

CAVER QUEST 3D VIRTUAL CAVE SIMULATION OF SNOWY RIVER IN FORT STANTON CAVE

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Abstract

Virtual worlds, or 3D simulations through which an avatar can travel, are becoming a common means to display products or provide training in new environments. This paper describes the steps in producing the 3D virtual simulation of Snowy River in Fort Stanton Cave, New Mexico. A traditional cave survey and map with cross sections was used to produce a 3D meshed surface of the cave walls using the *Blender* software package. Photographs were taken of the walls, ceiling, and floor and merged together. The merged montage was applied to the 3D mesh walls as a “texture”. *Unity3D* was used to integrate an avatar into the scene to view the cave. *Unity3D* was also used to generate pop-up educational cave notes with relevant text and more detailed photos. A gaming element was added to engage the public and test what had been learned before allowing access further down the passage. The detailed steps in this overall process, and the photographic techniques developed including recent updates are described in this paper.

Introduction

Methods for portraying the underground structure and complexity of a cave have advanced over the years since the first hand sketches of early explorers. Perhaps the earliest computer word game, *Colossal Cave Adventure*, was developed by caver Will Crowther and others, finding its way to most of the computer mainframes in the 1970’s. Survey tools allowed plan-view maps to be generated along with cross sections and vertical profiles. This enabled experienced cavers and cartographers to understand the nature of the cave, but those maps were not readily understandable to the general public. High quality photographs brought the beauty and majesty of the cave to the general public, and video cameras have extended that capability. Bill Franz created a virtual tour of Lava Beds caves a decade ago using Apple’s QuickTime (Ingham, 2013, personal communication).

Recently 360° panoramas have enabled the public to view a cave room in great detail in all directions from a

single location and zoom in to see the details of the walls (Four Chambers Studio, 2011, Bunnell, 2013, Burger, 2013). The *CAPS* program and website (Crowell, 2013) has combined such panoramas into an exploration program that jumps from panorama to panorama as you explore the cave.

This paper describes the next step in cave portrayals in which a 3D virtual world of the cave is generated where one can assume the role of a virtual caver as an avatar and walk through long extents of the cave, inspecting the entire passage as desired (Figure 1). In this world, an accurate model of the cave wall configuration is textured with actual cave photographs. The result simulates the feeling of caving because the viewer can explore as desired and become immersed in the experience.

The development of the Snowy River simulation in the Caver Quest software is used as an example (Lipinski et al, 2013). The software can be installed on a PC or a Mac with an OS X operating system. DirectX 9.0 video driving software (free download from Microsoft) would also be needed, but this is common software with most modern computers. K. Ingham’s team is developing a similar portrayal of selected lava caves in El Malpais National Monument for the National Park Service. The simulation incorporates many educational outreach techniques (Ingham, 2013, personal communication; Northup, 2013).

Use for Scientific and Public Outreach

The 3D virtual cave can be used as a public outreach tool since it can be hosted on a cave management web site or distributed as desired. Once the 3D model is created, it can be loaded with numerous educational opportunities. In Caver Quest, there are a series of icons on the cave walls that the user can click on and see a pop-up cave note with a description of scientific, historical, or cave protection information relevant to that area, as well as more detailed pictures. To further engage and educate

