Cloud Garden

Brendan Harmon
Louisiana State University

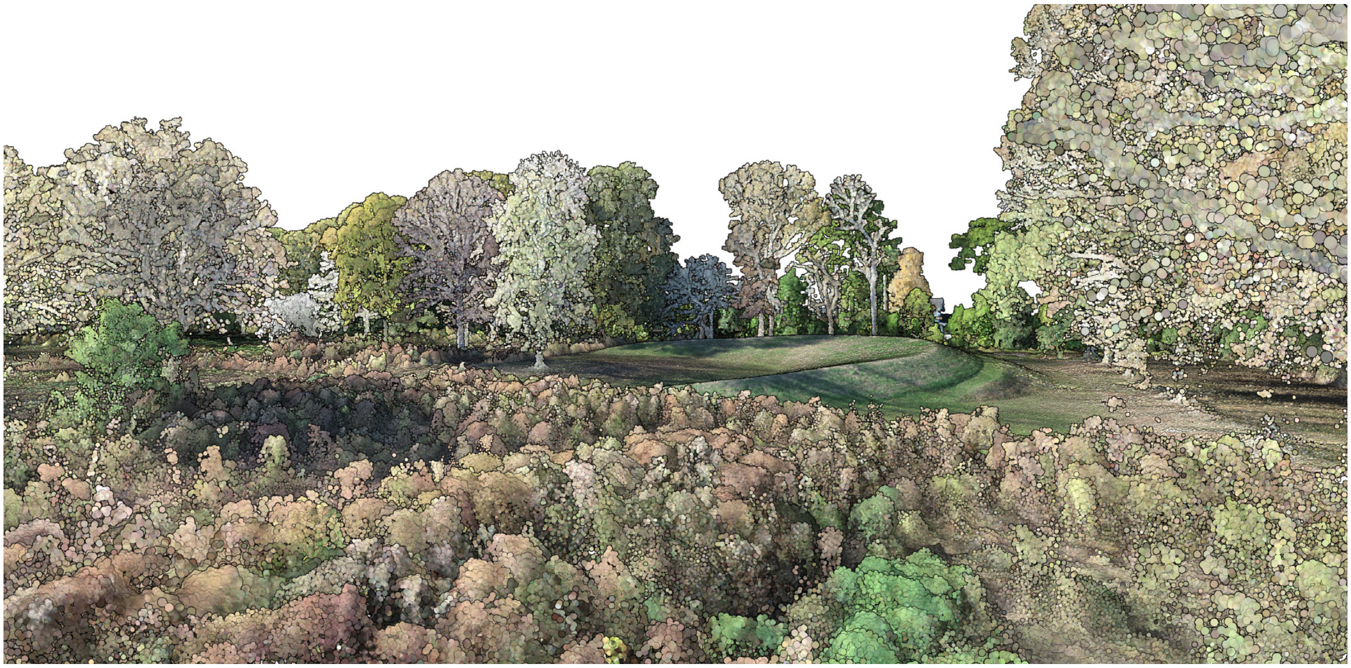
Hye Yeon Nam
New Jersey Institute of Technology

Neural Rendering and Point Cloud Modeling of Landscapes

1 Cloud Garden – a landscape modeled with point clouds from neural renderings.

ABSTRACT

While ecologists have long been using remote sensing techniques such as lidar to reconstruct and study ecosystems, landscape architects have recently begun exploring the potential of point clouds from lidar as a new creative medium. Lidar captures the messy complexity of landscape such as the form of the built environment, the morphology of trees, the shape and texture of the ground, and the incidental – the tangle of power lines, the stray bird, and the passerby. Point clouds from lidar can represent this complexity in precise, albeit often noisy, immersive detail, allowing for close readings of landscape. Landscape architects have been experimenting with processes for point cloud modeling so that they can design landscapes in more of their complexity. Landscapes can be designed from scans by disassembling, transforming, and reassembling point clouds. However, due to the limitations of lidar, plants, especially herbaceous ones, have only been represented abstractly as sparse point clouds in these experiments. The challenges of capturing and segmenting herbaceous plants with an immersive level of detail using lidar have limited the scale and versatility of this modeling process. We demonstrate how emerging techniques for neural rendering can be used to rapidly capture challenging elements of the landscape – such as trees, shrubs, forbs, grasses, and ground cover – in unprecedented detail for point cloud modeling. We have developed a process using point clouds from neural renderings to model landscapes in immersive, high fidelity detail across scales from territory to leaf, from forest to branch.



2 Point cloud acquired by uncrewed aerial system with lidar of Hilltop Arboretum, Baton Rouge, Louisiana.

INTRODUCTION

Landscapes are challenging to model since they are complex and in constant flux. The trees within a landscape, for example, have complex, irregular forms with fractal branching structures shaped by competition for space and light. To model this messy complexity with high fidelity, landscapes can be generated procedurally (Deussen et al. 1998; Deussen 2005) or reconstructed using remote sensing. Terrain can be algorithmically generated using procedural, cellular, and fractal noise and simulations of geomorphic processes like erosion and deposition (Musgrave, Kolb, and Mace 1989). Plants can be modeled procedurally using Lindenmayer systems (Prusinkiewicz and Hanan 1989; Prusinkiewicz and Lindenmayer 1990), space colonization algorithms (Palubicki et al. 2009), and growth equations (Yi et al. 2018). While procedurally generated plants are used extensively in landscape architectural visualizations, these simulated plants are uncanny, at once hyperreal, yet also synthetic. Alternatively, landscapes can be reconstructed using remote sensing to capture some of their complexity and uniqueness. Unlike simulations, reconstructions are indexically grounded in reality, but since reality is messy and dynamic, reconstructions are marred by noise, occlusions, and environmental change. With emerging technologies for remote sensing, landscapes can now be reconstructed and designed in immersive detail that is grounded in place.

