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A 3D subtractive brush system for an immersive, multilayered archaeological map

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Abstract

Digital archaeology is a rapidly evolving field, continually adapting new technologies to interpret diverse data sources. This paper details the superimposition of 2D maps and 3D data in an interactive 3D space, and their selective subtraction by a 3D brush system. The subject of study is the archaeological landscape of the medieval city of Angkor in Cambodia, an area of approximately 3500 square kilometres. By cutting through the superimposed layers of LIDAR point clouds, 2D mapping of the archaeological features, and the 3D reconstructions of the living city of Angkor, the brush system reveals both correspondences and discontinuities through interactive examination.

Introduction

Digital archaeological models require a combination of data sources to enable insightful exploration, especially where the models are three dimensional and include reconstructed elements. Designing a way to “see between” superimposed visualisation sets is a powerful way to facilitate this exploration. Relying on toggle switches to change from one data-source to another is a common solution, however this impedes contextual investigation and makes comparison between visualisation layers a cognitively demanding task. To address this, we have adapted the brush-lens interaction technique to the context of digital archaeology, allowing for local, contextual navigation between three layers of data sources - a 3D LiDAR point cloud, a 2D GIS map, and a 3D reconstruction of the medieval city of Angkor in the early 14th century.

Related Work

Comparing views of multiple data sources is a fundamental task in the visualisation process [1]. As such, a number of interactive visualisation techniques have emerged, ranging from simple toggled layers through to multiple coordinated views [2] and “slide-to-compare” style interactions [3, 4]. These techniques, while widely employed, have the disadvantage of reducing the amount of data that can be displayed on screen at any one time. Toggling and sliding between views also results in a loss of contextual information, making it difficult for users to retain information [3].

To enable efficient comparison between several visualisation layers, we use a brush tool that reveals local visual information through a brush-lens interaction. While “brushing” has been used successfully in previous applications [5, 6, 7], our work is novel in the sense that it operates over a hybrid 2D and 3D information space. While previous work has explored the use of a lens to reveal local changes in a data-set - e.g., the “MoleView” [8] or the colour tunneling technique that allows users to “dig” through visual information [9] - these tools operated exclusively in either 2D or 3D.

In the context of digital archaeology, 3D reconstructions have been placed over scanned environments in a number of virtual heritage studies [10, 11], and the interplay between 3D reconstructions and GIS data-sets has been well explored [12, 13], however the design of the visual navigation between different data-sources requires further investigation.

Context

The medieval Khmer empire once controlled most of mainland Southeast Asia. The city of Angkor, situated around modern-day Siem Reap in Cambodia, served as the empire’s capital, with minor interruptions, from the late 9th century through to the city’s decline and gradual abandonment in the 15th century. At its peak, Angkor is estimated to have supported a population of approximately 700,000 to 900,000 inhabitants [14], earning it the enduring legacy of the world’s largest pre-industrial city [15].

In comparison to most medieval cities, the cartographical features of Angkor are remarkably well preserved, mainly because no subsequent settlements were constructed over its remains. Though the world-famous temple of Angkor Wat was never abandoned and continued as a site of Buddhist pilgrimage, the creeping roots of ficus trees strangled and split apart much of the rest of the city’s stone architecture as Angkor’s population gradually abandoned the city in the 15th century. Paradoxically, this forest was as much a preserver as a destroyer, because it both smothered and protected the archaeological record embedded in the landscape. As a result, the unique urban form of Angkor continues to be the subject of extensive study by archaeologists and historians [16, 17, 18].

In 2013 and 2016, the Khmer Archaeology LiDAR Consortium conducted extensive airborne LiDAR scans of the Angkor Archaeological Park [19, 20], allowing for the tracing of archaeological features at scale and in areas where limited ground-based resources could be deployed. The results of these surveys, together with data from a web-accessible geospatial repository maintained by The University of Sydney and the EFEO, make up the foundation upon which our digital heritage application is based*.

Visualising Angkor

The Visualising Angkor project at Monash University explores the virtual reconstruction of Angkor at its peak, circa 1300 C.E. At the heart of this endeavour is the creation of a diverse set of hand-crafted, evidence-based 3D models. These range from small and distinct artefacts, such as ceramic vessels and textiles, through to the large-scale assemblies of stone temple complexes and the cultural landscapes around them. A library of animated human and animal characters completes the collection, allowing for the visualisation of a “living”, operational city.

