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METHODOLOGY OF SPATIAL DATA ACQUISITION AND DEVELOPMENT OF HIGH-DEFINITION MAP FOR AUTONOMOUS VEHICLES – CASE STUDY FROM WROCŁAW, POLAND

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Abstract

Autonomous drive systems are a dynamically developed sector of the automotive industry. The key problem in such technological solutions is to provide a reliable navigation system, which is typically based on high-definition (HD) maps supporting the identification of the position of a maneuvering vehicle. HD maps should include possibly up-to-date and detailed information on traffic lanes and on the traffic rules and regulations on such lanes. An effective development of an HD map should be based on the geodetic measurement methods, which ensure efficient and accurate acquisition of spatial data. This article presents the results of an experiment consisting in the manipulation of data obtained with the use of the mobile laser scanning method and further in employing this data in the development of an HD map in an open-source environment. The applied measurement technology and the processing method allowed data of high resolution (frequently above 1000 points per m^2) and of high accuracy (3D accuracy down to less than 5 cm). The obtained data were processed in the Vector Map Builder environment (which is accessible from the level of an internet browser) and the final product - HD map was created in the Lanelet2 open-source environment. The above-described experiments allowed two main conclusions. Most importantly, they demonstrate the importance of planning and performing in-field mobile laser scanning measurements. They also point to the important role of the human analyst who needs to manually vectorize the key elements of road infrastructure and to define traffic rules.

Keywords: mobile laser scanning, HD map, autonomous cars, autonomous driving, 3D modeling

1. INTRODUCTION

Over the period of several recent years, the development of electric vehicles has significantly accelerated, both in Europe and in other parts of the world. This trend can be observed in the case of individual, public and even freight transport (Pardi, 2021; Barroso, 2021). Such solutions are being developed in parallel to the concept of autonomous vehicles (AVs). Interestingly, the first vehicle that

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can be classified as autonomous (and more specifically – as driverless, i.e. a vehicle controlled by an operator with the use of a radio transmitter) was demonstrated as early as in 1925 by the company Houdina Radio Control (Stayton, 2015).

The autonomous drive system, although the principle behind it is very simple – to control the vehicle with the computer – faces a number of technological problems which require efficient solutions. One of such key problems is to develop high-definition (HD) maps. From the perspective of the computer controlling the vehicle, such a map is key in real-time navigation, aiding the identification of inter alia traffic lanes and signs or pedestrian crossings (Liu et al, 2022). Such information is critical in urban areas, which require particular emphasis on safety (Dokic et al., 2015).

For the above reasons, the predictable behavior of an autonomous vehicle on the road requires supplementing the information provided by the car sensors with HD maps. Currently manufactured sensors are not capable of identifying the location of a vehicle and predicting its behavior in relation to its environment. Although several research teams are working on navigation systems employing quantum positioning, these are still in early development stages. This technology is not expected to be commercialized in the perspective of the coming several years, and therefore current autonomous vehicles are operated on the basis of dynamic HD maps (Marks, 2014). They allow the spatial data to be modeled and vehicles to be positioned on the basis of landmarks.

HD maps comprising detailed information on road lanes are developed with the use of geodetic data. The two most frequently used geodetic methods for the acquisition of data employed in the development of HD maps include photogrammetry and laser scanning. Both techniques have their advantages and disadvantages. For example, the photogrammetric technique allows fast data acquisition and is more cost-effective. However, it requires the measurements to be performed during the day (due to the necessary day light) and in favorable weather conditions. It also has lower 3D data accuracy. Laser scanning, on the other hand, allows fast acquisition of large amounts of highly accurate data regardless of the time of the day. However, the required measuring apparatus is more expensive (Nang, 2021).
Therefore, one of the currently most common techniques is laser scanning technique, as it offers high efficiency and high 3D accuracy as well as an option of georeferencing three-dimensional data, allowing the optimization of costs in comparison to aerial photographs (Toschi et al., 2015).

Mobile laser scanning (MLS) is the most recent approach to fast and economical acquisition of precise 3D spatial data. MLS systems may be capable of recording up to 10,000 points/m2 (Toschi et al., 2015). Such level of detail is not easily available in the case of both aerial laser scanning (ALS) and terrestrial laser scanning (TLS). In addition, the high flexibility and speed of MLS data acquisition render it an optimal geodetic technique for generating HD maps required by autonomous vehicles. However, the processing of point clouds comprising such extensive quantities of 3D data requires not only substantial experience but also high-performance computers.

The acquisition and processing of the input data is only the first of the two key issues. The other is to develop the map. This task can be accomplished in commercial environments, e.g. NVIDIA (NVIDIA, 2024), HERE (HERE, 2024) or TomTom (TomTom, 2024) and in open-source tools, such as Lanelet2 (Poggenhans et al., 2018), OpenDRIVE (ASAM, 2024) and Apollo Maps (Gran, 2019).

The main goal of this study was to present a methodology and the results of an experiment regarding the development of a HD map based on MLS data. The main emphasis has been placed on the first of the components, i.e. on data acquisition with the use of mobile laser scanning, on the preliminary data processing and on the accuracy evaluations.

2. MATERIALS AND METHODS

The field tests involved in the development of the HD map were performed at the main campus of Wrocław Universisty of Science and Technology (WUST, see Fig. 1), located at Norwida and Wybrzeże Stanisława Wyspiańskiego streets. The campus represents typical Wrocław urban environment: a relatively dense network of individual buildings and rows of historic town houses several stories in height. The landscape also includes dense trees, as well as street greenery and recreational areas. The surface area of the entire complex is approximately 10 ha.

