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Reference Architecture for AI-based Urban Heritage Preservation Risks Monitoring Tool

Vladislav V. FOMIN, Marius PUTRIMAS, Tadas ŽIŽIŪNAS, Rimvydas LAUŽIKAS

Vilnius University, Vilnius, Lithuania

Vladislav.Fomin@knf.vu.lt, Marius.Putrimas@kf.vu.lt, Tadas.Ziziunas@kf.vu.lt, Rimvydas.Lauzikas@kf.vu.lt

Abstract. Urban heritage preservation (UHP) is an important venue of public administration, in which the adoption of novel IT solutions is highly desired, yet the novelty and the sophistication of the technology creates challenges to decision makers in their task of choosing and/or funding appropriate innovation projects. In this paper, we report on the development of a prototype tool for automated urban heritage preservation risk monitoring. Our aim is twofold: 1) to provide analysis on different reality capture strategies and AI-based imagery recognition in the domain of UHP, and 2) to explain the function and the interaction of different elements in the reference architecture for AI-based urban heritage preservation risk monitoring tool. Our research contributes to the rhetoric of digitization of government services. Specifically, the project reported findings are expected to reduce technology innovation-related uncertainties and facilitate government decision making in projects with comparable aims.

Keywords: reference architecture, urban heritage monitoring, reality capture, AI-based image processing, prototype development

1. Introduction

More than two decades since European Commission has proclaimed the developmental rubric of e-society (Council of the European Union, 1999, 2002), digitization of government services remains an important task for EU countries. Broadening the span of digitization of public administration helps national governments stay on the innovation track towards informational economy (Castells, 1996; Steinmueller, 2006).

Political developmental rhetorics aside, adoption of IT innovation in public administration sector is needed for sustaining efficient and effective operation at the backdrop of ever increasing range and scale of tasks the government is responsible for (Information Management Office, 2005).

On the one hand, digitization of public administration effectively became so critical to the developmental and operational rhetoric, that governments have to become active adopters of novel IT solutions (Fomin et al., 2008; Jansson and Erlingsson, 2014). On the other hand, adoption of novel IT solutions increases requirements towards IT-related expert knowledge and capabilities of the public officers and policy decision makers (Pang et al., 2014).

Urban heritage preservation (UHP) is one of such venues of public administration, where adoption of novel IT solutions is highly desired (Laužikas et al., 2022), yet the novelty and the sophistication of the technology requires promoters of technology to present to decision makers information in easy-to-understand format, explaining the advantages, limitations, and dependencies of one or another technological choice.

In this paper we present a reference architecture for IT-based urban heritage preservation risk monitoring. Our aim is twofold: 1) to provide analysis on different reality capture strategies and AI-based imagery recognition in the domain of UHP, and 2) to explain the function and the interaction of different elements in the reference architecture for AI-based urban heritage preservation risk monitoring tool. A reference architecture here is understood as a guidance for the development of similar in purpose and essence IT systems.

Our research contributes to the rhetoric of digitization of government services by reducing technology innovation-related uncertainties and facilitating government decision making in comparable projects.

2. The promises of advanced technologies for UHP

2.1. The need for digitization of urban heritage protection services

Preservation of urban heritage is one of the main challenges for contemporary society and an important task for governments. For the capital city of Lithuania – UNESCO world heritage site Vilnius – the importance of urban heritage preservation can hardly be underestimated. Urban heritage is closely connected with several domains of public administration: heritage protection, cultural tourism, investment flows management, new urban transport infrastructures development, as well as more loosely defined domains of concern to the government, such as global-local rhetoric, immigration, cultural changes, etc.

Urban heritage preservation (UHP) is concerned with monitoring of various risks, which may "vary from sudden and catastrophic events (such as major earthquakes, floods, fires, and armed conflict) to gradual and cumulative processes (such as chemical, physical, or biological degradation)" (Pedersoli et al., 2016, p. 10) and the risks connected to the intentional destruction of cultural heritage (including cases of purposeful rebuilding of the heritage objects).

At the national level, UHP monitoring is defined as "periodic observation and recording of the condition and alteration of cultural heritage objects and sites, assessment, systematization and forecasting of damage or damaging features," organized and coordinated by the Department of Cultural Heritage and the city municipality. The rather complicated regulatory framework blurs the borders of responsibility of different actors in UHP practice, which results in duplication of particular works and inefficiencies in the heritage risks monitoring, including the lack of attention to cases of destruction of heritage.

Preservation of urban immovable heritage in essence is preservation of *objects and sites.* Those objects, referred to as *valuables* by Lithuanian national laws are defined as being "worth for ethical, historic, aesthetic, or scientific reasons", and the associated *valuable properties* define the scope of UHP risks monitoring task.

