm	N/A
Z+F 5010 C	0.3–187 m	1 016 000 points/sec	320/360	1 mm	N/A
Riegl VZ400	1.5–600 m	122 000 points/sec	100/360	N/A	5 mm (1.5–100 m)

Measurements had to be planned when tunnel was empty and no tram traffic present. That means we had just 4 hours per day available between 00:00 AM and 4:00 AM. Moreover, the time for each scan was essential parameter due to the tie schedule. Also high accuracy and efficiency was expected for the laser scanning task that is why two phase based terrestrial 3D laser scanners Faro Focus X130 were chosen. Positions of the scans were planned in such way that at least 40% overlap was present and together with spherical and planar targets scanned and referenced on each side of the tunnel gives expected accuracy and control of the results. Individual scans were stitched afterwards to form a continuous 3D scan image called point cloud. There have been captured 155 scans along the rails in the tunnel and entrance ramps and additional 29 scans on both tram stations (Central Station and Politechnika Station). One of the scan positions in grayscale and panoramic projection is presented on Fig. 1. In total there have been collected 184 scans in the project (Fig. 2).

Fig. 1. Laser scan panoramic view in grayscale (Politechnika Station).

In the process of scanning and measurement local coordinate system was set primarily with starting points on each side or the tunnel. To transform the local coordinates into the National Coordinate System ending points were recalculated in accordance to the KRK reference station from the ASG – EUPOS System.

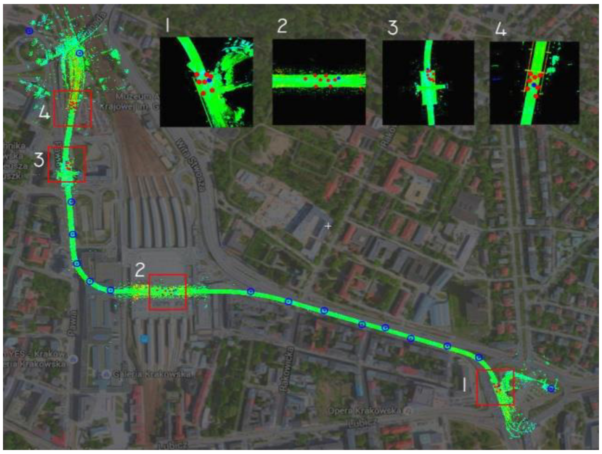


Fig. 2. Point cloud and reference points inside and outside the tunnel.

3. Data post processing

Scan data can be analyzed by various types of applications to generate detailed data set of coordinates and dimensions. This workflow including high-end terrestrial laser scanners and advanced software can be used to digitize items from small diagnostic artifacts to a large, complex sites or monumental architecture or industrial facilities (Novaković at al., 2010, Pejić, 2013, Biernat at al., 2014). Major scan data post process applications are given to work together with dedicated 3D laser scanners. Most common used are shown in the Table 2 and presented together with its flexibility related to the range of scan data types which can be handled.

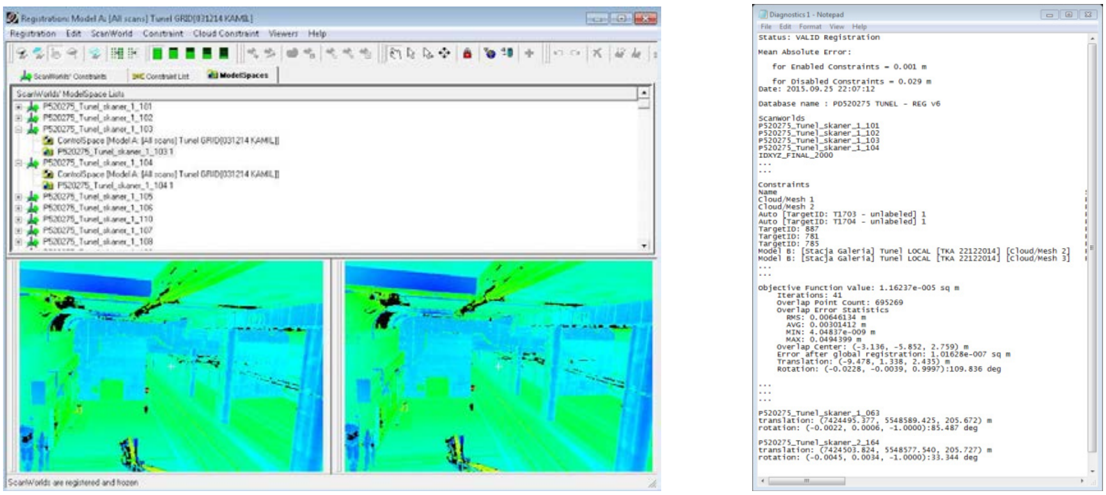
Table 2. Scan data post processing applications.