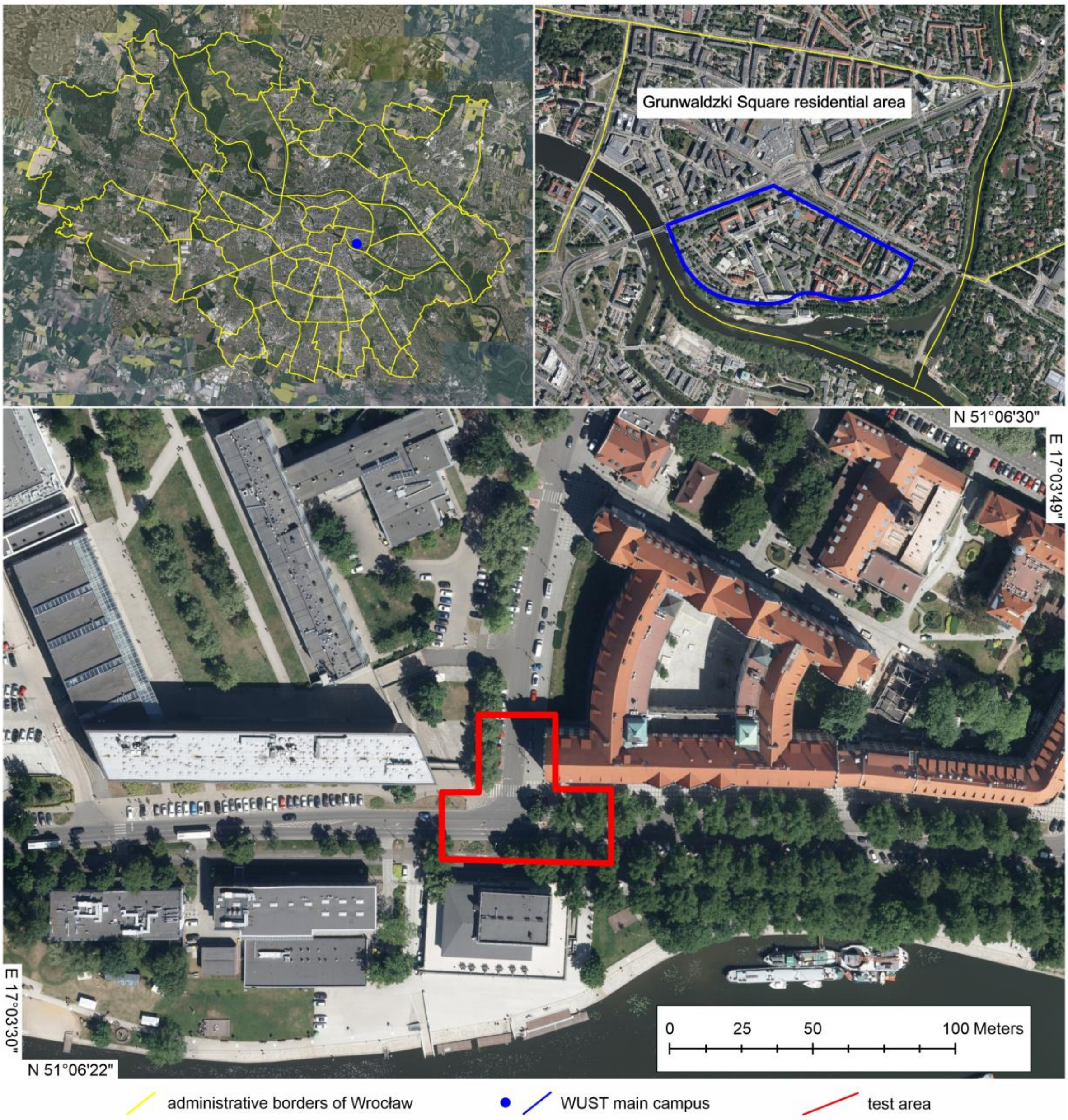

Fig. 1. Location of the research area

2.1. In-field tests

The data base required for the development of the AV HD map was acquired on May 11, 2022. The MLS measurements were performed with the use of the Riegl VMZ400i scanner additionally provided with a GNSS system employing two antennas with simultaneous trajectory measurements, an inertial measurement unit (IMU), and a distance measuring instrument (DMI). The instruments were installed on a Nissan Navara mobile platform (Fig. 2).

The measuring accuracy of the MLS Riegl VMZ 400i system is ensured by two GAMS (GNSS Azimuth Measurement System) antennas. Such an approach allows the elimination of the inertial drift errors typical of the single-antenna solution. In GAMS, the movement direction of the vehicle is identified with very high accuracy (0.03-0.05 grad), which translates into highly precise route identification and optimal efficiency even in demanding environments, e.g. in the case of an insufficient number of satellites available. The innovative scanner has a wide field of view: 100° vertical x 360° horizontal. Also, it is safe for human eyes and its declared range is up to 400 m. 800 m. Its complete technical specification is provided in Table 1.

During the data acquisition phase, the three systems cooperate in the following manner: the GNSS/INS system calculates the trajectory and records the scanning/operating time of the laser scanner; the laser scanner records the points; the data are synchronized with the displacement of the mobile platform recorded by the odometer (DMI). The DMI precisely records the start and stop times of the mobile system (as a result, the system is “immune” to downtimes due to e.g. traffic conditions). The acquisition process did not involve preparing photographic documentation of the scenery, which could be used to add the RGB color palette to the point cloud – such step was unnecessary in the case of an HD map. Each of the recorded points was assigned a time stamp, allowing the connection of the LiDAR data with the information on the trajectory and position of the laser in time. This operation was performed in the RiWORLD software.

Table 1. Riegl VMZ 400i technical specification

MLS system	value
minimum laser range	0.5 [m]
maximum laser range	800 [m]
accuracy/precision	5/31 [mm]
measurement speed	0.5 million [measurements/s]
vertical scan angle range	100 [°]
horizontal scan angle range	360 [°]
maximum scan speed	240 [lines/sec]
GNSS accuracy	20-50 [mm]
IMU accuracy	0.015/0.05 [°]
GAMS accuracy	?

Fig. 2. Riegl VMZ 400i during the data acquisition process in the Professor Alley (main WUST campus)

2.2. Preliminary data processing

The acquisition and preliminary processing of MLS data are based on precise times recorded by the measurement system. The principle behind the processing of an MLS point cloud is to synchronize the individual scan lines with the 3D trajectory in time. The combination of data obtained in individual records (one pass of the mobile platform provided 19 records) requires the so-called registration process. The georeferencing of the acquired scanner data requires precise information on the location (X,Y,Z) and orientation (R=Roll, P=Pitch, Y=Yaw). The inertia sensors of the IMU allow a relatively precise identification of the R and P angles, while the two GAMS GNSS antennas additionally record the Y angle of the platform during the MLS data acquisition. For the purpose of identifying the angles, the Applanix POSPAC MMS post-processing software is used to combine the navigation data (recorded in real time on board of the platform) with the data from the GNSS base station (this research was based on data from the WROC station used for differential corrections, Fig. 3) and with the parameters of the elements installed on the roof of the vehicle (arms of the GNSS antenna and the IMU angle). The software produces the so-called SBET (Smoothed Best Estimated Trajectory) file, providing optimal data on the position and orientation of the platform in the known time frame. With the SBET data, the position and orientation of the platform is fixed and allows calculations of the XYZ coordinates for all of the recorded points. The data necessary in the georeferencing process also include „boresight angles" (ΔR, ΔP, ΔY). These angles describe the non-coaxiality between the IMU and the scanner. All of the above data are recorded in time, allowing the data from different sensors to be processes into one consistent and precise set. The above procedure is schematically represented in Fig. 4.

Eventually, the integrating and processing of all the data acquired in the WUST campus resulted in the 3D positioning accuracy on the order of 4 cm. After being prepared in accordance with the above procedure, the data were exported to *.las format for further processing.

