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Automation of the process of reverse engineering of urban development projects based on the results of aerial photographic operations

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Abstract. 3D models of objects of urban development, created by the results of aerial photographic operations or laser scanning, have high metric accuracy, but require significant labor costs, both in terms of creation and visualization. To construct three-dimensional models that allow the user to perceive information in the usual spatial form, and satisfying the accuracy requirements for solving urban planning problems, it is proposed to automate the reverse engineering process based on the Metashape and ContextCapture software products.

Currently, Russia is implementing the national program "Digital Economy of the Russian Federation", in which much attention is paid to the development of geographic information technologies and the use of spatial data. The Smart City section, included in this program, is aimed at creating an effective urban management system, creating safe and comfortable living conditions for people. The development of this section involves the use of spatial data to construct digital models of buildings and structures, as well as for further operational management of urban areas [1].

Spatial data - digital data about spatial objects, including information about their shape, location and properties, including those presented with the use of coordinates. For the digital economy, spatial data is required in the form of three-dimensional coordinates X,Y,Z as well as information about the reliability and accuracy of their determination.

The digital three-dimensional model of geospace is a system of a number of elements: a three-dimensional model of the earth's surface, ground objects (real estate objects) and subsoil (geological models), etc. [4]. Spatial models are the basis of geoinformational design. 3D model can be created either manually (using CAD or GIS) or automatically. The initial data for building three-dimensional models are, as a rule, the data of geodetic and photogrammetric definitions. Digital models built according to various technological schemes have a number of advantages and disadvantages (table 1).

Table 1. Advantages and disadvantages of the main various types of three-dimensional models.

<table>
<tr><th colspan="6">THREE-DIMENSIONAL MODEL TYPE</th></tr>
<tr><th colspan="2">3D vector model</th><th colspan="2">3D model, created automatically</th><th colspan="2">3D stereomodel</th></tr>
<tr><td>+</td><td>–</td><td>+</td><td>–</td><td>+</td><td>–</td></tr>
<tr><td>high geometric detailing</td><td>complexity of creation</td><td>high speed of creation</td><td>Low geometric accuracy</td><td>high speed of creation</td><td rowspan="3">can be viewed only using a stereo monitor and stereo glasses</td></tr>
<tr><td rowspan="2">textures do not contain images of foreign objects</td><td>High metric accuracy</td><td>High photorealism</td><td>impossibility to separate building objects from the surface or from each other</td><td rowspan="2">High metric accuracy; most capacious of all types</td></tr>
<tr><td>low realism</td><td>low cost of model creation</td><td>low quality textures</td></tr>
</table>

Spatial body modeling can create functionally identical objects. The differences between them are mainly differences in how they are created and edited, and agreements on use in different areas, as well as differences in the types of approximations between the model and the reality [9].

Visualization of the urban environment model is widely used to solve various problems in such fields of activity as construction, urban management, education, culture, etc. Three-dimensional visualization allows the user to perceive information in a familiar spatial form [7].

Building a 3D model from scratch is labor or time consuming. For such cases, the software offers the best option: creating a mathematical 3D model or surface (set of surfaces) based on information obtained from a physical object. Currently, the term "reverse engineering" or "reverse design" for the most part refers to the process of obtaining a digital 3D model of a real product using automated design systems. The process begins with a 3D scanning, in which the shape of the object is converted into a mathematical image in the form of a point cloud. For this purpose, laser scanners, structured white or blue light devices, coordinate measuring machines (CMMs) and computed tomography are used. Reverse engineering is the process of designing a digital model that describes an object and its technological properties by performing a comprehensive analysis of its structure. This process is aimed at creating a virtual 3D model based on an existing physical object for its study, duplication or improvement [5].

In this paper, it is proposed to use aerial photographic data and application software packages that allow the implementation of this process to be used as starting materials for the implementation of reverse engineering technology.

