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Original paper

Integration of TLS and UAV data for the generation of a three-dimensional basemap

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Abstract: 3D maps are becoming more and more popular due not only to their accessibility and clarity of reception, but above all, they provide comprehensive spatial information. Three-dimensional cartographic studies meet the accuracy requirements set for traditional 2D stu-dies, and additionally, they naturally connect the place where the phenomenon occurs with its spatial location. Due to the scale of the objects and difficulties in obtaining comprehensive data using only one source, a frequent procedure is to integrate measurement, cartographic, photo-grammetric information and databases in order to generate a comprehensive study in the form of a 3D map. This paper presents the method of acquiring and processing, as well as, integrating data from TLS and UAVs. Clouds of points representing places and objects are the starting point for the implementation of 3D models of buildings and technical objects, as well as for the con-struction of the Digital Terrain Model. However, in order to supplement the spatial information about the object, the geodetic database of the record of the utilities network was integrated with the model. The procedure performed with the use of common georeferencing, based on the global coordinate system, allowed for the generation of a comprehensive basemap in a three-dimensional form.

Keywords: UAV, TLS, data integration, geospatial data, mapping 3D

1. Introduction

Due to the development of science and technology, the interest in analogic map is declining in favour of presenting its digital image, displayed with the use of computer programs. Over the centuries, thousands of cartographers have developed a wide variety of techniques, procedures, and rules to efficiently present and communicate information using maps. On the other hand, the popularization of computers and the introduction of digital maps required the introduction of new rules and techniques for cartographic presentation (Eremchenko et al., 2015). Thanks to this, it was possible to present three dimensions simultaneously in one study. This allowed for the presentation of space as a coherent whole, in the form of the socalled geovision of places and objects (Medynska-Guli, 2011).

Three-dimensional cartography is defined as the entirety of knowledge and scientific, technical and artistic activities related to the full life cycle of 3D maps, i.e. data collection, generation and distribution process, use of technologies and algorithms, as well as forms and methods of their use and application possibilities (Goralski, 2009). Three-dimensional cartographic studies are computer perspective views of the content of a map. Therefore, its method of generation and presentation is largely influenced by the preferences of the author of the study. The developed object is a derivative of the concept phase. It goes through the stage of modeling and symbolizing spatial elements, ending with creating a visualisation. These processes, known in the traditional 2D approach, are subject to modifications and introduce new rules for generating 3D spatial studies (Petrovic, 2003; Hájek et al., 2016). Individual spatial objects (Roberts et al., 2022) are subject to three-dimensional presentation, as well as a visualization of entire cities is generated (Mao et al., 2020).

Three-dimensional cartographic studies are created on the basis of data obtained from the field survey, digital photos, point clouds from laser scanning, statistical materials or other types of geospatial data. When generating three-dimensional cartographic studies, apart from knowing the location and range of phenomena, spatial information is also important. A frequent procedure of generating 3D maps is assigning altitude features to traditional 2D studies. Such studies are performed in situations that require locating phenomena in three-dimensional space or conducting spatial analyses (Jarzyna, 2016). Information about the third dimension may come from, inter alia: evidence, stereodigitisation, lidar data or the result of a superposition of two-dimensional data with spatial information presented by, for example, a numerical land cover model (Cislo, 2008). The process of assigning spatial parameters is possible provided that the source data is complete and consistent. The development of such solutions enables the control of the course and spatial scope of the occurrence of a given object, as well as enabling collision analysis of phenomena and improvement of the design processes of new elements of technical infrastructure and utilities networks (Mroz et al., 2014). An increasingly frequent process is the creation of cadastral maps presenting the three-dimensional range of the object's occurrence and the laws of ruling in the form of the socalled 3D cadastre (Aditya et al., 2020; Klapa, 2021).

More and more often, three-dimensional studies are based on aerial or UAV photos. The accuracy of the reconstruction of the 3D model depends mainly on the type of acquired photos, their resolution and their mutual coverage. To more accurately reproduce the subject, subsequent photo scenes can be supplemented with oblique and ground photos. The model can be created automatically by assembling consecutive photos into a uniform study or by generating a point cloud, and then performing the modelling process of its individual components. Data from UAVs are commonly used to develop orthophotos or thematic maps. However, with the help of such techniques and tools, it is also possible to create three-dimensional studies of buildings for which high accuracy is required, as well as the presentation of architectural details (Drzewiecki and Bujakiewicz, 2018; Collado, 2022). The photos used to build the model of the surveyed area from the UAV deck are characterized by high resolution, user controlled level of coverage of subsequent photos and the number and position of the images taken depending on the needs. UAV measurements are easy to perform and the ability to reach dangerous and hard to reach places. It is a cheap and quick alternative to groundbased photos, as well as those taken from a low ceiling (Nex and Remondino, 2014). UAVs allow to obtain in a controlled manner, reliable and accurate geospatial data, which is the starting point for generating largescale, three-dimensional cartographic studies (Lari and El Sheimy, 2015; Iheaturu et al., 2020).

The model and the 3D maps themselves can also be created using satellite images. Although the accuracy of such a study is lower, it allows you to quickly generate products covering a large area of the studied area. This type of study found particular application in historically and archaeologically valuable areas – often difficult to access (Malinverni et al., 2017). Based on the data obtained from satellite images, three-dimensional studies are performed, including mainly numerical models of terrain and land cover for the Earth's surface and other celestial bodies (Tao et al., 2021).

