Explicit Generation of 3D Models of Solution Caves for Virtual Environments

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Abstract – *Caves have a long history of use in virtual environments for entertainment purposes such as movies and computer games. Yet Speleology, the study of caves, is rarely drawn upon in the process of creating three dimensional cave models. In this paper, we discuss the formation of caves and how this knowledge can be applied in the creation of cave models for virtual environments. We propose methods to create three dimensional cave models based on the type of cave passages. Given curves representing faults in rock or flow of water, we can create a coarse level of detail model for a cave passage.*

Keywords: Synthetic Environments, Caves, Phreatic Passage, Vadose Passage, and Combination Passage

1. Introduction

Underground and cavernous environments have always been popular in level design of computer games, from as early as Dig Dug to more recent series such as Tomb Raider and Halo. The increasing complexity of environments in 3D computer games places a large demand for artist created content like textures, models, and maps. One solution to this problem is to increase the efficiency of the artist by developing more powerful or user friendly tools. Alternatively, the process of model and texture generation can be automated.

There is a large body of work on algorithmic generation of content. Procedural animation techniques can be used to create water [3], fire [7], and smoke [2]. Procedural texturing avoids the bandwidth cost associated with loading images [5]. Given methods to generate buildings and road maps, entire virtual cities can be made [9]. The creation and placement of artificial plant life in outdoor scenes has also been extensively studied [12]. Generation of cave environments is one area that has not yet been deeply explored.

Caves are natural voids underground that are large enough for a person to enter. The most common method of formation of caves is dissolution, when rock is dissolved by acidic water. This type of cave is referred to as a solution cave. The formation of a solution cave can take several thousand years, and can only occur if there is sufficient groundwater recharge to dissolve rock and enough drainage of the solution to remove sediment from the area. This type of cave also often features intricate mineral formations, called speleothems, which are formed by precipitation after the primary cave passages are made.

In this paper we introduce methods to create 3D models of solution cave passages that can be combined to represent an entire underground cave system. We describe the process that forms these caves in order to explain the shapes that they tend to have. Using this information, we describe methods to explicitly create surfaces for floors, ceilings, and walls of cave passages.

2. Related Work

Many caves are simple enough that they can be visualized using cave maps. A cave map consists of the plan, or overhead view, in addition to the extended profile, or side view, of a cave. Figure 1 shows an example of a cave map which was made by the San Diego Grotto [14], an affiliate of the National Speleological Society.

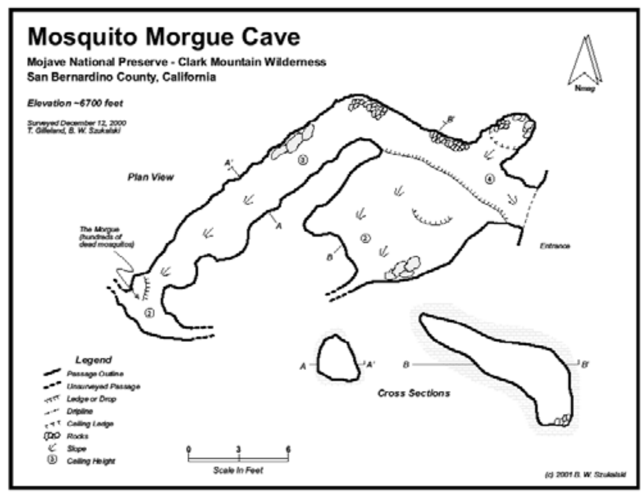

Figure 1: Cave map of the Mosquito Morgue Cave

Spatial information used to create cave maps is obtained by surveying. Locations in the cave are selected as survey stations where measurements are taken. Along with a position and orientation in space for each station, the distances to the walls, ceiling, and floor of the cave are recorded. While this spatial data is limited, it is suitable for software that can create 3D line drawings [20]. Other programs attempt to create polygonal models using surveyed data [4], [15], [18], and [21]. Some examples of these 3D cave models are shown in Figures 2 and 3. While these models provide more visual information than a cave map, they are not detailed enough for use in a realistically styled virtual environment.