Automatic designing is performed in special software products that contain algorithms for restoring the geometric shape of objects and building textures of building facades from their stereo images. The technological process of building a three-dimensional model involves the identification of characteristic points in the zone of mutual overlap of images, the formation of a point cloud that describes the earth's surface and objects towering above it. In the next step, the point cloud is triangulated to get the surface. In the resulting surface, a search for planes is performed for the best transfer of walls and roofs of buildings. The final product is a terrain three-dimensional model, presented with varying degrees of detailing.

Currently, 3D stereo models are created using the reverse engineering method based on aerial photography results using the PHOTOMOD software product. However, for this purpose, there are a number of software products on the Russian market that automate the process of preparing a digital model and significantly reduce the time of desk processing. These software products include Metashape and ContextCapture.

In the Metashape and ContextCapture programs, two 3D models of the same territory of the city, represented by objects of different geometric structures, were built. When comparing the models, it can be seen that in the ContextCapture program the buildings look quite realistic, and their walls are perpendicular to the surface of the earth (Figure 1, number 2). In the Metashape program, buildings are more rounded, blurred, without distinct right angles (Figure 1, number 1).

Fig. 1. 3D model of a city site in Metashape and ContextCapture, respectively

In the ContextCapture program, construction of objects can be performed not only in the form of a parallelepiped (Figure 1, number 1). The figure shows that three structures with a cylindrical shape are pointed almost without distortion. In the Metashape program, one of the cylinders was not built at all, and the other two do not have a clear outline (Figure 1, number 2).

The walls of buildings under construction in the ContextCapture program (Figure 2, number 2) and in the Metashape program (Figure 3, number 1), are completely blended with the ground.

Fig. 2. 3D model of a city site in Metashape and ContextCapture, respectively.

During a visual comparison of models built in the ContextCapture and Metashape programs, the advantages and disadvantages of each software product were identified (table 2).

Table 2. Formatting sections, subsections and subsubsections.

CRITERION	METASHAPE		CONTEXTCAPTURE	
	+	–	+	–
3D model texture	Clear texture prevails	Grainy texture is found	Clear texture, no distortion	
3D model realism	In these two programs, a realistic 3D model of the territory is built.			
Buildings construction	Buildings construction in progress	Most buildings have irregular geometric shapes.	Pretty clear geometric shape respected	In single cases, an irregular geometric shape is found
Drawing of facades, windows and roofs of buildings	Elements are displayed	Most often, the elements are blurred.	Clear drawing of elements	Blurred elements are rare.
Construction of fences and low elements		Completely blend with the surface	Do not blend with the surface	
Program availability	Widespread in Russia			Rarely used in Russia

After analyzing the advantages and disadvantages of each software product, it was concluded that the further construction of 3D models will be performed in the ContextCapture program.

To determine the possibilities of using this program to create three-dimensional models of cultural heritage objects, a 3D model of a cultural heritage object of regional significance “Outhouse from the Plotnikovs Manor” was built in the city of Tobolsk (Figure 3-4).

