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Short Paper

Augmented Reality for Sculpture Stability Analysis and Conservation

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Abstract

Augmented reality (AR) technology has provided museum visitors with more immersive experiences, but it has yet to reach its full potential for the conservators and historians who craft the exhibits and protect their cultural heritage. In this paper, we propose ConservatAR, an ongoing project that assists sculpture conservation in AR with physical simulation and data visualization. ConservatAR employs two techniques: a static analysis to predict tipping vulnerabilities for homogeneous sculptures, as well as a dynamic analysis for tipping detection and impact visualization of cracked and non-homogeneous sculptures during a user-controlled collapse. Formative user studies with conservators from the Museum of Fine Arts, Boston evaluate the usability and efficacy of our techniques, providing valuable insight on how AR can be best applied to art conservation.

1. Introduction

In 2002, Tullio Lombardo's Adam shattered after collapsing onto the Metropolitan Museum floor under the stress of its own weight: a tragedy lamented by the art conservation world for years to come [RMW*14]. In 2006, an accidental collision between a visitor at the Fitzgerald Museum in Cambridge, UK and an unsecured Qing dynasty-era vase triggered a domino effect that toppled a series of similar vases nearby [Jon06]. These pieces were eventually restored, but both incidents expose the potential for more robust conservation methods to predict vulnerabilities before damage occurs.

Computer simulation offers several potential benefits to current conservation tactics. At larger museums, it can act as a supplemental tool by exposing vulnerabilities that may not be visually intuitive to the conservators, prompting them to recruit a structural engineer for further investigation. Alternatively, smaller museums that lack access to structural engineers may adopt simulation software as a complete replacement for physical testing methods. This would not only save time and financial resources, but also eliminate the risk of damaging the piece during physical testing.

Augmented reality (AR) offers a unique mode of physical simulation with additional benefits for sculpture conservation, including more vivid data visualization. AR would also allow conservators to perform analyses where sculptures are displayed in practice, communicating a better sense of scale and position relative to the museum architecture, nearby objects on display, and surrounding visitors. As such, an AR application offers many valuable cues regarding potential vulnerabilities that an isolated, traditional 3D application lacks. Past work has applied AR to provide users with on-site guidance and information on famous archaeological locations and on-display artifacts [BPF*18, DCB*08, GD01, FZB*05].

Figure 1: *Conservators using our application at the MFA Boston.*

Hammady et al. [HMS20] suggested the use of mixed reality for improving engagement in the museum visitor experience. In contrast, the target users of our work are neither museum visitors nor the general public, but conservators and historians (Fig. 1).

We propose ConservatAR, implemented as an iOS application, to assist current sculpture conservation techniques by conveying vulnerabilities through AR visualizations specifically tailored for museum conservators. A group of conservators from the Museum of Fine Arts (MFA), Boston has tested our method, evaluated its benefits, and suggested additional functionality (Sec. 6).

2. Problem Statement

Model Acquisition and Import. To analyze the stability of a sculpture, we first construct a digital replica via photogrammetry. Supplying approximately 100 images of each sculpture captured at a range of view angles produces sufficiently detailed geometry

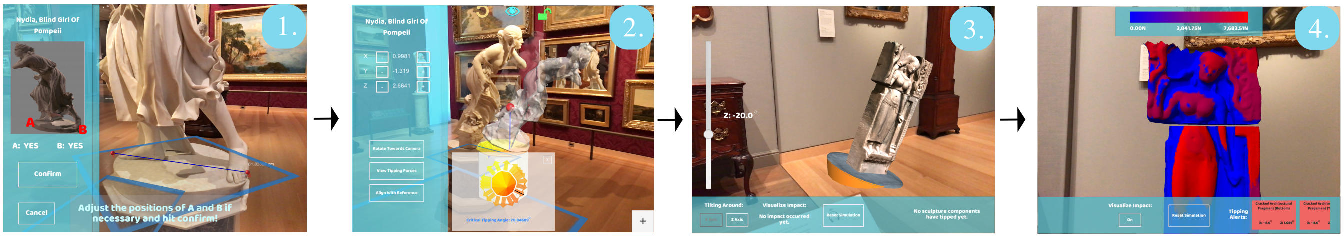

Figure 2: *User workflow pipeline for sculpture stability analyses. (1) The user configures reference points on a flat surface to import the AR model. (2) Within a static analysis, the user can visualize critical tipping vulnerabilities. (3) Then, in a dynamic analysis, the user interactively tilts the sculpture to observe tipping behavior and (4) visualizes the sculpture's ground impact upon collapse.*

with accompanying texture mapping. The models are then post-processed to correct artifacts and make appropriate separations for fully propagated cracks. During the import process (Fig. 2), the user places reference points on the base of the physical sculpture to generate the corresponding AR model with matching scale and orientation. ConservatAR arranges the AR replica adjacent to the physical sculpture (rather than an overlay) so that the conservator can more easily compare the two versions.