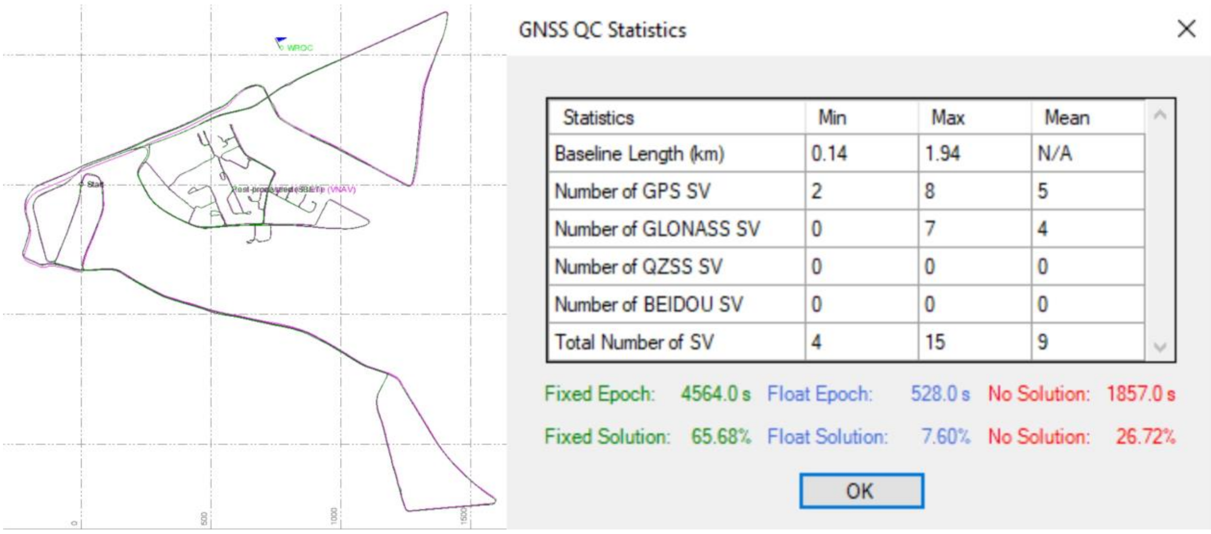

Fig. 3. Results of trajectory processing based on the GNSS WROC base station

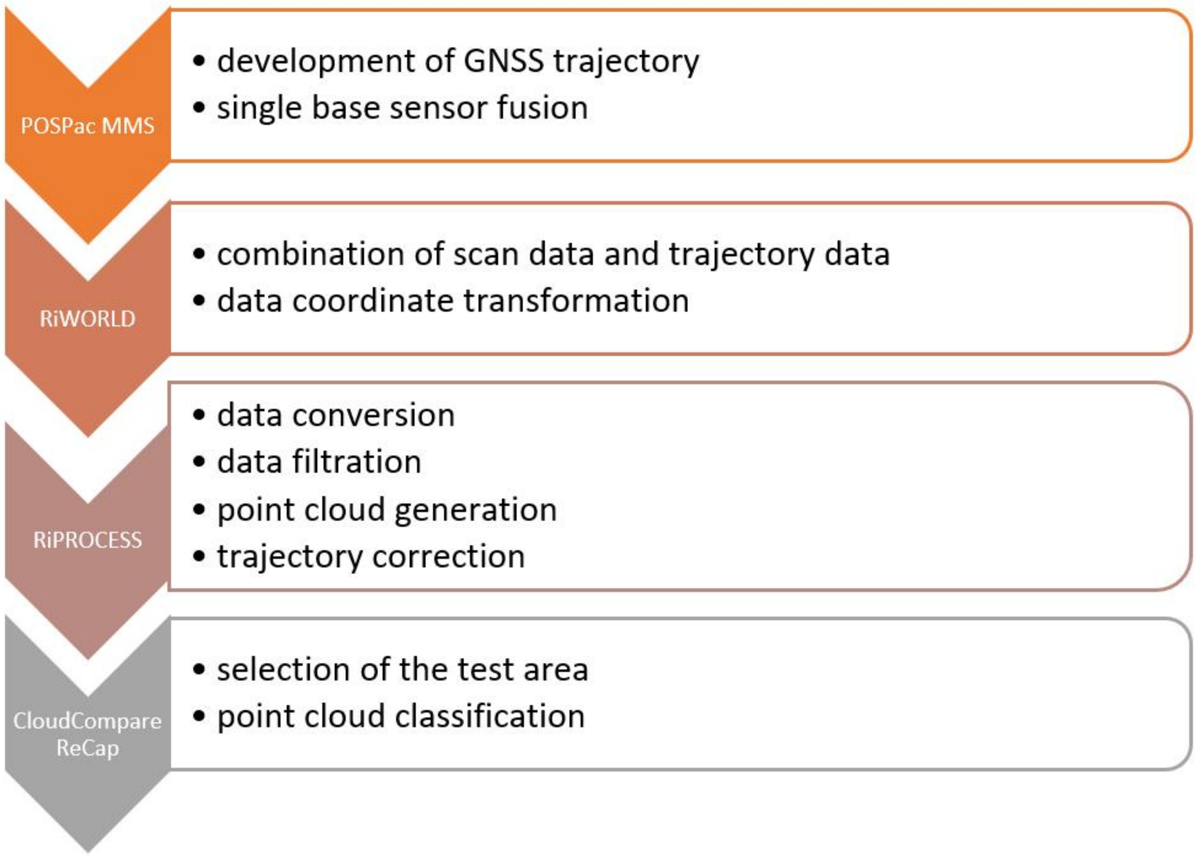

Fig. 4. Schematic diagram of MLS data pro-processing

2.3. Processing the point cloud

The measurement data (the so-called records) were processed in the dedicated RiPROCESS environment. This stage of data processing comprised the following subsequent steps: data conversion, trajectory correction, and point cloud generation.

In the first step, point clouds were prepared based on the POSPac trajectories. The adjustment of the trajectory to the individual scans (records) required the processing and using of data produced earlier, within a specified measurement time, i.e. on April 11, 2022, between 4:40 and 5:50 p.m., with the assumed GMT being +02:00 for the WROC station. This procedure provided a RiPROCESS input file – the already mentioned SBET. The calculated trajectory was added to the raw records of point clouds in order to combine the data with respect to time. Next, the shape of the acquisition path was analyzed and the SDCImport plug-in was used to convert the cloud from the scanner. Subsequently, the observations were combined with the trajectory in the RiWORLD module, thus converting the local polar coordinate system into global coordinates (ETRS89/UTM ZONE 34N, Fig. 5).

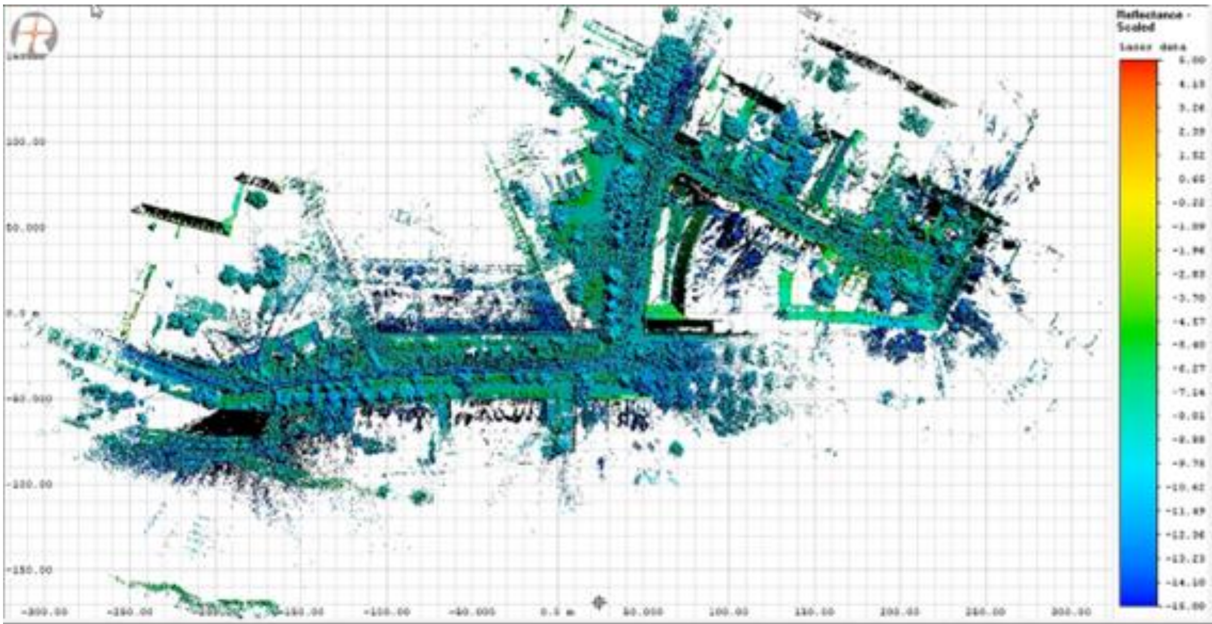

Fig. 5. 2D representation of the point cloud (data records) with the applied trajectory

The second step was the filtration process. The assumed parameters allowed the rejection of data acquired within a radius smaller than 2.5 m from the scanner head (thus eliminating artifacts being the result of scanning the mobile platform). They also included standard deviation within the range of 0 – 50 and the intensity within the range of -20 ÷ +5 dB. This procedure allowed the rough filtration of the point cloud. The above parameters were applied to all of the records.