Application name	Producer	Scan data input accepted
Cyclone	Leica Geosystems	ZFS (native), E57, PTX
Faro Scene	Faro	FLS (native)
Laser Control	Z+F	ZFS, SAT, E57, PTX,
LFM	AVEVA	ZFS (native), FLS, E57, PTX

Data collected during the tunnel scanning and measurements were processed in Cyclone Register module from Leica Geosystems. This advanced tool is one of the most popular industry application for registering and geo-referencing laser scan data to a common coordinate system. To speed up the process there have been used all available constraint setting features like (Zhang at al., 2013):

- Black and white planar targets (vertex to vertex)
- Spherical targets (vertex to vertex)
- Overlapping point clouds (cloud to cloud)
- Scene features recognition (object to object)

Cyclone Register provides detailed statistical reports clearly describing quality of the final data by individual constraints' RMS and global ones (Pejić, 2013). Below are some illustration from the scan matching process with available parameters and final point cloud registration statistic. Complete point cloud RMS for enable constraints in this projects is 1mm and 29 mm for disable ones. Screens from point cloud registration are presented on Fig. 3. Moreover transformation to the reference points outside the tunnel has RMS = 5mm.



```
Status: VALID Registration

Mean Absolute Error:

   for Enabled Constraints = 0.001 m

   for Disabled Constraints = 0.029 m
Date: 2015.09.25 22:07:12

Database name : PD520275 TUNEL - REG v6

ScanWorlds
P520275_Tunel_skaner_1_101
P520275_Tunel_skaner_1_102
P520275_Tunel_skaner_1_103
P520275_Tunel_skaner_1_104
IDXYZ_FINAL_2000
...
...

Constraints
Name
Cloud/Mesh 1
Cloud/Mesh 2
Auto [TargetID: T1703 - unlabeled] 1
Auto [TargetID: T1704 - unlabeled] 1
TargetID: 887
TargetID: 781
TargetID: 785
Model B: [Stacja Galeria] Tunel LOCAL [TKA 22122014] [Cloud/Mesh 2]
Model B: [Stacja Galeria] Tunel LOCAL [TKA 22122014] [Cloud/Mesh 3]
...
...

Objective Function Value: 1.16237e-005 sq m
    Iterations: 41
    Overlap Point Count: 695269
    Overlap Error Statistics
      RMS: 0.00646134 m
      AVG: 0.00301412 m
      MIN: 4.04837e-009 m
      MAX: 0.0494399 m
    Overlap Center: (-3.136, -5.852, 2.759) m
    Error after global registration: 1.01628e-007 sq m
    Translation: (-9.478, 1.338, 2.435) m
    Rotation: (-0.0228, -0.0039, 0.9997):109.836 deg

...
...
...

P520275_Tunel_skaner_1_063
translation: (7424495.377, 5548589.425, 205.672) m
rotation: (-0.0022, 0.0006, -1.0000):85.487 deg

P520275_Tunel_skaner_2_164
translation: (7424503.824, 5548577.540, 205.727) m
rotation: (-0.0045, 0.0034, -1.0000):33.344 deg
```

Fig. 3. Cyclone Register – registration window (left) and Cyclone registration diagnostic components (right).

4. Data storage and exchange

Raw and processed output data gathered during the laser scanning project usually contains many giga or terabytes of information. These days basic storage process is becoming to be less problematic then few years ago. Hardware capabilities and price is going significantly down as well as IT services. On the other hand other challenges are becoming important. Those challenges are:

- Data access
- Data indexation
- Data archive
- Data lifecycle

Point cloud scan database due to the complexity and amount of containing information shouldn't be used only for one particular purpose like 3D modeling or singular dimension check. Complete benefit of the gathered data can be taken only when captured information will be properly organized, indexed, stored and exchanged with the users.