** We are indebted to Dr. Damian Evans for providing us with the LiDAR point cloud and access to the geospatial repository of cultural and natural features in the Angkor area.*

The virtual reconstruction of Angkor in 1300 is guided by five primary sources [21]: detailed bas-reliefs carved into the remains of stone temples, the corpus of Khmer inscriptions, on-site excavations and aerial mapping, documented eye-witness accounts from 1296 C.E., and accounts from the French colonial era. The reconstructed 3D scenes are also informed by a range of supplementary sources, including architectural surveys, botanical and palynological studies, textile studies, musicology, and archival photography.

These 3D models form the visual grammar of the reconstructed city, and are the fundamental building blocks for visualisations of different scales, from fixed perspective views of daily life at ground-level to sprawling cityscapes of several thousand square kilometres, navigated with an aerial camera.

600 million points of spatial data makes a green metropolis

Building on our related work visualising and simulating a crowd of several thousand AI agents navigating the temple complex of Angkor Wat [22], in 2018 authors Chandler and Yeates embarked on a project to visualise the entire city of Angkor in the 14th century. While this endeavour is ongoing, the utility of a subtractive brush system was identified early in the process. Our virtual map assimilates three layers of historical data within a virtual space: the physical evidence of the present landscape of Angkor, captured from the LiDAR survey, the GIS layers detailing the historical form of the city, and a layer of 3D models that visualise the city's cultural landscapes in the 14th century.

Figure 1. *An aerial view from the virtual 3D map of Angkor showing the rice fields around the temple of Pre Rup.*

These distinct layers have been incorporated together with the Unity game engine and represent an area spanning 3500 square kilometres. The layers in this real-time 3D rendered digital heritage application are detailed as follows:

1. **LiDAR point cloud:** derived from the airborne survey, this layer captures the *modern-day ruins* of the Angkor archaeological park, including modern infrastructure such as the Siem Reap airport. As the trees have been removed, this layer represents the present-day landscape beneath the canopy.
2. **GIS:** a 2D map derived from GIS data-sets. This colour-coded layer represents a cartographical tracing of the *archaeological remains* of Angkor; the imprint of its historical waterways, settlement mounds, and village shrines.
3. **3D Reconstruction:** follows the colour codes in the 2D GIS map to procedurally pattern evidence-based, 3D reconstructed sets of wooden residences, agricultural vegetation and temple complexes. This layer envisages the *living cultural landscape* of Angkor around its peak, circa 1300 C.E.

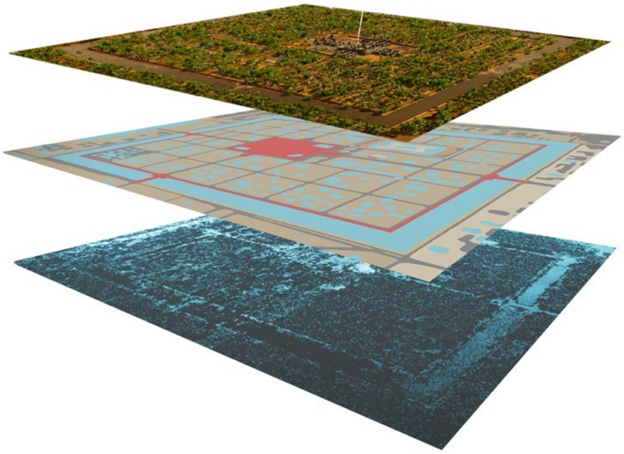

Figure 2. *A slice of the three layers of the virtual map, centred on the temple complex of Preah Khan. Top: our virtual reconstruction depicts a 'green city' in the 14th century, including 3D models of agricultural trees, wooden residences, rice fields and reconstructed stone architecture. Middle: the GIS reveals the historical grid pattern of the settlement mounds within the moat (with the imprint of temple architecture marked red, water blue, and settlement mounds beige). Bottom: the LiDAR point cloud of the present-day landscape, including the ruins of stone architecture.*

Setup

While our previous research has primarily concerned the creation of the 3D models used in the top layer (the 3D reconstruction of medieval Angkor) [23, 24, 25], subsequent sections in this paper will detail the visualisation of the LiDAR and GIS layers, and in particular how a 3D brush system can be used to cut through and interactively reveal each layer.