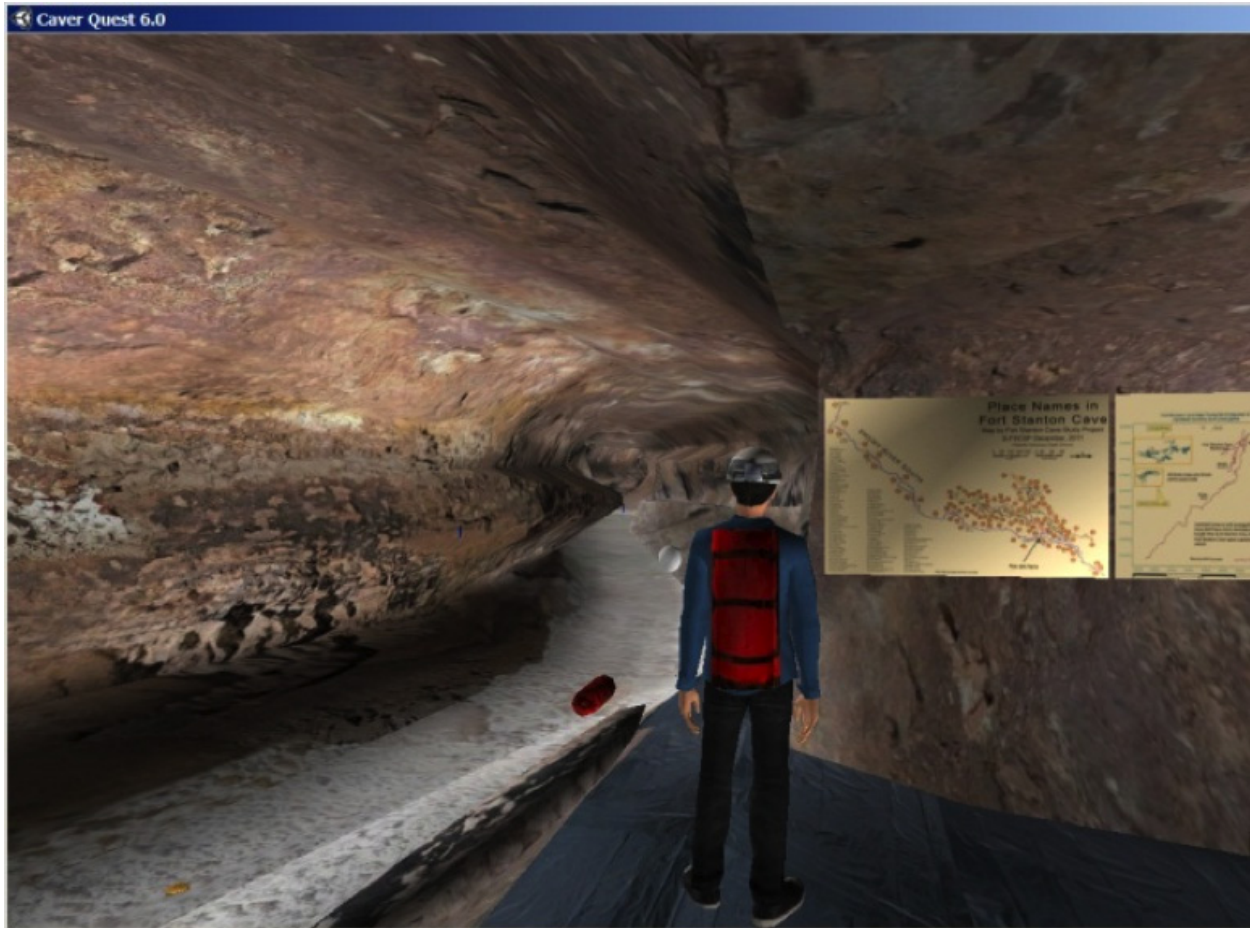


Figure 1. Screen shot from *Caver Quest* near Turtle Junction with Snowy River in Fort Stanton Cave.

youth, there are a series of barriers in the passages, which can only be passed when an exam that tests what has been learned is passed (Figure 2). There is also an overall challenge that the gamer is pursuing.

The 3D virtual cave portrayal has the potential to become a working scientific tool. The set of detailed photographs that are obtained for the wall texture can serve as a set

of “before” pictures relative to any unforeseen event, whether it be floods, vandalism, general wear on the cave floor, mineral growth, or biological changes as the climate changes. Having the individual photographs assembled into a montage that is textured onto the cave wall makes it much easier to understand positional relationships among them.

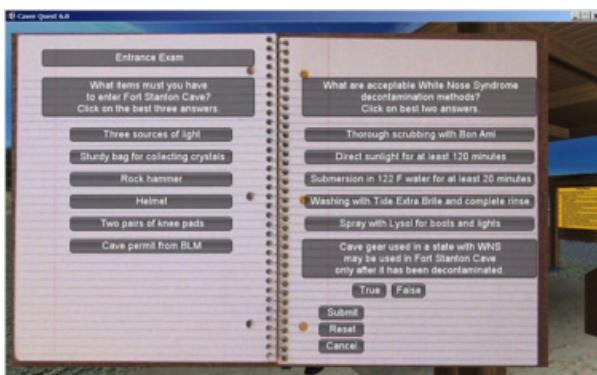


Figure 2. Exam to enter the cave.