In the subsequent step, the trajectories were corrected in the RiPRECISION module. The RiPRECISION MLS automatically corrected the GNSS/INS trajectories in order to merge the overlapping scan data. The result was a consistent point cloud with increased georeferencing accuracy. This automatic algorithm employing all of the information available from the individual sensors allowed the reduction/elimination of errors observed between multiple acquisition sessions along the entire scan path. Fig. 6 presents the 2D and 3D view of the final point cloud ready for export.

Such a prepared and processed data set served to define the test area (Fig. 7) which was exported in the *.las format.

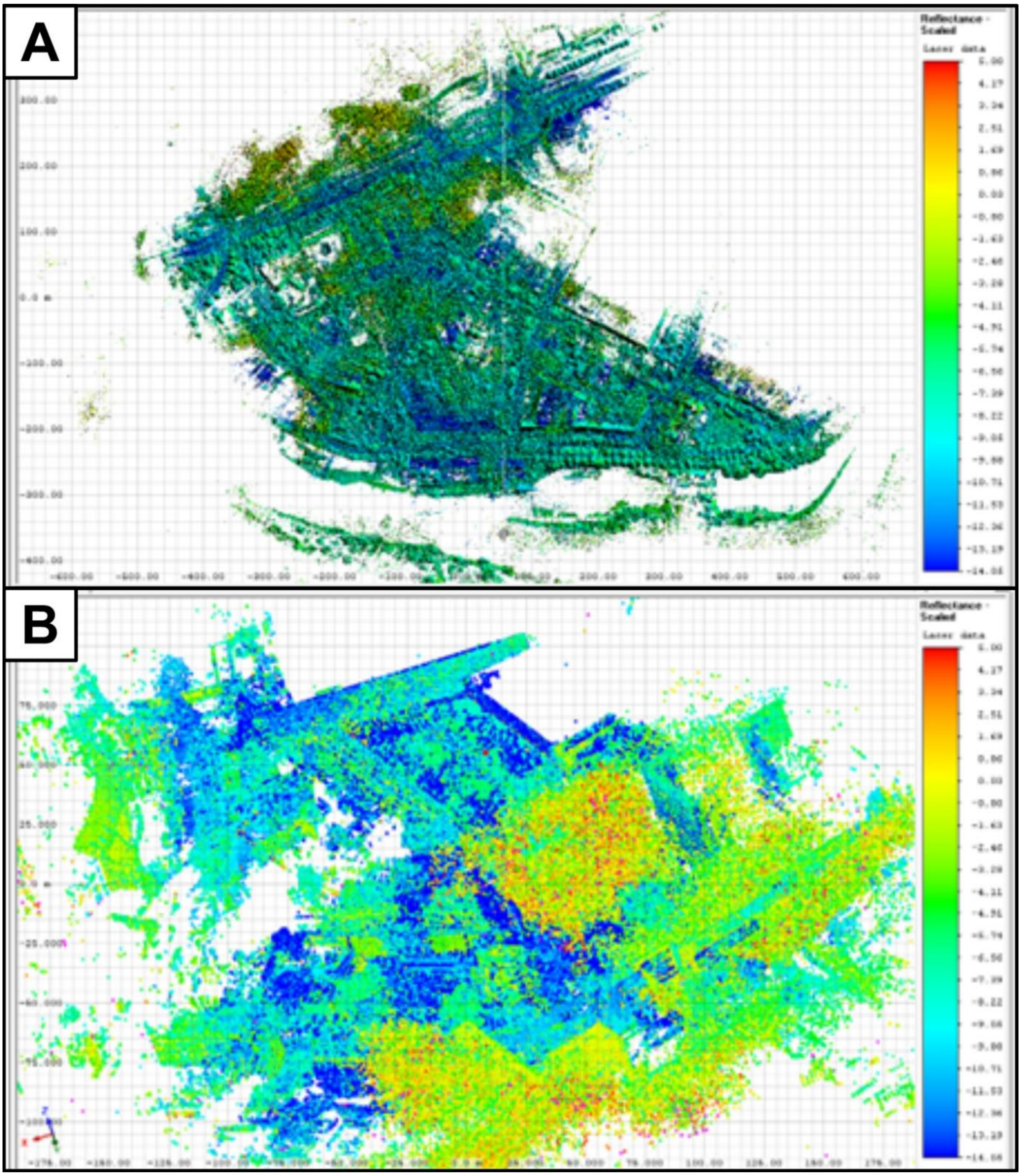

Fig. 6. 2D view (A) and 3D view (B) of the point cloud after the final processing stage

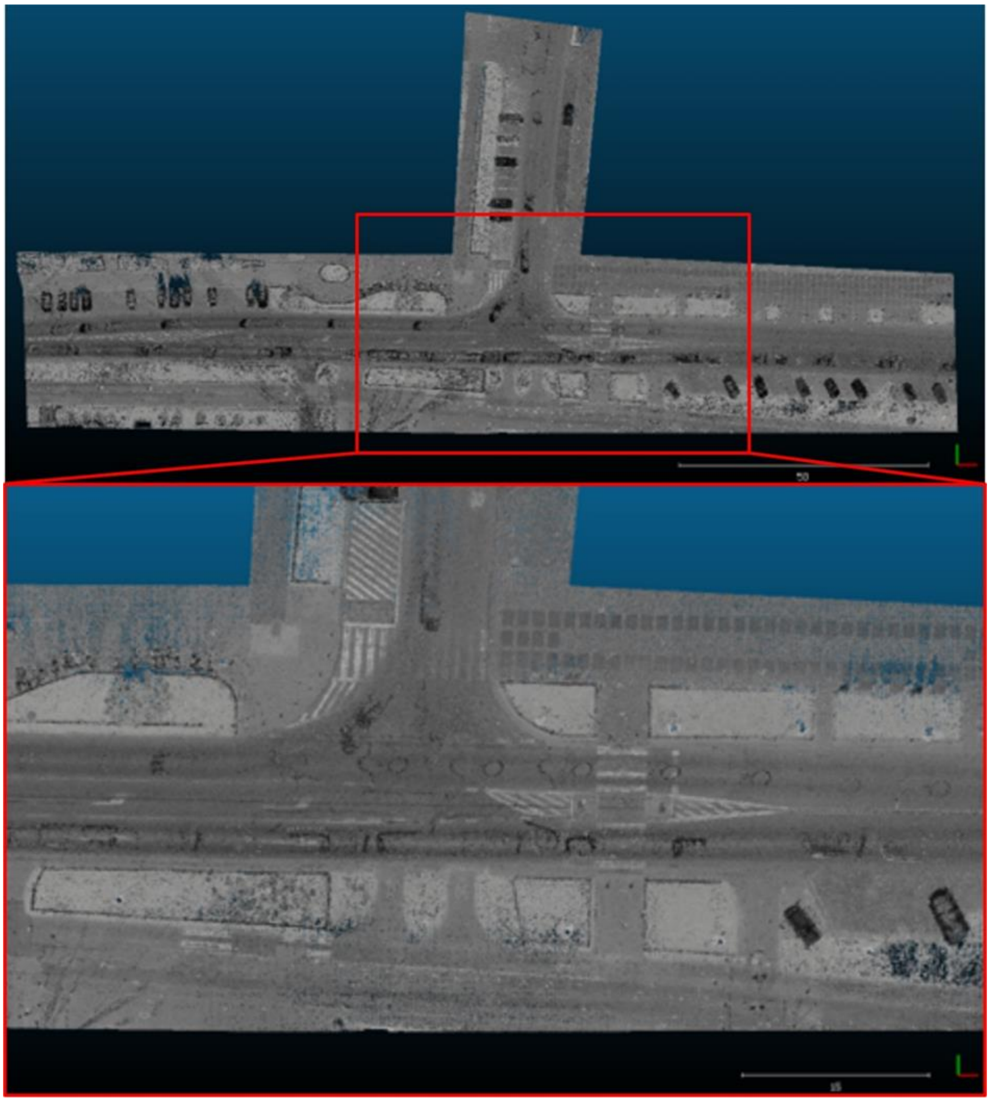

Fig. 7. Selected point cloud – test area for the development of the HD map

3. DEVELOPMENT OF THE HD MAP

Although precise and complete (HD) maps are essential for autonomous vehicles to travel independently, their development has not yet been standardized. A review of a number of publications (Seif, and Hu, 2016; Ilci, and Toth, 2020; Wong and Kamijo, 2020; Massow et al., 2016; Poggenhans et al., 2018; Liu et al., 2020; Bao et al., 2023; Zhang et al., 2023) indicates that such maps must primarily satisfy high standards with respect to precision, completeness and scalability.