LiDAR Point Cloud

The LiDAR point cloud consists of 586 million sets of X, Y, Z coordinates stored in a series of text files exceeding 15GB. Before we can render these points in Unity, the point cloud must first be pre-processed using a custom editor script. After parsing and mapping the points to the coordinate system used by our virtual world, the editor script combines the points together into a grid of meshes (each tile in the grid is approximately 800x800 metres in size - an arbitrary selection to balance low draw calls with efficient frustum culling). To facilitate efficient real-time rendering, each tile in the grid is duplicated several times and a percentage of points are automatically removed to produce four different levels of detail (LODs). At runtime, an appropriate LOD is dynamically selected for each tile based on its distance to the observer (for example, only 1 in 30 points are rendered for the tile farthest from the camera, while all points are visible for the tile(s) in the viewer's immediate vicinity). This optimisation limits the number of points rendered on screen at any one time to between 10 and 30 million, ensuring this real-time visualisation can render in excess of 120 frames-per-second on a mid-range gaming computer.

The high LOD chunks close to the camera are fed through a geometry shader to produce a camera-facing billboard for each point (each point becomes a quad/square). This geometry is then textured

__Figure 3.__ The LiDAR point cloud viewed from three different vantage points. Left: individual points are visible up close with the Baphuon temple present in the distance. Middle: the mountain temple of Phnom Bakheng in front of the moat of Angkor Thom. Right: the imprint of modern infrastructure can be seen as holes in the point cloud around Siem Reap airport.

to evoke the out-of-focus bokeh patterns present in shallow depth-of-field photography (the square geometry for each point now appears as a soft transparent circle). Distant points are rendered as a single pixel, allowing the LiDAR point cloud to appear solid and impenetrable from afar.

GIS

The 2D GIS map was exported from Esri's ArcGIS as a vector format, with each colour-coded layer housed in its own .svg file. Each vector layer was then imported into Autodesk Maya where it was converted into geometry. After import into Unity as a series of .fbx files, the GIS map was rendered in real-time as regular triangulated geometry.

In order to conveniently overlay the GIS map over the 3D reconstruction of the medieval city, the GIS was rendered using a separate camera which is stacked on top of the camera used to render the reconstructed 3D world.

A simple toggle interface was also provided to filter the visibility of the layers contained within the GIS (i.e., the user may elect to only view ponds and canals).

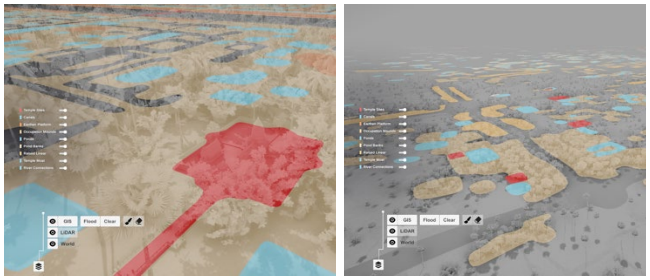

Figure 4. *The GIS layer viewed on top of the 3D reconstruction. Left: The temple of Chau Say Tevoda and its surrounds. Note the reconstructed 3D geometry of the temple can be seen placed on its red imprint in the GIS. The indication of trees and houses are also visible on the surrounding mounds. Right: a village among the rice fields approximately 9 kilometres west of the main city.*

Approach

While the LiDAR points, GIS, and 3D reconstruction can be superimposed with transparencies or viewed sequentially, their size makes discerning specific details difficult, especially as the layers "match" tightly when they are stacked on top of each other. Turning entire layers on and off with toggle switches can also prove problematic as it relies on the user's visual memory to make comparisons. A brush system allows users to reveal and examine the correspondence between 2D and 3D layers in finer detail, enabling new forms of contextual inquiry.

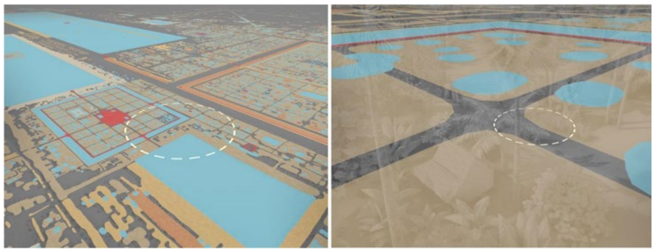

__Figure 5.__ Left: the brush – represented by a circle – positioned over the south-west quadrant of the temple complex of Preah Khan, ready to cut-through the GIS layer and reveal the reconstructed 3D world underneath. Right: a zoomed-in view showing a smaller brush positioned at the intersection of paths near the residences of Preah Khan.

