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Research paper

Integrating surveying, photogrammetric, and remote sensing data to generate large-scale maps

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Abstract: Integration means the combination of smaller elements into a coherent system that can function as a whole. In civil engineering, integration combines data from different sources to yield complete information about an object. Data synergy significantly helps consolidate all types of data while considering their content, quantity, and diversity of formats. It involves the removal of inconsistencies and redundant pieces of information from acquired data, resulting in a consistent image (dataset). A combination of survey data, maps, photogrammetry, and remote sensing gives a 3D spatial database. A holistic approach to object data acquisition with diverse methods, techniques, and measuring tools facilitates high-quality measurement results. Information acquired this way, supplemented with spatial data from official (state-controlled) surveying and cartographic resources, paves the way for generating large-scale maps, including the master map, in line with applicable legal and technical requirements. The paper describes the process of acquiring, processing, and integrating geospatial data of a specific structure and its surroundings, using point clouds from terrestrial laser scanning, an orthophoto, databases from the State Surveying and Cartographic Inventory, and classical tacheometric surveys and GNSS-RTK surveys.

Keywords: geodesy, cartography, master map, geospatial data, TLS, integrated surveying

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1. Introduction

Data integration significantly helps consolidate all types of information while considering their content, quantity, and diversity of formats. Information synergy through integrating data from various sources facilitates better, more accurate, and more comprehensive surveys, representations, and characterisations of the object as shortcomings and errors of individual survey techniques and methods are compensated for. The integration process should be simple and ensure efficient and proper synergy of survey data. An accurate data integration process should eliminate inconsistencies and redundant information from the data, yielding a consistent image (dataset) [1, 2].

Researchers have emphasised the potential of integrated surveying for decades [4–8]. Its implementations in geospatial research usually differ in terms of the method of integration of currently favoured surveying methods. Still, the idea, potential, and integration problem remain unchanged. Various surveying methods for acquiring information about an object or terrain (classical surveys [4], photogrammetry [7], close- [5] and wide-range remote sensing [2], orthophotos, geodetic databases, etc.) often fail to provide the same information or the same information reliability. None of the methods alone can offer complete geoinformation about the object. However, each is complemented by the others [4–8].

Today's growing trend of pursuing automation in geospatial data acquisition and processing is noticeable. A search is on for innovative technical solutions for acquiring data of high accuracy and reliability [9]. Engineering measurements, including surveying, more and more often make use of synergistic effects offered by data from various sources. At the core of integrated measurements lies the combination of multiple measuring techniques for purposes of comprehensive construction-process and inventory-taking surveys [10]. The data acquisition procedure can be optimised and yet remain compliant with requirements through combination and parallel processing of field measurement results in real-time. The marriage of benefits each method offers is another step towards improved efficiency and automation of the surveying and cartographic effort [9, 11].

Implementation of integrated surveying, ensuring data completeness and accuracy, has been appreciated for years in displacement and deformation surveys [3–5] or in the acquisition of spatial information on cultural heritage (CH) objects [7, 15]. Integrated surveying in displacement and deformation measurements is the starting point for structure monitoring systems [4, 12]. Furthermore, the synergy of surveys facilitates better data accuracy in civil engineering. For example, it reduces the georeferencing error for point clouds [16, 17] or orthophotos [18, 19] so that 3D data can provide the true image of an object's mechanics [20]. The trend towards BIM of CH objects (including scan-to-BIM [14]) apparent in research publications today requires integrated surveying. CH objects exhibit significant architectural diversity. Hence, their 3D reproduction at a satisfactory level of detail (LoD) requires a palette of methods of capturing 3D data [7]. Classical and satellite-based measurements, scanning, or photogrammetry, which are commonly used for this purpose, need to have a common reference frame to ensure complementarity and interoperability [7, 22, 23]. Integrated surveys of CH objects result in a complete and reliable measurement records for the object, which can be used in object management [24] by teams of such experts as restorers, architects, civil and environmental engineers, or hydraulics and geology specialists.

