Interactive Game-Based Exploration of an Underwater Paleontological Site

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***Abstract*—The Yucatan Peninsula contains many cenotes and underwater caves, some of which offer promising opportunities for archeological and paleontological research in the Americas. Here we describe the transdisciplinary research efforts as part of documenting and studying the skeletal deposits in the submerged Ice Age cave site of Hoyo Negro. We translate these efforts into a video game that represents the digital twin of Hoyo Negro for the public to explore. Through this game we seek to excite middle school children about opportunities in science through the rich content at Hoyo Negro and employing next generation science standards so that the game can be tested with middle school students and used as part of science curricula.**

Index terms—digital twin, NGSS, Hoyo Negro, digital archeology

I. Introduction

The underwater cave systems of the Yucatan Peninsula are one of the most promising frontiers for archaeological and paleontological research in the Americas. Following the end of the last Ice Age, rising sea levels flooded the region's maze of underground passageways and preserved a diverse Late Pleistocene fossil assemblage. A nearly complete, well preserved female human skeleton found in association with the remains of now-extinct megafauna in the submerged subterranean pit of Hoyo Negro presents a unique opportunity for interdisciplinary Paleoamerican and paleoenvironmental research [1]. This rarified setting offers a unique opportunity to share the work that served as a stage for a game in which players are divers searching the Hoyo Negro cave system for fossil remains of former inhabitants, including sabertooth tigers and giant ground sloths along with ancient relatives to modern bears and wolves.

Here, we describe the *Discover Hoyo Negro: The Cave of America's Human History* game that was developed as part of an interdisciplinary collaboration and neurodiverse internship program. We will describe the methods involved in initial data capture, converting the point cloud data into a representation that can be rendered in the Unity game engine, game design, planned alignment with K-12 next generation science standards (NGSS, [2]) and user experience testing. We intend for the game to be a tool that can be used over a semester or

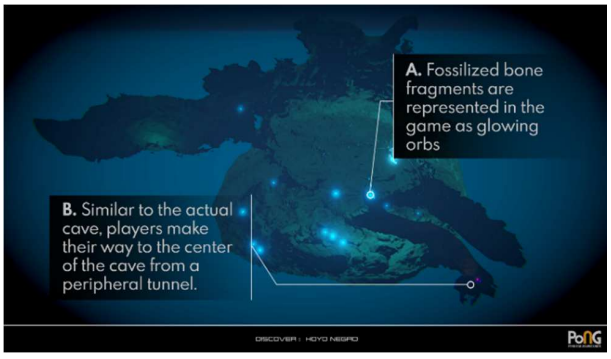

Fig. 1. Full model of Hoyo Negro underwater cave represented in Unity with fossil locations (A) and cave entry point (B) denoted.

the fauna, the methods and reflect on how each of these aspects impacts their own life in the modern day.

The setting, as well as the game, is visually compelling and invites players to search for fossils of several animals in progressively more challenging settings that demand use of technologies that involve sound-based localization and triangulation of locations to collect the fossils. In the process of the hunt for fossils, players will learn about field research including

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Fig. 2. Image of Hoyo Negro cave with diver on the right (photo by Roberto Chavez)

narratives of the divers involved in the Hoyo Negro cave documentation project. Players will learn about the technologies used to document the fossils *in situ*, including photogrammetry, and why this step is essential to recovering the story of each particular creature. Players will also learn about the ways in which fossil remains are examined once extracted and what data are obtained from these measures. We envision a fully-fleshed out game in which players can learn about paleontology, climate change, the high-tech tools involved with gathering and representing these data. Finally, the narratives of the vast array of scientists involved in the work which will challenge any individuals' imagined view of a scientist [3].

II. Data Capture

A. Photogrammetry

The Hoyo Negro Project has devised and deployed an innovative underwater reality-capture workflow capable of recording sites like Hoyo Negro in extraordinary detail providing scientists from across disciplines with the accurate and precise data needed for analyses and comprehensive site interpretation without impacting the integrity of the site. The Hoyo Negro Project team makes use of established structure-from-motion (SfM) photogrammetric techniques, though has developed an optimized image-capture methodology for such sites and has engineered a truly powerful and unique software solution for visualizing, analyzing, and sharing such sites [4].

The implementation of different image acquisition methodologies at different scales – site, feature, and object – has yielded multiple datasets, each comprising thousands of images. For each image set, camera pose estimates and 3D point cloud reconstructions are derived using computer vision and photogrammetry techniques – resulting in a set of geometrically accurate and complementary models of cave features as well as individual skeletal elements, together constituting a thorough digital record of the site appearance and topography.