Implementation

The brush system was designed to generate a mask texture to control each layer's visibility. As the brush is persistent – it is essentially a lens which leaves a trail behind it - an internal mask texture is required. While Unity allows for the direct manipulation of the pixel data within textures through code, this approach would not be suitable given the performance requirements for real-time rendering. Instead, we leverage a feature common in game engines which prevents virtual cameras from "clearing", where the image from the previous frame remains in the camera, and any changes in the current frame are accumulated on top. A "non-clearing camera" was therefore created and configured to only "see" the brush. The brush was represented in the world as a textured plane, and moves along the terrain – underneath the user's mouse cursor - as the user elects to paint. The movements of the brush accumulate in the non-

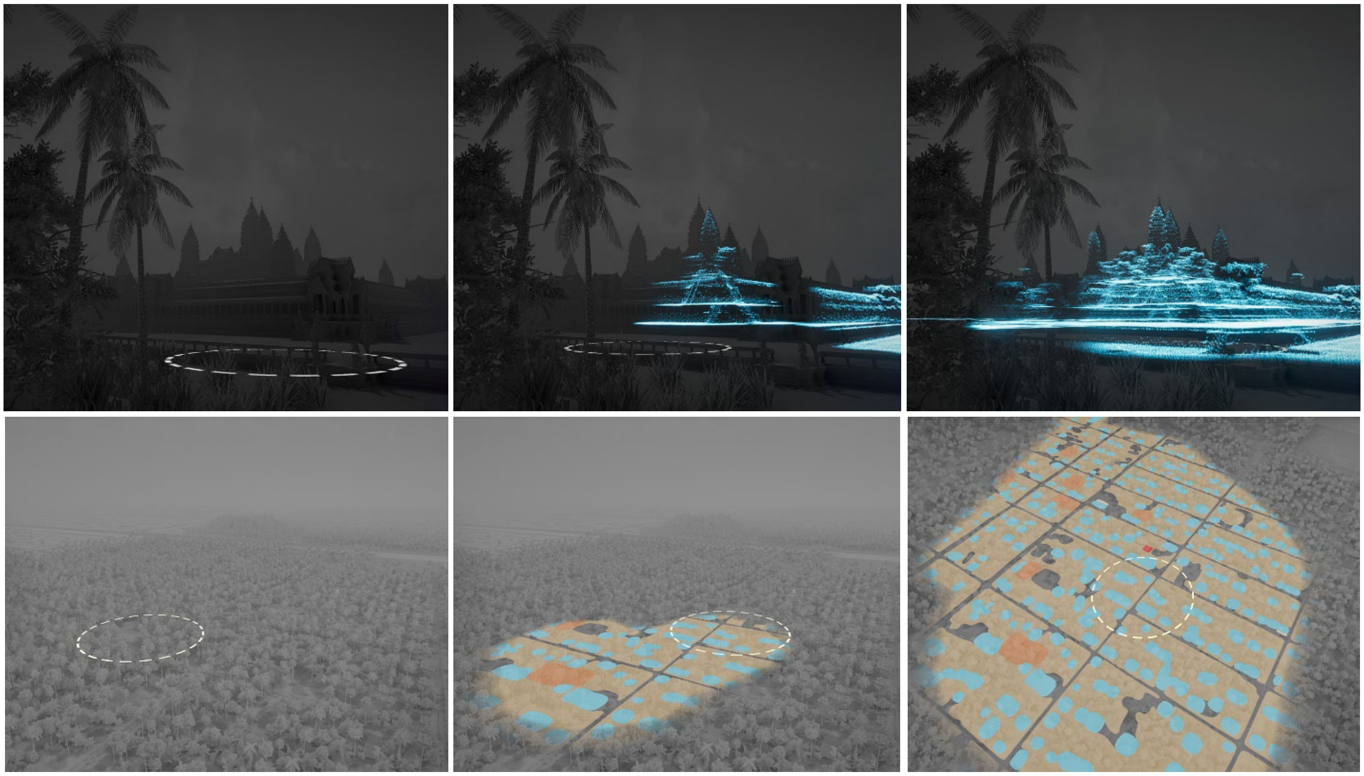

Figure 6. *Top row: the brush gradually reveals the LiDAR points (blue) for the temple of Angkor Wat, verifying the proportions and accuracy of this hand-modelled 3D architecture. Bottom row: the grid pattern of urban settlement is initially disguised by the 3D vegetation. Here, the brush reveals the 2D GIS layer which depicts the landscape features and city blocks beneath the canopy, similar to how an archaeologist gently brushes away at a surface to reveal details.*

clearing camera (similar to light-trails in long-exposure photography), and this camera writes what it sees directly to the mask texture. The custom shaders used by the LiDAR points and GIS layers simply sample this mask texture to determine which areas should be visible.