The process of generating three-dimensional cartographic studies may also consist in modelling objects based on geospatial data from laser scanning. Modelling is performed on the basis of a point cloud from LiDAR (Richter and Dollner, 2014). By processing individual measurement data and generating subsequent geometric models, elements are collected to create a 3D visualization. The LiDAR point cloud is used for modelling buildings, while digital photos are the basis for generating an orthophoto map, which is the background for the study (Guan et al., 2013; Bitelli et al., 2018). Terrestrial laser scanning is a source of geospatial data obtained directly in the field. Point clouds from TLS are commonly used to create 3D models of places and objects, and more and more often they are the basis for making and updating traditional cartographic studies (Klapa and Mitka, 2017). Due to the high accuracy and precision of recording points, they are also an excellent source of data for the needs of generating three-dimensional cartographic studies (Abdelazeem et al., 2021).

3D maps are widely used in GIS technology (Nishanbaev et al., 2021; Mazzei and Quaroni, 2022) and for the visualization of environmental data (Tong et al., 2015). For the purposes of creating three-dimensional cartographic studies, it is possible to integrate the already existing 3D models with the geospatial data of the studied area. The evolution of GIS tools and data integration modules, as well as numerous overlays and plugins for computer programs make this process simple and efficient. GIS database, including, inter alia, reconstruction of buildings, land and other spatial elements of the city can be integrated with measurement data obtained using digital photos (Bobkowska et al., 2017). The analysis of photogrammetric images makes it possible to obtain three-dimensional data with reference to geographic references. Although the very process of generating 3D maps is supported by numerous computational algorithms, the method of obtaining reliable and accurate spatial information is still a problem. It concerns measurement techniques, the type of information provided, problems with the accuracy and precision of their integration, the lack of information for hard to reach places, as well as data redundancy (Malumpong and Chen, 2008).

Currently, much attention is paid to the three-dimensional visualisation of terrain models as well as places and objects in order to present spatial data on the internet or numerous mobile applications (Atoyan and German, 2017). The development of technology and graphic software, as well as the availability of various types of geospatial data, facilitate the generation of three-dimensional cartographic studies. Such materials are used not only by experts and scientists in the field of geomatics, but also by numerous recipients of various fields and professions.

Creating detailed and realistic largescale three-dimensional mapping studies is difficult due to the variety and complexity of the generated geospatial data. The variety and multitude of data types allows the detection and elimination of measurement errors, generates parts of images not saved with the use of other technology, increases the accuracy of the generated maps, extends the range and scope of the possible use of the performed study. A whole range of data can be used for integration, ranging from point clouds from ground and aerial scanning – through clouds from ground, aerial and UAV images – to spatial data provided by Open Source Map. You can also use statistical data and numerous GIS analyses, or other spatial information – relating to places, objects and phenomena occurring in the natural landscape (Tully et al., 2015). In order to ensure the completeness of the information obtained about the surroundings, point clouds from TLS and UAVs can also be integrated (Tong et al., 2015; Son et al., 2020). It is also possible to integrate data from more than two sources, eg integration of data from terrestrial (TLS) and mobile (MLS) laser scanning with fotogrametric data from UAV and information obtained using GNSS (Chiabrando et al., 2019; Klapa, 2021).

The aim of the work is to examine the possibility of integrating TLS, UAV, GNSS data and other databases of spatial objects for the purposes of performing accurate and precise studies, which may be a data source for the needs of generating and updating accurate largescale thematic maps, as well as a three-dimensional forms of a basemap..

2. Materials and methods

The work uses spatial data generated with the use of various techniques and measurement tools: terrestrial laser scanner, unmanned aerial vehicle and a GNSS receiver. The DJI S1000 multirotor, equipped with a Sony ILCE 7R digital camera with a SEL 35F28ZA lens and a fixed focal length of 35 mm (Fig. 1a) was used for field work involving the execution of unmanned aerial vehicle flights. In order to acquire the point clouds, a Leica P40 ScanStation terrestrial laser scanner was used (Fig. 1b).

The purpose of integrating geospatial data from groundbased laser scanning and unmanned aerial vehicles is to obtain a homogeneous and coherent set of data. In order to carry out the measurement, as well as to integrate the measurement data with UAV and TLS, target plates (Fig. 2a) and specially designed and prepared reference spheres with spatial markers (Fig. 2b) were used. The reference points were used to connect

(a)

(b)

Fig. 1. Measuring equipment used: a) UAV – DJI S1000, b) TLS – Leica P40 ScanStation

individual point clouds from successive laser scanner positions, as well as photopoints in the process of aerotriangulation of images taken from the UAV deck. Additionally, they acted as control points for the obtained results of the work. They also served as a measurement network used to provide georeference in the rectangular plane coordinate system of the National Geodetic Coordinate System 2000: PL-2000 zone 7 (EPSG code: 2178) and in the elevation system of Kronstadt normal heights (PL-KRON86-NH).