These massive, image-derived datasets not only serve as documentation of the site, but enable project researchers from across disciplines to evaluate and annotate the digital site record remotely while guiding subsequent sampling and recovery activities. Reconstructed skeletal models have proven critical to current and ongoing paleontological analyses, allowing bones to be virtually studied *in situ* before (or without) removal from the cave. For skeletal elements that are selected for retrieval and further study and imaging, the digital record preserves the original spatial context and positions before removal. Additionally, imaging and analysis results for the retrieved object in turn become a part of the site record and can be inspected virtually alongside previously acquired data.

Viscore – the custom point-based visual analytics engine developed by Petrovic [5] – enables virtual access to sites such as Hoyo Negro, visualizing the entirety of the collected site record – multiple full-resolution point clouds, various imagery sets, including raw site photographs, as well as additional auxiliary and derivative data products – within a 3D virtual environment, on hardware ranging from a laptop, to a desktop-powered VR HMD (such as the HTC VIVE or Oculus Rift), to room-scale immersive visualization systems (e.g. tiled-display walls). The system provides a scripting environment for implementing custom tools and workflows leveraging the capabilities of the engine—while acting directly on the full data collection.

B. 3D Point cloud data data into Unity

The 3D point cloud data from Viscore was converted into Blender as a mesh and cleaned up substantially before importing the final mesh into Unity. Once in Unity, the fossil bones and bone fragments embedded in the matrix and represented as part of the mesh were highlighted as glowing orbs (see Fig. 2). With this conversion in place, players can explore the Hoyo Negro cave system rendered much as it is in the immersive visualization systems used for scientific research. There were some challenges for the team in implementing mesh objects in Unity requiring objects to be sliced down to basic polygons and reassembled to achieve accurate shading.

III. Game Design

The goal of our early game design was to render the Hoyo Negro cave system in an accessible manner for children to learn more about digital archeology and

paleontology, this particular Paleoamerican site, and more about now-extinct megafauna that lived in the region. The primary game mechanic required the player to navigate through the underwater cave system to find and collect fossilized bone fragments. Upon finding a collection of fragments for a particular animal, the animal was added to a digital journal (see Fig. 3) where the player can learn more about that animal. There are a total of six animal fossils in the game. These include the fossils of Naia (*Homo sapiens*), ground sloth (*Nothrotheriops shastensis*), cave bear (*Arctotherium wingei*), coyote (*Canis latrans*), sabertooth (*Smilodon fatalis*), and elephant-like gomphothere (*Cuvieronius*). In this initial version, players could collect fossil fragments from 54 orb locations, each unlocking a piece of information about a particular animal. We later recognized through play-testing that this phase took players too long and was not sufficiently rewarding, so the next phase contained 30 orb locations unlocking one of five pieces of information about the six fossil types (see Fig. 3) including: formal species name, species image, a discovery fact, a fun fact, and finally a collection of information that includes common name, age, size and weight. By putting these last pieces of information together, we were able to convey the same information while reducing the number of fragments that needed to be found. A robotic guide named Probe 7 assists players in activating additional game features for identifying fossils (see Fig. 4).

The initial game development work was conducted as part of a paid summer internship program for neurodiverse young adults at the Power of NeuroGaming (PoNG) Center [6] to help them gain workforce experience and skills. The team worked with a client (Rissolo) to develop a game that represented the Hoyo Negro project. Huang was the coach for the team and worked with Petrovic to convert the data and oversaw the design and development. After eight weeks of design and development, the game was presented at a showcase event online in August 2020 [7].

A. Updated game features

In early 2021, Huang and Chen had an opportunity to add features to the game to make it more engaging and to better align with the notion that fossil bone fragments are typically challenging to find than glowing orbs would suggest. Once identified and digitally captured, the fossil fragments need to be carefully extracted. As such, the team added different levels of difficulty for locating the fossil fragments that included triangulation and sound-based localization methods. The game was updated to include several new features, mainly a storyline along with a set of in-game features intended to make gameplay more immersive and complex. Probe 07 is a small robot character that was created to accompany the player while explaining the objective, story, and mechanics of the game as it does so (see Fig. 4).

Two search devices were created an implemented as tools to make the game more challenging and recognize the fact that locating the fossil fragments in the field is challenging. After completing the first stage of collecting the bones, players unlock a sonar device that rings and reveals a hidden bone when the player is in close