Static Analysis Mode. We developed an interactive method for deriving a sculpture's tipping vulnerabilities from its base geometry and mass distribution (Sec. 3). This method determines possible directions a sculpture may fall, highlighting the most critical scenarios. We assume sculptures are solid with a homogeneous material composition for mass distribution calculations. A combination of 3D AR visualizations and user interface graphics help communicate the range of vulnerabilities to a non-technical audience.

Dynamic Analysis Mode. As a second mode of stability analysis, our dynamic method allows the user to interactively tilt the sculpture in a desired direction and observe an animated collapse according to realistic physical simulation (Sec. 4). We developed a tool to automatically detect and report the corresponding tipping angle in real time and visualize the sculpture regions that withstand the highest impact with the ground. Unlike the static method, the dynamic method relies on user interaction rather than analytical stability calculations. Yet, it handles a wider variety of cases, including sculptures with widely propagated cracks and stacked segments of varying material composition. This method assumes that cracks are fully propagated across the sculpture, forming an approximately planar slice that separates the segments. Sculpture pieces remain intact as they collide with the ground during the dynamic analysis.

3. Static Analysis Methodology

Tipping Predictions. A sculpture tips by hinging around edges of the convex hull of its base. ConservatAR calculates the minimum tipping angle in each direction as a function of the sculpture's center of mass and convex hull base geometry (Fig. 3). The center of mass C is obtained from the sculpture's triangle mesh using a Divergence theorem method discussed by Bächer et al. [BWBSH14]. Let C_{proj} be the projection of C onto the sculpture's convex hull base. θ_i indicates the minimum tipping angle for edge $\mathbf{e}_i$: the angle of rotation around $\mathbf{e}_i$ at which the sculpture becomes unstable

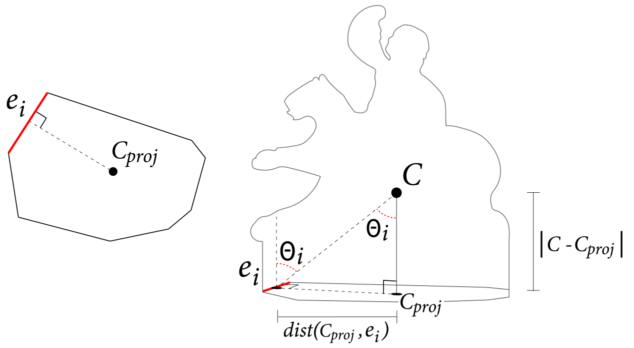

Figure 3: *Minimum tipping angle for a particular edge $\mathbf{e}_i$ of the sculpture base. (Left) Top view of the base with center of mass projection C_{proj}. (Right) Sculpture with potential tipping angle θ_i.*

and will fall due to gravity. Intuitively, this occurs when C passes outside one of the base edges. θ_i is calculated as follows:

$$\theta_i = \arctan\left(\frac{dist(\mathbf{e}_i, C_{proj})}{|C - C_{proj}|}\right) \quad (1)$$

where *dist* is the closest distance between a point and line segment.

Tipping Visualization. ConservatAR renders a 3D outline of the convex hull base around the AR sculpture, with each of its edges colored according to the severity of their tipping angles (Fig. 4). Each edge color is interpolated between red, yellow, and green according to the magnitude of its tipping angle, with red representing the smallest tipping angles (i.e., the highest vulnerability) and green the largest. On the user interface, ConservatAR programmatically generates a graphic of the convex hull base with an identical coloring scheme. This graphic is constantly rotating on the screen, such that it aligns with the user's perspective of the 3D AR base visualization. An arrow icon is placed perpendicularly to each edge of the base graphic, representing that edge's tipping direction.