(a)

(b)

Fig. 2. Reference points – measurement network points: a) target plates and b) reference spheres with a spatial marker

Giving references to the spheres was possible by measuring GNSS-RTK at a central point. The reference sphere is commonly used to connect point clouds with TLS between individual stations, due to the unambiguous identification of the spherical geometry and the possibility of automatically fitting the spheres into the cloud (even with a small number of points) (Klapa et al., 2017). They are a tool that allows you to perform the cloud connection process at a very high level of accuracy. By pointing to a ball fitted to point cloud, we get the values of the spatial coordinates of its centre point and its diameter or radius. By adding the value of the sphere's radius to the value of the altitude coordinate, we obtain the values of the coordinates of the point in its zenith part. In addition, if the ball is stable and centered on a tripod (shaft or other stabilizer), it is possible to measure and determine the values of the X, Y, Z coordinates of the ball tip, which indirectly gives us the coordinates of the ball centre – automatically determined on the cloud after fitting the sphere. By adding a graphic symbol that allows to indicate the zenith point on the sphere, we get the possibility of identifying this point in the photos, e.g. from the UAV deck. The scheme is covered by the reserved patent law with the number Pat.235753 and the industrial design number: Wp.26231 (Klapa, 2021).

2.1. Characteristics of the research facility and field works

The research area is located in the western part of the city of Krakow (Poland, Malopolskie Voivodeship). The buildings are the property of the Agricultural University of Krakow (Fig. 3). The area of the research area is 1.0 ha. The facility includes a complex of buildings with a large number of spatial objects, located on one level. It is a facility that requires a large number of TLS stations and an detailed UAV flight plan. Containing numerous elements inaccessible to only one measuring device, i.e. vertical walls and roofs of buildings. It is an area with complex geometry and difficult measurements (due to the lack of visions), an area with a large number of situational elements.

Fig. 3. Location of the research site (N:55°22′55″; E:19°49′44″)

The UAV flight was performed in one mission using the raid plan made in the Mission Planner software. UAV flight parameters: height – 50 m, longitudinal coverage – 70%, transverse coverage 40%. The field pixel size is 0.007 m. 70 digital photos were obtained in *.jpeg format with dimensions of 7360 × 4912 pixels. The acquired images were processed in the Agisoft Metashape Professional software, where the aerotriangulation process was carried out, and then a point cloud was generated, as well as an orthophoto map of the studied area. For the conducted photogrammetric project, the accuracy of the obtained results was checked. The mean square error at the photopoints was –0.013 m, while the mean square error at the control points was –0.017 m.

The data from the terrestrial laser scanning was processed in the Leica Cyclone software. The work consisted in combining individual measuring stations into a uniform point cloud for the entire facility. The absolute error on the point cloud bindings was 0.020 m. There is an accuracy of combining all results from individual measurement stations into a uniform point cloud for the entire research facility. Using spheres and reference discs, a transformation was made to the appropriate coordinate system – giving georeference to the obtained geospatial database. Accuracy analysis was carried out at the control points located in the facility. The mean error for the control points was 0.028 m.

2.2. Development and processing of measurement data

In the integration process, a point cloud from TLS (Fig. 4) and from UAV photos (Fig. 5) was used.

The analysis of the TLS point cloud for the research area (Fig. 4) indicates places with a diversified structure of points recording, which proves the nonuniform spatial

Fig. 4. TLS work result – point cloud

Fig. 5. Point cloud – derived from UAV photos

acquisition of points during the measurement. There is a visible lack of information on the roofs of the buildings and the occurrence of the so-called "Shadows", created when the area is obscured by another object during scanning. The redundancy of points in the cloud occurs in the areas around the scanner stations and in the area, as well as on vertical planes (walls of buildings).

Analysis of the point cloud generated on the basis of the images from the UAV deck (Fig. 5) shows nonuniform data acquisition for the entire area. In the process of generating the cloud, the points are evenly distributed, however, this ratio is not maintained in space. There are places with a disturbed cloud structure. Deficiencies are noticeable in places that are difficult to reach for UAVs – vertical walls and places covered with eaves or under trees. However, there is a redundancy of information on the roofs of buildings.

The use of common reference points for all measurement techniques made it possible to obtain common georeferencing. Such a procedure allowed to eliminate the influence of errors related to georeferencing and the results of field work for individual measurement tools. The obtained data is characterised by homogeneity of georeference, and the geometric accuracy of the location of points in the cloud results from the precise parameters of the measurement technologies used. Using common georeferencing, TLS–UAV data integration was performed (Fig. 6).

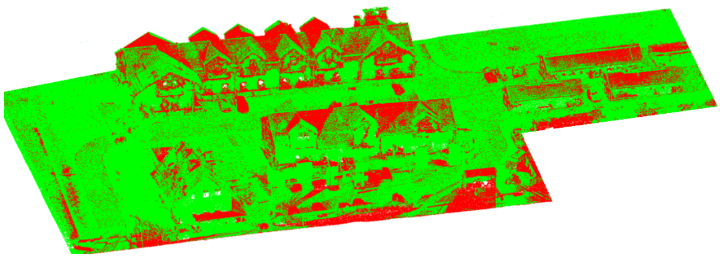

Fig. 6. Point cloud for TLS (green) and UAV (red) data integration

The distribution of points in the cloud after TLS–UAV data integration shows the distribution of points throughout the area. The clouds complemented each other, providing a comprehensive picture of the entire space of the examined object. Information synergy allowed for the elimination of gaps and measurement imperfections in both TLS and UAV technologies. In the process of integration, the spatial density equalization took place for almost the entire area. The missing elements of the cloud were supplemented – this proves a significant improvement in data quality in relation to both UAV and TLS.