The 3D simulation also allows scientists with diverse areas of expertise to walk through and examine the cave without needing to be there in person. This opens up the scientific investigation of the cave to a much larger range of experts, who might not otherwise be able to access the cave because of lack of funding, lack of time, handicaps, age, physical fitness, or limited access due to bat closures. The first step in the scientific method is observation, from which a hypothesis, experiment, and conclusion can follow. The cave simulation opens this first step to a very large audience, which can then be followed up with targeted research.

As an example, the observation of boxwork in the ceiling of Snowy River at Turtle Junction was first made (by J. Corcoran) in *Caver Quest* (Figure 3). The recognition that a spring-like feature in the Snowy River bed occurs below a major surface drainage was first made in *Caver Quest*. Observations like these could lead to hypotheses about the origins of boxwork, or the role of surface drainages in water insurgence in the river bed. This could be followed by targeted mineralogical studies and radionuclide dating to establish the timelines for water transport and mineral buildup. An assessment of difficulty in obtaining specimens, or the tools needed to do so, could be had using the virtual cave simulation.

Method for Generating the Simulation

The steps in generating the simulation are as follows:

1. Obtain an accurate survey, map of the cave, (including plan view and cross sections), and survey line digital data
2. Use the map and data to generate 3D mesh of the cave walls, floor, and ceiling).
3. Obtain a complete set of overlapping photographs of the cave walls, ceiling, and floor in the areas of interest.
4. Merge the photographs into one or more montages, remove dark spots and boundary lines, and adjust scale as needed.
5. Apply the photo montages to the cave wall as texture.
6. Import the textured 3D set of cave walls into an avatar gaming engine.
7. Add a caver avatar with assorted camera views and animations, then add educational cave notes, challenges, tests, etc.
8. Export to the desired platforms (PC, Mac, iPad, etc.)
9. Deploy as desired (museums, visitor centers, web sites, universities, etc.)

Obtain Survey and Map of Cave

There are several options for obtaining a good cave survey file and map. For this project we obtained the data set and maps that were generated by J. Corcoran using *Compass* software by Fountainware (Fish, 2013). This step is essential for establishing dimensional control for the simulation.

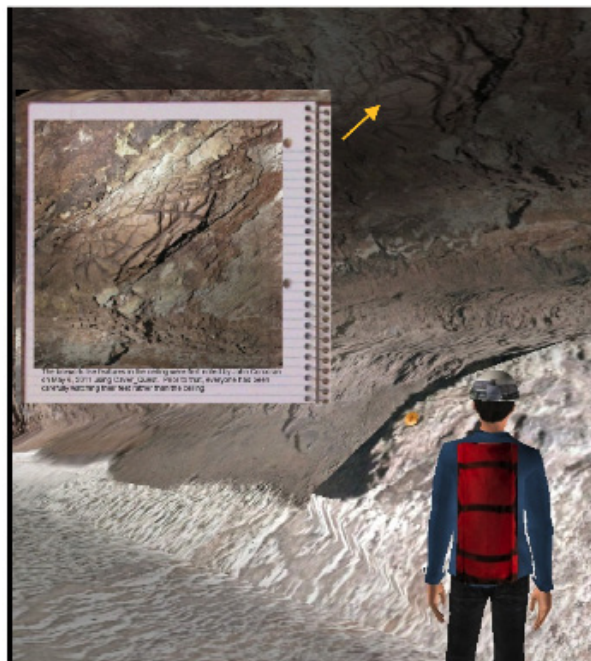


Figure 3. Box work in Snowy River ceiling in *Caver Quest*.

Generate 3D Mesh of Cave Walls

There are numerous 3D modeling tools to choose from, such as *Blender* (Blender Foundation, 2013), *Maya* or *3DS Max* by Autodesk (Autodesk, 2013). For this project, we used *Blender*. *Compass* has an option to export the survey line and the cave walls in DXF format, which can be imported by *Blender* (and other 3D software). The walls are based on left, up, right, and down measurements at each survey station, so this portrayal is very approximate. But it does give a rapid portrayal of the full cave.

For public or scientific outreach, a more accurate portrayal is needed. For this work we used the following process:

1. Import the survey line as a DXF file into *Blender* to serve as a proper scale for the maps and to serve as a control on the floor elevation.
2. Create a multi-point closed ring in *Blender* and oriented it vertically to serve as a cross section; we used 32 points, but using more points yields greater fidelity.
3. Import a scanned image of the cave cross section map at a particular survey station into *Blender* and adjust it to the correct scale.
4. Adjust the cross section points so that they approximated the cross section map shape.