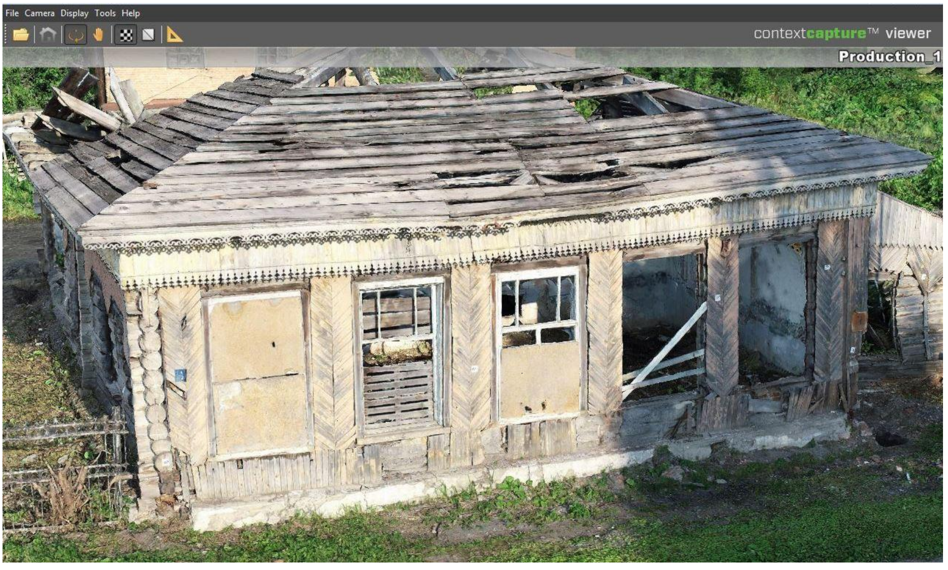

Fig. 3. 3D model of the cultural heritage object of regional significance “Outhouse from the Plotnikovs Manor” in the ContextCapture program.

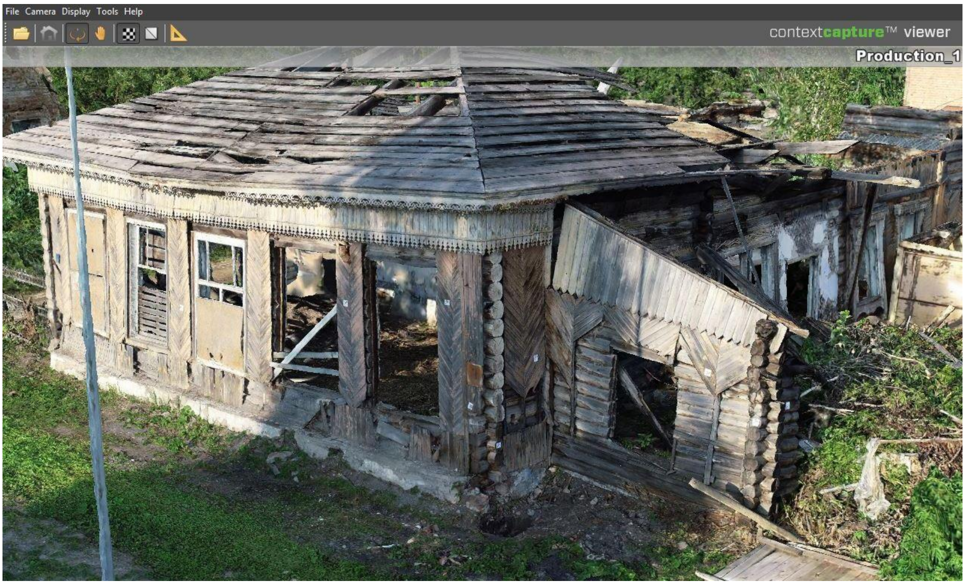

Fig. 4. 3D model of the cultural heritage object of regional significance "Outhouse from the Plotnikovs Manor" in the ContextCapture program.

To automatically create a 3D model, aerial photographs obtained by performing several types of aerial photogrammetric survey (hereinafter - APS) were used:

- planned APS from a height of 30 m from the building. Overlap 80/80%;
- planned APS from a height of 15 m from the building. Overlap 80/80%;
- perspective (oblique) APS around the building from a height of 30 m from the building, a distance of 30 m from the corners of the building;
- perspective (oblique) APS around the building from a height of 15 m from the building, a distance of 15 m from the corners of the building;
- perspective (oblique) APS around the building from a height of 2 m from the ground, a distance of 15 m from the corners of the building;

Aerial photography was carried out using the DJI PHANTOM 4 PRO quadcopter, and markers were also placed on the walls of the building.

The three-dimensional model of a cultural heritage object of regional significance was created to compare the three-dimensional coordinates (X, Y and Z) of characteristic points on a 3D model obtained automatically and on a 3D stereo model built in PHOTOMOD. Sixteen wall markers and eleven characteristic points were selected for measurement, some of which are marked in Figure 6.

Fig. 4. Fragment of a 3D model with several wall markers and characteristic points involved in measurements.