In order to check the correctness of the TLS–UAV point cloud integration, the information compliance assessment was carried out in the form of Cloud-to-Cloud Distance in CloudCompare. The inspection covered areas of 1x1 m on paved surfaces (roads, roofs, pavements) (Fig. 7). The average distance of TLS–UAV clouds, resulting from integration for various surfaces, was in the range of 2–5 cm.

However, in places easily accessible for both measurement techniques, there was a redundancy of data, therefore the process of their unification was carried out using the algorithms of point cloud optimization in the Leica Cyclone software and the uni-

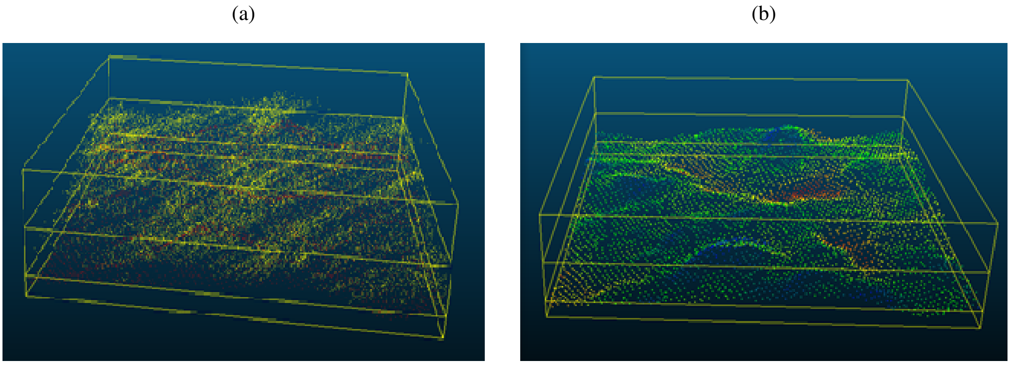

Fig. 7. Point cloud comparative analysis: a) red (UAV), yellow (TLS) and b) scalar field which is an analysis of the similarity (differential model) of the point cloud from the UAV to the TLS

fication level of 0.001 m was applied for the entire area. This allowed increased work efficiency and to standardize the amount of information in the entire area by removing data redundancy.

3. Results: Generation of a three-dimensional basemap

The preparation of three-dimensional cartographic studies based on the processing of geospatial data into the form of 3D models should be carried out in accordance with the adopted level of accuracy and appropriate detail, and also located in the global reference system.

According to the Polish Act of Geodesy and Cartography (1989), the base map is a large-scale cartographic study, containing information on the spatial location of: geodetic control points, cadastral plots, buildings, contours of land, classification contours, utilities networks, buildings and construction devices and other topographic objects, as well as selected descriptive information about these objects (Polish Act of Geodesy and Cartography, 1989). The basemap is a source of information on spatial and cadastral data. With its help, it is possible to determine the location in the adopted frame of reference. It contains information on the main natural and artificial elements, such as reservoirs, roads, buildings, fences, as well as information on administrative borders. The information on the basemap is presented in the form of symbols and descriptions. By means of graphic symbols it is possible to characterize places and objects (National Academies of Sciences, Engineering, and Medicine, 1983).

The implementation of the development of a three-dimensional form of the basemap could only be comprehensively implemented thanks to the synergy of TLS–UAV–GNSS measurement data. Obtaining a common georeferencing made it possible to generate geospatial databases, constituting a reliable source of data about the surroundinds, while maintaining the consistency and compatibility of the results from various measurement techniques. Optimisation works were carried out while maintaining the assumptions and accuracy requirements for largescale cartographic studies. The optimization of the point cloud consisted in the removal of redundant information, limiting the cloud to the scope of performed works, as well as unifying the cloud to the appropriate level of density. Appropriately selected parameters and cloud optimisation tools allowed for the adjustment of its features depending on the required level of detail in accordance with Polish technical standards for the performance of surveying works (Polish Regulation of the Minister of Development, 2020).

The point cloud after integration, optimization and georeferencing was used as a source material for making individual components. The first procedure was the classification of the terrain points and then the generation of the Digital Terrain Model. For this purpose, the Leica Cyclone 3DR software was used. The mean distance between the grid points was defined at 0.10 m (Fig. 8a). The second, more complex procedure was generating 3D models in a semiautomatic and manual way, using the MicroStation V8i software. The generated 3D model corresponds to the LOD2 level of detail, and for the purpose of supplementing the spatial information, details were added for the objects, i.e. columns, lanterns, windows, doors and stairs for LOD3 (Fig. 8c). After making the spatial elements based on the point cloud, the synergy of data from the Polish State Geodetic and Cartographic Resource: Krakow – city (BIP Krakow, 2022) in terms of the network of utilities was made. Information on the location of objects was obtained from the database, while the altitude data was obtained from the descriptive database.