The specific subdomain of the UHP risks monitoring addressed in this research are elements of buildings and urbanism: facades, windows, roofs, pediments, dormers, doors, gateways, roofline, skylights, balconies, pillars, and the complexity of the Old Town (town plan, infrastructure, panoramic views). According to the regulations of Ministry of Culture of Lithuania (2009), monitoring shall take place at least once every five years and the objects must be inspected on-site, wherein objects' condition is compared with the conditions recorded in previous inspections and values fixed in the heritage object's electronic passport.

Being one of the most important tasks of UHP, heritage risks monitoring requires effectiveness and efficiency (Pedersoli et al., 2016; Veldpaus, 2015). Those critical to public administration requirements (Simon, 1994), however, can hardly be satisfied by the currently manual UHP practices. Organizations responsible for UHP often lack resources to establish proper risk monitoring methods and procedures (UNESCO, 2019, p. 26). The dearth of resources is further aggravated by obsolete legislative system which today references pre-computer-age practices in the field of UHP (Laužikas et al., 2022). All in all, the situation can be best described as regulatory failure by design, where the substantial statutory base comprised of national and international legislative and normative acts is (mis-)matched by inadequately low resources to implement the monitoring in practice.

Introduction of novel advanced technologies, such as reality capturing of urban landscapes and AI-based processing of the collected imagery could provide a technology fix to the problem (Žižiūnas and Amilevičius, 2020) and thus create public value in terms of transitioning of public administration to e-services (Jansson and Erlingsson, 2014) and the broader context of Network society (Manuel Castells, 2009).

As attractive and promising as novel technologies can be in addressing ineffectiveness of the existing public administration practices in the domain of UHP, to date there is no proven IT solution for urban heritage monitoring. This problem is reinforced by several other. First, there is a conservative position of government towards adoption of "unproven" technologies. This position stems from the past experience of carrying out digitization initiatives without proper strategic and budgetary controls, resulting in poor quality and often lacking interdepartmental interoperability digitized services (Laužikas and Varnienė-Janssen, 2015). Second, adoption of novel IT solutions requires acquisition of new technological expertise by responsible public administration units, including for those in charge of making decisions on the feasibility/value of adoption of novel technologies given the aforementioned obstacle and possible drawbacks. To be effective and efficient in employment of novel technology, public administration policy decision makers and UHP responsible staff must acquire a good understanding of the whole technological process before committing resources to developing or deploying any one part of it (Gottlieb and Blair, 1971, p. 30). To this end, description of main technological elements and the associated of a novel IT system – what we refer to as a reference architecture here - becomes a valuable asset in catering to the knowledge needs of professionals and policy decision makers.

3. The concept of AI-based system for urban heritage preservation risk monitoring

3.1. Project goals

The idea to introduce novel technologies in urban heritage preservation (UHP) monitoring practices in Lithuania dates to 2014, when The Ministry of Culture funded a university-industry collaborative pilot project "Creation of automated urban heritage monitoring software prototype". This initiative was seen as a response to UNESCO call for "scientific and technical studies and research and to work out such operating methods as will make the State capable of counteracting the dangers that threaten its cultural or natural heritage" (UNESCO, 1972). Success with the original project led to the initiation of the project reported in this paper, which was launched in 2018, this time funded by the Research Council of Lithuania.

The goal of the project was to research into and combine the best technological tools and techniques in one complex, cost effective, suitable for large scale real-life application solution to replace the currently established manual UHP monitoring practice.

3.2. The general concept of the tool

The general concept of digital tool for urban heritage monitoring was previously presented by Žižiūnas and Amilevičius (2020). The concept is based on the idea to 1) bring digital world copies of heritage sites into an IT system 2) in recognizable formats for 3) further imagery data processing using AI tools to 4) recognize, record and compare changes in physical heritage objects based on the digital world copies.

Recent research (Žižiūnas, 2019) has argued for important preconditions to enable digital heritage monitoring. These stipulate that physical heritage objects and their valuables can be expressed as simple geometrical forms or mathematical expression. This implies that physical objects can be represented and processed photogrammetrically (Kodors, 2019). The photogrammetrical copies of the physical heritage objects are suitable for assessment of the evolving state of the object. Detection of valuables and changes in them can be done by deploying AI tools. Such approach to UHP risk monitoring is referred to as non-invasive and non-destructive and is expected to result in considerable efficiencies as compared to currently established manual practices both in terms of required resources to carry out the monitoring, and in terms of veracity, verifiability, and shareability of the produced results (Žižiūnas, 2019). The digital copy of the object is obtained in the field measurement stage by capturing 2D images and performing laser scanning of a physical shape of the urban heritage area. This combination of capturing and scanning techniques is referred to as photogrammetry[1] and