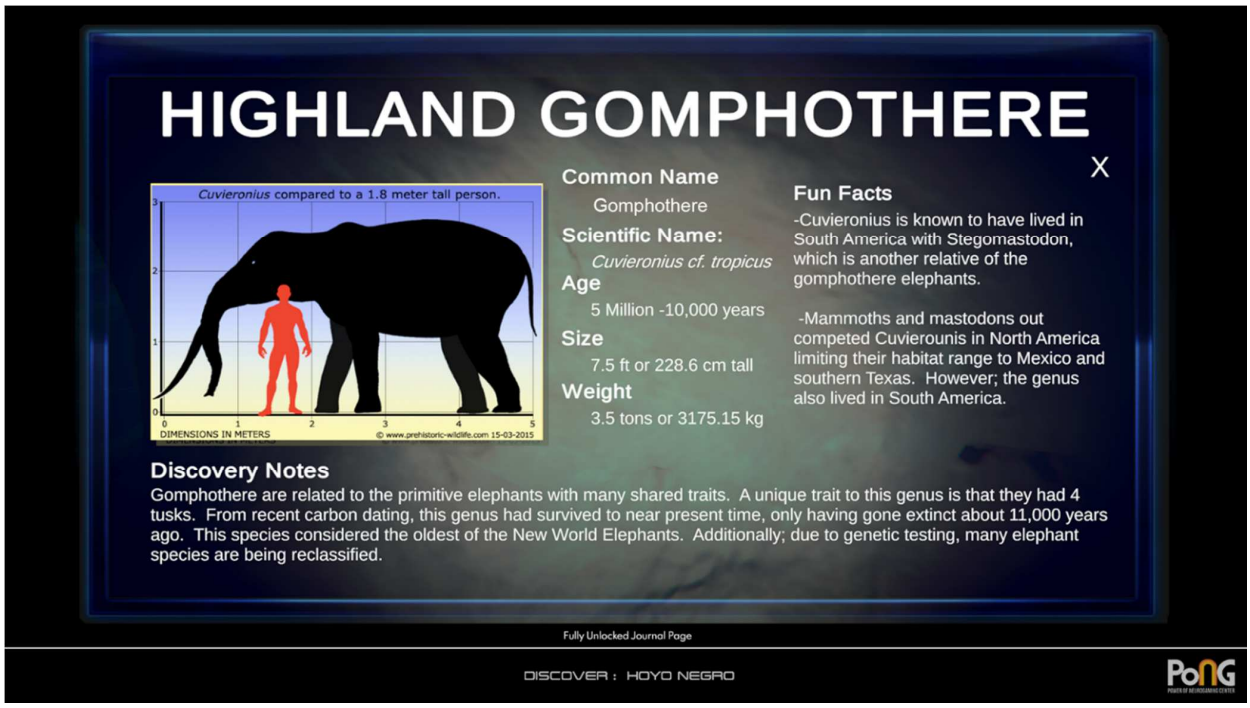

Fig. 3. Journal entry for the Highland Gomphothere. One of six journal entries in the game.

proximity. In the final stage, players unlock a triangulation radar that lights up in accordance with the located direction of a hidden bone. Probe 07 also provides power ups that the player can pick up to increase the precision of the search tools. The current version of the game can be found at https://pongcenter.itch.io/hoyo-negro.

B. Planned additions for NGSS

The NGSS were reviewed by the National Academies [2] to be consistent with the sought-after Framework. Guidance has been provided to implement NGSS in the curriculum and in terms of providing professional development [8]. The *Discover Hoyo Negro* game engages different practices, disciplines, and crosscutting concepts as defined by NGSS. In particular, the discipline that is most applicable is Engineering, Technology and Applications of Science. In the game, players learn about different technologies for digitally capturing the fossil site, for careful removal, testing and dating, for safety of the divers among many others. Virtually all of the NGSS practices described could be used with the game as part of a curriculum in part because the game involves various stages of data collection and interpretation. The crosscutting concepts that we see as best engaged through the game are patterns, cause and effect, systems and models, stability and change, interdependence of science, engineering and technology, and the influence of engineering, technology, and science on society and the natural world. We provide two specific examples of how *Discover Hoyo Negro* is appropriate for use in this Framework and can be adapted for different curricular needs.

The cenotes of the Yucatan contain a wide range of fascinating fossilized remains that tell a story of life in the region approximately 13,000 years ago (towards the end of the last Ice Age). Using the technologies employed by field and lab researchers working on the Hoyo Negro project, the resulting evidence tells a story of how the climate has changed during that time. By connecting the data observed at this site with other sites from the same era, we can examine patterns of the range of fauna that lived during that time. This knowledge can invite children to ask about how their own local environment would have been different 13,000 years ago and consider the flora and fauna living there. Since the remains of a nearly complete young female, called Naia, was found at the site, students who engage the game can then consider sociocultural relevance of science and technology to telling a story of who the earliest American people actually were. Other sociocultural issues emerge such as how might we respectfully examine these artifacts while recognizing that were part of a life of ancient people with goals, hopes and dreams for the future. As such, the transdisciplinary presentation of Discover Hoyo Negro offers a wealth of opportunities to engage different aspects of the NGSS Framework.

Fig 4. Probe 7 assisting player with features throughout the game.