To fulfill this requirement proper system has to be utilized. Below diagram is presenting the process from collection of the data until the exchange with the user over the WWW. Schematic process is presented on Fig. 4.

4.1. Data online access

Constant development of the communication, data accessibility and user interfaces become something what makes it easy to exchange all kind of engineering information. Within the others, the measurements and survey results can be available almost live to everyone connected to the network. It brings extraordinary possibilities within the project team during project execution, in relation to the customer on part and final delivery stage and for asset owner when the data can be used again for example as a reference in facility shape deformation study.

Properly built and configured web service gives internet user possibility to access the data from every location in the world in the same way. The term “Web services” describes a standardized way of integrating Web-based applications using the XML, SOAP, WSDL and UDDI open standards over an Internet protocol backbone. XML is used to tag the data, SOAP is used to transfer the data, WSDL is used for describing the services available and UDDI lists what services are available. In general a Web service is a method of communication between two electronic devices over a network. It is a software function provided at a network address over the Web with the service always on as in the concept of utility computing. Sample system architecture is presented on Fig. 5.

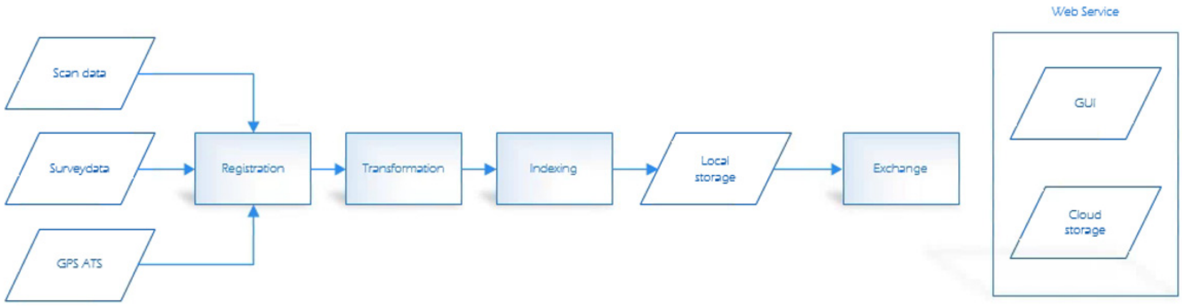


Fig. 4. Data post processing – from data capture until data exchange.

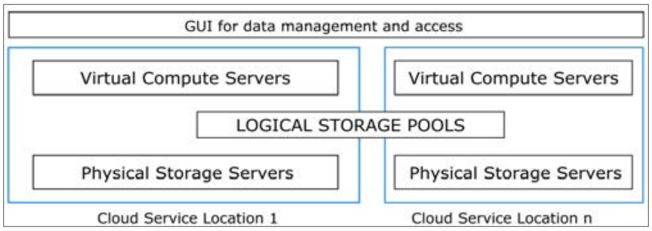


Fig. 5. Web service architecture including cloud storage.

Web protocol and applications is one required item. The second is the storage, but storage within the net. Traditional database system is installed on a server at an organization’s site and data is stored and accessed directly or over a local area network (LAN). A cloud database management system, on the other hand, runs on a cloud provider’s platform and data can only be stored or accessed when there is an Internet connection.

Point cloud datasets captured in the KSZT project have been tested and published into two WEB based solutions. The first one contains Leica Geosystem product – TruView which is HTML and Java Script based spherical viewer with linked image and geometrical coordinate data container (.DAT files) (Zhang at al., 2013, Biernat at al., 2014). The output data generated by Leica Geosystems application requires web / cloud server to be accessible online. The other tested solution is Websharecloud service provided by FARO. Faro product is not only the spherical viewer and data container this is complete web service with the cloud storage database and user friendly administration and navigation. TruView and WebShare publications sample are shown on Fig. 6.

To make the Leica TruView dataset available online there need to be used independent web server and adequate storage space. The work required in relation to the TruView is already done while Faro SCENE WebShare Cloud is considered. The WebShare Cloud solution eliminates the need of having your own server.

Both solutions provide similar functionalities in regards to the online measurements, markups and data preview. Most important features are presented in Table 3.