The implementation of integrated surveying for the generation of maps is another application trend in tapping the potential of geospatial databases. It gravitates towards small-scale maps, in which case photogrammetric and wide-range remote–sensing data are integrated [25, 26]. This is because small-scale maps are employed to investigate large-area problems, such as degradation of the coastline [26] or environmental monitoring [25, 27]. Still, survey integration for large-scale terrain maps is just as effective a technology solution. In this case, three data sources are usually integrated [28, 29]. The first one is the source of information on the frame of reference (GNSS measurements, tacheometry, etc.); the second source is terrestrial spatial data (usually TLS, but also terrestrial photogrammetry or MLS); the third source provides information on terrain, usually from the air (UAV).

The technology of integrated surveying combines years-long classical measurements with tacheometers or GNSS measurements with ever more modern technologies using UAVs and various laser scanners. Their integration can compensate for individual weak points of all the methods. This way, the procedure yields better accuracy in modelling, classification, or environment interpretation [11].

Even though documentation generated to date provided terrain information sufficient for producing large-scale maps in line with national regulations on topographic map databases, research is yet to offer actual validation of these surveying methods. The question is, what is the potential accuracy of large-scale maps generated from integrated surveying and to what extent is such a map consistent with the national database? The paper aims to integrate surveys and object databases to generate a large-scale terrain map and validate the outcome against a terrain map from a state Surveying and Cartographic Documentation Centre. During the integration, scientific research aimed to express the geospatial database in an external frame of reference, the georeferencing accuracy of which meets the requirements for vertical and horizontal measurements. Another critical factor was maintaining data continuity and consistency across various sources integrated into a single geospatial database with comprehensive information about the object.

To validate the integrated surveys for purposes of large-scale terrain maps, the paper is organised as follows. The introduction on surveying integration is followed by section two concerning research methodology. It describes the research object, data acquisition procedures, and postprocessing of measurement results. The third section presents the outcome of integrating tacheometric, TLS, orthophoto, and geospatial database data [30] to generate a large-scale terrain map, namely a base map for a complex of objects, as an example. Sections four and five present and discuss the results and conclusions. The versatility of base map makes it an ideal subject for analysis, enabling researchers to delve into diverse aspects of in land surveying and spatial relationships. Moreover, the base map serves as a common ground for integrating and analyzing additional layers of thematic information, making it a powerful tool for exploring complex spatial phenomena.

2. Materials and methods

2.1. Object

The object is the Schoen Manor at 253 Balicka Street in Kraków (Mał opolskie Voivodeship, Poland) (Fig. 1a, 1b) with its immediate surroundings (Fig. 1c, 1d). It was built in the 1880s and is now the property of the University of Agriculture in Kraków.

Fig. 1. Location of the object; a) in Poland [31], b) in Kraków [31], c) 3D visualisation of the area, [32] d) the surveyed object, Photography courtesy A. Sokołowska, 2023

2.2. Cquisition and processing of geospatial data

The following equipment was used for field measurements:

– The Leica TS6 total station: tacheometric measurement of the control and features
– The Leica Sprinter 150 digital level: height measurement of the control

– The Leica P40 terrestrial scanner: terrestrial laser scanning for a point cloud of the object (Fig. 2c)
– The Trimble R8 GNSS receiver: GNSS-RTK check measurement of features.
– Reference marks and spheres for data integration through a common point for all techniques (Fig. 2b).

Fig. 2. Survey components; a) laser scanner, b) control point, c) reference sphere

The object scanning procedure includes the use of scanning in the entire vertical and horizontal range. At the scanning station, apart from capturing of point cloud data, point cloud labeling by tie points was performed. Tie points in the scanning procedure were black and white targets and white reference spheres. The former were located above the control network points. The latter were a geometric complement to the former, which was necessary for correct registration.

Coordinates of the control points and features were determined with angular-linear measurements using the Leica FlexLine TS06. Measurement of each new control point was connected to at least two points of the detailed national control whose coordinates were known. The elevation of these control points was determined by geometric levelling with the Leica Sprinter 150M (Fig. 3a).