Maps having such complexity can work properly only with a carefully designed framework. The experiment here presented was performed in the Lanelet2 open-source environment. This format was first used in the vehicle Bertha-Benz (Ziegler et al., 2014). Based on the acquired point cloud, it allowed the definition of all map elements required by autonomous vehicles.

In Lanelet2, the traffic rules are represented by the so-called regulatory elements, i.e. speed limits, traffic lights or horizontal stop lines. Lanelet2 is based on the C++ library, whose versatility allows its users not only to define routes but also to plan individual maneuvers. A map in the Lanelet2 format is divided into the physical layer, which typically comprises real, visible elements identified from the point cloud, and a relational layer, in which the elements of the physical layer, such as lanes, are related to the traffic rules. Elements of the relational layer are combined into a network of regions potentially available to car traffic – adjacent traffic lanes.

The Lanelet2 format is based on the known Liblanelet format and was designed in such a manner that it can be represented on an XML-based OSM (OpenStreetMap) format, which has multiple publicly available browsers or editors. The actual format of the HD map is not important and can be changed as long as it can be transferred and initiated in the AV without losses. Data correctness is the crucial aspect in map storage. Therefore, a fixed reference system is used, such as ETRS 1989 in Europe, in which the geographical coordinates (latitude/longitude) are not subject to change. As the map is loaded, the geographical coordinates are transformed into a local, metric coordinate system in order to allow effective calculations. Such tasks are performed with the use of the UTM (Universal Transverse Mercator) coordinate system.

3.1 Lanelet2 in HD map development

The first tool used in the development process of the HD map was Vector Map Builder provided by the company TierIV, which is the leader in the field of AV systems. Owing to its graphical user interface, Vector Map Builder facilitated the effective construction, edition and final production of the HD map. The previously filtered point cloud converted to *.pcd (Point Cloud Data) was used as input. The map was developed for the previously defined test area, represented by a cloud comprising approx. 28 000 points. Prior to vectorization, the intensity parameter of the point cloud had to be normalized, as the dedicated tool works in the range of 0-255. The input data are schematically shown in Fig. 8.

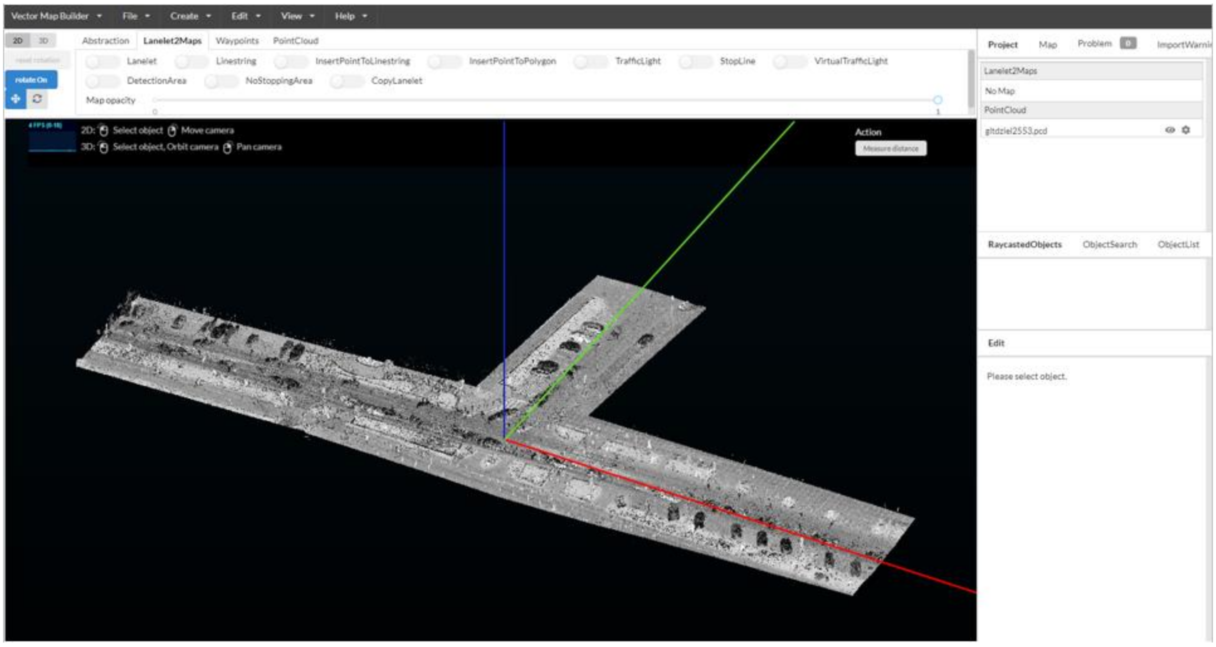

Fig. 8. Input point cloud in the Vector Map Builder environment

The next step was to reclassify the data into two subsets representing the land surface area and the elements of land cover, respectively (McAllister et al., 2017). This task was performed with the use of the RANSAC algorithm which identified the normal (horizontal) surface in the road plane as well as other elements in the vertical plane which are necessary in the further processing (Natan and Jun, 2022), as exemplified by traffic lights or road signs. The selected test area does not have traffic lights, and only road signs. However, a decision was made not to include RGB images from a camera in the input data and instead to base the project on the Google Street View service which allowed inter alia the precise identification of the types of road signs and not only their locations (Fig. 9).