[1] Photogrammetry literally means the act of deriving precise measurements from photographs. It involves taking a set of overlapping photos of an object (a building or environment), and converting them into a 3D model using a number of computer algorithms. For a detailed description of the technique, see e.g., (Martinez-Rubi et al., 2017)

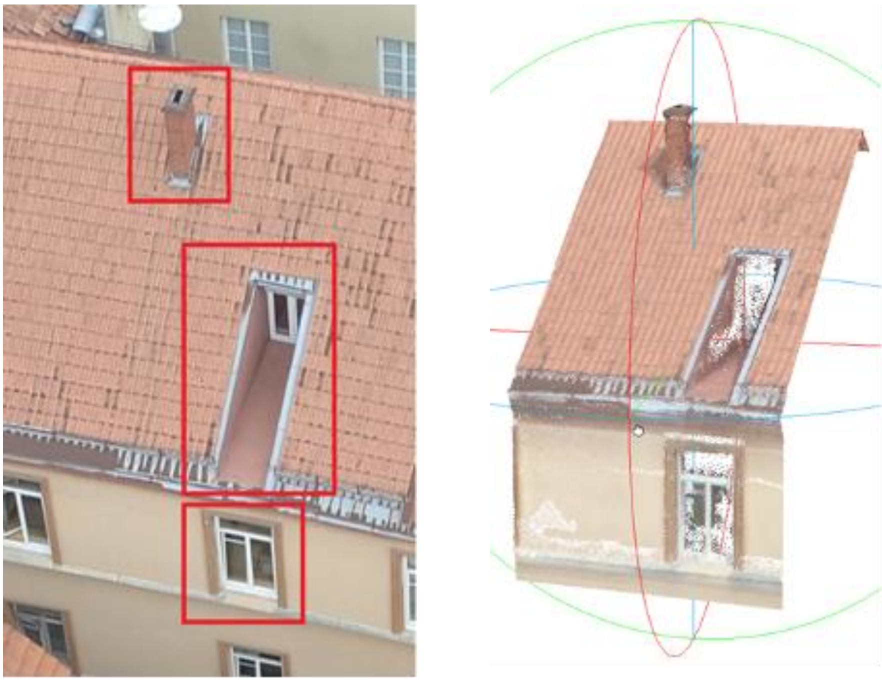

Fig. 1. 2D image captured by a drone (left) and 3D point cloud model (right) of a heritage object

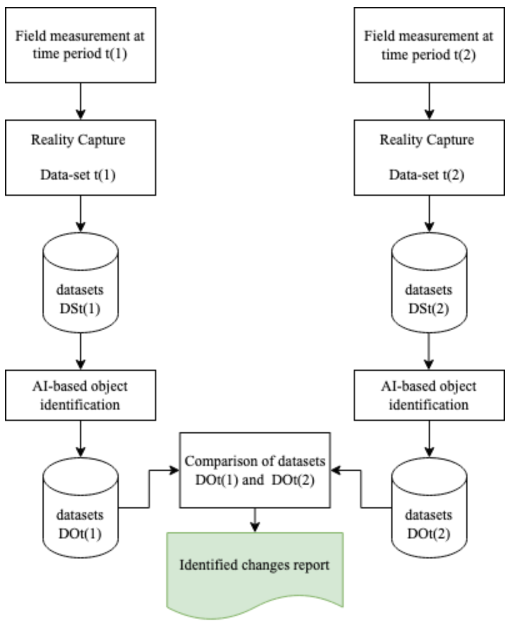

Fig. 2. Simplified model of the use of reality capturing and AI-powered data processing for UHP monitoring risk assessment.

allows obtaining 3D point cloud from 2D images. Processed field measurements reality capture data set contains 2D images an 3D point cloud (see Fig. 1).

AI image processing is used to identify relevant objects on 2D images. The AI-identified objects can be algorithmically linked to their 3D geometry in the 3D point cloud data. Using those processes, field measurements of heritage valuables at different time periods allow identification of changes in the valuable heritage objects – the valuables. To enable (automated) evaluation of evolution of the object, relevant imagery data has to be converted into a database structure, where each valuable heritage object has attributes defining the object's location in real world, time of digital imagery capture and the actual mathematical geometric shape of the object (see Fig. 2).

The combination of AI-powered imagery object identification and algorithmic object geometry analysis presented in Fig. 2 allows to fully automate the process leading to the first level interpretation: i.e., information on geometrical changes. Using logical operators and simple terminology, such as "status quo unchanged" or "increase of area/volume by x%", identified changes in heritage valuables are presented to human experts in a simple to understand report in plain text (see Table 1) or by combining graphical and textual information (Fig. 3).