The as-is survey of the object and its surroundings was performed also by radiation and trigonometric levelling with the Leica FlexLine TS06 with internal data logging and with the Leica ScanStation P40.

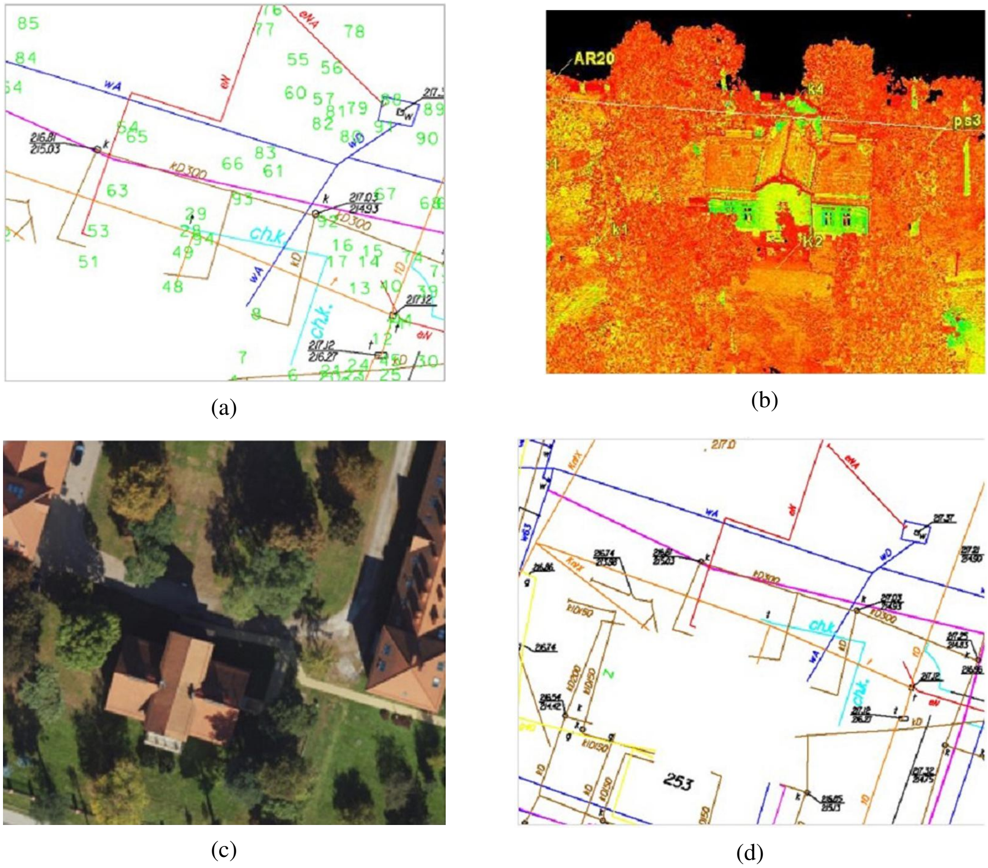


Fig. 3. Measurement outcomes: a) tacheometric measurement, b) TLS point cloud, c) orthophoto, d) geospatial databases

The field angular-linear measurements were adjusted in GEONET, which yielded adjusted coordinates of the national control and the new minor control points. The average error of position mp was 0.042 m. The levelling network was adjusted in GEONET as well. The average mean elevation error mH was 0.035 m. The points measured with the tacheometer were rigorously adjusted in GEONET. Measurement accuracy initial data indicate that mean horizontal and zenith angle measurement errors were 3.0 cc. The mean distance measurement error was 0.0030 m (constant error) and 0.0010 m/100 m (proportionate error).

Point cloud registration involves the combination of data from individual stations into a single (comprehensive) dataset (Fig. 3b). It was done in Leica Cyclone Core. The mean point cloud registration error MAE was 0.004 m.

The GNSS-RTK check measurement of points had an average error of position of 0.011 m and an average error of elevation of 0.013 m. Moreover, an average of 13 satellites was available during the measurement. The parameter determining the impact of satellite configuration on 3D positioning accuracy PDOP was 1.2 on average.

