ARTICLE

RAPID PROTOTYPING OF PALEONTOLOGICAL RESOURCES FACILITATES PRESERVATION AND REMOTE STUDY

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ABSTRACT—Fossil reproductions or replicas generated by rapid prototyping technology (3D printing) can aid public land managers achieve preservation, research, education and outreach goals. Replicas are a tool commonly used for remote study of scientifically important specimens. Specimens commonly rendered as reproductions include fossils or archeological artifacts. These specimens are generally susceptible to degradation or destruction if maintained in situ, whether through natural processes (e.g., weathering) or anthropogenic impacts. A reproduction is a viable substitute for the actual specimen, but traditional casting materials and procedures, such as plaster or latex molds, can lead to resource degradation. Photogrammetric methods to produce a digital record of two in situ fossils were utilized to create scale reproductions using a 3D printer.

INTRODUCTION

Photogrammetry, the science of using photographs to extract three-dimensional data through photo-documentation strategies, employs a non-contact method for acquiring resource information for monitoring and analysis (Matthews, 2008). Computer-aided photogrammetry generates digital information (virtual models) that when combined with recent advances in rapid prototyping technology, also known as 3-dimensional (3D) printing, allows for generation of accurate and precise reproductions with minimal or no physical contact to the original specimen. These 3D-printed reproductions can achieve sub-millimeter-scale resolution and rapidly provide models that will help facilitate the aforementioned goals of public land managers. We present two case studies where fragile and/or ephemeral fossil vertebrate tracks from National Park Service areas were photographed to create scientifically accurate replicas. This article emphasizes the methods used to generate scale reproductions via 3D-printing technology.

Fossil vertebrate tracks are a valuable scientific resource, are of great interest to the general public, and are present in at least 30 NPS managed areas (Santucci et al., 2006, 2009). Vertebrate tracks are sources of diagnostic information such as the morphologies of pes and manus impressions for extinct taxa. Because these types of fossils are valuable for the scientific information, they often represent challenges for preservation when maintained in situ, often at risk from weathering and anthropogenic impacts (Santucci et al., 2009). As such, these fossils are potential targets for vandalism, including poor attempts to make molds or casts, and loss from unauthorized collection (Santucci, 2002).

The two tracks photographed and prototyped for this study were from Gettysburg National Military Park (GETT) in Pennsylvania and White Sands National Monument (WHSA) in New Mexico. A single dinosaur track of the ichnospecies *Anchisauripus* was selected from GETT. The *Anchisauripus* track is one of three late-Triassic track morphotypes found on the stones quarried by the Civilian Conservation Corps (CCC) for the construction of a bridge during the 1930s (Santucci et al., 2006). This track was vandalized in the summer of 2013, highlighting the need for enhanced monitoring and preservation strategies for this resource. An unidentified carnivore track from WHSA is preserved in soft gypsiferous sediment, and is one of thousands of ichnofossils found in the late Pleistocene Otero Formation of the Tularosa Basin (Lucas and Hawley, 2002; Lucas et al. 2002). Further study of this significant track is hindered by the ephemeral nature of these tracks which rapidly weather once exposed at the surface. Utilizing standard model-making techniques would be impractical or ineffective for both of these examples and would result in damage to the resource. Instead, we collected photogrammetric data that in turn were used to create physical models of these fossils (Fig. 1A) using digital data and rapid prototyping technology.

METHODS

Rapid prototyping is used to generate 3D models of these valuable paleontological resources. The resolution and detail of a 3D model is dependent on several factors including photograph quality, software for model generation, and the rapid-prototyping hardware. Photograph quality is often described as proper geometry, and Matthews (2008) reports 66% overlap between adjacent images are critical to obtaining high-resolution results. Images of the selected specimens were obtained using a digital single-lens reflex camera with a 28 mm (1.1 in) lens; the focus and aperture settings were locked to ensure consistency between photographs. Scale was provided by a calibrated ruler and a stationary 12-bit photogrammetric target within each photograph series (Fig. 1B). Post-processing software such as Adobe® Bridge* was used to automatically adjust for the lens chromatic aberration but distortion was left in place. The processed images were rendered into a