Skylight	APPARED	➡	Polocko Str. 18	51.6622, 83.7721
Window	DISAPPEARED	➡	Stoties Str. 34	57.4563, 43.8567
Roof	ENLARGED	➡	Parko Str. 34	67.8563, 53.8567
Balcony	CHANGED	➡	Aukų Str. 34	57.4563, 43.8567

Fig. 3. A sketch of urban heritage monitoring report: detected changes in heritage valuables

Information presented in the automatically generated reports (see Table 1 and Fig. 3) is likely to require human expertise (Lyytinen et al., 2020; Fomin, 2021) for further evaluation of risks to urban heritage valuables. For example, the identified changes must be evaluated against particular legal status and local legislation for specific valuables, or other factors: the meaning of the detected changes in the context of public administration depends on specific rules or legislative norms for specific heritage objects. For example, the first level interpretation “reduction in volume” may signal the fact of illegal demolition work, or the result of planned and legitimate city development work.

Table 1. Logical operators of alteration detection.
Source: (Žižiūnas and Amilevičius, 2020, p. 368)

Logical operator	Previous measurement data	Latest measurement data	Sequence of alteration	Heritage risk level
destruction	XYZ	-XYZ	is-> non	Primary
creation	XYZ	XYZ + 1	non-> is	Primary
increase of area/volume	XYZ	XYZ + 1	is-> is (increase)	Secondary
decrease of area/volume	XYZ	XYZ -1	is-> is (decrease)	Secondary

4. The reference architecture for IT-based urban heritage preservation risk monitoring

The overall complexity of the project (Schneberger and McLean, 2003) led the project participants to the decision to share the project-generated knowledge on key elements and their interdependence in the development of IT-based system for urban heritage preservation risk monitoring. As the result of that decision, a reference architecture is provided here, comprising the description of main elements of the system with the purpose to facilitate the development of similar in the aims and scope IT systems (Solodovnikova and Niedrite, 2020). The task of drafting a reference architecture is particularly justified in situations when different software tools and digital object handling formats are available, but no specific architectural system solution for deploying the available systems and formats is known.

Development of the automated heritage monitoring tool required specifying the scope of the monitoring task. While the heritage objects and their properties are defined by existing regulatory framework, the scope had to be redefined due to the restrictions imposed by 1) the properties of reality capture data, 2) the capabilities of AI to detect the objects, and 3) the capabilities of AI to assess the changes in object properties. Specifically, the following decisions were made by the project group:

1. Selection of the valuable properties of urban heritage to be captured and monitored, and separation of valuable features of the two levels – location (plan structure, volumetric spatial structure) and building (height and / or altitude, volumetric spatial composition, facade architectural solution, etc.).
2. Identification of damage factors destroying valuable properties, and separation of damage factors of two groups – natural (climate change, microclimate conditions, etc.) and anthropogenic (construction and development, transport infrastructure, pollution, socio-cultural use of heritage, etc.).
3. Linking of specific valuable properties of urban heritage to specific damaging factors in order to define the functionality of heritage monitoring tool.

In the following subsections we detail important discoveries and choices made during the prototype development which necessitated or justified specific reality capture or data processing strategies and methodologies. The reported architectural and operational choices establish a foundation for replication and further development for scholars and public administrations.

4.1. Reality capture strategies

Having conducted the first experiments with reality capture, it became clear that different field measurement technologies have to be deployed for complete and proper capturing of valuable objects. This assertion is based on the combination of two factors: 1) there exists a large variety of valuable objects (facades, windows, roofs, pediments, dormers, doors, gateways, roofline, skylights, balconies, pillars), and 2) the non-uniformity of the urban layout of the Old City of Vilnius (narrow streets, gated inner yards, etc.). Accordingly, four main strategies were chosen to perform field measurements (see Fig. 4.):

1) Handheld SLAM scanner (GEO-Slam Horizon)
2) Mobile mapping
3) Terrestrial laser scanning (TLS)
4) Drone mapping (Nadir + oblique direction)

