

REMOTE RESEARCH OF ARCHAEOLOGICAL SITES OF THE SOUTHERN TRANS-URALS USING GEOPHYSICS AND MACHINE LEARNING

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Abstract: The so-called "Country of Cities" discovered in the second half of the 20th century in the Southern Trans-Urals — more than two dozen fortified settlements of the Middle Bronze Age belonging to the Sintashta culture (about 3–2 thousand years BC) is a unique object of interdisciplinary research. In this paper the study of the architecture of these settlements is carried out by interpreting aerial photographs, space photographs and geophysical methods: magnetometry and areal electromagnetic profiling with the AEMP-14 induction system. The construction of orthophotoplans and a digital relief model is made based on UAV survey data and ground surveys using GNSS and tacheometry. Fundamentally new opportunities are provided by applying modern methods of detection, classification and segmentation of objects based on the use of convolutional neural networks to the obtained data. This paper presents and discusses the results of applying neural networks based on graphs and transformer architecture to the problem of 3d archaeological sites segmentation and methods of their detection based on residual neural networks and networks with transformer architecture.

Keywords: Southern Trans-Urals, Bronze Age, Sintashta culture, fortified settlement, remote research methods, graph convolutional neural networks, data segmentation.

Citation: Vokhmintsev, A. V., A. V. Melnikov, N. S. Batanina, E. V. Kupriyanova, L. A. Muravyev, and M. A. Romanov (2025), Remote Research of Archaeological Sites of the Southern Trans-Urals Using Geophysics and Machine Learning, *Russian Journal of Earth Sciences*, 25, ES2012, EDN: ERYSGY, <https://doi.org/10.2205/2025ES000971>

RESEARCH ARTICLE

Received: 15 November 2024

Accepted: 15 April 2025

Published: 23 May 2025



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1. Introduction

Natural scientific methods are currently widely used to study the material culture of mankind in the past — archaeological sites. Non-destructive mapping is a necessary part of archaeological site's study, allowing the selection of specific parts of interest for planning excavations. These are mainly geophysics and remote sensing methods – photographs obtained from satellites, manned and unmanned aerial vehicles, in optical range and multispectral cameras. UAV surveys allows obtaining accurate and detailed digital terrain models (Digital Terrain Model, DTM), which serve as a basis for research and reconstruction of the structure of an archaeological site, confirming the results of excavations, as well as finding relationships between "digital images" of various sites in geophysical fields, photographs and terrain models. In the last 10 years, machine learning (ML) methods have begun to be used in archaeology, which make it possible to increase the effectiveness of the above research methods. At the end of the 20th century, analysis of aerial photography revealed a number of fortified Bronze Age (21st–18th centuries BC) settlements in the Southern Urals – Sintashta archaeological culture. Each object is a unique architectural

ensemble, surrounded by massive fortifications. The largest and most famous settlement of this group is Arkaim, and the whole system was named as “Country of Cities”. 23 such fortified settlements were discovered until recently and now it is a unique object for interdisciplinary research aimed at studying the material culture of the age of the ancient Egyptian pyramids, the way of life, technology and techniques that people possessed at that time. Geophysical methods for research of these settlements have been used since the 1990s to the present day. It is high-precision magnetometry, symmetrical electrical profiling, resistance method and with ground penetrating radar. Another two fortified settlements were discovered in 2023 in the northern parts of the territory. The finds are located in the area between the two northernmost settlements (Stepnoe and Chernorechye) and the other monuments.