The project also employed geospatial data, an orthophoto from the State Surveying and Cartographic Inventory (Fig. 3c), ground sample distance 0.10 m), the Geodetic Utilities Network database, and the Land and Property Register (Fig. 3d).

3. The results of the integration of geospatial data and generation of the large-scale map

The geospatial data were integrated according to common georeferencing. It was done in a common coordinate system PL-2000, zone 7 (EPSG 2178). The coordinate system was realised:

- for the TLS point cloud through control points included in the survey (reference spheres and targets),
- for the tacheometric measurement through angular-linear connections to the detailed control,
- for the GNSS-RTK measurement by selecting the appropriate coordinate system,
- for the orthophoto through the transformation from the PL-92 coordinate system,
- for geospatial databases by employing the appropriate coordinate system.

The integration was based on common georeferencing, spatial coordinate system, and reference points. The procedure was visualised in MicroStation V8i. The integration of the measurement results, databases, and orthophotos is shown in Fig. 4 and Fig. 5.

During assessment (integration verification), analyses of the accuracy of each data acquisition method were performed. To this end, control objects were selected which were attempted to locate using all the available data sources. The results of the analysis are visualised with colour markers (Fig. 6).

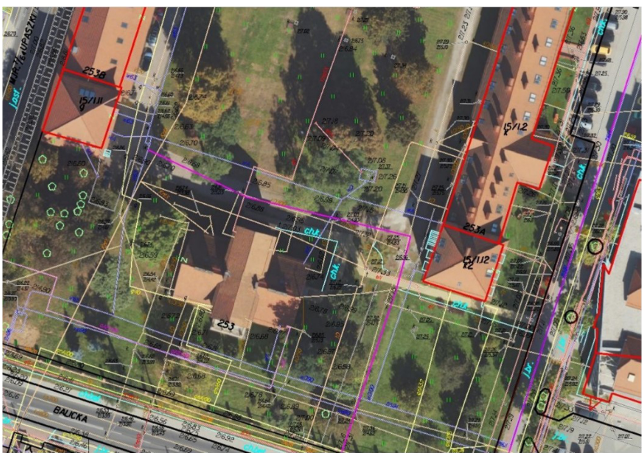


Fig. 4. Integration of geospatial databases and tacheometric measurements on a base orthophoto for control

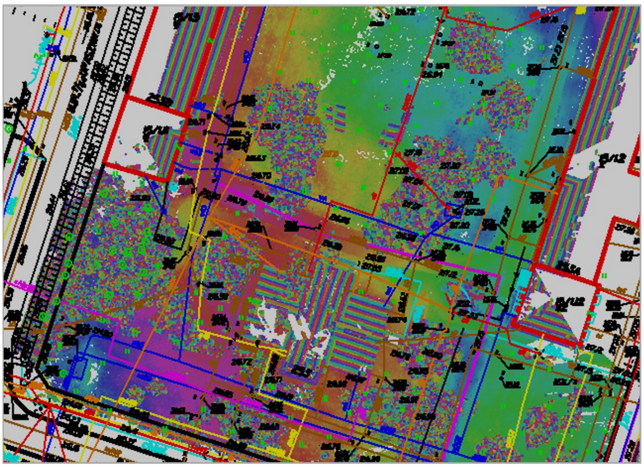
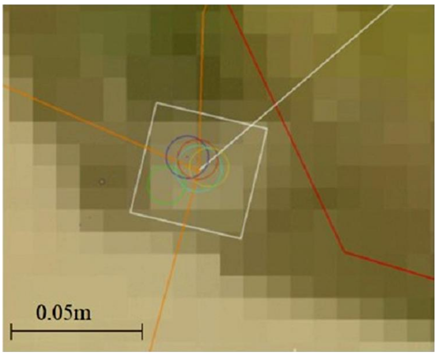
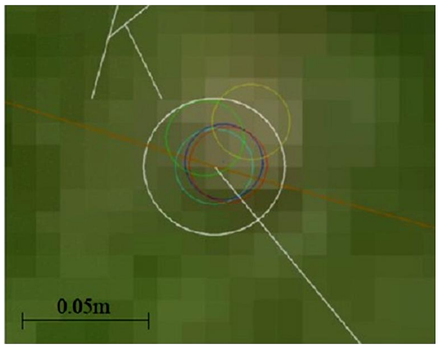


