Merging Fossil Specimens with Computer-Generated Information

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Augmented paleontology—the use of augmented reality technologies to clothe fossil skeletons with soft tissues and skin—will let paleontologists bring their bare-bones specimens to life.

Paleontology is filled with mysteries about the plants and animals that lived thousands, millions, even billions of years before the first humans walked the earth. To answer questions about these organisms, paleontologists rely on the excavation, analysis, and interpretation of fossils. Embedded and preserved in the earth's crust, fossils are the remains or traces of ancient life forms, including bones, teeth, shells, leaf imprints, nests, and footprints.

Fossils can disclose how organisms evolved over time and their relationship to one another. While they reveal much, such as the general shape and size of ancient living things, fossils keep us guessing about these organisms' color, sound, and—most significantly—their behavior.

For several years, modern paleontologists have used 3D computer graphics to help reconstruct these pieces of the past.[1] State-of-the-art scanning technology produces 3D fossil replicas that scientists can process and study without physical constraints.

Paleontologists typically generate volumetric data sets for analysis, such as magnetic resonance imaging or computed axial tomography scans, and they use surface models for digital preservation and reproduction. To study ontogeny—an organism's growth and form—paleontologists apply mathematical models for simulation and visualization. Likewise, computer animations help study dinosaur locomotion. Beyond building knowledge of our world, the results of this work influence how dinosaurs appear in museums, illustrations, and movies, and as toys.

In the past 40 years, technological advances have continued to blur the boundary between real and computer-generated worlds. Augmented reality leverages this technology to provide an interface that enhances the real world with synthetic supplements. Paleontologists can use AR to present virtual data, such as 3D computer graphics, directly within a real environment rather than on a flat monitor. We coined the term *augmented paleontology* to refer to the application of AR to paleontology. AP seeks to

- support paleontologists in their research, and

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Augmented Paleontology Tools

Paleontologists can use the following tools, which embody several developing technologies, to create augmented paleontology displays.

The Virtual Showcase

This museum display provides an imaginative method for accessing, presenting, and interacting with scientific and cultural content. Conceptually, the Virtual Showcase is compatible with conventional showcases. It also allows the display of computer-generated 3D graphics, animations, and real artifacts within the same 3D space.

Potentially, such interactive presentations can be more entertaining and engaging than conventional, passive showcases. The Virtual Showcase turns the exploration of cultural and scientific objects into an interactive process that can enhance the museum visitor's experience and facilitate the learning process.

Driven by off-the-shelf PCs with conventional 3D graphics cards, the Virtual Showcase, shown in Figure A, provides stereoscopic viewing, a high and scalable resolution, better support for eye accommodation, mutual occlusion between real and virtual objects, and multiple user support. The Virtual Showcase is a projection-based, optical see-through display that consists of two main components: a convex assembly of half-silvered mirrors and a graphics display. It uses video projectors as controllable light sources that illuminate the showcase's contents on a per-pixel basis while the system presents view-dependent stereoscopic graphics to observers. A wireless infrared tracking device provides user tracking, which lets the system render the augmented graphics from the correct perspective.

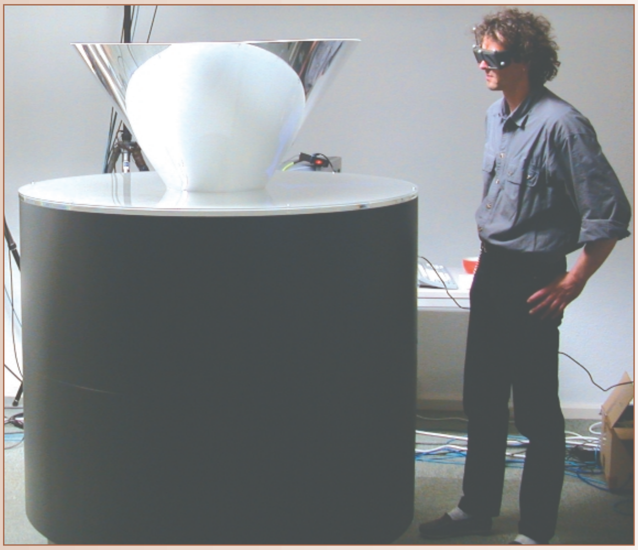

Figure A. Virtual Showcase. This example of a cone-shaped prototype supports two to three users, wireless user tracking, and a seamless surround view.