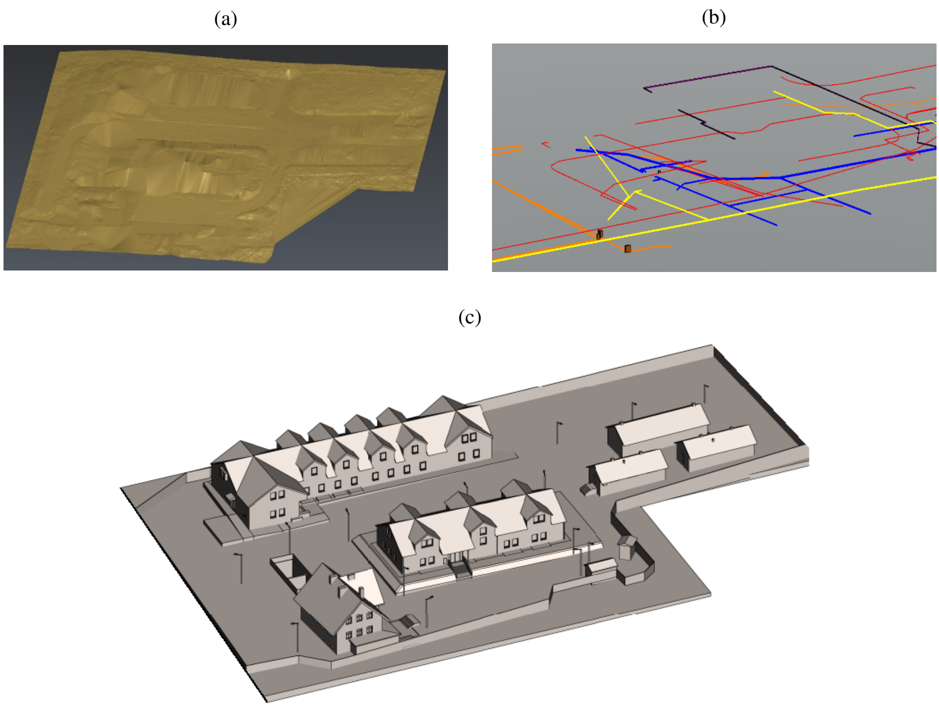

Fig. 8. Components of a three-dimensional map: a) Digital Terrain Models, b) network of utilities in a three-dimensional form and c) spatial model of buildings

As a result, spatial values of X, Y, Z were obtained for individual objects of each network (Fig. 8b).

The synergy of the geospatial database presented by means of individual 3D models and spatial objects (Fig. 8 a,b,c) allowed for the generation of a three-dimensional cartographic study (Fig. 10). The three-dimensional basemap enriched with spatial elements is a selfcontained visualisation of the entire object, and at the same time it is a reliable, accurate and comprehensive source of data about the place, objects and terrain. The individual components of the map, as well as its final version, is excellent material that can be used to control and update the basemap, expressed in the traditional two-dimensional form, supplemented with descriptive elements (Fig. 9).

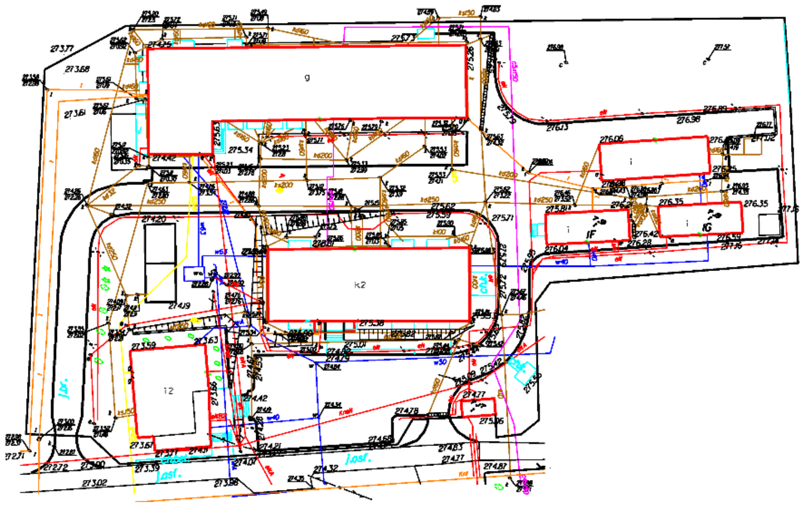

Fig. 9. Updating the basemap in a traditional two-dimensional form

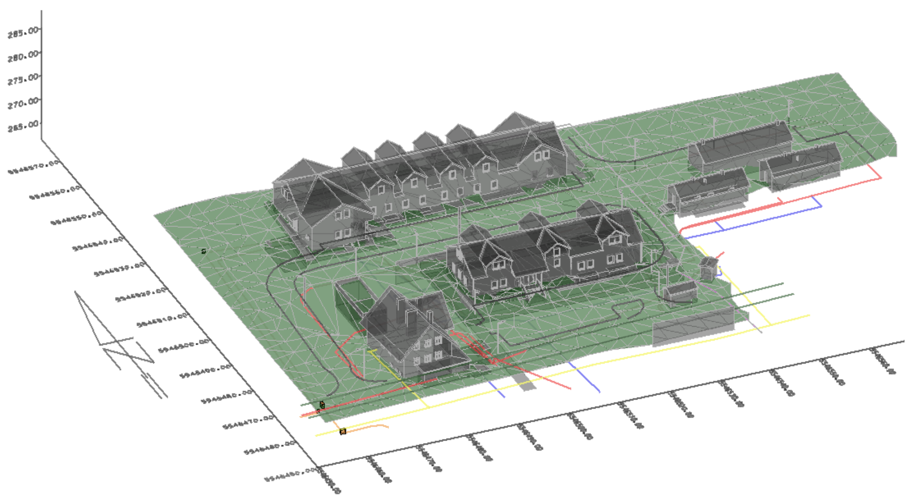

Fig. 10. Three-dimensional basemap

For the completed cartographic studies, field verification of the results obtained from the 3D map was carried out. Using the GNSS receiver, the control points in the field (curbs, sewage drains and other characteristic points) and the corresponding spatial objects on the map were measured. The average value of the differences of the obtained spatial coordinates (X, Y, Z) in the field and from the 3D map was 0.035 m, which proves the high accuracy of the generated material.