When the user selects a base edge's tipping arrow, ConservatAR configures a static visualization of the tipping angle in that direction (Fig. 4). The original AR sculpture model remains upright, but is now given partial transparency. An opaque copy of the AR model is generated on top of the original, which ConservatAR rotates around the base edge by the corresponding tipping angle. As

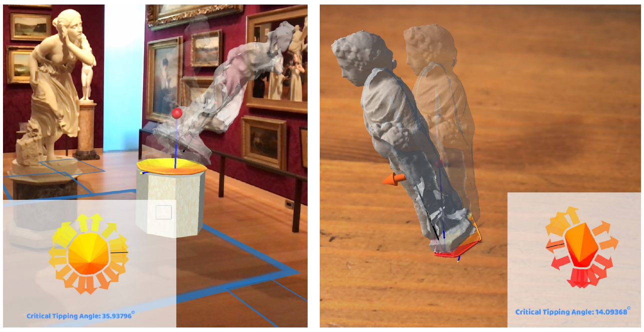

Figure 4: *Static tipping visualization for a particular base edge. Opaque copy is rotated around the edge by its critical tipping angle. Models: Nydia, Blind Girl of Pompeii (Left, MFA Boston), The Child Dionysus (Right, MFA Boston).*

Figure 5: *Convex hull base without edge clustering (left) and with clustering (right). Model: Portuguese Soldier (MFA Boston).*

such, the opaque copy demonstrates the pose at which the sculpture will begin to tip over in the direction selected by the user. An AR arrow is rendered against the opaque copy, indicating the potential tipping direction in world space.

Base Edge Clustering. Photogrammetry artifacts can often produce erratic edges on the base of the sculpture, which can be difficult to manually smooth out before a stability analysis. Individual edges may be of negligible length, or adjacent edges may only be distinguished by a nearly straight angle, causing our method to produce an abundance of extraneous tipping directions. This can clutter the base graphic and overwhelm the user. To solve this, we developed a greedy edge clustering algorithm for ConservatAR to consolidate a sculpture's base geometry in real time (Fig. 5).

4. Dynamic Analysis Methodology

Tipping and Impact Visualizations. Once the user starts the simulation, ConservatAR renders a circular ground object at the base of the sculpture to enable tilting. The user can tilt the sculpture around the x and z axes in real time by adjusting a slider (Fig. 6-2). The lower right portion of the interface reports the rotation angle at the frame when each sculpture piece started tipping. After at least one sculpture piece has fallen to the ground and returned to rest, the user can select "Visualize Impact." Doing so will return the entire sculpture upright and replace its texture with a color scheme indicating impact severity. The sculpture portions with the smallest impact force are colored blue, while those with the highest are colored red (Fig. 6-3). The user can toggle between the tipping simulation and the current impact visualization at any time.

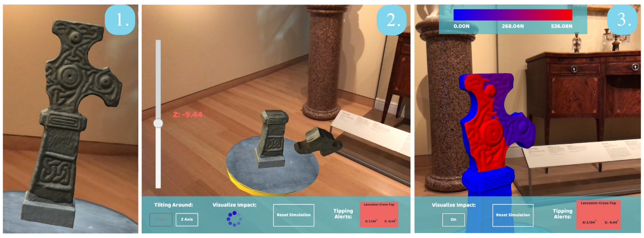

Figure 6: *(1) User interactively tilts the sculpture during dynamic simulation; (2) top segment collapses; (3) ground impact visualization. Model: Lancaster Cross (The British Museum).*

Collision Physics. ConservatAR forms a collision boundary around each sculpture segment based on the geometry of its 3D convex hull and approximates the gallery floor as a horizontal plane. This ensures that ConservatAR can compute collisions at interactive rates. Due to the planar floor surface, a segment's convex hull is as accurate as mesh-tight boundaries for collision detection. For accurate simulation of a segment's motion, we derive the mass, center of mass, and moment of inertia directly from its mesh, using the Divergence theorem method from Bächer et al. [BWBSH14].

Tipping Detection. ConservatAR uses simulation to determine tipping angle when in dynamic analysis mode. The critical tipping angle for a sculpture piece is detected when a non-negligible angle forms between its up vector and the up vector of the circular ground object, indicating the piece has started to collapse under gravity.

Impact Measurements. Once a sculpture piece has reached its tipping angle, ConservatAR begins checking for collisions with the ground. For each frame where collision occurs, ConservatAR records the impact force along with the collision locations on the sculpture mesh. Impact measurements terminate once the sculpture piece returns to rest. We define objects at rest as ones that have maintained negligible translational and angular velocity for 20 consecutive frames. ConservatAR stores the highest impact forces withstood across the sculpture surface for display in our impact visualization (Fig. 6-3).