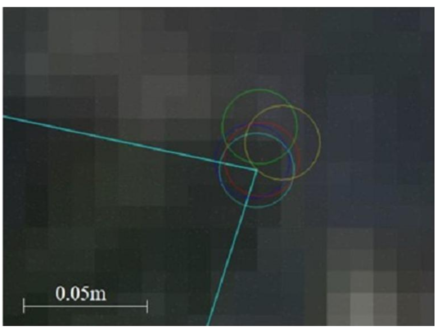
Fig. 5. Integration of geospatial databases and TLS point cloud



(a)



(b)



(c)

Colour coding:
Blue – tacheometry
Red – GNSS-RTK
Green – TLS point cloud
Sky-blue – map from District Land Surveying and Cartographic Documentation Centre
Yellow – orthophoto

Fig. 6. Analysis of data integration accuracy. Feature identification/location error for a) gas gate valve, b) manhole cover, c) building corner

4. Summary of results and discussion

Each of the data sources employed here provides reliable spatial data. Each can be used to generate a large-scale map, including a base map, in line with applicable regulations and technical requirements [33]. The large-scale base map for the object were generated by using information from a geospatial database (District Surveying and Cartographic Documentation Centre), a tacheometric survey connected to the state control network, and a TLS point cloud (Fig. 7).

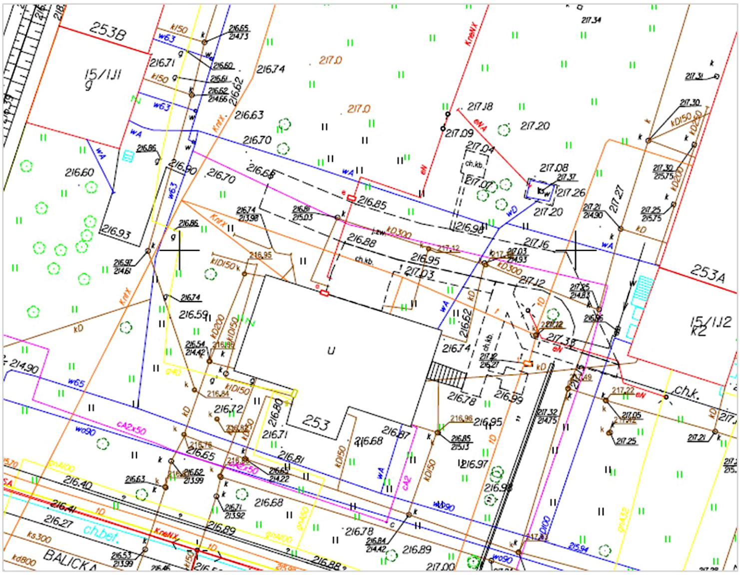


Fig. 7. Excerpt from the base map for the surveyed object

Integration of data from various sources is commonly used today, from the simplest surveying jobs to various research projects related to geodesy and cartography. In their research on modification and integration of data from various sources aimed at spatial analyses and developing 3D models of buildings, Lewandowska and Doskocz concluded that a complete large-scale map and its 3D visualisation require surveying data and LiDAR aerial scanning data. Point clouds alone would not ensure building reproduction accuracy identical to the level of detail of a 1:500 master map. Also necessary are envelopes of buildings and other objects of the first accuracy group from detailed surveys. In their summary, they claimed that maps and survey data combined with reference inputs (LAS, DTM, 3D models of buildings) could help transform the existing data into a new form of 3D spatial presentation, which would be more transparent for experts in associated industries and more user-friendly for amateurs interested in putting the data to use [34]. Mika and Siejka [9] demonstrated in their publication on the application of integrated surveying techniques to preliminary flood risk assessment that using integrated photogrammetric and GNSS techniques with IT tools for preliminary flood risk assessment can be beneficial in terms of costs and time effectiveness. Moreover, it is advisable to employ existing cadastral base maps in addition to direct measurements and photogrammetry to improve the level of detail of flood risk maps [9]. Their study integrated data from various sources, which directly indicates the prevalence of this process, broad application opportunities, and its advantages for geodesy and cartography, as well as many other disciplines where geospatial data need to be acquired.