4. Discussion

The perspective of perceiving a generalized and symbolically presented geographical space provides a better understanding of the relationships between objects present in the environment. The 3D image complements the classic presentation of orthogonal maps. Three-dimensional presentations are easier for most people to perceive due to their similarity to the natural elements of the observed landscape. The advantage of such studies is also in higher detail, as well as interactivity and dynamics of the presented image of the map content (Haeberling, 2005).

The three-dimensional image is a reconstruction of space, making it possible to capture the geometry and appearance of individual landscape elements or the entire scene. In recent years, there has been an increased interest in the use of 3D geovisualisation. 3D cartography and its products – 3D maps, have found a whole range of applications. These techniques are used for: interactive presentation of relief and topography, presentation of places and objects, forecasting the occurrence and effects of natural disasters, as well as for the implementation of video game resources, virtual tours, 3D reconstruction mobile applications, CAD software, graphics and computer mathematics, medical imaging, cultural heritage (HBIM), BIM, virtual and augmented reality and many others. Over the last few years, numerous techniques and algorithms for image reconstruction and generation of three-dimensional cartographic studies have been developed. Starting from active methods requiring the use of specialized equipment to obtain information about the geometry of objects, i.e. laser scanning (ground based, airborne, structured light), to passive tools based on optical imaging techniques (Bianco et al., 2018).

Among the basic possibilities of using three-dimensional cartography is the construction of Numerical Terrain Models. Development of 3D maps of vast areas requires the acquisition of a large amount and highquality geospatial data. You can get such, among others by using TLS technology and photos from UAV decks. Highaccuracy data allows you to build highresolution three-dimensional images in the form of maps, diagrams and models. By basing the measurement on common GCP and using the appropriate work environment, it is possible to obtain comprehensive information about the area, and then transform it into a model embedded in a three-dimensional space, constituting a real representation of the natural environment (Tong et al., 2015). The 3D map (Fig. 10) shows the possibility of generating three-dimensional cartographic studies based on the integrated spatial data obtained with the help of TLS and UAV. Geospatial data generated in this way constitute a three-dimensional, real representation of the measured area. The cloud itself has the features of a spatial model – showing the shapes, sizes and nature of the objects it contains. It is a spatial representation that meets the assumptions of 3D cartography. The accuracy of such a study may be as high as 2-3 cm and depends on the precision of the selection of common points and the accuracy of determining the coordinates of reference points in the field (Aicardi et al., 2016). In the 3D cartographic presentation, it is possible to precisely, accurately and completely present the condition of the existing object in combination with a reconstruction generated on the basis of TLS data, digital photos or other source materials (Reiss et al., 2016, Klapa, 2021).

5. Conclusions

The development of measuring targets in the form of reference spheres with a ground control point for data integration (TLS, UAV, GNSS) made it possible to obtain homogeneous data in terms of geospatial reference (geometry of the network points homogeneous for the entire study and common to all measurement techniques). Such an operation allowed to eliminate the influence of errors related to assigning georeferences to the results of field work for individual measurement tools. The obtained data is characterized by georeference homogeneity, and the geometric accuracy of the location of points in the cloud results from the precision parameters of the measurement technologies used. The information prepared in this way allows to define the optimal procedure of data acquisition, which enables obtaining homogeneous precision parameters of the study (Klapa, 2021).

Depending on the nature of the data, the scale and type of the study performed, the techniques of obtaining information about the objects, as well as the available funds, geospatial data is generated at various levels of accuracy both qualitative and quantitative. It is important to focus more on the accuracy of the generated measurement information and the integration of individual data groups than on the selection of the level of detail, which depends on the quality and quantity of the input data (Biljecki et al., 2018). Although the subsequent process of generating 3D maps is supported by numerous computational algorithms, the method of obtaining reliable and accurate spatial information still presents a problem. It concerns measurement techniques and the type of information provided, problems with the accuracy and precise integration, as well as the lack of information that is difficult to access and the lack of publicly available information (Malumpong and Chen, 2008).

The accuracy of three-dimensional cartographic studies depends on the quality and accuracy of the data on the basis of which they were generated. The software used as well as the experience and skills of the cartographer also have an impact. The purpose of the study performed determines the scope of accuracy that must be achieved. For this purpose, appropriate sources of data about space are selected, as well as methods and techniques for generating studies.

The synergy of TLS and UAV data allows us to obtain a comprehensive point cloud for the entire facility. The use of reference spheres allowed for almost automatic data integration, thanks to common ground control point (common georeferencing) for all UAV, TLS and GNSS measurement techniques. The obtained geospatial database can be easily enriched with further attributes of spatial information in the form of, for example, cadastral data or network of utilities. All databases are fully compatible with each other. Of course, it is possible to further and almost unlimited extension of the base, thanks to the use of common georeferencing – the same embedding in the spatial coordinate system. Such a database is an excellent source material for the needs of generating both two- and three-dimensional maps. Modelling of objects for the needs of 3D maps can be supported by using numerous tools for automatic generation of spatial objects. Modelling and visualisation tools as well as other options supporting the creation of maps are included in numerous CAD programs.