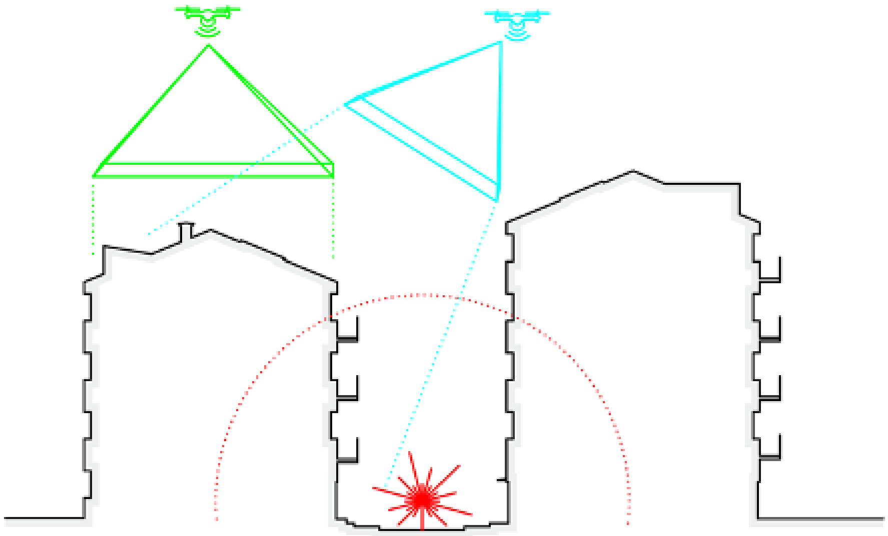

Fig. 4. Reality capture methods for field measurements: terrestrial and aerial.

Even though each of the aforementioned techniques is suitable for reality capture, depending on the chosen method field measurements are performed differently and produce different results. For example, the dotted lines on Fig.4 delineate the field of view (FOV) of different reality capturing methods: terrestrial measurement cannot capture objects located higher from the ground, yet the missing data can be captured using aerial scanning technologies. Each technology and method has specific advantages and disadvantages and can complement one another, as outlined below.

Handheld SLAM scanner provides 3D point cloud data in relation to the axis of motion. As it is a handheld device, the use of it allows accessing courtyards, passages, etc. – wherever a pedestrian can pass – which is an essential advantage in the context of the task of monitoring Old City heritage objects. This device provides full 3D coverage of measurement objects, but the data quality is inferior to other stationary or mobile scanning devices.

The main shortcoming of using handheld SLAM scanner became clear in the process of prototype development - this reality capture method does not provide 2D or 360 degrees images which are needed for enabling AI-based tools for object detection and recognition.

Terrestrial 3D laser scanner (TLS) deployed at fixed measurement stations is an alternative handheld SLAM terrestrial measurement technology which can provide reality capture data as 360 panoramic images and 3D point cloud. This method provides the best quality 3D point cloud data as measured by density to data noise ratio.

Similarly to handheld SLAM, this field measurement method offers the flexibility to move along different routes, but it is a much slower measurement method compared to any mobile measurement technology.

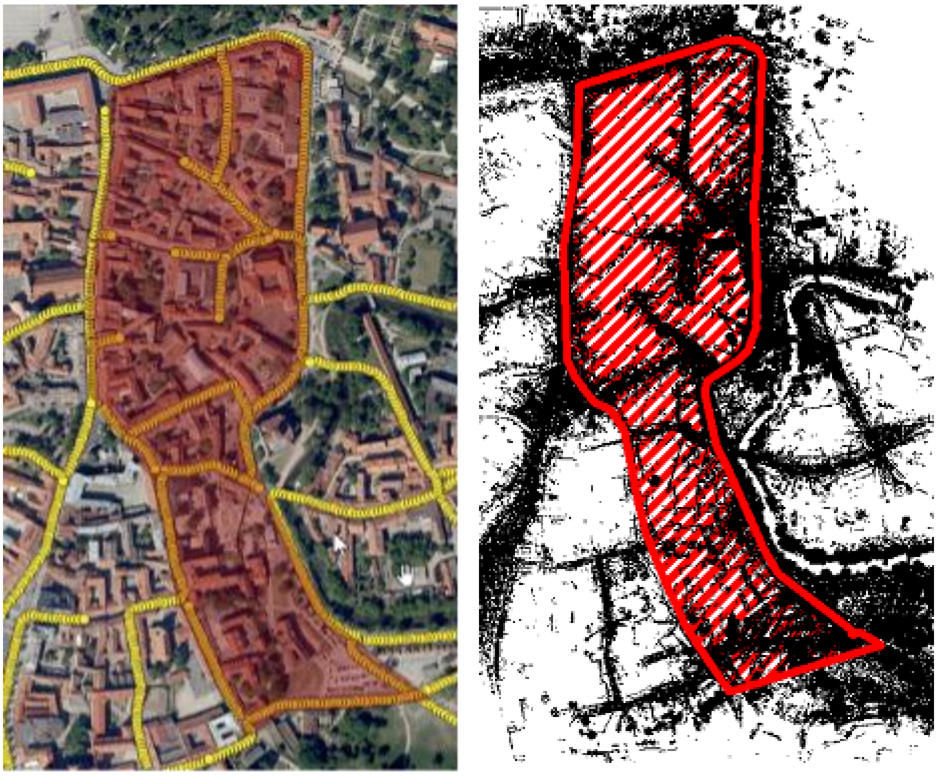

Fig. 5. Mobile mapping data coverage. Yellow dots on the left image indicate locations where panoramic 360 degrees image capture took place. Image on the right depicts 3D point cloud data coverage from the same trajectory where 360 degrees images were taken.