Video mixing

Originally developed for television special effects, video mixing combines video streams from cameras with computer-generated graphics, merging captured images of the real environment with synthetic images prior to displaying or recording them.

Using this technique to augment a 3D environment with computer graphics requires continuous knowledge of the physical cameras' parameters to ensure consistency between the two streams. To realize this goal, researchers apply computer vision algorithms to analyze captured video images and detect integrated landmarks within the real environment. These algorithms use knowledge of the landmarks' properties and of the camera's internal parameters, such as field of view and focal length, to reconstruct the camera's external parameters—its position and orientation. Knowing this information, a corresponding virtual camera can be defined that will render the graphical augmentation from the physical camera's perspective.

Projector-based augmentation

By replacing a physical object—with its inherent color, texture, and material properties—with a neutral object and projected imagery, projector-based augmentation can directly reproduce either the object's original or altered appearance. This approach effectively lifts the object's visual properties into the video projector.

Projector-based augmentation is ideal when the physical object is available for visualization, even if it forms a complex geometric shape. Multiple users can view the augmented object simultaneously, without using stereo glasses or head-mounted tracking devices.

For a high-quality augmentation, the system computes an image of the original object's textured 3D graphics model from the projector's viewpoint. When projected, the rendered image appears smoothly registered with the neutrally colored object, which changes its appearance accordingly.

- communicate the results of paleontology to museum visitors in an exciting and effective way.

An interdisciplinary team of paleontologists, graphics designers, and computer scientists has already applied the AP interface to soft-tissue reconstruction and the study of dinosaur locomotion.

SOFT-TISSUE RECONSTRUCTION

Despite the volumes of data paleontologists have already amassed, many questions about dinosaurs remain. Paleontologists seek to discover what dinosaurs looked like and how they breathed, smelled, and ate. Generally, only the fossilized bones and teeth—the hard parts—of dinosaurs are preserved. But these creatures' soft tissues, which formed their bodies and animated their bones, provide the keys to unlocking the secrets of dinosaur biology.

Previous research sought to remedy this situation by reconstructing soft-tissue components such as muscles, veins, arteries, and cartilage.[2] Soft tissues carve distinct marks in the bone's structure