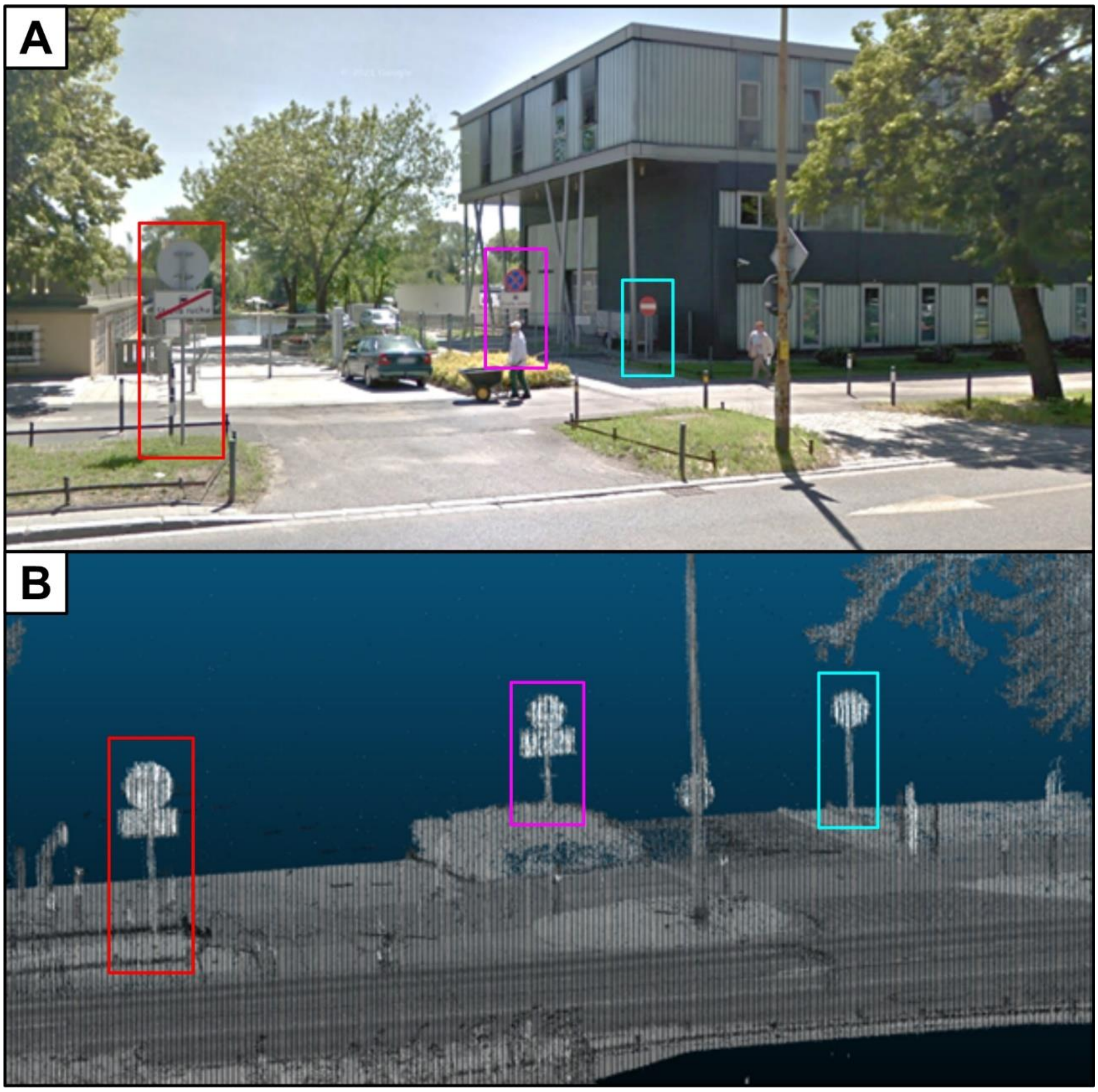

Fig. 9. Identification of road sign types: (A) Google Street View; (B) point cloud

The stage of preparing the actual HD map in the Lanelet2 format consisted in the defining of points and lines in the physical layer. These were then used to identify traffic lanes and areas comprising road infrastructure (e.g. sidewalks and parking lots). Subsequently, relations with the traffic regulations were set for individual locations. The reflection intensity of individual points allows the direct identification of objects on the traffic lane. Each vectorized element had its unique number-based identifier (used when establishing the relations). Such identifiers included e.g. the stop line or the sidewalk edge. Such an object, the “give way” road sign, is shown for illustrative purposes in Fig. 10.

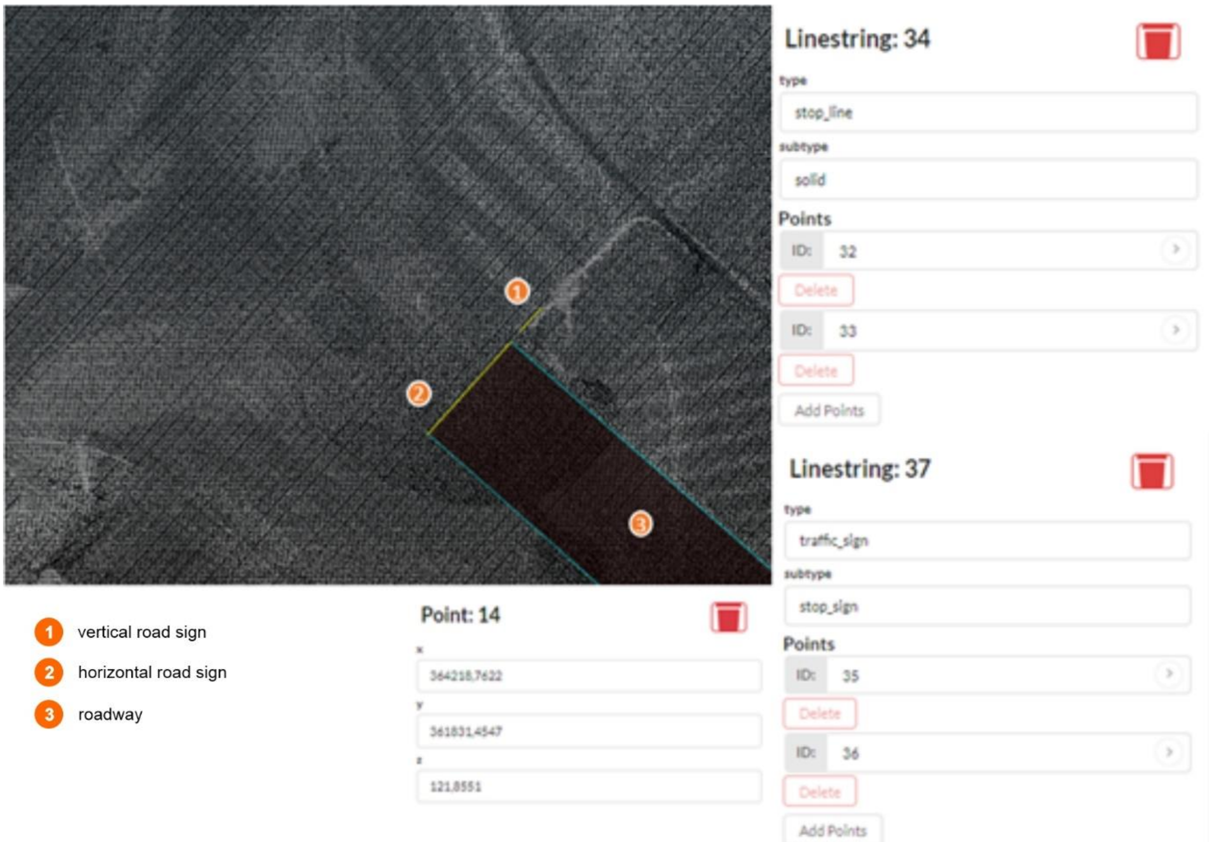

Fig. 10. The vectorization and encoding process of individual horizontal elements

The map is constructed of points (vertices), which are typically parts of linear structures. They represent e.g. vertical structures, such as lamp or signposts. The horizontal “stop” sign is represented by a single point related to it.

Each point is described by its three-dimensional location represented with the use of metric coordinates. The linear structures comprise an organized table of two or more linearly interpolated points. They are used to vectorize linear objects, such as road marks, curbs, fences etc. Additionally, virtual marks are also used, such as hidden, assumed lane border lines in front of the pedestrian crossing. This option was used to describe single-dimension objects with high level of detail.

However, the most important element of the map is the road lane, which defines the key fragment of the map – the spaces carrying the road traffic. Examples of such spaces include not only regular road lanes, but also pedestrian crossings and tram crossings, which have not been, however, recorded in the analyzed area. Fig. 11 shows a representative straight road lane.