Mobile map data collection method is yet another terrestrial measurement technology. Its greatest advantage is the speed of data capture – modern technology ensures 360 photos and 3D point cloud data can be collected at speeds of up to 70 km/h. Specifically in the context of our project, where the cultural heritage areas are located in the Old City where movement by motor means is restricted, data collection using mobile mapping could not ensure seamless data coverage for whole area of interest (AOI) (See Fig. 5).

Drone mapping and photogrammetry workflow produces 2D images as output data, which are ideal for use with AI-based imagery processing tools. The produced data can be easily converted into 3D point cloud by performing photogrammetric calculations. **Nadir** method is suitable for capturing the rooftops of building, whereas **oblique** can complement terrestrial measurements in capturing higher floors of buildings facades (see Fig. 4 above).

4.2. AI-based object recognition

For AI object recognition TensorFlow 2.4.1 and Mask RCNN software was used. Identification of valuables (labelling of data) was done using Labelbox software and Pascal Visual Object Classes (VOC) data format.

Specifics of the labelling process and the associated data handling techniques made the project team choose drone-produced imagery for identification/labelling of roof elements (chimneys, roof windows), and 2D crops[2] of mobile 360 degree panoramic imagery for mapping façade elements. For the labeling process, imagery from different parts of the Old City were chosen to ensure the variety of styles of valuable objects.

The object labeling was performed using polygon tool in LabelBox software. In total, 12 object classes were created: balcony, fronton, dormer, chimney, pillar, pilaster, skylight, gate, roof, pediment, door, window). The total of 52699 valuables were labaled manually based on 3418 photos.[3] The labeling job took 203 hours and was performed by 3 people.

4.2.1. AI model training

For the AI training we chose a strategy of staged training with decremental learning rate. For example, training for the object ‘window’, good results were obtained after the third training stage, deploying 0.001, 0.0001 and 0.00001 learning rate parameters for each of the consequent stages (See Fig. 6).

The high drops on Fig. 6 indicate new training and validation stages. Substantially smaller drop on the validation curve at the third stage signal lower rate of validation errors. This, in turn, implies higher capability of the AI model to identify the given type of an object. The training has started with a single largest class of objects -window- with subsequent labelling of other classes of objects. To simplify AI training and use, at the beginning we used only aerial images from drones captured in Nadir direction and processed as orthophoto mosaic.

[2] 360º photos were cut (with Equirec2Perspec library) into 45°, 90°, 135°, -45°, -90°, -135° directions with 15° horizon limit for avoiding redundant parts and for faster segmentation tasks.

[3] To maintain a good balance between the volume and quality of photos, image resolution of 800x800 px was chosen.

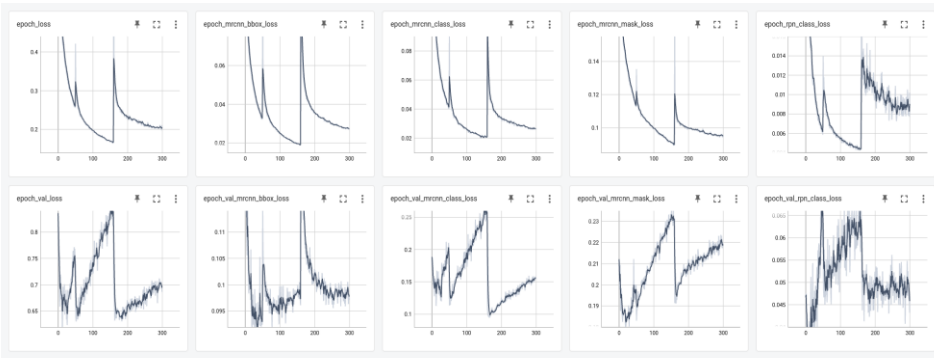

Fig. 6. AI training (1st row) and validation (2nd row) results.

Following the training, AI engine was capable of identifying the defined classes of objects even on photos taken at different angles towards the facade of a building (see Fig. 7). The achieved precision of the AI engine in identifying the defined classes of objects is 90 to 100 percent.