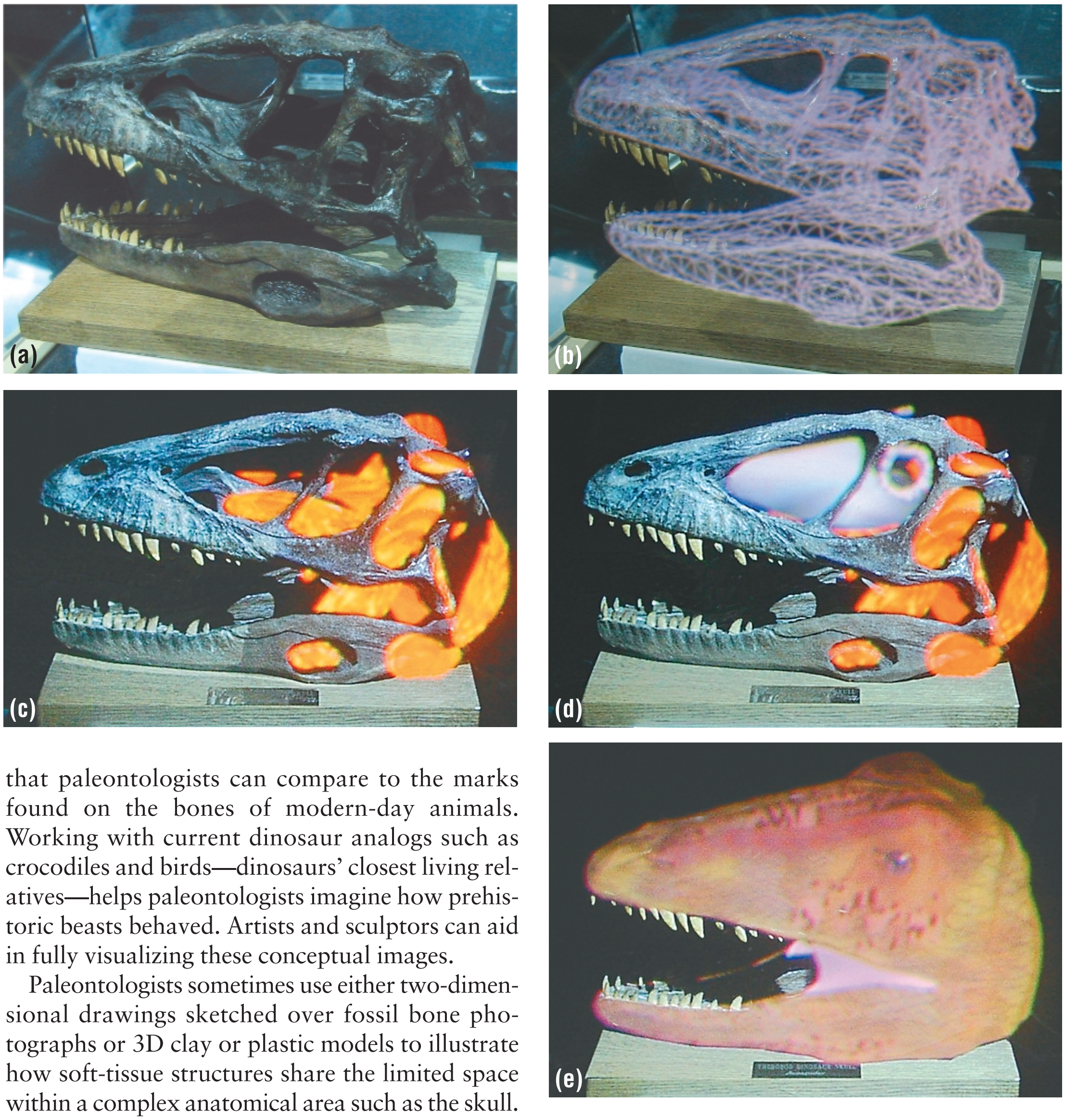

Figure 1. Visualization with the Virtual Showcase: (a) the physical skull of Deinonychus is placed inside the display, (b) a scanned skull geometry is registered to the real counterpart, (c) different muscle groups are augmented, (d) the paranasal air sinuses and the bony eye rings are integrated into the skull, and (e) the skin is superimposed on the skull.

that paleontologists can compare to the marks found on the bones of modern-day animals. Working with current dinosaur analogs such as crocodiles and birds—dinosaurs' closest living relatives—helps paleontologists imagine how prehistoric beasts behaved. Artists and sculptors can aid in fully visualizing these conceptual images.

Paleontologists sometimes use either two-dimensional drawings sketched over fossil bone photographs or 3D clay or plastic models to illustrate how soft-tissue structures share the limited space within a complex anatomical area such as the skull. Although museum displays commonly feature these forms of expression, a major drawback is that they lack dynamics and interactivity. Further, modifying these static drawings and sculptures is difficult.

Paleontologists can use AP to dynamically visualize reconstructed soft tissues that have been fully integrated with the fossilized bone structure. Then they can assess the conformational relationships of the reconstructed components to test the soft-tissue anatomy model. For example, paleontologists can use AP to directly assess how diverse anatomical elements, ranging from the eyeballs and tongue to the jaw muscles and nasal cartilage, share the skull's limited interior. AP lets paleontologists study how soft tissues accomplish biological tasks such as muscle contraction of the jaw, and how the bulging of those contracting muscles dynamically affects the conformation of surrounding structures.

For museum visitors, AP combined with digital storytelling enables a more exciting and interactive experience, and it has the potential for improving knowledge transfer.

FROM ANATOMICAL PACKING TO DIGITAL STORYTELLING

To demonstrate AP's benefits, consider the cast skull of a Deinonychus, an Early Cretaceous dinosaur, augmented with 3D computer models of reconstructed soft tissues and missing bones. Observers can perceive the real and virtual components together in stereo from any perspective using the Virtual Showcase,[3] a special projection-based AR display device that the "Augmented Paleontology Tools" sidebar describes in detail.

The bone and soft-tissue data sets for Deinonychus have been acquired from different sources. The skull bones, for example, were captured using 3D laser-scanning technology. After paleontologists assembled reconstructed muscles, eyeballs, nostrils, ears, sinuses, and skin in the lab, media designers premodeled them with an off-the-shelf modeling tool.

As Figure 1 shows, to visualize the packing process and present the final results with Virtual Showcase,

Figure 2. Superimposing foot motion: A mix of rendered graphics and live video superimposes the animated theropod foot skeleton over the real track.

the physical skull is placed inside the 3D display, then augmented with the reconstructed soft tissues.