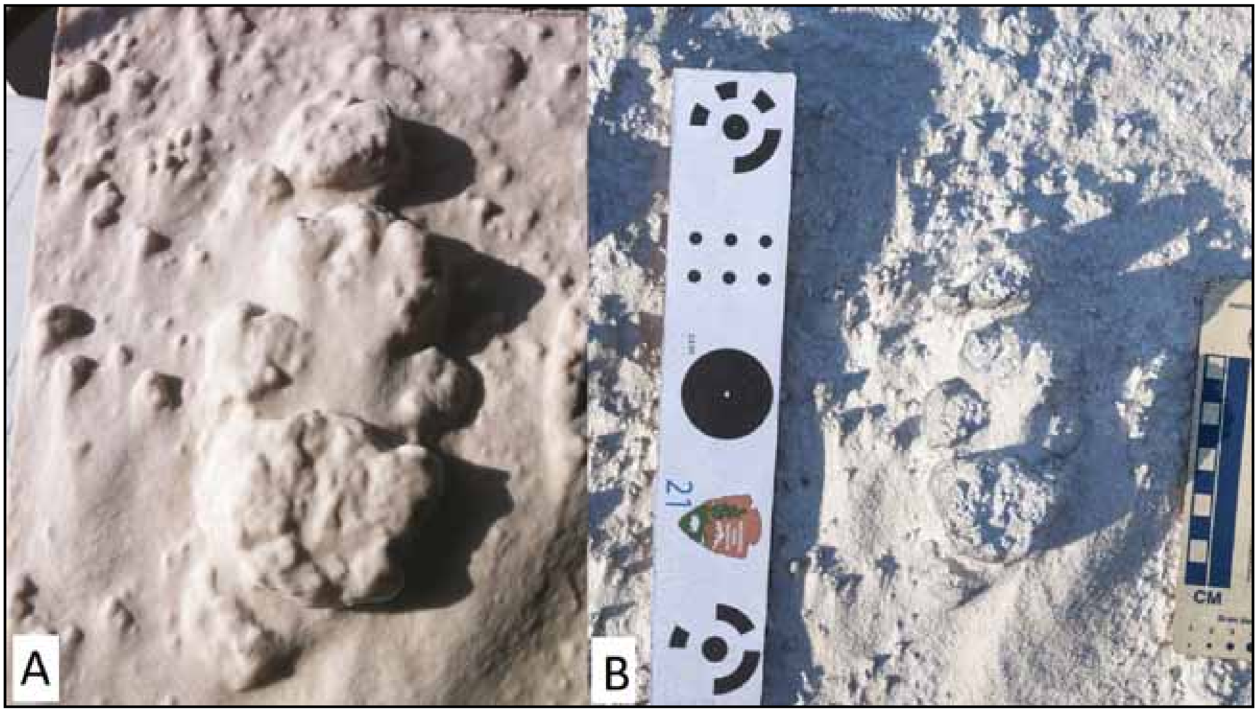

FIGURE 1. **A**, Full scale reproduction of an unknown ichnospecies track found in gypsiferous sediments at White Sands National Monument. This model was generated with photogrammetric data and 3D-printing technology; **B**, The track in situ, as digitally rendered by the software PhotoScan. Scale on right side is 10 cm (4 in); on the left side circular 12-bit targets on both ends of the scale bar aid the automatic photograph alignment process.

3-dimensional virtual surface model using the photogrammetric software PhotoScan Professional available from AgiSoft, LLC (http://www.agisoft.ru).