The technologies and methods used for finding, capturing, recovering, digitally representing, and analyzing the fossil fragments found at the site offer another way to engage the NGSS Framework. We plan to build out a pre-game preparation module in which students learn about the technologies and skills needed to serve as members of the Hoyo Negro scientific team. In this module aspects of the various technologies are presented for students to explore and apply. This module will also include sections on the various backgrounds and preparations of the scientists participating in the project. We find this last part to be particularly exciting because it challenges common notions of who a scientist is and what she does. As a particularly telling example, one of the lead scientific divers working at the Hoyo Negro site was Susan Bird. Scientific diving is a very physically-demanding and dangerous activity that requires considerable training to engage it safely. In addition, however, scientific divers must be exceedingly perceptive and careful to not disturb the milieu of the site in which a fossil fragment is found so that it can be captured via photogrammetry. Bird was selected by the dive team to perform the recovery of Naia's skull due to her exceptional ability to execute delicate recovery tasks. This orientation to the many diversely skilled scientists participating in the transdisciplinary Hoyo Negro project will challenge student's notion of who a scientist is, what they look like and what sort of work they do [3].

C. User experience testing

The current game has been tested for quality assurance but not yet for usability largely due to the pandemic. We typically have a large number of individual middle and high school students visiting us at PoNG but due to schools and universities shutting down and/or dramatically reducing campus density, this has not been an option. Our group has developed ways to work remotely with undergraduate students and different adult populations but observing how children engage different game elements as part of a user experience evaluation and development plan has proven to be challenging to implement remotely. We would like to directly observe student game play once schools re-open and it is safe to engage in this type of testing. Fortunately, in person UX

testing with appropriate social distancing measures appears to be on the horizon in San Diego County, with local schools planning to re-open in mid- April 2021. We plan to work with middle school teachers and a focus group of students for initial user experience testing and to test our ideas for developing the preparatory module.

IV. Future Directions

We see the collaboration between the Hoyo Negro team and PoNG to be one that can develop an excellent STEM learning game for middle school children that engages a wide array of practices, disciplines and crosscutting concepts in the NGSS framework. As we look to the future of this line of work, we want to extend our thinking into the realm of citizen science. How might we represent the 3D photogrammetry data with sufficient precision in a game-like format that interested individuals after some training can participate directly in the scientific process. There is a history of citizen science in field work [9], [10] as well as on that has developed over the last decade in citizen science for digital reconstruction [11]. We see the work of faithfully capturing and representing archeological sites as a digital twins to be valuable not only for representing the in high fidelity for archival and academic purposes but as a means of engaging the public around scientific discovery and our shared history.

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References

[1] J. C. Chatters, D. J. Kennett, Y. Asmerom, B. M., Kemp, V. Polyak, A. Nava Blank, P. A. Beddows, E. Reinhardt, J. Arroyo-Cabrales, D. A. Bolnick, R.S. Malhi, B. J. Culleton, P. Luna Erreguerena, D. Rissolo, S. Morell-Hart, & T. W. Stafford, Jr. “Late pleistocene human skeleton and mtDNA link Paleoamericans and modern Native Americans”. *Science*, vol. 344, no. 6185, pp. 750–754, May 2014, doi: 10.1126/science.1252619.

[2] National Academies of Science, Medicine, Engineering, and the Division of Behavioral and Social Sciences and Education, and Board on Science Education, “Design, Selection, and Implementation of Instructional Materials for the Next Generation Science Standards: Proceedings of a Workshop”. National Academies Press, 2018.

[3] D. W. Chambers. “Stereotypic Images of the Scientist: The Draw-A-Scientist Test”. *Science Education*. vol. 67 no. 2, pp. 255-265, 1983.

[4] http://hoyonegro.ucsd.edu/

[5] http://chei.ucsd.edu/viscore/

[6] http://pong-center.ucsd.edu

[7] https://pong-center.ucsd.edu/ponginternship2020/

[8] National Research Council. Guide to implementing the next generation science standards. National Academies Press, 2015.

[9] K. Lambers, W. B. Verschoof-van der Vaart, & Q. P. J. Bourgeois. "Integrating Remote Sensing, Machine Learning, and Citizen Science in Dutch Archaeological Prospection" *Remote Sens*. 11, no. 7: 794. 2019. https://doi.org/10.3390/rs1107079410

[10] M. L Smith. "Citizen science in archaeology." *American Antiquity,* pp. 749-762, 2014.

[11] S. Cooper, A. L. R. Sterling, R. Kleffner, W. M. Silversmith, & J. B. Siegel. "Repurposing citizen science games as software tools for professional scientists." In *Proceedings of the 13th International Conference on the Foundations of Digital Games*, pp. 1-6. 2018.