5. Import a scanned image of the cave plan view at that location and adjust the scale.
6. Extrude the ring of points a set distance (one or more passage diameters).
7. Adjust the end of the extrusion to match any changes in shape indicated by the plan view.
8. Make additional adjustments based on the next cross section or passage photos.
9. Add features indicated by the plan view map or passage photos.
10. Repeat extrusions and adjustments until the next station is reached.
11. Adjust the elevation of the last extrusion (and intermediate ones) as needed, based on the line survey.
12. Repeat steps 6-11 until you have a significant amount of passage modeled and are ready to apply the texture to the walls.

Figure 4 shows a *Blender* screen shot with a top view of the extruded cave walls superimposed on a plan view from the map. The insert shows an isometric view of the resulting passage walls.

Obtain a set of wall photos

This step can be done at any time. The goal is to obtain a set of photographs that can be assembled into a smooth collage and used as texture on the 3D cave walls. There are standard techniques for obtaining a 360° azimuth panorama from a single location, but a 360° panorama is not appropriate for this application. Photos looking down the cave passage will have very oblique views

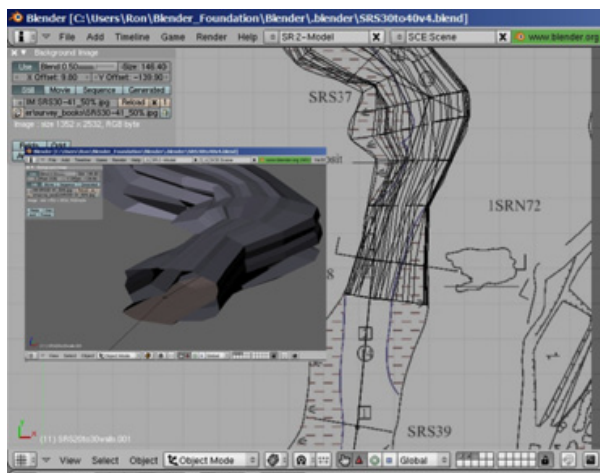


Figure 4. Extruded passage walls overlaid on plan view map of Snowy River in Blender3D.

of the walls and will result in pixels that are extremely stretched horizontally when applied to the wall. The passage will look good when viewed from the original camera location, but will look smeared and bad from other locations. Experience has led to the following recommendations:

1. Shoot the photos looking directly at the wall, not down the passage.
2. Shoot a cylinder of photos about the cave passage axis before moving to the next photo station.
3. Move the camera along the passage a distance that allows at least 20% overlap with the previous “cylinder” of photos. Use a tripod placing the lens at eye-height (~1.6 meters).
4. The photo line should be in the center of the passage horizontally.
5. Use a lens with at least a 90° field of view to minimize the number of photos at each station.
6. Use stitching software like Photoshop or Hugin, but do not expect it to work automatically. The near objects will move more than the far objects as you move the camera down the passage. You will need to manually merge photos using layers to smoothly blend them.
7. Provide uniform lighting across each individual photo to avoid dark blotchy areas. Currently we are using the compact Nikon SB-20 units, which have 5 levels of strobe power and a wide-angle lens setting. Two assistants hand-hold and point the strobes, one about 20 feet from each side of the camera. The resulting exposure is checked and improved as required.

Clearly, digital photographs are needed for this application, although one could use film and scan the result later if preferred. Five to ten megapixel cameras are sufficient for efficient blending. But high-resolution photos could be taken to serve as a database and then scaled to a smaller size for the 3D simulation as needed. Current work using a Nikon D-60 in RAW format requires a 1/4 reduction in JPEG file size for best final blending. Precision alignment of multiple frames simplifies stitching by reducing the need for rotation of each photo. There should be enough “bookkeeping” to properly relate the photos to the cave map.

Both near “projections” and far away “flat walls” must be included. Special fixtures such as the Nodal Ninja 3

(NN3) may be required so that camera rotation from a single viewpoint can be obtained to minimize parallax (Figure 5). Lighting uniformity and speed of operation will increase as the lighting team gains experience.