5. Construction gauge diagnostic and geometry of the tram track

Post processed and referenced point cloud is a base for various researches and analyzes. There have been generated transverse sections every 5 m in the whole tunnel. Thicknesses of each section was limited to 10 cm and choose according to point cloud density in the subject area. Detailed scientific description covers about 300 m distance in tunnel. Inside that testing field there are two tracks: A and B, located near the tram station. Tracks in this area contain both rectilinear and curvilinear sections. Proper set of the transition and circular curves was guided by the track aberrance and laying it along with the tram station platform edge.

Coordinates of points of the inside part of the split heads were designated on each section 14 mm below rail running surface. Those points represent position of the rail and allow calculating tram track geometry parameters and its spatial position.

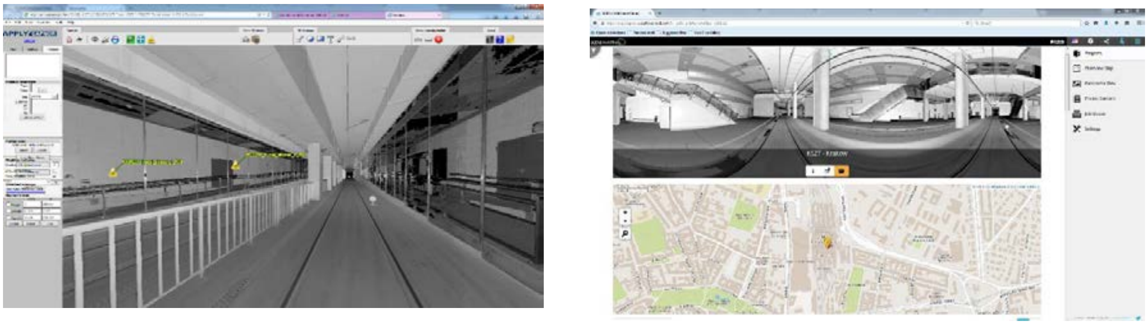


Fig. 6. Single scan position published into TruView (left) and single scan position published into WebShare Cloud (right).

Table 3. Scan data post processing applications.

Function / feature	Leica TruView + web server	Scan data input accepted
Point cloud publication	yes	yes
3D model publication	yes	no
Viewer type	spherical	spherical
Coordinate measurement	yes	yes
Distance measurement	yes	yes
Area measurement	no	yes
Text markups	yes	yes
Single position size	20–50 MB	50–150 MB
On market since	2006	2014

5.1. Structure gauge

59 transverse sections have been generated on selected distance. Structure gauge control was executed on each section and additionally in characteristic locations. There have been used equations for structure gauge for tram

tracks according to the PN-K-92009:1998 (Fig. 7). Proper extension for the gauge contour was taken into account during analyzes on curved part of the track. Curved track centre-lines require extra horizontal clearance both to the outside and inside of the curved track to allow for the effects caused by the cant elevation and the centre and end throw of rolling stock. On the horizontal curve it is required to extend by half of the undeveloped spread. It is also required to lower the bottom edge of the structure gauge on the vertical curve. Executed analyze proved that structure gauge is kept on all sections of the route. Meanwhile, on 9 sections near the Main Station a transgression of the gauge was noted. Flagstone of the station platform is located in the structure gauge's envelope and its elevation is 0.01 m too high (Fig. 7).

5.2. Geometry of the tram track

In the following part of the study verification of the selected tram track geometry was taken. Analyze covers two major items: track gauge and cant. Results are presented on Fig. 8. On the cant graph it is possible to recognize rectilinear and curvilinear sections. Differences in cants between theoretical and as-built parameters are small and reach 4 and 8 mm for A and B track. Moreover, base description statistics were designated for the differences in track gauge between real and theoretical value (Table 4). Maximum track gauge deviation is 9.3 mm and is related to rail side wear on the circular arc.