The scanned geometric representation must be registered against its physical counterpart first. Doing so lets the Virtual Showcase compute the illumination and occlusion effects directly onto the skull's surface. A simple mouse-based interface can then interactively place the premodeled soft tissues inside the skull so that the paleontologists can investigate contact points and collisions with the physical bones and other soft tissues.

The display uses a stereoscopic graphics presentation to position the virtual components within the same 3D space as the skull bones. Multiple users can wear head-tracking devices to walk around the display and simultaneously observe the augmented artifact from different perspectives.

Simulating realistic occlusion effects between the physical bones and the virtual soft tissues is essential for packing and presentation. The Virtual Showcase is an *optical see-through display*. A drawback of such displays is that achieving realistic occlusion effects between real and virtual components is difficult. To overcome this difficulty, the Virtual Showcase uses controllable video projectors instead of simple lightbulbs.

The video projectors create view-dependent lighting effects on the real skull's surface. Generating shadows on the physical object exactly beneath the overlaid graphics, for example, lets virtual parts mutually occlude the underlying real surfaces. Having the skull's depth information, on the other hand, lets us cull the occluded graphics before they display. Thus, the physical bones can occlude virtual components and vice versa. This strongly enhances the interactive packing process and the presentation's realism.

To simulate interaction and behavior in different situations, we animate the virtual components during packing and presentation. To render the graphics, we use a conventional game engine that provides both high-quality animation and interactive frame rates. Enhancing the presentation with synchronized audio output and projector-based illumination lets us achieve an effective form of digital storytelling by dynamically fading in and out specific parts of the physical skull. During the presentation, different soft-tissue layers and components display over time, while a variety of multimedia aids—such as voice, text annotations, graphical animation, and lighting effects—explain their functions and relationships.

STUDYING LOCOMOTION

Paleontologists use AP to analyze fossilized dinosaur footprints left by theropods 210 million years ago.[4] Discovered on rocky exposures in eastern Greenland, the tracks of these bipedal carnivorous dinosaurs reveal how they moved about on two legs and how their locomotor pattern evolved over time.

These footprints can help paleontologists discern the similarities and differences between early theropods and birds, their living descendants. Shallow footprints made on firm mud record the shape of the bottom of the foot, but provide little information about how the limb moved while on the ground. Many of the Greenlandic trackways, however, were made by theropods that sank to varying depths in soft mud. Such deep prints record the path of the foot through a volume of sediment in three dimensions, thereby allowing reconstruction of limb motion.

This dynamic perspective has helped yield functional explanations of the deep tracks' many unusual