Both floor shots and ceiling shots must be included. The initial Snowy River work illustrated in this paper used a “4-around” cylinder at each tripod location. Recently teams implemented a “6-around” cylinder. This allowed a direct view of the left and right walls, and two oblique views of the floor and ceiling for each wall. The extra overlap for the six shots allowed a significant improvement of the post-processing time with little impact on the in-cave time. Care was taken to minimize shadows from the tripod legs on the white floor surface, but always expect post-processing adjustment of tripod effects.

Adequate photo coverage is a function of lens field of view, cave dimensions and tripod spacing. Initially this project used 3-meter increments down the passage, but recent work used a 1.5-meter spacing to achieve better overlap. We have found that using modern equipment in a “manual” instead of an “automatic” mode is faster because you can pre-set the focus. A 1-2 second shutter opening with hand control of a radio sync unit and no



Figure 5. Our initial “light weight” tripod, NN3 fixture and CP-5000 camera were only chest high.

on-camera flash provides good results, as long as bright headlamps are not aimed at the target area.

The choice of proper lens is very important, but involves trading the number of photos at each station against the lens field of view, strobe coverage and post-processing distortion correction. Initial work used a WC-E68 converter lens on a Nikon Coolpix 5000 with an NN3 fixture. More recent work has been done with a 16 mm Nikkor (manual lens) on a Nikon D-60. We used *Lightroom* by Adobe (Adobe, 2013) to correct lens distortion and adjust the color and tone curves on the 16 mm fisheye photos.

Merge the wall photos

There are numerous programs for merging photos, such as *Photoshop* by Adobe (Adobe, 2013), *Hugin* (Hugin, 2013), and *ICE* by Microsoft (Microsoft, 2013). Such programs might work automatically for merging sections of flat walls. However, for sections where there is considerable relief, such as where the wall meets the floor, or there are large breakdown boulders in the foreground, the foreground will shift more than the background when the tripod is moved from the first position to the next position. For such cases the photos will need to be merged manually. Use of layers can help smooth the transition between photos. It helps if the lighting is fairly uniform in the original photos. The software can help flatten the lighting, but often there is still a visible mismatch.

Figure 6 shows a montage of 16 photos of the wall, ceiling, and floor of Snowy River between survey stations SRS12 and SRS13. The east wall has been inverted to make a continuous picture. This montage is ready to be wrapped onto the 3D meshed wall as a texture. Note that there are visible lines between the photos. This photo set was taken during the first trip for such photos in April 2011, and the techniques for good acquisition were still being developed. At that time we were using a compact CP-5000 with a wide-angle adapter and a NN3 panorama head. The original photos had dark shadows on each corner and required considerable pushing and processing. Due to White Nose Syndrome restrictions, we only recently had access to the cave to acquire better photos using the “6-around” process described above.

Figure 7 above shows a montage of 48 photos between SRS08 and SRS09 obtained recently using the improved

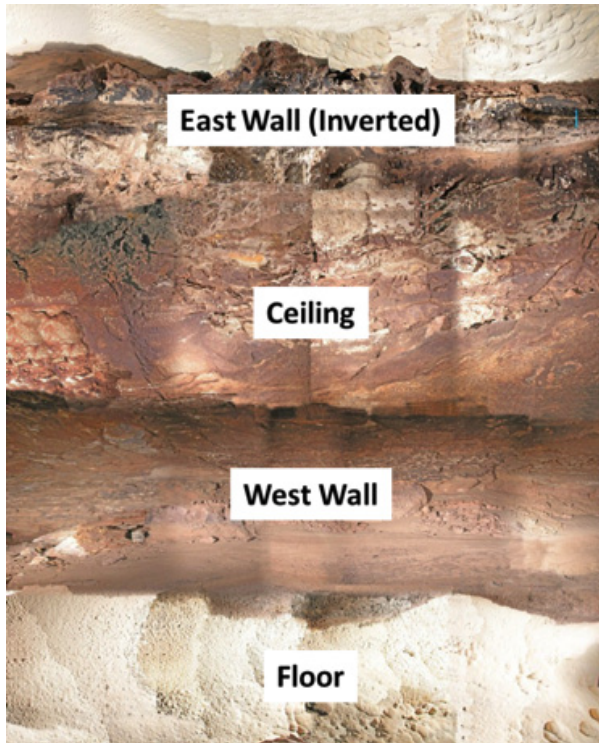


Figure 6. Merged photos from Snowy River (SRS12-SRS13).

techniques. The result is much more continuous and realistic. In addition, the use of a white card for color calibration resulted in a more accurate color rendition. Nonetheless, when the image in Figure 6 is applied to the 3D cave walls as a texture, the result looks fairly good and the interface lines are not as apparent.