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Table 3 presents the coordinates of wall markers and characteristic points, as well as the measurement tolerances ΔX, ΔY, ΔS, ΔZ.

Table 3. The coordinates of sixteen wall markers and eleven characteristic points with measurement tolerances ΔX, ΔY, ΔS, ΔZ.

PHOTOMOD			3D MODEL			TOLERANCE			
target 28									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
101.3057	105.5167	102.7466	101.3050	105.5190	102.7480	0.001	-0.002	0.002	-0.001
target 22									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
108.4479	108.4041	102.8614	108.4530	108.4020	102.8650	-0.005	0.002	0.005	-0.004
target 20									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
104.1673	111.4815	101.5908	104.1760	111.4980	101.5910	-0.009	-0.017	0.019	0.000
target 19									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
105.1736	110.8782	102.0341	105.1880	110.8760	102.0400	-0.014	0.002	0.014	-0.006
target 16									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
107.8736	109.1401	100.6807	107.8800	109.1610	100.6900	-0.006	-0.021	0.022	-0.009
target 15									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
108.2822	108.9947	101.3130	108.2900	108.9940	101.3210	-0.008	0.001	0.008	-0.008
target 13									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
113.8538	98.1493	100.8391	113.8590	98.1553	100.8430	-0.005	-0.006	0.008	-0.004
target 12									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
113.7231	97.6635	102.0343	113.7210	97.6614	102.0360	0.002	0.002	0.003	-0.002
target 10									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
105.7813	93.5523	102.6012	105.7780	93.5529	102.6000	0.003	-0.001	0.003	0.001
target 9									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
105.5834	93.3735	101.3216	105.5810	93.3699	101.3180	0.002	0.004	0.004	0.004
target 7									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
98.7419	90.7226	101.6727	98.7312	90.7218	101.6720	0.011	0.001	0.011	0.001
target 6									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
95.4687	91.5969	101.8743	95.4683	91.5837	101.8690	0.000	0.013	0.013	0.005
target 1									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
89.7496	99.2619	101.4856	89.7483	99.2625	101.4770	0.001	-0.001	0.001	0.009
target 3									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
91.0840	96.9191	102.5256	91.0842	96.9209	102.5220	0.000	-0.002	0.002	0.004
target 22									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
108.4479	108.4041	102.8614	108.4490	108.4100	102.8680	-0.001	-0.006	0.006	-0.007
target 23									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
109.5483	106.4476	102.5378	109.5500	106.4500	102.5360	-0.002	-0.002	0.003	0.002
No. 1									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
98.7790	88.9700	104.3960	98.7846	88.9823	104.4070	-0.006	-0.012	0.013	-0.011

Continuation of **Table 3.** The coordinates of sixteen wall markers and eleven characteristic points with measurement tolerances ΔX, ΔY, ΔS, ΔZ.

No. 2									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
99.0440	89.7330	104.5030	99.0452	89.7403	104.5640	-0.001	-0.007	0.007	-0.061
No. 3									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
99.1260	89.5480	101.3370	99.1280	89.5520	101.3280	-0.002	-0.004	0.004	0.009
No. 4									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
100.3340	90.1980	104.4400	100.3280	90.1909	104.4740	0.006	0.007	0.009	-0.034
No. 5									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
99.2970	91.0170	104.6890	99.3001	91.0049	104.7070	-0.003	0.012	0.012	-0.018
No. 6									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
101.4630	94.7160	104.5500	101.4680	94.7023	104.5910	-0.005	0.014	0.015	-0.041
No. 7									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
105.5350	100.5440	107.2060	105.5150	100.5670	107.2190	0.020	-0.023	0.030	-0.013
No. 8									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
108.4370	110.0840	104.7800	108.4380	110.0840	104.8120	-0.001	0.000	0.001	-0.032
No. 9									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
114.8790	97.4580	104.3710	114.8850	97.4851	104.4900	-0.006	-0.027	0.028	-0.119
No. 10									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
108.0850	109.3300	99.8010	108.0910	109.3520	99.9256	-0.006	-0.022	0.023	-0.125
No. 11									
X, m	Y, m	Z, m	X, m	Y, m	Z, m	ΔX, m	ΔY, m	ΔS, m	ΔZ, m
101.0570	97.9750	104.1770	101.0600	97.9931	104.1990	-0.003	-0.018	0.018	-0.022