The problem of spatial data integrity is inherent to any context where a new system is built with data from multiple sources. They are usually incoherent and diversified in many ways. Therefore, clear integration principles are necessary to generate the final product [35], for example, a master map from various databases. As source databases grow and spatial information is more and more easily accessible, the need for data integration within systems grows more relevant. Duplication of source information is an alternative to integrated databases, but in most cases, it would mean data redundancy that is unacceptable in modern geoinformatics solutions [35]. The integration of modern measurement technologies is a new trend in acquiring spatial data. Apart from the advantages related to data synergy and their mutual complementation, there are some disadvantages. They usually result from technological limitations (e.g. inability to use non-contact, UAV or satellite measurements in areas with dense development, etc.) [36, 37]. So far, similar conclusions about the potential of integrated geodetic measurements have been drawn by researchers from Italy [5, 6] and Russia [25].

5. Conclusions

Modern land surveying increasingly often employs combinations of various measurement methods and integrates inputs from multiple sensors to determine the shape and condition of objects or assess the statics and dynamics of object's condition changes. By combining and parallel processing field measurement results, one can optimise data acquisition while ensuring high accuracy and reliability of the results. Their integration can compensate for individual weak points of any method. This way, the process yields better modelling, interpretation, and environment classification accuracies. The benefit of integration is that geospatial databases gain new features, such as point clouds coloured based on digital photographs or 3D model texturing based on a point cloud [1–3].

In pursuit of the synergy of combined data from various sources, one should consider multiple interrelated factors, such as labour cost, time cost of measurements and data processing, or type and mobility of equipment. Data currency is also essential as it might significantly affect the outcome. The observations were processed a single software application compatible with various data types of diverse content, quantity, and formats, namely MicroStation V8i [10]. Integration of the data by parallel processing of measurement results optimised the data acquisition process while ensuring high accuracy and reliability of the results.

The concept of integrated surveying is another crucial advancement of land surveying as a widely interoperational domain in terms of spatial data acquisition technology. The integrated methods combine the best features of surveying techniques while ensuring complete conformity with new standards, leading to accuracies exceeding legal requirements [11]. Integration offers a multitude of benefits for surveying and cartography. They include the potential to combine various types of data sources and verify data with another source, such as surveying equipment. It is necessary to integrate surveying with data from other sources when a single measuring instrument is incapable of acquiring all necessary object information, for example, for cataloguing purposes.

Proper planning and implementation of all operations yielded a complete database with spatial coordinates of the entire object, namely the Manor House of the University of Agriculture in Kraków with its surroundings. Each surveying method contributed some coordinates, which were then processed and analysed statistically to verify their accuracy and measurement correctness. The correctness of the coordinates was further confirmed with information from other sources (National Geoportal and District Surveying and Cartographic Documentation Centre).

To conclude, integrated surveying is necessary when a single measuring tool cannot acquire all the information about an object necessary to produce its complete documentation or when it is necessary to check acquired data against a different data source (measuring system) to fill in blanks left due to limitations of measuring equipment, for example. The effort is made to obtain a comprehensive and coherent (geospatial) database for an object or to complete a database (or measurement) when the original device/system is unavailable, which can happen if the survey was taken years ago, the device has been damaged, or resurvey is impossible.

The employment of diverse sources to generate large-scale maps is a way of ensuring complete and accurate information about objects and features. Different sources complement each other through information synergy. Multiple databases can lead to information redundancy, which poses a challenge but can also be used to verify the correctness of values. Such a geospatial dataset facilitates a holistic approach to the object and acquisition of all, even the most detailed, pieces of information when generating a map.