The presented methodology, the results and solutions, as well as the verification of the presented data allow us to claim that the presented solutions meet the accuracy standards (Polish Regulation of the Minister of Development, 2020) for generating base maps not only for the traditional 2D map, but also for a three-dimensional map. The proposed solution is universal and can be implemented to any scope and level of accuracy defined by the legislation of individual countries in the world.

Author contributions

Conceptualization: P.K., B.M. and M.Z; software development: P.K.; data collection and analyses: P.K. and B.M.; writing and editing: P.K.; critical revision: B.M and M.Z; review and editing: P.K., B.M. and M.Z.

Data availability statement

The data used in the study are available from the corresponding author upon reasonable request.

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References

Abdelazeem, M., Elamin. A., Afifi A. et al. (2021). Multisensor point cloud data fusion for precise 3D mapping. *Egypt. J. Remote. Sens. Space Sci.*, 24(3), 835–844. DOI: 10.1016/j.ejrs.2021.06.002.

Aditya, T., Laksono, D., Susanta, F.F. et al. (2020). Visualization of 3D Survey Data for Strata Titles. *ISPRS Int. J. Geo-Inf.*, 9, 310. DOI: 10.3390/ijgi9050310.

Aicardi, I., Dabove, P., Lingua, A. et al. (2016). Integration between TLS and UAV photogrammetry techniques for forestry applications. *iForest – Biogeosciences and Forestry*, 10(1), 41–47.

Atoyan, V., and German A. (2017). New Technologies in 3D Mapping. *Bulletin of Geography, Physical Geography Series*, 12, 31–40.

Bianco, S., Ciocca, G., and Marelli, D. (2018). Evaluating the Performance of Structure from Motion Pipelines. *J. Imaging*, 4, 98. DOI: 10.3390/jimaging4080098.

BIP Krakow (2022). Public Information Bulletin of the City of Krakow. Applications for the provision of materials from the County Geodetic and Cartographic Resource: Krakow – city. Retrieved from: https://www.bip.krakow.pl/?dok_id=53246.

Biljecki, F., Heuvelink, G., Ledoux H. et al. (2018). The effect of acquisition error and level of detail on the accuracy of spatial analyses. *Cartogr. Geogr. Inf. Sci*, 45, 2, 156–176. DOI: 10.1080/15230406.2017.1279986.

Bitelli, G., Girelli ,V.A., and Lambertini A. (2018). Integrated use of remote sensed data and numerical cartography for the generation of 3D city models. In The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII–2, 2018 ISPRS TC II Midterm Symposium "Towards Photogrammetry ", 4–7 June 2018, Riva del Garda, Italy.

Bobkowska, K., Szulwic, J., Tysiac P. et al. (2017). GIS threedimensional Modelling with geoinformatics techniques In "Environmental Engineering" 10th International Conference, 27–28 April 2017, Vilnius, Lithuania.

Chiabrando, F., Sammartano, G., Spanò, A. et al. (2019). Hybrid 3D Models: When Geomatics Innovations Meet Extensive Built Heritage Complexes. *ISPRS Int. J. GeoInf.*, 8, 124. DOI: 10.3390/ijgi8030124.

Cisło, U. (2008). An outline of a concept for three-dimensional multiresolution topographic database. *Archives of Photogrammetry, Cartography and Remote Sensing*, 18, 49–57.

Collado, A., Mora-Navarro, G., Heras, V. et al. (2022). A Web-Based Geoinformation System for Heritage Management and Geovisualisation in Canton Nabon (Ecuador). *ISPRS Int. J. GeoInf.*, 11, 4. DOI: 10.3390/ijgi11010004.

Drzewiecki, R., and Bujakiewicz, A. (2018). Assessment of accuracy for the building model acquired from a high dense points cloud based on images of different geometry. *Archives of Photogrammetry, Cartography and Remote Sensing*, 30, 83–93.

Eremchenko, E., Tikunov, V., Ivanov R. et al. (2015). Digital Earth and Evolution of Cartography. *Procedia Comput. Sci.*, 66, 235–238.

Goralski, R. (2009). *Three-dimensional interactive maps: Theory and practice*. PhD thesis, University of Glamorgan.

Guan, H., Li, J., Zhong, L., Yu, Y. et al. (2013). Process virtualization of large-scale LiDAR data in a cloud computing environment. *Comp. Geosci.*, 60, 109–116. DOI: 10.1016/j.cageo.2013.07.013.

Haeberling, Ch. (2005). Cartographic design principles for 3D maps – A contribution to cartographic theory. *Proceedings of ICA Congress Mapping Approaches into a Changing World*.

Hájek, P., Jedlička, K., and Čada V. (2016). Principles of cartographic design for 3D maps focused on urban areas. In Proceedings, 6th International Conference on Cartography and GIS, 13-17 June 2016, Albena, Bulgaria, 297–307.

Iheaturu, C.D, Ayodele, E.G., and Okolie C.J. (2020). An assessment of the accuracy of structure-from-motion (SFM) photogrammetry for 3D terrain mapping. *Geomatics, Land management and Landscape*, 2, 65–82. DOI: 10.15576/GLL/2020.2.65.

Jarzyna, A. (2016). Three-dimensional geological map of the Szczerec area near Lviv. *Bulletin of the Polish Geological Institute*, 466, 103–114.