TOTAL NUMBER OF POINTS (N):	**27**	
$\sum \Delta S^2$	**0.0048 m^2**	
RMS error ($m_{\Delta S}$)	**0.01 m**	
Permissible $m_{\Delta S}$	**0.03 m**	
$\sum \Delta Z$	**0.5520 m**	
Average point error in height ($\Theta_{\Delta Z}$)	**0.02 m**	
Permissible $\Theta_{\Delta Z}$	**0.03 m**	
	ΔS	**ΔZ**
Number of points included in the tolerance	**27 (100%)**	**27 (100%)**

The three-dimensional model of a cultural heritage object of regional significance “Outhouse from the Plotnikovs Manor” in the city of Tobolsk was created by order of a construction company for the further development of a reconstruction project. The terms of reference provided for the mean square error of the location of the characteristic points, not exceeding 0.03 m.

The accuracy of this three-dimensional model made it possible to carry out the necessary measurements and draw up a project for further reconstruction of the cultural heritage object of regional significance “Outhouse from the Plotnikovs Manor” in the city of Tobolsk (Figure 6).

An analysis of the results obtained by measuring the points showed that the method of obtaining coordinates and heights using the 3D model corresponds to the tolerances established by Russian legislation.

Fig. 6. Graphic part of the reconstruction project.

At present, in Russia much attention is paid to digitalization in the field of geoinformational technologies. The development of modern society led to the fact that the implementation of activities in various fields requires obtaining relevant and reliable information about the state of the world using 3D models. Thanks to the introduction of uncrewed aerial vehicle, aerial photography become a less time-consuming process. The development of the computer sphere contributed to the emergence of special software that can turn a set of images into a 3D model of a building, structure or the whole city.

Real-time visualization of the 3D model makes it possible to completely immerse yourself in the model space and thereby transmit the most complete information about the object to the user. This approach allows to gain experience in operating facilities even at the stage of development of their concept. In urban management, the 3D model allows to carry out engineering calculations and to plan social infrastructure [8].

The stereo model allows to determine the horizontal and vertical coordinates of the object at the same time, which eliminates the need to measure the height of the points with geodetic means, using a digital elevation model or horizontally on a graphical plan. The regulatory legal acts contain requirements for the accuracy of determining the coordinates and heights of characteristic points when measuring a stereo model.

For automatic creation of the 3D model of the cultural heritage object of regional significance “Outhouse from the Plotnikovs Manor” in the city of Tobolsk, the images obtained during planned aerial photography along with perspective (oblique) were used in the ContextCapture program. The obtained three-dimensional model of the object of cultural heritage had high accuracy, the values of ΔS, ΔZ were included in the tolerance at all selected characteristic points. Also, this 3D model was used to draw up a project for the reconstruction of the building and allowed to reduce significantly real measurements in-situ.

However, to carry out planned aerial photography along with perspective (oblique), it is necessary to fly around the building twice or re-equip the aircraft and then to make a survey with two cameras at once (the axis of one camera is directed vertically downward and the other is tilted). Shooting the facades of each building at different heights and at different angles will take much longer. This type of aerial photography has a higher monetary value compared to the planned one, which is most often used to create stereo models.

Today, the stereo model is affordable and familiar to the user. It is widely used for complex cadastral works, design, decryption, etc. The requirements for its accuracy are regulated by the legislation in the field of spatial data. At the moment, when automatically creating a 3D model, it is difficult to achieve results close to the stereo model.

The automatic construction of 3D models requires further study, development and improvement through various experiments. In addition, for its wide distribution, it is necessary to begin the development of a special regulatory legal base, as well as provide enterprises with special software products for 3D model creation.

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