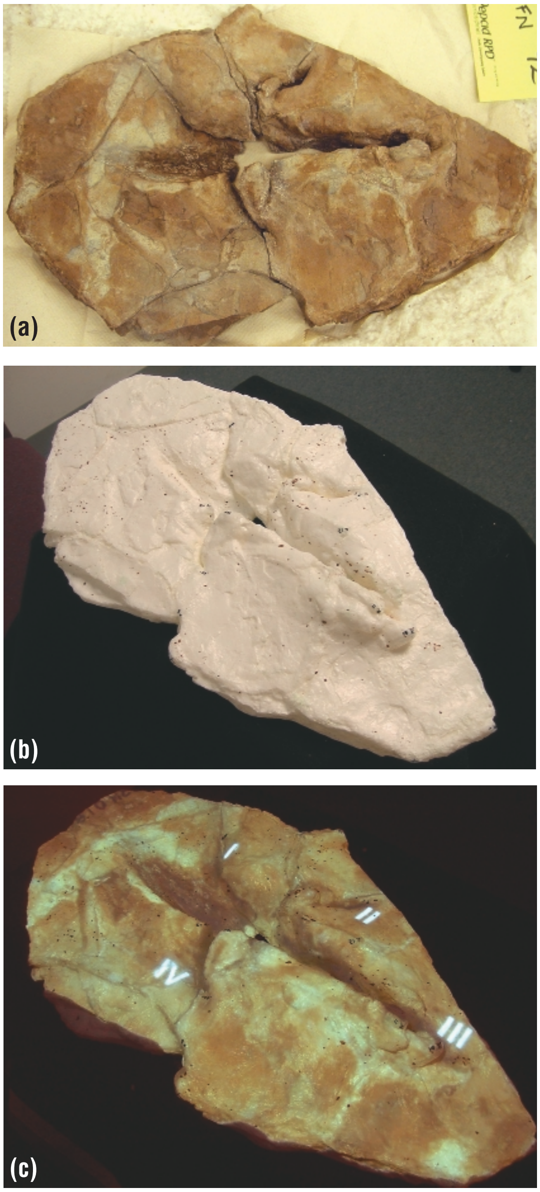

Figure 3. Projector-based augmentation of a therapod track. (a) The original track, preserved in Greenland's Triassic Fleming Fjord formation; (b) handmade cast of the shallow track; and (c) texture of the original track, with additional annotations that indicate the imprints of the toes, projected directly onto the cast.

features. For example, the elongate front of deep Greenlandic tracks strongly resembles the tracks living birds make, as when turkeys walk through deep mud. This finding verifies that the early theropods' toes converged as they lifted them from the substrate, a feature that many birds still retain today.

Other features provide evidence of important differences. Birds leave no sole prints because they quickly lift their ankles after contacting the ground. In contrast, all deep tracks from early theropods show a substantial sole print, indicating that the ankle did not rise up until much later in the stride cycle. The impression left by the first toe points backward in Greenlandic tracks, whereas the toe itself points forward in all of this age's fossil skeletons. Although characteristic of perching birds, a reversed first toe is surprising in these ancient theropods. In this case, however, the fossil record may be misleading. Three-dimensional computer simulations that use a particle system reveal that a forward-pointing first toe *can* create a backward-pointing slash in the surface as it plunges down and forward into the mud.

Tracking the motion

Video-based AR may help paleontologists analyze limb motion in extinct animals by allowing animated models to interact with physical casts of dinosaur footprints. To capture the live video stream of the surrounding environment, we use a desktop-based video mixing configuration and a conventional Webcam. The system uses a pattern-matching algorithm to recognize integrated markers, detect their appearance within the images, and estimate the camera's position and orientation relative to the markers. We then apply these parameters to set up a corresponding virtual camera that renders the graphics scene from the same perspective as the real camera. Finally, we merge both images and display them in real time on a desktop screen. As Figure 2 shows, this technique lets us superimpose a computer-animated model of a theropod's foot skeleton over a real track and verify the animation with the physical toe marks on the imprint.

Moving into the spotlight

In many cases, original fossils are not available to either museums or paleontologists. Further, local politics or concerns that moving the fossil might damage or destroy it can limit its availability. Even when fossils are available, various researchers and institutions often must share them.

In these situations, handmade casts sometimes must substitute for the real fossils. A cast can easily express the fossil's shape, but not its original texture and detail information, such as skin impressions. However, photographs *can* capture this information.

Instead of painting the cast with a texture, we use video projectors to seamlessly map existing photographs and rendered images directly onto the cast's surface. Figure 3 shows how combining a projector-based augmentation[5] with physical replicas can recreate artifacts in laboratories and museums located hundreds or thousands of miles from the original specimen.

A projector-based augmentation also provides interactivity. The display can dynamically change the lighting conditions and the surfaces' color properties. The augmentation can display additional information, such as annotations and highlights, directly on the cast as part of an interactive or linear storytelling installation. In contrast to a completely virtual model such as a textured 3D scan, a physical cast provides haptic and tactile feedback and natural, autostereoscopic, 3D perception.

The past decade's technological progress has improved hardware and software significantly, opening potential application areas for AR in general6 and AP specifically. Although today's AR technology resembles the early stages of virtual reality, researchers foresee AR developing at a much faster rate and offering a wider range of applications.

Initially, researchers will use AR for applications that do not require high-precision technology. Within the paleontology domain, AR should soon be feasible for educational purposes. Interactive digital storytelling setups in museums, for example, would let paleontologists display and communicate their findings more effectively. Such installations must, however, be stable, childproof, and affordable.

In terms of supporting paleontologists in their research, technology must evolve and become more cost-effective. Specifically, researchers must improve displays and tracking technology and make them affordable so that paleontologists, preparators, and restorators can effectively apply AP in their laboratories.

In the long term, mobile AR may become robust enough to support paleontologists during field trips and at dig sites. However, outdoor AR presents a much greater challenge than indoor AR, given the associated environment's larger scale and limited adaptability. User tracking and controlled illumination remain two of the main challenges confronting mobile AR. ■

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