2. Geophysical research

Currently, geophysical mapping covered more than a dozen fortified settlements, corresponding burial mounds and ancient mines [Noskevich *et al.*, 2022]. The main method is magnetometric survey, performed using Overhauser magnetometers [Epimakhov *et al.*, 2021; Narkhov *et al.*, 2017]. The second was the SIR-3000 ground penetrating radar for reconstructing the internal structure of individual parts of settlement (wells, furnaces, mines) and three-dimensional modeling [Fedorova *et al.*, 2020]. However, the study of the fortified settlement Stepnoye showed that magnetic survey is ineffective due to the intense magnetization of the soils. This created the prerequisites for using a new method of soil research — the dipole electromagnetic profiling device AEMP-14 [Karin *et al.*, 2018]. The efficiency of field work performed by the AEMP-14 induction system was comparable to the speed of magnetic survey in motion. Electromagnetic survey of the Stepnoye was completed in 2023 (Figure 1). The map revealed some details complementary to other studies. The walls and similar structural elements are characterized by increased resistivity, while the rows of housing depressions and ditches have reduced resistivity. The outer defensive wall is clearly visible in the western and eastern parts of the site. Overall, the complex structure of the site corresponds to the interpretations made earlier based on the aerial photographs interpretation. New rectangular and sub-square structures were built and reconstructed in several stages on the early oval fortified settlement. The electrical resistivity map shows new elements — walls separating the rows of housing depressions. Future research will focus on the heterogeneous structure of the ash pit revealed in the map. The territory of the recently discovered fortified settlements of Nizhneuspenskoe and Verkhneuralskoe was also surveyed using the AEMP-14 and results allowed us to understand the structure of these sites.

3. Application of machine learning methods in archaeology

The authors of this study proposed a methodology for non-destructive research of archaeological sites [Vokhmintsev *et al.*, 2024b]. The data involved in its comprehensive study can be divided into two groups. This is 2D data as rasters: space images and aerial photographs, and 3D data as point clouds with an irregular structure (results of tacheometry, stereophotogrammetry from UAVs, LIDAR, geophysical methods - magnetometry, electrical survey). Each type of source data corresponds to groups of ML methods aimed at solving specific problems. On two-dimensional data, the problems of detecting objects and determining their contours are solved. On 3D data, ML methods we can solve problems of semantic segmentation, classification and segmentation of instances. For the detection task, based on the accumulated experience of studying Bronze Age sites in this region [Zdanovich *et al.*, 2003], 8 types of classes of objects of interest were selected: burial cult complexes with wall-shaped horseshoe or dumbbell-shaped structures (M-1), burial grounds with stone fences from the Middle Ages (M-2), fortified settlements of the Bronze Age (P-1), unfortified settlements of the Bronze Age (P-2), four types of stone barrows of the early Iron Age or the Middle Ages (K1, K2, K3, K4), a soil or stone barrow of the early Middle Ages with “whiskers” (K5). To study the internal structure and architecture of an archaeological site

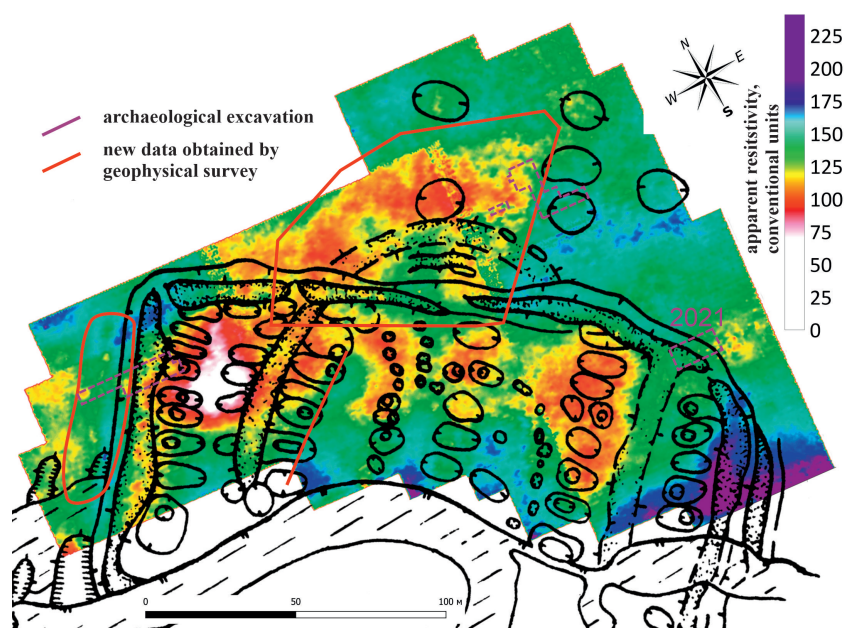


Figure 1. Electromagnetic survey of the Stepnoye settlement, combined with data from the interpretation of an aerial photograph from 1956.