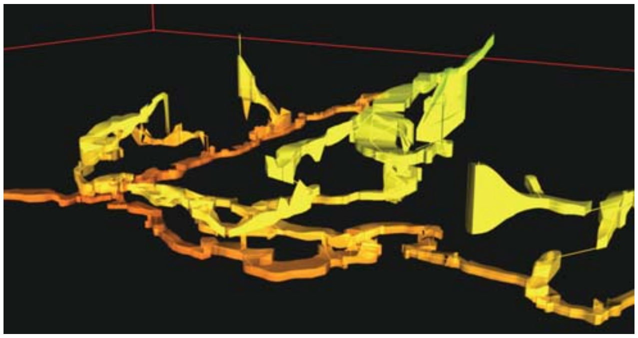

Figure 2: 3D cave model from [15]

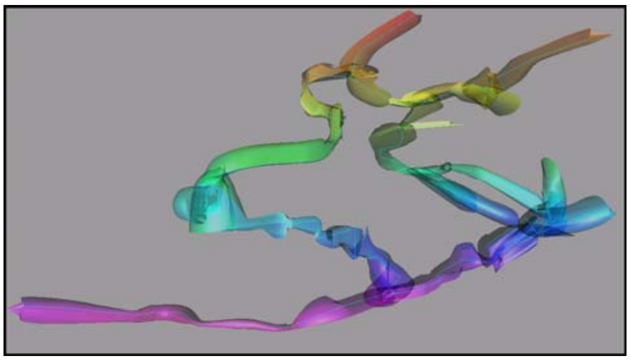

Figure 3: VRML model generated using Compass [4]

It is possible to obtain more accurate spatial data by taking laser or ultrasound scanning equipment into a cave [13] and [16]. In addition to the expense of the hardware, there is a large time investment as well. In the process of scanning the Wakulla Springs underwater cave, on average one hour of work produced raw data for 84.2 meters of cave passages [1]. With a total passage length of 6,409 meters, the amount of time spent to scan the entire cave was 76.1 hours.

Since survey data is limited and scanned data contains no information specific to caves, there is no standard data structure for representing caves. Some geographic information systems use surfaces for splitting a volume into regions [19]. Volume elements, octrees, and constructive solid geometry can also be used to represent regions [17]. An object oriented model for representing a cave is introduced by Gong, Lin, and Yin [8]. The bottom and top surfaces of a cave passage are stored in triangulated irregular networks, or TINs. TINs are similar to heightmaps in that they store singular height values in a two dimensional grid. This restriction means that they cannot represent a surface with arches or overhangs, which are common in landforms like canyons.

3. Solution Cave Morphology

When water absorbs carbon dioxide, a weak carbonic acid is formed. This can occur during rainfall or from contact with dead plants within the soil. Water descends through soil and other porous materials until it reaches the surface known as the water table. At this surface, groundwater pressure is equal to the opposing atmospheric pressure, so the volume beneath is fully saturated with water.

Solution caves are formed by acidic water dissolving rock. Groundwater flow moves the solution containing the sediment out of the cave system. Nearly all caves form by expansion of existing openings or weak points in solid material, such as joints and bedding planes [10]. Joints are gaps in rock and bedding planes are divisions between strata of sedimentary rock [6].

The general shape of a cave passage is determined by where it forms: above or below the water table [10]. Underneath the water table, phreatic passages are formed. An example of a phreatic passage widening over time is displayed in the top left of Figure 4. Since the region is fully saturated with water, dissolution occurs evenly and the passage widens in all directions over time, resulting in rounded, horizontal shapes.

Vadose passages form above the water table by rapidly moving and descending water. The bottom left of Figure 4 depicts a vadose passage. The speed and amount of water flowing through a vadose passage is variable. As the floor lowers over time, the width of the passage varies as well. The resulting passage looks similar to a slot in a canyon.

Since the water table can rise and fall due to hydrogeologic activity, passages may have characteristics of both types. These are called combination passages. The two types of combination passages are shown in the right-hand images of Figure 4.

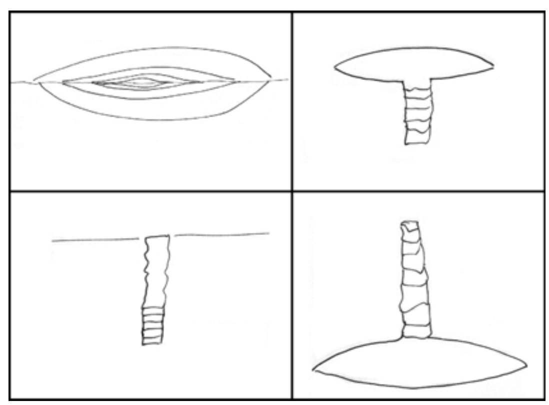

Figure 4: Cave passage cross sections

(Top left) Phreatic passage: The series of curves indicates the opening of the passage along the horizontal bedding plane over time.
(Bottom left) Vadose passage: The horizontal lines indicate the removal of material over time.
(Right) Combination passages.