5. Implementation

We reconstructed 3D digital models of sculptures from the MFA Boston using Agisoft's Metashape for initial photogrammetry and Maya for manual post-processing. For additional test cases we utilized models offered publicly by the British Museum (sketchfab.com/britishmuseum). Our ConservatAR application is developed on top of Unity, which offers a host of built-in functionality via its physics engine. Given objects' mesh geometries, collision boundaries, and physical properties such as mass, center of mass, and moment of inertia, Unity automatically handles their physical trajectories and collision behavior. We implemented custom C# scripts to calculate and supply those properties to the engine, compute the tipping vulnerabilities described in Eq. 1, and facilitate user interactions and data visualization. Unity's ARKit plugin handles the core augmented reality features (e.g., surface detection and coordinate system mapping).

6. Expert User Feedback from Museum Conservators

To evaluate the clarity and efficacy of both stability analysis techniques with expert users, we solicited feedback from several conservators at the MFA Boston during formative user studies. We first provided a demonstration of each feature, then asked the conservators to explore the application themselves (Fig. 1). The conservators expressed that ConservatAR could be a useful supplement to current methods, is "great for deciding whether a structural engineer is needed," and may even be a vital tool at a smaller museum with limited conservation resources.

Static Analysis Feedback. An earlier version of the static analysis allowed the user to choose a tipping force direction from a circular dial with a continuous range, rather than discrete tipping directions. It was difficult for the conservators to distinguish the force direction controlled through the UI from the tipping direction visualized on the AR model. Moreover, a continuous range of all possible force directions was overwhelming; the conservators preferred a discrete subset, even if that meant receiving less stability data. As such, we replaced the continuous dial with discrete tipping directions aligned against a graphic of the convex hull base (Figs. 4,5). At the request of the conservators, the base graphic also rotates to align with the user's current perspective of the sculpture. This more clearly conveys the correlation between the base graphic and the sculpture model itself.

The conservators had several questions after exploring an initial version of ConservatAR, which only supported static analyses. "How will the sculptures fall?" was a particularly common one; the minimum tipping angle does not convey a complete story. Further, the assumption of fully connected sculptures excluded many of the conservators' most concerning cases. "It is very rare for an object to be undamaged", so sculptures will "almost always" have cracks. To solve these concerns, the next iteration of ConservatAR introduced dynamic analysis.

Dynamic Analysis Feedback. After exploring our dynamic analysis mode, the conservators suggested we use more specific, conceptual tipping visualizations than abstract numerical values. It is difficult to envision tilted rotation angles as equivalent realistic scenarios, such as earthquakes or accidental collisions with visitors. Simulations of these specific scenarios would be a valuable supplement to our generalized method. We also learned that sculptures are rarely displayed without a pedestal base attachment, which can drastically change their tipping vulnerabilities. Conservators requested that we integrate customizable base designs into both simulation methods. This feature would serve as a design exploration tool and improve conservators' intuition regarding the stability of certain base shapes over others.

7. Conclusion

We have demonstrated a technique for assisting sculpture conservation with augmented reality technology. ConservatAR can visualize tipping vulnerabilities of homogeneous sculptures with static analysis. Through dynamic analysis, it can determine tipping behavior of widely cracked sculptures and visualize ground-sculpture impact severity. Formative user studies with conservators from the MFA Boston further informed our understanding of current conservation methods and revealed how augmented reality can best solve some of their challenges.

Limitations. The material composition of a sculpture may not be homogeneous, which would affect mass distribution calculations. ConservatAR also does not account for supports such as armatures or pins placed in the sculpture interior by the conservators. Additionally, cracks may take a highly erratic path throughout the sculpture interior. In this case, our planar crack approximation would attribute inaccurate volume to each partition, affecting the accuracy of collapse simulations.

Future Work. Many avenues exist for expanding ConservatAR's features. User-controlled rotation during dynamic testing could be transformed into automated behavior that models realistic scenarios, such as visitor collisions. Customizable pedestal geometry would further improve the realism of our simulations and offer design opportunities. Additionally, advanced physical simulation methods could help ConservatAR predict damage. Finite element analysis could suggest where new cracks are more likely to form from internal stresses, while a fracture analysis technique could predict the crack geometry likely to form at regions impacted by ground collisions.

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