In practice, and to allow the user to reveal separate areas of the LiDAR, GIS, and 3D world, we created separate masks and non-clearing cameras for each layer.

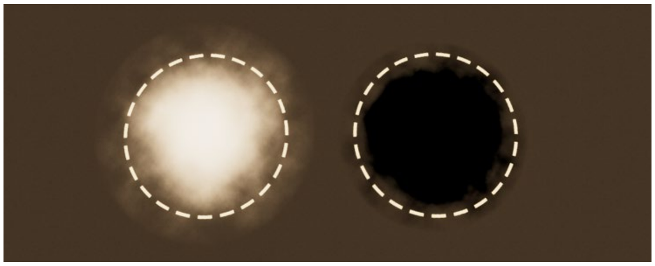

Figure 7. *The additive (left) and subtractive/eraser (right) brushes. While the boundary of the brush is visually represented to the user as a dotted circle, the actual shape/influence of the brushers are internally stored as custom textures (invisible to the user).*

The user can adjust the size of the brush while painting, and also swap between additive and subtractive (eraser) modes. To facilitate this, a simple user interface inspired by the layers section of Adobe Photoshop was created, which also allows the user to flood and clear individual layers, and toggle their visibility.

Outcomes

The 3D subtractive brush system has applications for both archaeologists and virtual heritage practitioners. For archaeologists, the brush tool can be used to rub away the LiDAR points to inspect the 2D layers underneath the map, revealing correspondences between the modern landscape and the cartographic features of the historical city. For virtual heritage practitioners, the ability to rub away either the LiDAR points, the 2D archaeological map, or the overlay of the 3D models that comprise Angkor's reconstructed cultural landscape, offers a more defined tool to check the results of a visualisation procedure.

Throughout our own development on the broader Visualising Angkor project, we have found this tool to be particularly useful to validate the positioning and proportions of our hand modelled 3D architecture against the LiDAR of the modern-day ruins and the cartographical imprint of the historical city.

Significance

We have adapted the brush-lens visualisation technique to digital archaeology for dimensional truthing and ground-truth verification in a real-time 3D rendering environment. We contribute significant improvements to address problems with current data visualisation techniques in digital archaeology: (1) we add a persistent brush mode to retain information when moving the mouse, (2) we allow for the alteration of the brush to delete or refine the selection and (3) our brush technique is the first to merge 3D scanned point clouds, 2D GIS maps and 3D reconstructed historical models together in real-time. Moreover, most combinations of scanned 3D landscapes, virtual heritage models and GIS layers deal with small and defined areas, whereas the application we have described in this paper operates over a scale of several thousand square kilometres.

Conclusions and Further Research

This work is part of an iterative and incremental endeavour that gradually layers new methods of visualisation over a defined urban space; the Visualising Angkor project is practice-based [26], and rather than seeking to bring forth a known end, we learn through making and value process more than outcome.

One promising future iteration could involve the adaptation of the interactive brush system to a virtual reality (VR) format. Our previous experiments with VR (see figure 8) presented the reconstructed cultural landscape of Angkor as a hologram at waist-level - more realistic rendering techniques resulted in discomfort for the user. This aesthetic is already well suited to LiDAR and could be adapted to present GIS data-sets as well.

The examination and subtraction of 2D and 3D archaeological layers would be especially well-suited to VR setups with room scale tracking. If the world were positioned at waist-level and rendered at a smaller scale, the user would be able to crouch down and inspect the layers from limitless vantage points (including from beneath the terrain and looking upwards). The VR controllers would also likely prove an intuitive device to rub out sections of the layers around the user. Environmental soundscapes and field recordings could be “placed” near temples and fields, adding an extra sonic dimension to the exploration of the map of medieval Angkor. Such an application would allow a user to navigate the model physically, by walking over it and ducking under it, while they were immersed in multiple data sets, both in simulated space and historical time.

***Figure 8.** The 3D reconstructed cultural landscape of Angkor presented in Virtual Reality using a hologram aesthetic.*

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