Figure 5 is a photograph of a phreatic passage inside of Mammoth Cave National Park. The round, tube-like shape of the passage is indicative of its origin. Figure 6 displays a photograph of a vadose passage, also in Mammoth Caves. The floor meanders like a stream and the passage width varies at different heights.

Figure 5: Photograph of a phreatic passage

Figure 6: Photograph of a vadose passage

Cave passages can be used as a coarse level of detail when making a 3D model of a cave. Just as water flow creates the general shape of cave passages, it also carves fine surface details, called scallops. Cave scallops are spoon-shaped, asymmetrical depressions that are made by eddies next to the floor, ceiling, and walls in a cave [11]. Their size ranges from a diameter smaller than an inch to larger than a foot. A scallop's size is determined by the velocity of the water that formed it: the quicker the flow, the smaller the depression.

4. Cave Model Generation

In this section we describe methods to create 3D models of cave passages.

4.1 Curve and Surface Modeling

Given an ordered set of points, connecting them with line segments forms a zero order continuous curve. For higher levels of continuity, we can use the points as parameters to create a Bezier or B-Spline curve. Points on a Bezier curve B defined by the control points $\{P_0, P_1, \ldots, P_N\}$ for $t \in [0,1]$ are defined as:

$$B(t) = \sum_{i=0}^{n} \binom{n}{i} (1-t)^{n-i} t^i P_i$$

Figure 7 depicts two Bezier curves. The black squares are control points.

There are many methods to generate a surface given curves as input. Rotation of a curve around an axis creates a surface, as does extruding the curve along a vector. Swept surfaces are made by specifying a curve to extrude on instead of a vector. Figure 8 is the swept surface created using the curves from Figure 7. The curve on the left acts as the trajectory for the curve on the right.

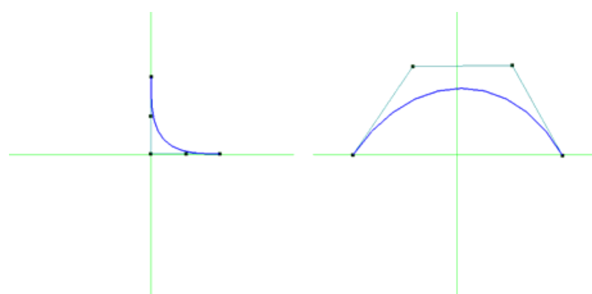

Figure 7: Bezier curves

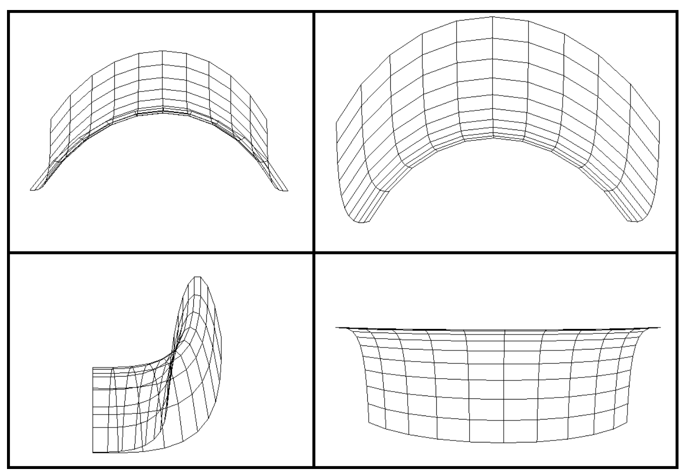

Figure 8: Swept surface made from curves in Figure 7

The views for each image are: (top left) front, (top right) back, (bottom left) side, and (bottom right) top.

4.2 Phreatic Passages

In order to generate a 3D model of a phreatic passage, as input we require a planar curve with no self intersections that represents the original gap that will be opened into a cave passage. This curve can also be thought of as the path of water movement. It will be used as a trajectory curve for sweeping.

Since phreatic passages form by uniform dissolution of surrounding rock, their shapes are also fairly uniform, mostly differing in size. The ceiling of a phreatic passage mirrors the floor, so we need only generate one surface and reflect it to create the passage. We could input the second curve manually, resulting in a passage like the one in Figure 9. The 3D model from sweeping and reflection shares the same characteristics as a phreatic passage.