using 3D data, the following set of classes was selected: dwelling (s1); ditch (s2); defensive wall (s3); burial ground (s4); internal wall (s5); well (s6); entrance to the settlement (s7). For object detection, two approaches were proposed: one based on residual neural networks ResNet 50 with a modified fully connected layer in the form of a radial basis network RBF, and another using the Pointview-GCN transformer architecture [Mohammadi et al., 2021], which showed the following results: for classes K-1, K2, K3 average value of metric F1 0.93, precision 0.82, recall 0.88, for class P-1 F1 0.90, precision 0.96, recall 0.88, for P-2 F1 0.77, precision 0.84, recall 0.81. The detection results based on ResNet-50 showed [Vokhmintcev et al., 2024b] the worst values for all metrics and classes.

For the semantic segmentation task, original models for 3D semantic segmentation based on a dynamic weighted graph convolutional neural network (DWG*CNN) were proposed, and for 3D segmentation of instances, an improved version based on the Mask3d [Schult et al., 2023] transformer architecture was proposed. Using a combination of neural networks DWG*CNN+Mask3d* [Vokhmintcev et al., 2024a], a set of geophysical data and DTM of two objects was analyzed: the fortified settlements of Stepnoye and Levoberezhnoye. Preliminary preparation of 3D data includes: division into semantic blocks; determination of special points and calculation of normals in the cloud; formation of a multimodal feature vector consisting of object coordinates, their normalized coordinates, normals and data on the color of the point in the cloud; upsampling or downsampling of the point cloud depending on the morphology of the 3D data. For example, the terrain data from UAV stereophotogrammetry or LIDAR may contain overly detailed data, so downsampling may be required. In contrast, the tacheometric terrain data of individual site in our collection contain sparse and uneven data, and for them, data upsampling is performed based on the RepKPU algorithm [Rong et al., 2024]. The collection of geophysical data and elevation models of the Stepnoye and Levoberezhnoye sites included 116 original point clouds containing markers of the 7 classes indicated above. Augmentation of the original set of point clouds was performed using the Real3D-Aug algorithm [Šebek et al., 2022]. As a result, 928 different point clouds were obtained, each with a uniformly dense structure. The input for DWG*CNN is a dense irregular point cloud $C = \{c_1, \dots, c_n\}$ in $\mathbb{R}^3$, where $i = 1, \dots, n$, each element of which is a point features vector the form of its coordinates and normals, for depth data obtained from LiDAR, the feature vector is extended with

color components in RGB format. The DWG*CNN model allows eliminating the main drawback of known graph convolutional networks — dependence on the dimensionality of the analyzed point clouds by approximating the convolution signal with a 3-order Chebyshev polynomial. For the Mask3d model, modification of the data preprocessing process in the feature map construction module, an adaptive scheme for dealing with outliers in the decoder module, and a modified scheme for concatenating local and global features of the neural network made it possible to significantly increase the efficiency of solving the problem of segmenting instances for sparse, noisy, and heterogeneous 3D data. Computer simulations made it possible to compare the efficiency of the proposed model based on DWG*CNN and models based on graph networks DGCNN [Wang *et al.*, 2019] and RGCNN [Te *et al.*, 2018]. A comparison of metrics shows the advantage of the DWG*CNN method for all metrics (Table 1).

Table 1. Results of 3d semantic classification for graph neural networks.

Metric	RGCNN	DGCNN	DWG*CNN
Accuracy	0.730	0.685	0.910
IoU	0.695	0.530	0.781
F1	0.734	0.695	0.934

Computer modeling for instances segmentation task show that according to the quality metric F1 (see Table 2), the proposed modified method Mask3d* allows to obtain better segmentation quality (Figure 2) for classes s1–s4 relative compared to state-of-the-art methods: Mask3d and OneFormer [Kolodiazhnyi *et al.*, 2023]. For classes s5–s7, all methods showed unsatisfactory results.