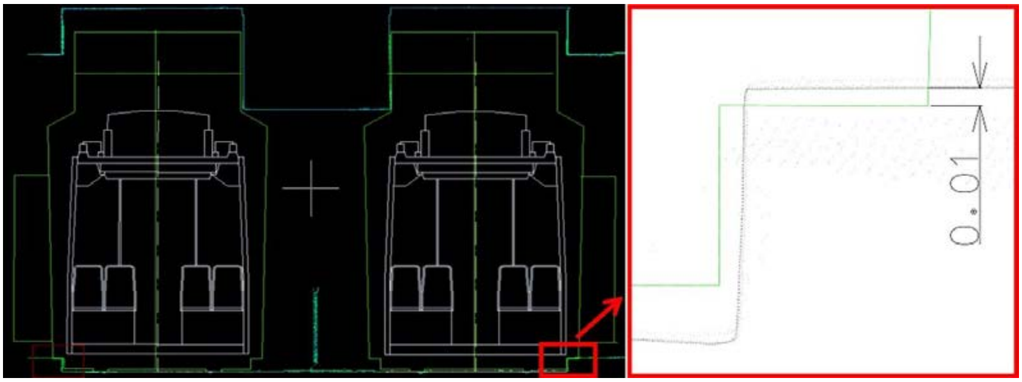


Fig. 7. Structure gauge.

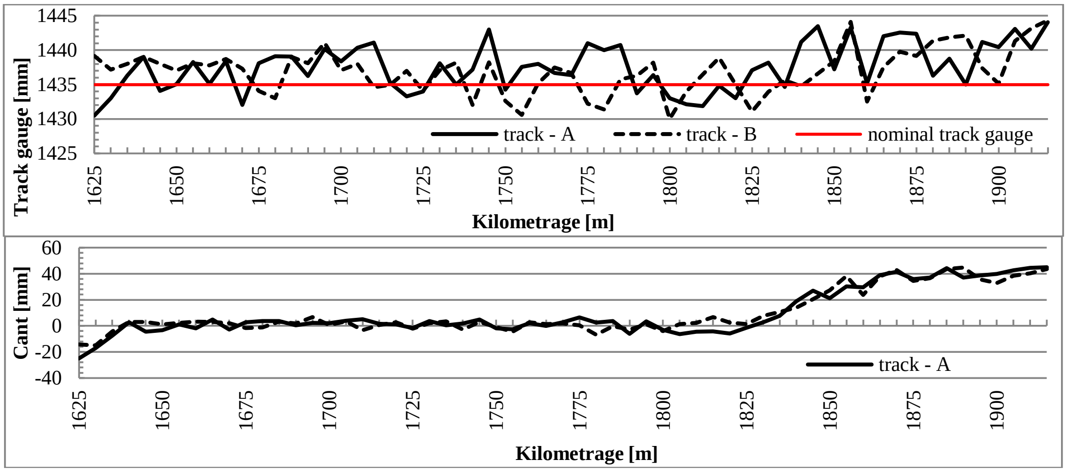


Fig. 8. Parameters of the track geometry diagram: track gauge and cant.

Table 4. Descriptive statistics for differences in track gauge between actual value and the nominal.

Track	Count	Mean [mm]	SD [mm]	Min. [mm]	Max. [mm]
A	59	2.6	3.4	-4.5	9.0
B	59	1.9	3.3	-5.0	9.3

Information about spatial position of both tram tracks allows defining track centres (Fig. 9). Outside of the station it is 4.2 m while in the station it is extend to 4.75 m.

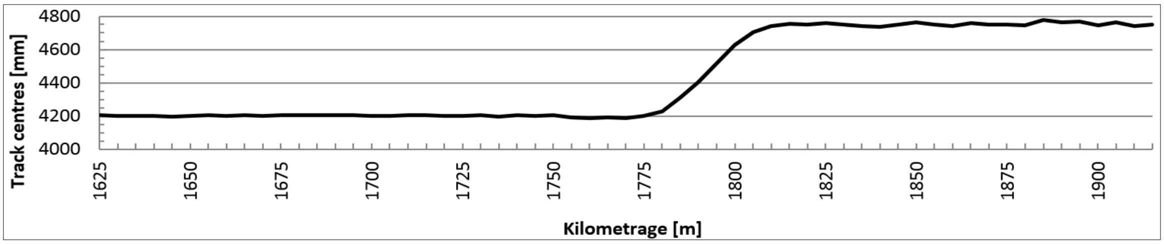


Fig. 9. Track centres diagram.

The next task was to restore geometry of the analyzed track A on horizontal plan. Spatial coordinates of the tram track centres are base to prepare horizontal track alignment design. The goal of the project was to restore optimal and design track geometry as well as to find deformation parameters. Track alignment design was executed in specialized application (Bentley Rail Track), based on multiple horizontal element regression analysis using least squares solver – Gauss-Jordan method. Following factors were taken into consideration: minimizing horizontal slew (horizontal displacement of the actual railway track from the nominal track) and to maintain similar to the design geometrical parameters of the curvilinear sections and proper structure gauge.