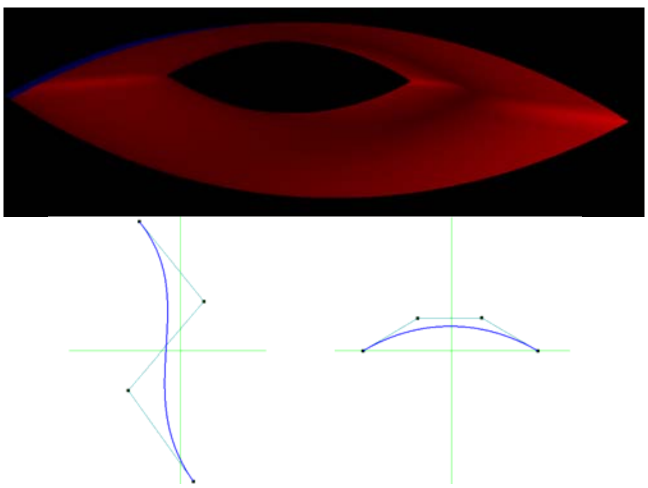

Figure 9: Phreatic passage and its generating curves

For further automation, we can parameterize a quadratic equation to generate the second curve. The width of a phreatic passage is proportional to its height, so to construct the curve C we use the formula:

$$C(x) = -\left(\frac{1}{size}\right) \cdot x^2 + \left(\frac{size}{shift}\right), \text{ for } C(x) > 0$$

As *size* increases, the passage becomes taller and wider. Since we only want the top of the arched curve, we omit points below a threshold. This threshold is adjusted by the user's selection of *shift*. For example, setting *shift* to fifteen will generate the curves in Figure 10, which are similar to the upper curve in the phreatic passage in Figure 4.

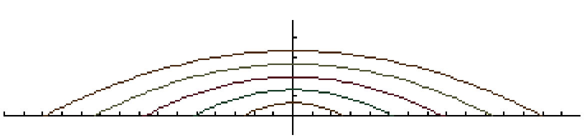

Figure 10: Quadratic curves

Curves for size = 10, 20, 30, 40, and 50, *SHIFT* = 15

4.3 Vadose Passages

Vadose passages are symmetrical to the center of the stream of water dissolving neighbouring rock, so again we take an input curve indicating the flow of water that we can use for trajectory in sweeping. As with phreatic passages, we could create a passage by manually entering a second curve. It should be a closed loop shaped like a cross section of the cave passage.

The shape of vadose walls is determined by how much water was present while that region was close to the floor, so we can use a second curve that is defined by the amount of water present for a given time. One wall of the vadose passage is made by sweeping this curve along the path of water. Rather than reflecting the surface, in this case we reflect the curve and sweep again since the symmetry of the passage is with respect to the flow of water rather than a plane. The floors and ceilings of vadose canyons are simpler surfaces, so to form them we connect the two walls at user specified heights. A passage made using this method is presented in Figure 11.