Table 2. Results of 3d instance segmentation.

Method	s1	s2	s3	s4	s5	s6	s7
OneFormer3d	0.680	0.582	0.470	0.568	0.522	—	—
Mask3d	0.730	0.593	0.602	0.635	0.478	—	—
Mask3d*	0.876	0.910	0.803	0.844	0.664	0.398	0.393

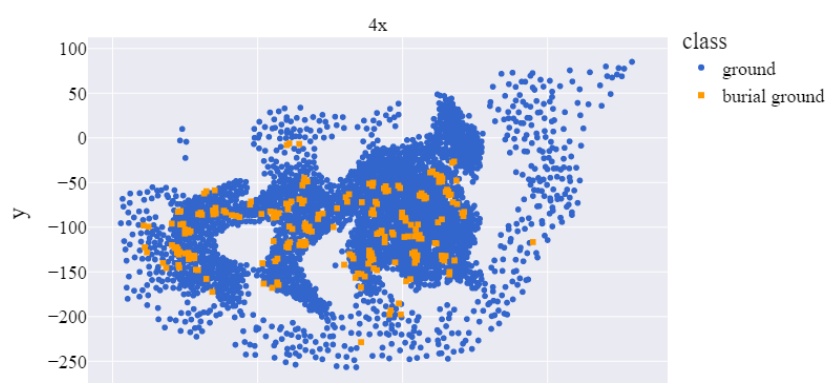


Figure 2. Results of 3d semantic segmentation for the burial ground Kamenka 2.

4. Conclusions

The integrated use of geophysical and remote sensing methods made it possible to create a digital model of the territory along the middle reaches of the Sintashta River, to provide a detailed description of the settlements and burial grounds of the Bronze Age, housing depressions and various types of burials. Analysis of the model of the largest

fortified settlement near the Sintashta river -Levoberezhnoye area made it possible to trace the dynamics of the number of housing depressions during different stages of the Bronze Age. It is shown that ML methods can help archaeologists in studying the structure of an archaeological site and its interpretation. Using the example of fortified settlements of the Bronze Age in the Southern Trans-Urals, we can conclude that the complex use of several non-destructive methods allows us to form an idea of the structure of a site that is in an unsatisfactory state of preservation or has even been completely leveled in the landscape as a result of human anthropogenic activity.

Acknowledgments. The study was supported by a grant of the Russian Science Foundation No. 23-11-20007, <https://rscf.ru/project/23-11-20007/>