Fig. 11. Visual representation of a road lane vectorized with Vector Map Builder and with defined relations

A road lane has several characteristic elements (Poggenhans et al., 2018):

- one road lane is regulated by constant traffic rules,
- topological relations between successive areas are constant, i.e. they are inseparable even if they change shape,
- the road lane is defined by border lines on both its right and the left side, and the end points of these lines are elements in which successive objects are connected,
- traffic in opposite direction is possible, in which case the left lane line becomes the right lane line and vice versa,
- the road lane may additionally comprise several elements regulating traffic on the particular lane.

All of the vectorized road lanes were assigned appropriate relations and their characteristics were modified and generalized in accordance with the traffic rules and with the signs verified against the Google Street View service and own in-field observations.

The next stage of the HD map development process consisted in identifying areas in which the traffic is not carried in any particular direction or is impossible, and which is still not only adjacent to the road lane line but also part of the roadway. Such areas include parking lots, access roads, sidewalks, bike roads, green areas or building structures. This study focuses mainly on curbs, parking lots, and to some an extent on sidewalks and bike roads. In the test area, the buildings are not adjacent to streets and therefore they were removed from the data set already during the filtration process. As was the case with road lanes, these objects were also related to regulatory elements, mainly to the right of way rules. The figure below (Fig. 12) presents an area of the roadway which does not carry road traffic. A similar approach was used for green areas, bike roads and sidewalks, as they are not accessible to cars. Other identified elements included parking lots and pedestrian crossings.

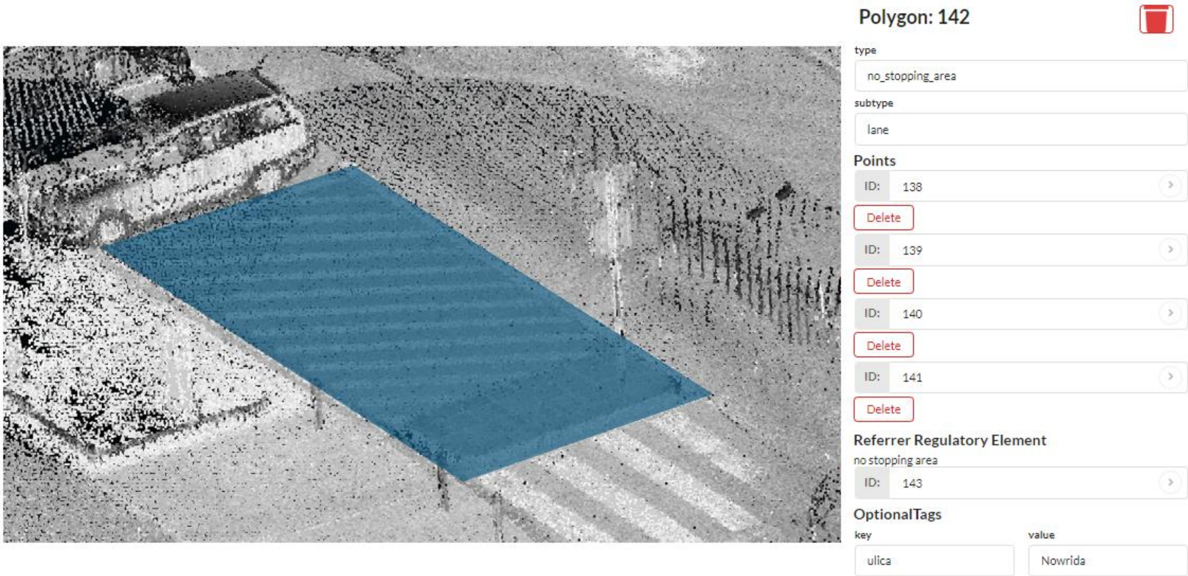

Fig. 12. Visual representation of a fragment of the test area which does not carry the traffic defined in the HD map

Regulatory elements are essential elements of an HD map. They frequently apply not only to one road lane or area, but to series of objects. Road regulations are complex and therefore the relations between some segments may significantly different. In the test area, such situation is observed within the borders of cross-roads in which speed limits change. The resulting single road lanes are defined by successive road signs limiting the speed or indicating changes between the lanes. When defining these assumptions, the key problem was to also analyze the terrain in front of and behind the test area in order to correctly identify the traffic regulations in such locations and allow for them in the metadata. The majority of the relations describing the regulations on the road were defined with the use of polygons.

Eventually, the Vector Map Builder application enabled an intuitive development of a simple HD map for the defined aera in the WUST campus (Fig. 13). The vectorization process was performed with a precision allowed by the density and accuracy of the obtained data. The map, exported to the OSM XML format, matches the precision of the base point cloud, fulfilling one of the aims of the experiment.

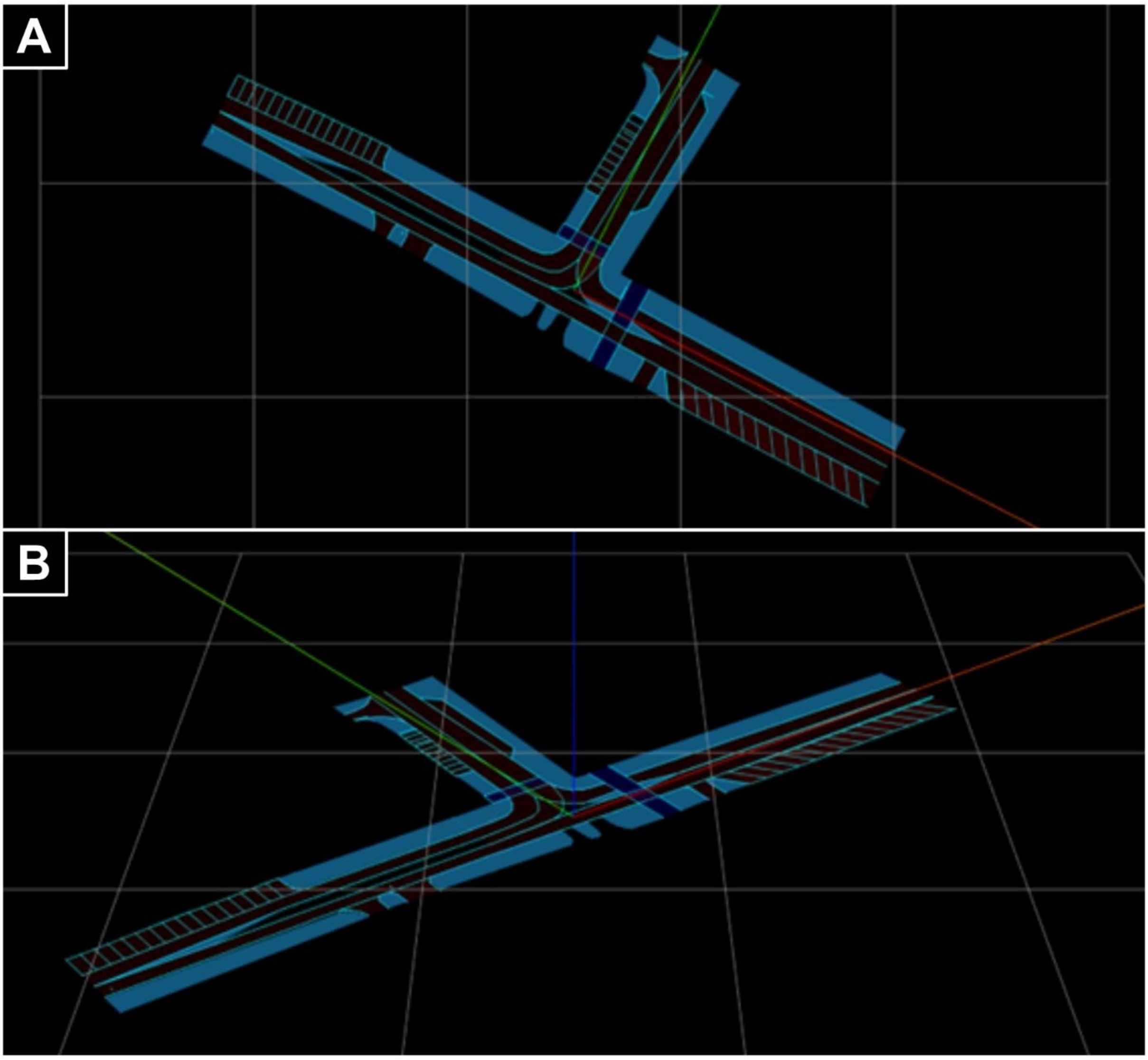

Fig. 13. Visual representation of the final HD map for autonomous vehicles developed for the WUST campus: (A) – 2D view; (B) – 3D view