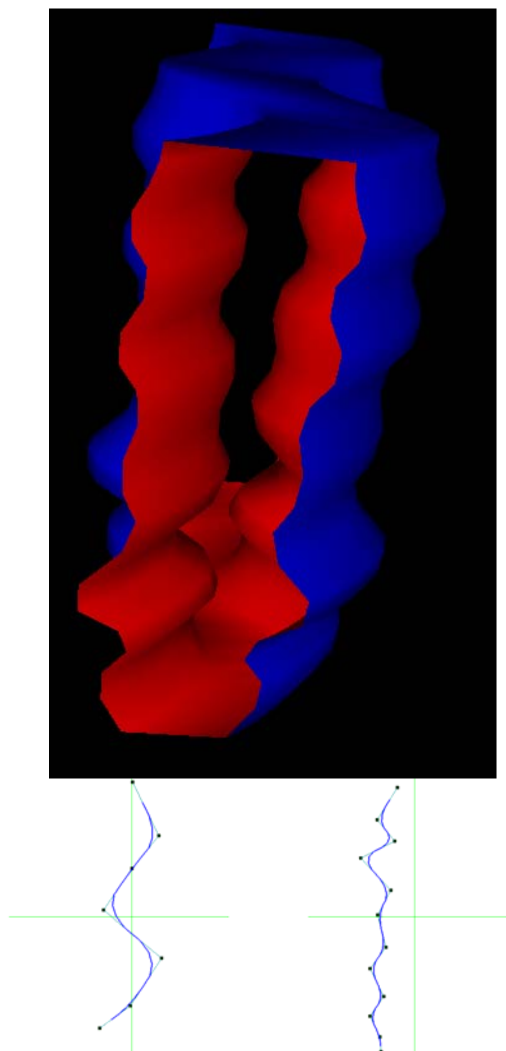

Figure 11: Vadose passage and its generating curves

4.4 Combination Passages

We can manually create a combination passage by sweeping a cross section along the flow of water just as with the two previous passage types. An example is provided in Figure 12. Alternatively, given a model of each passage type, we can combine them to form a combination passage. After selecting the location of each passage in world space, we need to eliminate vadose passage faces whose vertices are all within the phreatic passage and vice versa. Faces with some, but not all vertices in the other passages must be adjusted to avoid clipping through the other surface. Figure 13 demonstrates this process. Intersecting sections are clamped while fully contained sections are eliminated.

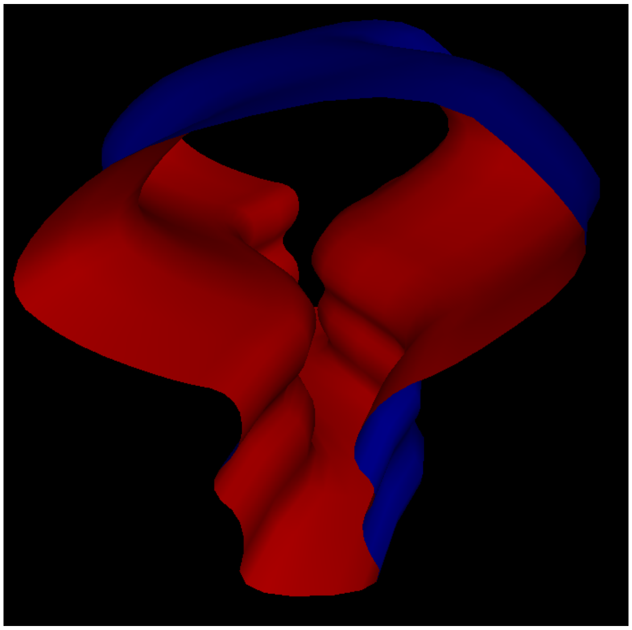

Figure 12: Combination passage

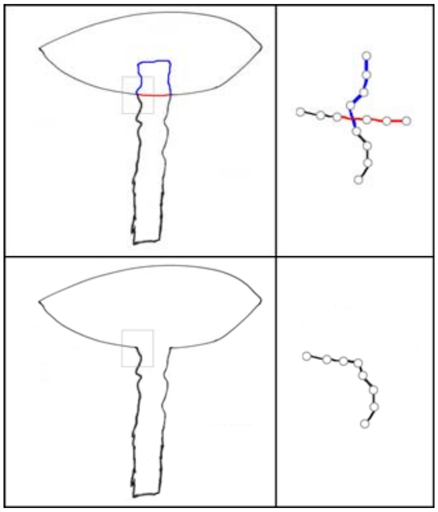

Figure 13: Passage overlap

(Left images) Combination passage before and after correction. (Right images) Closer view of discrete curves in the gray box on the corresponding images on the left.

5. Conclusion

We have described several methods of creating models of cave passages that take into account the process that forms solution caves. Figure 14 is a screenshot of a textured phreatic passage. While these models do not provide all of the visual details present in physical caves, since the models are surface based, we can use techniques like bump mapping and displacement mapping to add the remaining surface detail: cave scallops. The challenge of procedurally creating and populating a cave with speleothems is a task similar to covering terrain with procedurally generated plants. The task is feasible, but out of the scope of this paper.

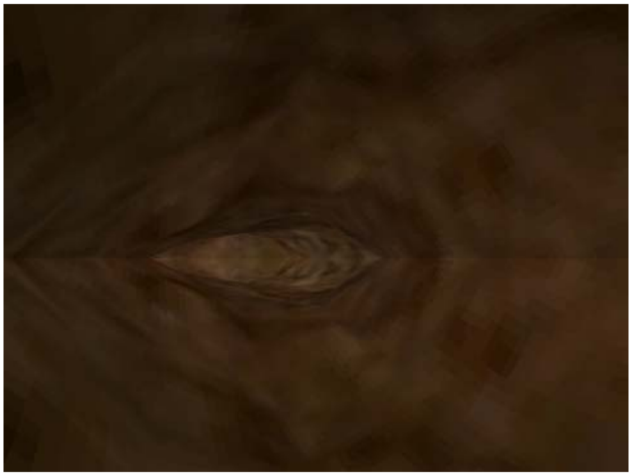

Figure 14: Artificial phreatic passage

Combining several models of passages to form a larger cave system requires additional work, removing intersections and patching gaps. Using procedural surface generation to make caves is also an area of further work. Figure 15 illustrates a cave made by reflecting a procedurally generated surface to make a second wall, similar to the process of making a vadose passage.