Apply merged photos to 3D walls

The photo montages are applied to the 3D walls in the *Blender3D* program (Figure 8). It is important to preserve the proper orientation of the photo and any features such as layers. If there are ledges in the passage, the application will stretch the photo on the horizontal sections of the ledges. This is unavoidable unless direct shots are taken above and below the ledges and included in the montage.

Import textured 3D walls into game engine

Once the 3D walls are textured in *Blender*, they need to be imported into a game engine that allows generation of a full simulation, including an avatar. *Blender* can be used as a game engine to make avatars and games, if desired. But there are other options that may have features not available in *Blender* (Galuzin, 2012). We

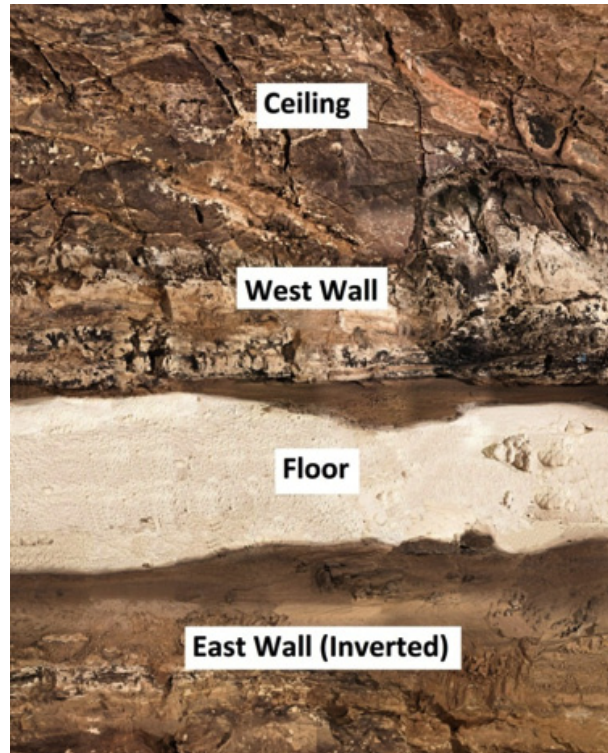


Figure 7. Improved merged photos from Snowy River (SRS08-SRS09).

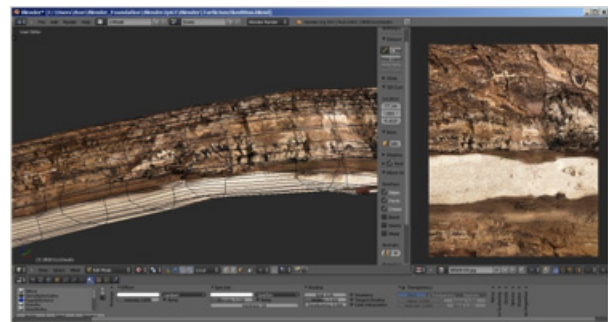


Figure 8. Merged photos applied to 3D walls.

initially used the *URU* game engine from Cyan Worlds (Cyan Worlds, 2013) (with gracious permission) to prove out the concepts, and then moved to *Unity3D* (Unity Technologies, 2013) to allow additional flexibility and deployability (Figure 9). Lighting can be adjusted as needed. It is important to select “mesh collider” for the cave walls and floor so that the avatar does not fall through them when imported.

Add cover avatar

An avatar can be built from scratch, with clothing, face, hair, and moving joints, and animations developed for it. But purchasing an avatar and importing it into *Unity3D*

can avoid this tedious process. The commercial market has developed many such options at reasonable prices, including animations. *Mixamo* (Mixamo, 2013) works directly with Unity3D, but there are also other options.

The avatar can be customized. For example, a caving helmet can be built in *Blender3D* and then attached to the avatar's head, where it will move smoothly with the head. A light source can be attached to the helmet if desired. A cave pack can be added similarly. All these are attached to the various body parts of the avatar via a parent-child relationship, which in *Unity3D* is a simple click and drag operation (Figure 10).

