**Introduction**

Denisova Cave, in northwestern Gorny Altai, is one of the key stratified archaeological sites of northern Eurasia, highly relevant to understanding the evolution of Paleolithic culture and its environment. Soft sediments of the cave fall into 20 lithological strata that contain archaeological materials of various epochs – from the Middle Paleolithic to the Late Middle Ages. Finds from the cave’s Central Chamber, two galleries, and from the entrance zone amount to tens of thousands. The most important discoveries are associated with the Paleolithic strata. One of the most important findings of the Denisova project is the discovery of human fossils associated with the Initial Upper Paleolithic horizon and representing a previously unknown hominin species. Given the critical importance of Denisova Cave, one of the key tasks was to generate its virtual 3D model.

The term ‘virtual archaeology’ was first introduced in 1990 by P. Reilly, a pioneer of application of 3D modeling and visualization in archaeology (Reilly, 1990). The main objectives of this research field include 3D documentation of archaeological objects, their virtual reconstruction, visual analysis of data, verification of...
hypotheses, provision of access to obtained information, and development of virtual museums. Virtual archaeology is a subdiscipline that has been developing over two decades. Large-scale international conferences are regularly held and results of the projects are published in leading periodicals. It is estimated that there are thousands of existing 3D models of archaeological objects (Bawaya, 2010; Borodkin, Zherebyatyev, 2012).

Three-dimensional modeling of Paleolithic cave sites based on laser scanning is a specific direction of investigations. One of the first projects of this type was carried out in 1994. Laser scanning was used for development of a textured 3D model of the underwater Cosquer Cave in France (Thibault, 2001). Later on, 3D models were made for Arago Cave in France, Grotta dei Cervi in Italy, as well as for caves such as Parpalló (Lerma et al., 2010), Altamira (Donelan, 2002), and Peña de Candamo (González-Aguilera et al., 2009) in Spain, and for Wonderwerk Cave in South Africa (Rüther et al., 2009). An examination of the projects focused on modeling Paleolithic cave sites has shown that most of them were aimed at 3D recording of rock art. Visualization of archaeological finds in the virtual space of 3D models has received less research attention. This task was fulfilled in the project entitled, “A Virtual Model of Denisova Cave in the Altai Mountains”***. This work is the first attempt at virtual 3D modeling of a Paleolithic cave site made in Russia.

**Virtual 3D model of Denisova Cave**

In August 2012, the present authors performed laser scanning and detailed photography of the cave. Thirty-seven scan stations were made; full point cloud contains about 50 millions of points. Then, a textured polygonal 3D model based on results of laser scanning and photography was made. The model consists of 88,254 polygons including 86,000 representing the cave and 2,254, artificial objects (decks, rails, and stairs). The resolution of a texture varies for the different parts of the model from 30 to 100 thousand pixels per 1 sq. m of the model surface. Thus, a detailed 3D model of the cave that preserves its geometry and appearance with high accuracy and resolution was made (Fig. 1).

The created 3D model was referenced in archaeological coordinate system (ACS). This system is used by archaeologists for spatial referencing (registration of location) of finds. The Y axis of the ACS is turned 62 grades clockwise from the North direction; it roughly coincides with the entrance line and the longitudinal axis of the Central Chamber. The X axis is perpendicular to Y in the plane tangent to the Earth at the origin of coordinates. The Z axis is vertical, supplementing the coordinate system. The origin of coordinates of ASC is located in some virtual point in space near the cave’s drip line. ACS is fixed in the cave by five permanent marks in the cave’s walls. These marks were scanned during the laser scanning. During post-processing, the model of the cave was converted in ASC. The accuracy of referencing was about 5 cm (Fig. 2). Thus, a means to compare the 3D model and existing archaeological schemes was provided, and it became possible to transfer directly the existing archaeological database in a virtual space of the 3D model (Fig. 3).

In addition, several stone implements attributable to various periods of human occupation of the cave were scanned, photographed, and 3D modeled (Fig. 4). The created models of the artifacts consist of about 50 thousands polygons. During texturing, normal maps based on more detailed models (500 thousands polygons) were used. Thus, high visual realism and resolution of virtual models with a relatively small number of models and textures were achieved. This is particularly important for interactive visualization in stereo mode.

In order to visualize the created 3D model of the cave, an interactive 3D presentation (software based on OpenSceneGraph) was elaborated. The presentation supports both mono- and stereoscopic visualization. It provides visualization of a point cloud, 3D model of the cave, 3D models of finds, 3D models of wooden decks, rails and stairs, as well as visualization of the spatial distribution of finds in various archaeological strata (Fig. 5). It also supports visualization of additional data such as cardinal directions, axes and grid of ASC, and location of permanent marks of ASC. The 3D model of the cave can be virtually cut at any horizontal layer; this option makes it possible to analyze visually the geometry of the cave and spatial distribution of finds (Fig. 6).
Fig. 1. Textured polygonal 3D model of Denisova Cave.

a, b – entrance zone; c – Central Chamber.
Fig. 2. 3D model of the cave cut at 0 m level; coordinate grid is shown.

Fig. 3. Visualization of the location of archaeological finds in the virtual space of the 3D model.
Fig. 4. Textured polygonal 3D model of lithic artifacts. 
a – sidescraper (stratum 12); b – Levallois point (stratum 11).

Fig. 5. “Cloud of finds” in the eastern gallery.

Fig. 6. 3D model of the cave cut at +1 m level.
Fig. 7. User interface of the application. “Cave” window.

The presentations have four windows that can be switched arbitrarily. In the “Globe” window, user can explore the virtual globe with embedded model of a cave, and analyze the location of a cave and surrounding landscape. The “Cave” window presents the 3D model of the cave and other objects (Fig. 7). The “Cloud of Finds” window visualizes only the location of archaeological finds within archaeological horizons. In the “3D Model of an Item” window, a user can explore 3D models of finds and switch between them.

Conclusions

The created 3D models and software can be used for presentations as well as for various research tasks. Thus, the function of horizontal cuts with 10 cm scale spacing makes it possible to make accurate plans of the whole karst cavity or its particular portion at any elevation level. Vertical sections of the cave can be made and distance between objects inside it can be measured. The model can also be used for verification of existing archaeological schemes and creation of a new topographic base. A wide variety of filters provides an opportunity to rapidly pinpoint any artifact or group of artifacts relative to other objects. Importantly, the model can be used for visualization and analysis of horizontal and vertical orientation of an artifact within the layer. The model allows the planigraphic analysis in any scale – from square or sector to the cave as a whole. The presentation can also be used for virtual travel in the cave, including free online tours. This is especially important for the remote and hard to access heritage sites such as Denisova Cave.

Acknowledgments

The authors would like to thank S. Baykova, A. Ivanov, and D. Linovsky (Trimetari Consulting LLC) for laser scanning and 3D modeling; and S. Kotelnikov (Navgeocom LLC) for useful consultations.
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Received February 11, 2014.