Figure 15: Artificial cave passage

It is difficult to model caves to a high level of detail. Much of the spatial data for caves is limited and higher quality data is costly to obtain. One element of cave formation is the porosity and the presence of gaps in rock, which is difficult to measure. The other element, the water cycle, takes thousands of years to create caves. Both of these factors make physical simulation a daunting challenge for use in procedurally creating caves. When the cost of simulating the cause is too high, instead we can observe the effect and attempt to create it directly.

Acknowledgements

We would like to thank Professor Edwin Scott Bair for his insight on Cave Geology as well as photos of passages inside Mammoth Cave National Park.

References

[1] B. am Ende, 3D Mapping of Underwater Caves. *IEEE Computer Graphics Applications*, *21*(2), 2001, 14-20.

[2] A. Angelidis, F. Neyret, K. Singh, & D. Nowrouzezahrai, A controllable, fast and stable basis for vortex based smoke simulation. *Proceedings of the 2006 ACM Siggraph/Eurographics Symposium on Computer Animation*, SCA, 2006.

[3] R. Bridson & M. Müller-Fischer, Fluid simulation: SIGGRAPH 2007 course notes. *ACM SIGGRAPH 2007 Courses*, San Diego, CA, 2007, 1-81.

[4] Compass, http://fountainware.com/compass/

[5] D. S. Ebert, K. F. Musgrave, D. Peachey, K. Perlin, & S. Worley, Texturing & Modeling: A Procedural Approach, Third Edition (Morgan Kaufmann, 2002).

[6] M. Filipponi & P.-Y. Jeannin, What makes a bedding plane favourable to karstification? - The role of the primary rock permeability. *Proceeding of the 4th European Speleological Congress*, 2008.

[7] A. R. Fuller, H. Krishnan, K. Mahrous, B. Hamann, & K. I. Joy, Real-time procedural volumetric fire. *Proceedings of the 2007 Symposium on interactive 3D Graphics and Games*, 2007.

[8] J. Gong, H. Lin, & X. Yin, Three-dimensional Reconstruction of the Yaolindong, *Cartography and Geographic Information Science*, *27*(1), 2000, 31-40.

[9] Y. I. Parish & P. Müller, Procedural modeling of cities, *Proceedings of the 28th Annual Conference on Computer Graphics and interactive Techniques SIGGRAPH*, 2001.

[10] A. N. Palmer, Origin and morphology of limestone caves, *Geological Society of America Bulletin, 103*(1), 1991, 1-21.

[11] A. N. Palmer, *Cave Geology* (Cave Books, 2007).

[12] P. Prusinkiewicz, & A. Lindenmayer, *The Algorithmic Beauty of Plants* (Springer-Verlag, 1990).

[13] K. A. Robson Brown, A. Chalmers, T. Saigol, C. Green, & F. d'Errico, An automated laser scan survey of the Upper Palaeolithic rock shelter of Cap Blanc. *Journal of Archaeological Science 28*(3), 2001, 283-289.

[14] San Diego Grotto homepage, http://www.sdgrotto.org/

[15] P. Schuchardt & D. A. Bowman, The benefits of immersion for spatial understanding of complex underground cave systems. *Proceedings of the 2007 ACM Symposium on Virtual Reality Software and Technology*, 2007.

[16] W. I. Sellers & A. T. Chamberlain, Ultrasonic cave mapping. *Journal of Archaeological Science 25*(9), 1998, 867-873.

[17] X. Tan, F. Bian, & J. Li, Research on object-oriented three dimensional data model, *Geospatial Theory, Processing and Applications*, 2002.

[18] Therion, http://therion.speleo.sk/

[19] A. Keith Turner & C. W. Gable, A Review of Geological Modeling, *Three-Dimensional Geologic Mapping for Groundwater Applications*, 2007.

[20] The Survex Project, http://survex.com/

[21] WinKarst, http://www.resurgentsoftware.com/winkarst.html