4. CONCLUSIONS

This article presents an experiment related to the development of an HD map for autonomous vehicles. The study involved the vectorization of the necessary map elements, the definition of the relations between the adjacent areas, and the addition of data on the traffic regulations. The study was also supplemented with the results of in-situ reconnaissance and with the data obtained from the Google Street View.

The input data were obtained with the use of the mobile laser scanning technology, whose efficiency and precision was proven to be sufficient to build HD maps. The measurement data were acquired with the 3D accuracy on the order of 4 cm, which exceeds the accuracy of 5-20 cm required for HD maps.

The MLS data acquisition process demonstrated the importance of the measurement preparation phase. The data used in the experiment were acquired during the measurement campaign performed in May 2022, not only during favorable weather conditions, but also at an hour of limited road and pedestrian traffic.

In the presented approach, the development of an HD map requires solving two groups of difficulties. The first group is related to the acquisition of the input data, and the second – to the post-processing.

The input data acquisition with the use of terrestrial laser scanning allows a relatively fast acquisition of large amounts of high-resolution and high-accuracy data. As the HD map was in this experiment developed for public roads, access to the road infrastructure was not a problem or a source of conflict. Interestingly, the acquired data comprises significantly more information than regarding the geometry of the traffic lane. Nevertheless, all of the information acquired during the measurements was used only to develop a digital twin of the traffic lane and to define the traffic rules for the lane. Therefore, no privacy-related issues are involved.

In the case of input data acquisition based on mobile laser scanning, consideration should be also paid to the financial cost of the operation. The cost of a highly precise scanning system for data acquisition is currently at approximately € 300,000.00, together with the software. A decision about its purchase should involve calculation whether it is more cost-effective to buy the system and perform the measurement campaign or to buy the data developed by an external entity.

The other group of the difficulties related to the development of an HD map can be attributed to the limited accessibility of open source applications which could be used for the purpose of developing such maps.

Also, the manual character of the process requires high diligence, and thus much time to be invested in the project. The data were processed in the Vector Map Builder environment which, although it is operated from the level of an internet browser, was found to be satisfactory and allowed the construction of the HD map of the selected test area. The HD map consists not only of the vector layer but also of relations which interpret the road traffic rules and, by encoding this set of information in its own OSM XML format, allow the user for example to correctly change the road lane. Eventually, the HD map comprises an additional functionality allowing its own coordinates to be transformed into local coordinates, offering much higher precision in autonomous drive mode.

In the future, the authors plan to perform two tasks. The first task is to perform comparative tests regarding LiDAR data acquisition with the use of UAV (compare the effectiveness and quality for USV and MLS). The second task is to prepare an HD map for the entire main campus of Wroclaw University of Science and Technology and to start preparations for a test drive of an autonomous vehicle provided with the developed map.

REFERENCES

1. ASAM 2024. https://www.asam.net/standards/detail/opendrive/, access date 25.02.2024
2. Bao, Z, Hossain, S, Lang, H, & Lin, X 2023. A review of high-definition map creation methods for autonomous driving. Engineering Applications of Artificial Intelligence 122, 106125.
3. Barroso, D G, Yang, Y, Machado, F A, & Emadi, A 2021. Electrified automotive propulsion systems: state-of-the-art review. IEEE Transactions on Transportation Electrification 8(2), 2898-2914.
4. Dokic, J, Müller B, Meyer G 2015. European roadmap smart systems for automated driving. European Technology Platform on Smart Systems Integration 39.

5. Gran, C W 2019. HD-maps in autonomous driving, M.S. thesis, Dept. Comp. Sci., Norwegian Univ. of Sci. and Tech., Norway.
6. HERE 2024. https://www.here.com/platform/HD-live-map, access date 25.02.2024
7. Ilci, V & Toth, C 2020. High definition 3D map creation using GNSS/IMU/LiDAR sensor integration to support autonomous vehicle navigation. Sensors 20(3), 899.
8. Liu, R, Wang, J & Zhang, B 2020. High definition map for automated driving: Overview and analysis. The Journal of Navigation 73(2), 324-341.
9. Liu, Y, et al. 2022. "VectorMapNet: End-to-end Vectorized HD Map Learning." arXiv preprint arXiv:2206.08920.
10. Marks, P 2014. Hop in, I'm flying. New Scientist 224(2992), 19-20.
11. Massow, K, Kwella, B, Pfeifer, N, Häusler, F, Pontow, J, Radusch, I, ... & Haueis, M. 2016. Deriving HD maps for highly automated driving from vehicular probe data. IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), 1745-1752.
12. McAllister, R et al. 2017. Concrete problems for autonomous vehicle safety: Advantages of Bayesian deep learning. International Joint Conferences on Artificial Intelligence.
13. Nang, H X 2021. A comparison between 3d high-definition maps created by photogrammetry and by laser scanning applied for an autonomous vehicle. Vietnam Journal of Science and Technology 59 (3) (2021) 402-411
14. Natan, O and Jun, M 2022. DeepIPC: Deeply Integrated Perception and Control for Mobile Robot in Real Environments. arXiv preprint arXiv:2207.09934.
15. NVIDIA 2024. https://www.nvidia.com/en-us/self-driving-cars/hd-mapping/, access date 25.02.2024
16. Pardi, T 2021. Prospects and contradictions of the electrification of the European automotive industry: the role of European Union policy. International Journal of Automotive Technology and Management 21(3), 162-179.
17. Poggenhans, F, Pauls, J H, Janosovits, J, Orf, S, Naumann, M, Kuhnt, F, & Mayr, M 2018. Lanelet2: A high-definition map framework for the future of automated driving.21st international conference on intelligent transportation systems (ITSC), 1672-1679.
18. Seif, H G & Hu, X 2016. Autonomous driving in the iCity—HD maps as a key challenge of the automotive industry. Engineering 2(2), 159-162.
19. Stayton, E L 2015. Driverless dreams: technological narratives and the shape of the automated car. Diss. Massachusetts Institute of Technology.
20. TomTom 2024. https://www.tomtom.com/newsroom/behind-the-map/how-we-make-our-hd-maps/, access date 25.02.2024
21. Toschi, I et al. 2015. Accuracy evaluation of a mobile mapping system with advanced statistical methods. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 40.5.
22. Wong, K, Gu, Y, & Kamijo, S 2020. Mapping for autonomous driving: Opportunities and challenges. IEEE Intelligent Transportation Systems Magazine 13(1), 91-106.
23. Zhang, F, Shi, W, Chen, M, Huang, W, & Liu, X 2023. Open HD map service model: an interoperable high-Definition map data model for autonomous driving. International Journal of Digital Earth 16(1), 2089-2110.
24. Ziegler, J et al. 2014. Making bertha drive—an autonomous journey on a historic route. IEEE Intelligent transportation systems magazine 6.2, 8-20.