References

- Epimakhov A. V., Berseneva N. A., Fedorova N. V. Fortification lines of the Kamennyi Ambar settlement // The Bronze Age in the Karagaily-Ayat Region (Trans-Urals, Russia). Culture, Environment and Economy. — Bonn : Verlag Dr. Rudolf Habelt GmbH, 2021. — P. 101–158. — EDN: ADHHQM.
- Fedorova N. V., Noskevich V. V. Geophysical Researches at Belousovsky Copper Mine of the Bronze Age (Southern Urals) // Geoarchaeology and Archaeological Mineralogy. — Springer International Publishing, 2020. — P. 38–44. — DOI: [10.1007/978-3-030-48864-2_6](https://doi.org/10.1007/978-3-030-48864-2_6).
- Karin Y. G., Balkov E. V., Fadeev D. I., et al. Electromagnetic Profiling by Compact Apparatus: New Approach and Results of Application // Vestnik NSU. Series: Information Technologies. — 2018. — Vol. 16, no. 4. — P. 68–78. — DOI: [10.25205/1818-7900-2018-16-4-68-78](https://doi.org/10.25205/1818-7900-2018-16-4-68-78). — In Russian.
- Kolodiazhnyi M., Vorontsova A., Konushin A., et al. OneFormer3D: One Transformer for Unified Point Cloud Segmentation. — 2023. — DOI: [10.48550/ARXIV.2311.14405](https://doi.org/10.48550/ARXIV.2311.14405).
- Mohammadi S. S., Wang Y., Bue A. D. Pointview-GCN: 3D Shape Classification With Multi-View Point Clouds // 2021 IEEE International Conference on Image Processing (ICIP). — IEEE, 2021. — P. 3103–3107. — DOI: [10.1109/icip42928.2021.9506426](https://doi.org/10.1109/icip42928.2021.9506426).
- Narkhov E. D., Muravyev L. A., Sergeev A. V., et al. Applications of modern high-precision Overhauser magnetometers // Physics, Technologies and Innovation (PTI-2017): Proceedings of the IV International Young Researchers' Conference. Vol. 1886. — AIP Conference Proceedings, 2017. — DOI: [10.1063/1.5002972](https://doi.org/10.1063/1.5002972).
- Noskevich V., Fedorova N. Geophysical Studies of Wells in the Settlements of Konoplyanka 1 and Konoplyanka 2 (Bronze Age) // Interdisciplinaria Archaeologica Natural Sciences in Archaeology. — 2022. — Vol. XIII, no. 1. — P. 19–28. — DOI: [10.24916/iansa.2022.1.2](https://doi.org/10.24916/iansa.2022.1.2).
- Rong Y., Zhou H., Xia K., et al. RepKPU: Point Cloud Upsampling with Kernel Point Representation and Deformation // 2024 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR). — IEEE, 2024. — P. 21050–21060. — DOI: [10.1109/cvpr52733.2024.01989](https://doi.org/10.1109/cvpr52733.2024.01989).
- Schult J., Engelmann F., Hermans A., et al. Mask3D: Mask Transformer for 3D Semantic Instance Segmentation // 2023 IEEE International Conference on Robotics and Automation (ICRA). — IEEE, 2023. — P. 8216–8223. — DOI: [10.1109/icra48891.2023.10160590](https://doi.org/10.1109/icra48891.2023.10160590).
- Šebek P., Pokorný Š., Vacek P., et al. Real3D-Aug: Point Cloud Augmentation by Placing Real Objects with Occlusion Handling for 3D Detection and Segmentation. — 2022. — DOI: [10.48550/ARXIV.2206.07634](https://doi.org/10.48550/ARXIV.2206.07634).
- Te G., Hu W., Zheng A., et al. RGCNN: Regularized Graph CNN for Point Cloud Segmentation // Proceedings of the 26th ACM international conference on Multimedia. — ACM, 2018. — P. 746–754. — DOI: [10.1145/3240508.3240621](https://doi.org/10.1145/3240508.3240621).
- Vokhmintsev A., Khristodulo O., Melnikov A., et al. Application of Dynamic Graph CNN* and FICP for Detection and Research Archaeology Sites // Analysis of Images, Social Networks and Texts. — Springer Nature Switzerland, 2024a. — P. 294–308. — DOI: [10.1007/978-3-031-54534-4_21](https://doi.org/10.1007/978-3-031-54534-4_21).
- Vokhmintsev A. V., Melnikov A. V., Romanov M. A., et al. Remote Research System of Archaeological Sites Using Deep Learning // Pattern Recognition and Image Analysis. — 2024b. — Vol. 34, no. 3. — P. 574–582. — DOI: [10.1134/s105466182470038x](https://doi.org/10.1134/s105466182470038x).
- Wang Y., Sun Y., Liu Z., et al. Dynamic Graph CNN for Learning on Point Clouds // ACM Transactions on Graphics. — 2019. — Vol. 38, no. 5. — P. 1–12. — DOI: [10.1145/3326362](https://doi.org/10.1145/3326362).
- Zdanovich G. B., Batanina I. M., Levit N. V., et al. Archaeological atlas of the Chelyabinsk region. Issue 1. Steppe-forest-steppe. Kizilsky district. — South Ural Book Publishing House, 2003. — 256 p. — In Russian.