A standard third-person (synthetic) camera can be added to follow the avatar, using a camera-following script supplied by *Unity3D*. A first-person camera can be added by placing it inside the head of the avatar and adding a script to switch between the two. This is useful to allow closer inspection of the cave walls, both to enhance the experience, and for the benefit of scientists or cave managers wishing to view small details in a more natural manner.

Add educational cave notes and features

For educational outreach it is useful to have a means to provide pop-up information relevant to the area that the avatar is exploring. This is done in *Unity3D* with

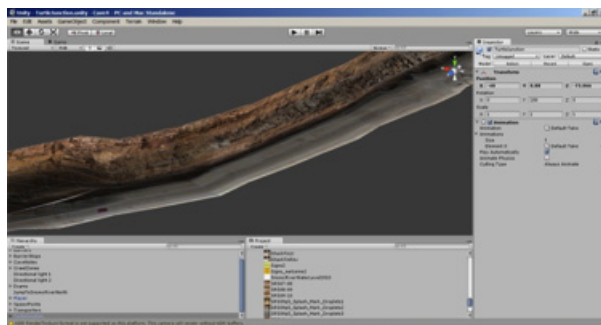


Figure 9. Import to Unity3D via *.fbx file.



Figure 10. Cave avatar added.

the standard graphical user interface (GUI) scripts and functions. In *Caver Quest* we use an icon on the cave wall to indicate the existence of such a cave note. When the icon is clicked, a notebook appears with relevant detailed pictures and text (Figure 11).

To enhance the appeal to youth, there is a game mode in *Caver Quest*. As the player moves down the cave passage, he encounters transportation devices that he can activate. Once activated, he can instantly teleport between them and save much time in exploring the cave. The ultimate goal is to activate all the transporter devices in the cave to make it ready for the next survey team that must survey the far reaches of Snowy River, over ten miles from the entrance. For management, there is an unlimited access option using these transporters.

There are also barriers in the cave passage obstructing progress in game mode. These barriers can be raised by passing an exam that tests the knowledge of the player. Answers to the exams can be found in the cave notes, so this motivates the player to stop and read each cave note, thereby increasing their knowledge of the cave.

Export to desired platforms

The nominal platform for the simulation is a personal computer with a large screen (or a projector, for large audiences). The free version of *Unity3D* can generate an executable and associated folder for a Windows-based PC, and an application package for a Mac OS-X. The purchased version of *Unity3D* has options for other platforms, such as Linux, Web based, iOS, Android, Xbox 360, PS3, and Wii. The small screens of some of the devices, (e.g. Android) may not display the cave to its full potential, but such devices are becoming very popular means for accessing information and will allow

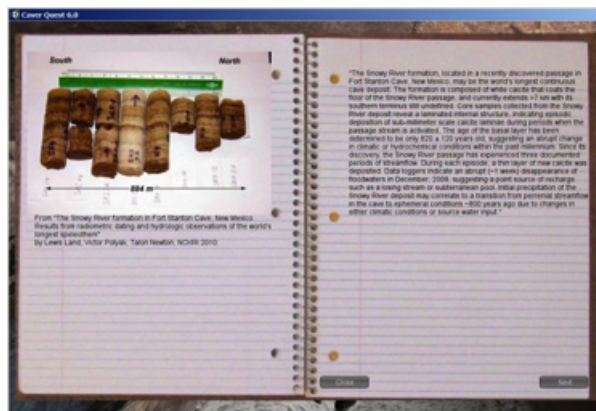


Figure 11. Pop-up cave notebook.

reaching a much broader audience. Nonetheless, in a dark room with a large screen, the 3D simulation can be a very good portrayal of the caving experience.

Deploy

Having a 3D virtual cave simulation opens up numerous options for its use. If there is a visitor's center associated with the cave, it can be displayed on computers at that location, or used as part of a presentation to an audience. It also can be placed on an agency web page, either as a web-based product that runs interactively directly from the web page, or as a stand-alone software package that can be downloaded. If the simulation is used for extensive outreach to the general public, some thought must be given to protection of the cave. The simulation is likely to encourage visits to the cave, which can be good for the community if there is a controlled access of the cave itself. The simulation is a good opportunity to instill proper cave ethics and conservation practices in those who use it. The simulation can also be made available to cave researchers via websites and conferences, or even as part of solicitations for research ideas.