Fig. 7. The results of AI training: highlighted are different classes of objects identified by AI engine on photos taken at different angles towards the facade of a building

4.2.2. Image processing using AI tools

All of the reviewed reality capturing methods, except SLAM, allowed us to obtain 3D digital copies of heritage sites, consisting of 2D and 360 panoramic photos and 3D physical shape (3D point cloud data). The obtained imagery was used to train AI model to recognize objects in images, and extract their geometrical shapes from 3D point cloud. AI was trained to process 2D aerial (drone) images and 360 panoramic photos from TLS/MLS systems (see Fig. 8). JPG format was selected for image processing. For use of 3D Point Cloud vendor-neutral format E57 was selected. [4]

Fig. 8. AI-image processing and recognition for aerial (drone) images

A crucial issue which came forth during the project implementation was that main data set for AI-tools processing can not be restricted by orthophotos and panoramic photos from MLS and TLS systems, as they do not provide coverage for all relevant objects. Especially on narrow streets where no windows are visible on the upper floors in panoramic photos. Therefore, it was decided to use oblique shooting photos from drones mapping that provide coverage of the upper floors, and also provided coverage for courtyards where access is restricted (see Fig. 9).

[4] See https://www.libe57.org/

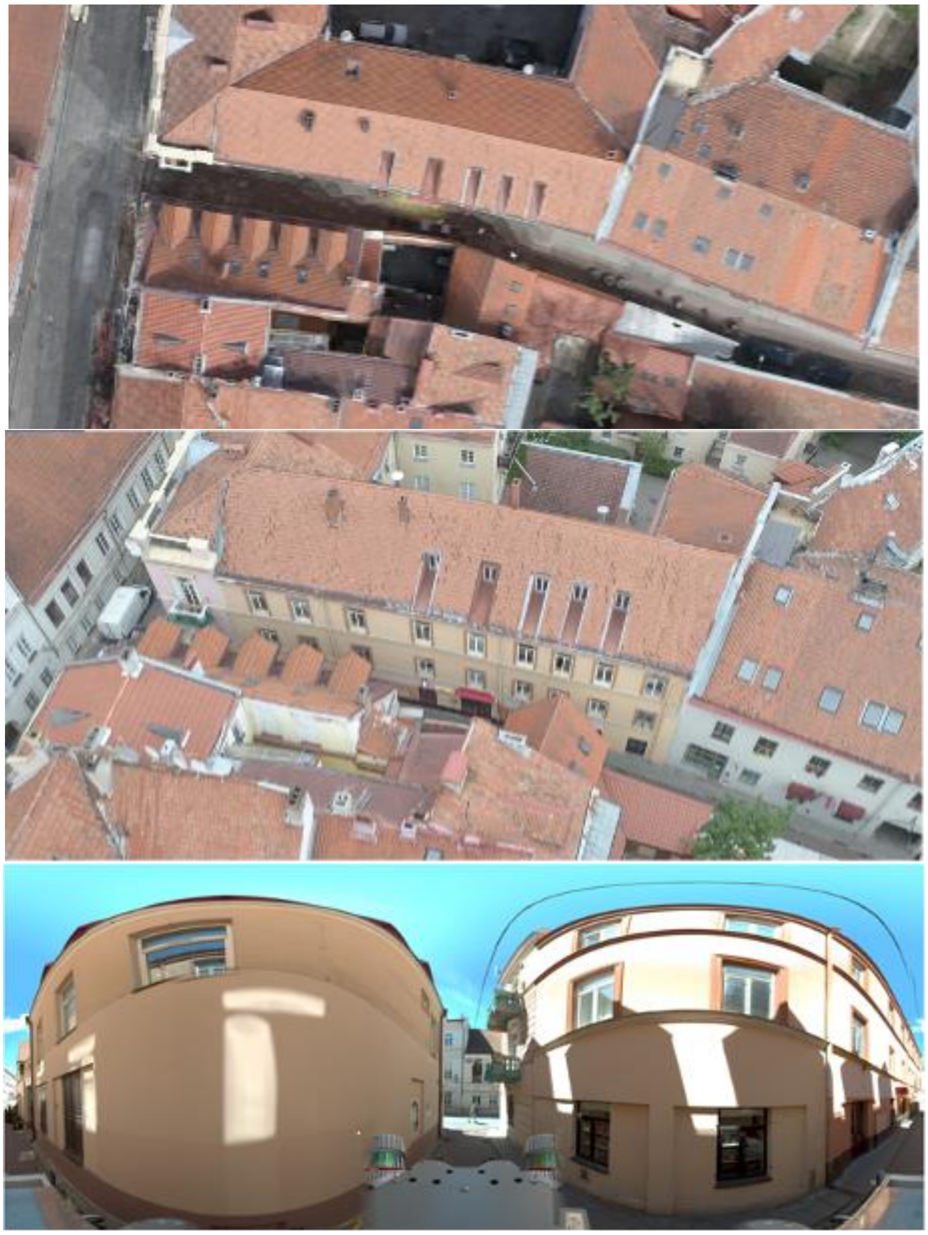

Fig. 9. The first image (Drone mapping – Orthomosaic); The second image (Drone mapping - oblique image); The third image (Mobile mapping – 360 degrees panoramic image)

4.3. Automated workflow for data processing

The concept of an "automated tool" for heritage preservation risk monitoring required implementation of data processing pipeline automation. This, in turn, required many rounds of modifications to find consistent data processing that accepts input data produced by different reality capture techniques. The resulting model of the automated pipeline is presented in Table 10.