There are four principal steps to make a computer-generated surface model for creating a 3D-print. First, PhotoScan aligned the images by identifying and matching common pixels between the overlapping portions of photographs. These pixels were then used to generate a point cloud, and each dot was assigned a spatial reference with an X, Y, and Z coordinate. Second, the point cloud was refined using PhotoScan to eliminate poorly referenced pixels. The third step was the generation of a surface model, which was made by creating faces between the dots of a point cloud. The surface model was then exported to the open source software MeshLab version 1.3.2 (http://meshlab.sourceforge.net/), which was used to remove duplicated and null faces from the surface model. The fourth step was to transform the surface model into a 3D block model. The block model was created from open source software, and Blender for Windows, release 2.69 (http://www.blender.org) was used to add the base directly onto the surface model, to provide rigidity and support. The replica was printed using a Z Corp Z-310 3D-printer that employs gypsum powder and a binder, and constructs the model at a layer thickness of 0.076 to 0.254 mm (0.003 to 0.01 in).

RESULTS AND DISCUSSION

The processing time from collecting photographs until obtaining the replica in-hand was two weeks for both test cases. However, this length of time can be reduced: taking the photographs in the field required about 1 hour, processing time for the software was approximately 16 hours, and the actual printing took 4 to 6 hours to complete. With a concerted effort, one could photograph an object and have a replica delivered within a few days, depending on the scope of the project. It should be apparent that this time will increase with anything beyond hand specimens, such as the examples presented here.

The resolution of the printed replica tracks is correlated with image geometry and distance between the camera and the subject. The images of the *Anchisauripus* track were taken oblique (image angle was 40° to 60°) to the surface, creating inconsistent overlap within adjacent images. The images of the carnivore track were captured near parallel (angles between 85° and 90°) to the ground surface, providing a consistent overlap amongst adjacent images and thus provided a more uniform geometry between adjoining photographs. Furthermore, the replica of the *Anchisauripus* track was created using images that were taken 1 m (3.3 ft) above the actual track, whereas the unidentified carnivore track was photogrammetrically captured at a distance of 0.3 m (1 ft). As such, mm-scale features such as cracks in the *Anchisauripus* track are not apparent in the reproduction. In contrast, the quality of the carnivore track reproduction approaches the printer limitations. Submillimeter features are rendered in the replica, such as the mm-scale micro-dunes that are apparent on the surface of the track. Resolution is however restricted because sand-grain size features (~0.25 mm/0.01 in) in the digital model are not present in the 3D model.

High-resolution photogrammetry and associated 3D-prints of paleontological resources could be considered a form of preservation. The photogrammetric data can provide insights to degradation of resources using episodic photo-sets, thus monitoring can qualitatively assess change in resources (Matthews, 2008). The 3D-printing and digital data provide a means to record, collect, and study fossil tracks like those found within WHSA which are ephemeral and are otherwise too fragile to collect. Even when fossils are collected, they are quite often too sensitive for transportation because of the rarity or risk for loss. With photogrammetric data and the resulting digital information, a model can be prepared and shipped, or the fossils can be sent electronically, easily allowing others to print their own reproduction if desired. In the example of the Anchisauripus track, a 3D-print represents a mode to expand outreach and education for resource interpretive staff. A 3D-print will not compromise the security of the actual location, yet provides a tangible artifact to enhance the connection between the resource and the public beyond just a photograph.

CONCLUSIONS

The 3D models rendered from the photogrammetric information improve efforts for the protection, preservation and understanding of sensitive and easily disturbed or damaged resources. The photogrammetric data enhances documentation and long-term conservation efforts by providing a baseline 3D specimen to measure for subsequent photogrammetric analysis. Furthermore, photogrammetric data can be disseminated anywhere. Photogrammetry combined with the ability to generate a scale reproduction enhances public land managers' ability to share resources for remote study by researchers and can also provide material for visitor education and outreach.

ACKNOWLEDGMENTS

The authors are grateful to the assistance of the staff at Gettysburg National Military Park and White Sands National Monument. We are also grateful to N. Matthews, T. Noble, J. Kenworthy, J. Wood, and H. Pranger for their comments, suggestions and encouragement through the earlier versions of this paper. Furthermore, we wish to thank R. Wesseling of Ionic Models* in Louisville, CO for his expertise and providing the 3D-printing service for creating these reproductions.

*Mention of trade names, businesses or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

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