Calculated track shifts are shown on Fig. 10, while the basic description statistics in Table 5. On the 150 m straight section of the track shifts didn’t exceed 8 mm. The other part of the analyzed rout contains a set of reverse curves, the transition curve and a circular curve. In the area of reversed curves there are the biggest deviations up to the 27 mm (Table 5). Rail side wear railway track degradation curvilinear sections may have influence on those results. Confirmation of the results was the tram track repair executed on July 2015 by the city.

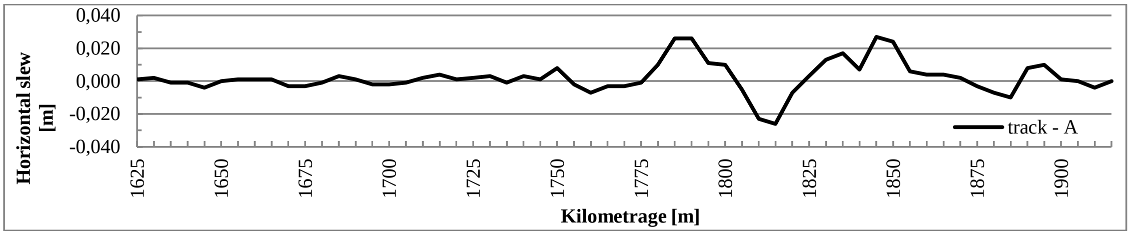


Fig. 10. Horizontal slew diagram.

Table 5. Descriptive statistics for horizontal slew.

Track	Count	Mean [mm]	SD [mm]	Min. [mm]	Max. [mm]
A	59	2	9	-26	27

6. Conclusion

Received results prove extraordinary possibilities in regards to the laser scanning technology. Combination of the scanning together with total station and GNNS satellite surveying allows for point cloud orientation in any common coordinate system. Presented technology can be adopted to all disciplines where a millimeter accuracy is required. Point cloud provides information for spatial objects visualization. Based on that it is possible to run an inspection, measurements and analyzes directly in 3D environment. Laser scanning technique is especially valuable in industrial facilities and communication routes surveying. As a standard this technique is being used in detailed analyze of structure gauge. It is also definitely possible to use it in a tram tracks and surrounding infrastructure measurements especially if the tracks are located inside of the tunnel as in presented example. High accuracy and redundancy allows for identification and gathering points which represents each splint. Precise information about tram track position are the base for various analyzes and development in surveying services and diagnostic studies. In tram track measurements it is vital to properly configure and plan laser scanning measurements. It is related to the importance of proper spatial positioning of the tram track which is partly located below the level of the tunnel sill. Influence on the resulted point cloud has following factors: setting proper point cloud resolution, localization of the stations and distance between each one of them. Objective verification of the laser scanning data accuracy and quality needs to be verified against the reference measures done with classical equipment dedicated to the particular task. With some modification of the driving elements and items applied directly to the tram track it is possible to use trolleys and measuring systems from the train track metrology.

Results based on the point cloud are good but time demanding. Unfortunately it is related to the analyze workflow which is currently manual or semi-automatic. Improvement on the workflow algorithms and adaptation of proper software might allow to improve the process.

During site measurement innovative solutions in regards to the tram track maintenance were used. Special surveying control network was established in the field. There are many similarities within its functionality to the railway geodetic network. Such network can be used in challenging track sections, like: fast tram tracks and tram tracks in tunnels. Fixed points positions are basing on metal plates mounted to the side wall of the tunnel or traction poles. Magnetic reflectors or scanning targets applied to the reference points are being used in the laser scanning. Those points might be used as a reference for any kind of surveying measurement and diagnostics taken in the tram track and tunnel area. Grid points' specification and coordinates' high accuracy can secure any kind of execution or surveying tasks related to rail transportation.

Important limitation during the work with point cloud is the big size of the data. It requires high capacity hard drives and extremely efficient computers for a comfortable and fast data processing. Mentioned challenges are being partly solved by development of the computer and software technology. Computing power of the hardware and software abilities is growing rapidly. Further, more and more solutions is being transferred to a virtual services. This brings a possibility to exchange the data with anyone who needs to get access to use and take the best from it.

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