Klapa, P., and Mitka B. (2017). Application of terrestrial laser scanning to the development and updating of the base map. *Geod. Cartogr.*, 66 (1), 59–71. DOI: 10.1515/geocart-2017-0002.

Klapa, P., Mitka, B., and Zygmunt, M. (2017). Study into Point Cloud Geometric Rigidity and Accuracy of TLS Based Identification of Geometric Bodies. In IOP Conference Series Earth and Environmental Science, 95(3), 032008.

Klapa, P. (2021). *Integration and optimisation of geospatial data in the process of generating three-dimensional cartographic materials*. Ph.D. Thesis, University of Agriculture in Krakow, Kraków, Poland, 23 March 2021.

Lari, Z., and El Sheimy, N. (2015). System considerations and challenges in 3D mapping and modeling using low cost UAV systems. In The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-3/W3, 2015 ISPRS Geospatial Week 2015, 28 Sep – 03 Oct 2015, La Grande Motte, France, 343–348.

Malinverni, E.S., Pierdicca, R., Bozzi, C.A. et al. (2017). Analysis and Processing of Nadir and Stereo VHR Pleiadés Images for 3D Mapping and Planning the Land of Nineveh Iraqi Kurdistan. *Geosci.*, 7, 80.

Malumpong, Ch., and Chen, X. (2008). Interoperable three-dimensional GIS city modelling with geoinformatics techniques and 3D modelling software. In The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2008, XXXVII Part B2.

Mao, B., Ban, Y., and Laumert, B. (2020). Dynamic Online 3D Visualization Framework for Real Time Energy Simulation Based on 3D Tiles. *ISPRS Int. J. Geo-Inf.*, 9, 166. DOI: 10.3390/ijgi9030166.

Mazzei, M., and Quaroni, D. (2022). Development of a 3D WebGIS Application for the Visualization of Seismic Risk on Infrastructural Work. *ISPRS Int. J. Geo-Inf.*, 11, 22. DOI: 10.3390/ijgi11010022.

Medynska-Gulij, B, (2011). Cartography and geovisionization. Warsaw, Poland.

Mroz, R., Wisniewska, A., and Fijalkowska A. (2014). Converting the digital base map to a three-dimensional form for visualization and spatial analysis of underground devices. *Roczniki Geomatyki*, XII, 4(66), 417–425.

National Academies of Sciences, Engineering, and Medicine (1983). Procedures and Standards for a Multipurpose Cadastre. Washington, DC: The National Academies Press. DOI: 10.17226/11803.

Nex, F., and Remondino F. (2014). UAV for 3D mapping applications: a review. *Appl. Geomat.*, 6, 1–15. DOI: 10.1007/s12518-013-0120-x.

Nishanbaev, I., Champion, E., and McMeekin, D.A.A. (2021). Web GIS Based Integration of 3D Digital Models with Linked Open Data for Cultural Heritage Exploration. *ISPRS Int. J. Geo-Inf.*, 10, 684. DOI: 10.3390/ijgi10100684.

Petrovic, D. (2003). Cartographic design in 3D maps, Cartographic Renaissance. In Proceedings of the 21st International Cartographic Conference (ICC), 10–16 August, Durban, South Africa.

Polish Act: Geodetic and Cartographic Law, Poland (1989).

Polish Regulation of the Minister of Development of 18 August 2020 on technical standards for the performance of geodetic situational and height measurements as well as the development and transfer of the results of these measurements to the state geodetic and cartographic resource (2020).

Reiss, M.L.L., Rocha, R.S., Ferraz, R.S. et al. (2016). Data integration acquired from micro UAV and terrestrial laser scanner for the 3D mapping of Jesuit ruins of São Miguel das Missões. *The Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, XLI–B5, XXIII ISPRS, 315–321.

Richter, R., and Dollner, J. (2014). Concepts and techniques for integration, analysis and visualization of massive 3D point clouds. *Comput. Environ. Urban Syst.*, 45, 114–124. DOI: 10.1016/j.compenvurbsys.2013.07.004.

Roberts, J.C., Butcher, P.W.S., and Ritsos, P.D. (2022). One View Is Not Enough: Review of and Encouragement for Multiple and Alter-native Representations in 3D and Immersive Visualisation. *Comp.*, 11, 20. DOI: 10.3390/computers11020020.

Son, S.W., Kim, D.W., Sung, W.G. et al. (2020). Integrating UAV and TLS Approaches for Environmental Management: A Case Study of a Waste Stockpile Area. *Remote Sens.*, 12, 1615. DOI: 10.3390/rs12101615.

Tao, Y., Michael, G., Muller, J.-P. et al. (2021). Seamless 3D Image Mapping and Mosaicing of Valles Marineris on Mars Using Orbital HRSC Stereo and Panchromatic Images. *Remote Sens.*, 13, 1385. DOI: 10.3390/rs13071385.

Tong, X., Liu, X., Chen, P. et al. (2015). Integration of UAV Based Photogrammetry and Terrestrial Laser Scanning for the Three-Dimensional Mapping and Monitoring of Open Pit Mine Areas. *Remote Sens.*, 7, 6635–6662. DOI: 10.3390/rs70606635.

Tully, D., El Rhalibi, A., Carter, Ch. et al. (2015). Hybrid 3D Rendering of Large Map Data for Crisis Management. *ISPRS Int. J. Geoinf.*, 4, 1033–1054. DOI: 10.3390/ijgi4031033.