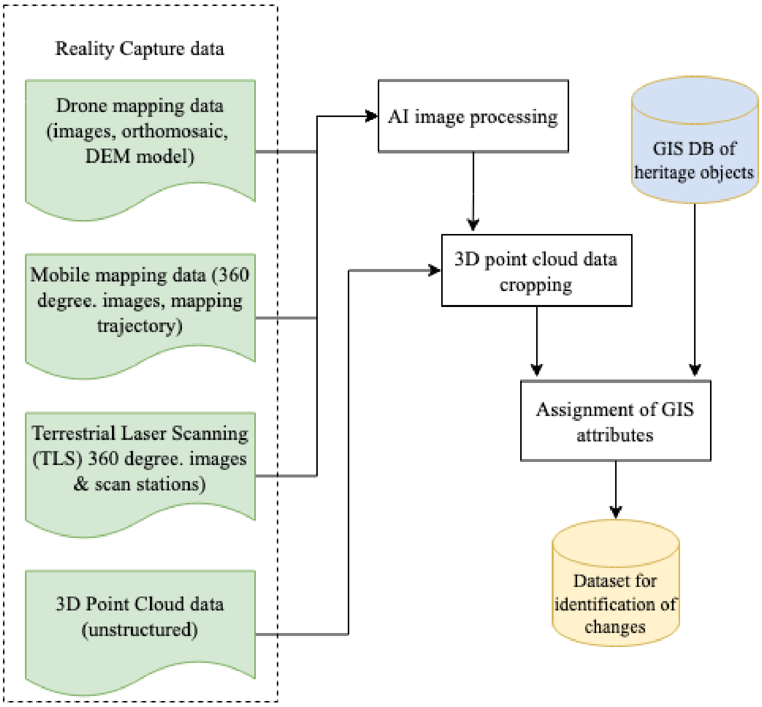

Fig. 10. The project developed pipeline for automated urban heritage risk monitoring input data processing and converting into set DB for subsequent comparison of valuable objects' properties.

An important realization of the project was that different pipelines had to be created in order to track various heritage valuables using different reality capturing strategies. For example, to track changes of windows of the facades and to track urbanistic elements like valuable panorama spots, imagery produced by Terrestrial Laser Scanning (TLS) and Mobile laser scanning (MLS) had to be used, whereas to track changes of skylights and chimneys, drone imagery had to be used. The prototype development was aimed to hide the complexities of the data handling from the end user. From the perspective of the end user (the UHP public administration staff), the prototype user interface is presented as one-and-the-same digital monitoring tool. The (complexities) of source imagery choices are also hidden from the end user. The datasets (field measurements) are represented by the specific time periods (see Fig. 2 above), not by type of technique used to capture the reality.

5. Conclusions

Earlier studies have addressed certain aspects of digital imagery capturing (Kodors, 2019), imagery annotation for AI training purposes (Kazakeviciute-Januskeviciene et al., 2015), or conceptualizing heritage-related smart systems (Korzun et al., 2018). In this work we take a holistic perspective on critical tasks and elements in the development of AI-based urban heritage preservation monitoring system. This work builds on the earlier theoretical conceptualization of such system (Žižiūnas and Amilevičius, 2020) and offers description of technology- and process-related choices made by the project team in the development of a prototype for automated heritage monitoring tool. Description of those choices establishes what we refer to as a reference architecture, as it can help guide similar in aims and scope developments in the future.

Given the availability of a variety of competing and complementary tools and methods for reality capture and the resulting imagery processing, the contribution of this work is in explaining or justifying how features, advantages or limitations of specific tools and techniques contributed to the development of a prototype of automated UHP risk monitoring tool. The reported architectural and operational choices establish a foundation for replication and further development for scholars and public administrations.

Given the variety of possible reality capture strategies/methods, following the completion of the prototype development additional evaluation of imagery data collection techniques should be performed. Specifically, our research findings reported here can be complemented by a comparative analysis of cost-effectiveness of different imagery capturing techniques for valuable object monitoring.

List of abbreviations

2D – Two-dimensional (images)
3D - Three-dimensional (images)
AI – Artificial intelligence
AOI – Area of interest
FOS - Free-and-open-source software
FOV – Field of view
MLS - Mobile laser scanning
TLS - Terrestrial Laser Scanning
UHP – Urban heritage preservation

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