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Integracja danych geodezyjnych, fotogrametrycznych i teledetekcyjnych dla potrzeb generowania wielkoskalowych opracowań kartograficznych

Słowa kluczowe: geodezja, kartografia, mapa zasadnicza, dane geoprzestrzenne, TLS, zintegrowane pomiary geodezyjne

Streszczenie:

Integracja jest działaniem polegającym na łączeniu mniejszych elementów w spójny system, dzięki czemu może on działać jako jedność. W aspektach inżynierii lądowej jest to zabieg łączenia danych pochodzących z różnych źródeł w celu zapewnienia kompletności zebranej informacji o obiekcie. Synergia danych pomaga w znaczącym stopniu skonsolidować wszystkie typy danych, uwzględniając ich treść, ilość i różnorodność formatów. Polega na usuwaniu sprzeczności i nadmiarowych informacji z pozyskanych danych z otoczenia, co pozwala na uzyskanie jednolitego obrazu (zestawu danych). Łącząc ze sobą dane geodezyjne z materiałami kartograficznymi oraz opracowaniami fotogrametrycznymi i teledetekcyjnymi otrzymujemy trójwymiarową bazę danych o przestrzenni. Zintegrowane pomiary geodezyjne są niezbędne w sytuacjach, kiedy jednym narzędziem pomiarowym nie jesteśmy w stanie pozyskać wszystkich niezbędnych informacji o obiekcie, celem jego pełnej inwentaryzacji, bądź jesteśmy zmuszeni do przeprowadzenia kontroli poprawności pozyskanych danych przy pomocą innego źródła danych (sprzętu pomiarowego) np. w celu uzupełnienia braków wynikających z ograniczeń sprzętu pomiarowego. Takie prace są realizowane, aby pozyskać kompleksową i spójną bazę danych (geoprzestrzennych) o obiekcie, bądź celem uzupełnia braków informacji w bazie danych (pomiarze) w sytuacji ograniczenia dostępu do urządzenia, czy też systemu pierwotnego (np. pomiar wykonywany był kilka lat wcześnie, sprzęt pomiarowy jest uszkodzony bądź nie ma możliwości powtórzenia pomiarów). Holistyczne podejście do pozyskiwania informacji o obiekcie pomiarowych, przy wykorzystaniu różnych metod, technik i narzędzi pomiarowych umożliwia pozyskanie wysokiej jakości wyników pomiarów. Tak zgromadzona informacja dodatkowo wzbogacana o dane przestrzenne pozyskane z urzędowych (państwowych) zasobów geodezyjnych i kartograficznych umożliwia generowania wielkoskalowych opracowań kartograficznych, w tym również mapy zasadniczej – zgodnie z obowiązującymi wymaganiami prawnymi i technicznymi. Wykorzystanie różnych źródeł danych dla potrzeb generowania wielkoskalowych opracowań kartograficznych umożliwia kompleksowe oraz dokładne pozyskiwanie informacji o obiektach i szczegółach sytuacyjnych. Synergia informacji powoduje ich wzajemne uzupełnianie Liczne bazy mogą powodować powstawanie informacji redundantnych, co z jednej strony utrudnia pracę, jednakże umożliwia kontrolę poprawności prezentowanych wartości. Generowanie mapy w oparciu o taki zbiór danych geoprzestrzennych umożliwia całościowe podejście do obiektu, a także pozyskanie wszystkich, nawet bardzo szczegółowych informacji. W pracy przedstawiono proces pozyskiwania, przetwarzania oraz integracji danych geoprzestrzennych na przykładzie obiektu budowanego wraz z jego otoczeniem, dla którego wykorzystano dane zapisane w postaci chmur punktów z naziemnego skanowania laserowego, ortofotomapy, a także baz danych z Państwowego Zasobu Geodezyjnego i Kartograficznego oraz klasyczne geodezyjne pomiary tachimetryczne oraz GNSS-RTK.

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