Generation time and file size limitations

Much of the simulation generation effort is labor intensive. We started with a *Compass* file of Snowy River and a well-drawn map with cross sections in November 2010. After developing the appropriate techniques and skills with the requisite software packages, it took about 30 hours to extrude 300 m (1000 ft) of cave passages in *Blender* that matched the map. This included the varying width and depth of the river bed. Obtaining the photos took about 15 hours for 300 m of passage. Photo processing and stitching into a montage took about 10-15 minutes per photo, or about 60 hours for 300 m of cave passage (average diameter of about 5 m). From this we estimate that the time to extrude a mesh for the known 18 km of Snowy River could be about 2000 hours. Merging photo montages could take about 4000 hours. Acquiring the photos could take about 1000 hours. Adding cave notes and other features will add to the total, depending on the note density. These are substantial efforts, but not out of the realm of possibility. Shorter caves would take less time.

The full-resolution photographs in jpg format are about 1.5 MB each. The 18 km of Snowy River would require about 20,000 photos, or about 30 GB in jpg format. At full resolution, the simulation would convert those

photos into images of about 4 MB each, increasing the simulation size to about 80 GB. But at about 1/16 resolution, it would still show good wall detail, and the simulation would be about 5 GB.

Photogrammetry and Lidar

All of this might get faster and easier, or more detailed and accurate, with the implementation of photogrammetry or lidar. Photogrammetry uses two or more images that fully overlap but are taken from a known distance apart. One option might be to use two identical tripods with quick detach heads to speed the process. A Disto (simple laser rangefinder) can be used for quick distance measurements. Computer software then generates a 3D picture of the image surface based on pattern recognition for each small section of the two photos, and considerable math. Commercial software can generate a 3D surface mesh that can be imported by *Blender3D* or *Unity3D*, and also apply the photographs themselves to the surface as a texture. One example is *PhotoModeler* by Eos Systems, Inc. (Eos Systems, Inc. 2013).

Another example is Autodesk's *Catch 123D* (Autodesk Catch123D, 2013). With *Catch 123D*, no measurement of the camera location is needed; with a four-shot overlap, the software will determine by itself where the camera was located relative to the wall. A trial run with a video camera aimed directly at the wall as the photographer (J. Cox) walked down the passage resulted in a fairly good 3-D mesh and stitched photo rendering, even with marginal lighting. With good lighting, this might be the recommended approach for photogrammetry in caves. Results of our photographic work in Fort Stanton Cave may be found on the fscsp.org web site and also in Figure 12. The figure shows that the software correctly identified the four locations of the camera used for the series of photos.

Lidar (distance mapping with a laser) is another option for generating the 3-D mesh of the cave walls. However, it tends to require heavier equipment and more electrical power in the cave. It also is more expensive than simple photography. Nonetheless, it should be kept in mind when planning a 3-D mapping project.

Summary

Computer software and digital photography have advanced to the point where it is possible to generate a 3D virtual cave simulation that can be explored by an

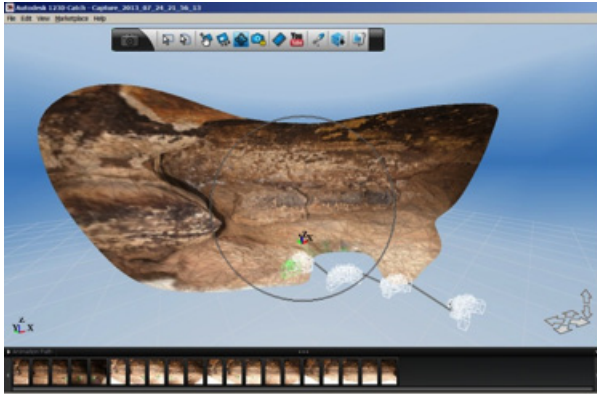


Figure 12. Photogrammetry example using *Catch 123D*.

individual through an avatar. The Fort Stanton Cave Study Project has generated such a simulation for Snowy River because of both the very limited access to that section of the cave and also the high level of interest in this unique resource. The effort was done entirely via volunteer hours using mostly free or low-cost software available on the internet and existing camera equipment. This suggests that cave managers and agencies might make this a tool for public and scientific outreach for sensitive caves or cave areas to reduce impact to those sections, and to allow participation by a greater audience, virtually.

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