Remote sensing technologies like lidar and image-based modeling can be used to computationally reconstruct landscapes in high fidelity with immersive detail. Lidar – remote sensing with lasers – has been used to reconstruct terrestrial ecosystems at scales ranging from the globe (Dubayah et al. 2021) to the organism. Advances in lidar have ushered in revolutions in forest science (Danson et al. 2018) and landscape architecture (Girot 2020). While ecologists are using lidar analytically to computationally reconstruct forests in order to estimate their biomass stocks and study their carbon dynamics, landscape architects are using lidar creatively to redesign reconstructed landscapes. Now with emerging techniques for neural rendering (Mildenhall et al. 2021), even small plants can be reconstructed rapidly in precise, immersive detail with only a camera.

Forest Science

Ecologists use lidar to reconstruct terrestrial ecosystems such as forests in three dimensions in order to estimate their structure, above ground biomass, and carbon dynamics (Malhi et al. 2018; Calders et al. 2020; Jackson et al. 2020). Laser-scans of forests are also used for radiative transfer modeling and to calibrate and validate other remote sensing products such as satellite imagery. With airborne lidar, entire forests can be captured rapidly from above at submeter point densities, while uncrewed aerial systems which fly lower and slower, can record hectares of woodlands from above at subcentimeter point densities. Tree canopies, however, partially occlude the capture of aerial lidar, so terrestrial laser scanning is used to better capture the woody biomass of the forests from the ground up. Terrestrial laser scanning in forests, however, is challenging due to their structural complexity. To reconstruct trees in high fidelity for biomass estimation in forests,

3 Point cloud acquired by uncrewed aerial system with lidar of Mulatto Bend Cemetery, Port Allen, Louisiana.

ecologists scan in dense grids with an overlapping scan every hundred square meters (Wilkes et al. 2017). These surveys are challenging, time intensive, and expensive due to the scale and complexity of forests, the need for dense sampling, the logistics, and the cost of equipment.

Landscape Architecture

While the sciences have focused on analytical applications for lidar, the design disciplines are exploring creative applications for lidar. Architects, for example, have been experimenting with creative applications of terrestrial laser scanning such as parametric modeling (Zwierzycki, Evers, and Tamke 2016) and scanning irregular timber for robotic assembly (Vestartas 2021). Meanwhile, landscape architects have been exploring the creative potential of point clouds from lidar as a new design medium (Girot 2020). Lidar point clouds are also used by landscape architects for computational terrain modeling (Hurkxkens and Bernhard 2019), autonomous earthworking and dry-stone construction (Jud et al. 2021; Johns et al. 2023), and heritage conservation (Harmon and Nam 2024).

Point clouds from laser scanning can document the complexity of landscape in much of its messy, unruly detail, capturing, for example, the fractal branching structure of trees, the rustle of grasses, sedges, and forbs in a windblown meadow, the texture of the ground, and the muted color palette of midwinter (Figure 2). By capturing slices of time, these point clouds can capture some of the phenomenological character of landscape – such as traces or cues of seasonal change, meteorological, ecological or geomorphological processes, disturbance regimes, and agricultural or industrial practices (Figure 3) – precisely, albeit noisily, in three dimensional detail. As precise multidimensional data that can record the built environment, the structure of ecosystems, traces of cultural practices, and the aesthetic character of landscape, point clouds from remote sensing are emerging as a new medium for landscape architecture with a unique set of representational affordances. As indices of light, they represent multidimensional slices of space and time that are physically and casually connected to reality, but as digital media they are algorithmically mediated, symbolically encoded, and iconically, albeit abstractly rendered (Harmon and Serrano 2022).

Landscape architects have developed creative processes – such as the acquisition, preparation, disassembly, transformation, reassembly of point clouds (Urech 2019; Urech et al. 2020; Urech, Von Richthofen, and Girot 2022) – for modeling with this medium. In the initial acquisition phase of this process, point clouds are either collected by remote sensing – such as uncrewed lidar missions or terrestrial laser scanning surveys – or are retrieved from existing data repositories. In the disassembly phase, the point cloud of the landscape is segmented into classes such as terrain, vegetation, buildings, and infrastructure. Discrete elements from the landscape – such as trees, streetlamps, and landscape furniture – can be segmented and compiled into a library of modeling assets. Then, in the transformation

4 Point cloud of bald cypress captured with terrestrial laser scanning.

5 Point cloud of American sycamore from neural rendering of drone video.

phase, the landscape point cloud is edited; points are selectively segmented out, transformed, or segmented in to remove buildings and other landcover, sculpt the terrain, and place new buildings, trees, and other elements. In this phase, not all geometry need be point clouds; buildings, hardscape, and landscape furniture may be modeled as surfaces or meshes, while the terrain may be transformed using mesh, distance field, or raster operations. In the final reassembly phase, all geometry is converted into point clouds and fused together. Point cloud modeling has been used to analyze and design landscapes (Bartesaghi-Koc 2020; Urech 2016). It has also been used to simulate how design interventions might change physical processes such as wind currents (Urech, Mughal, and Bartesaghi-Koc 2022) enabling a feedback loop between science and design (Salliou et al. 2023).

Limitations

Despite the promise of point cloud modeling, there are many challenges to the adoption of this emerging medium. Barriers to adoption include the limitations of technologies like lidar and the dearth of libraries of point cloud assets. Modeling a landscape at a site scale requires a library of point clouds with enough detail to express the character of the design. The landscapes designed to date using point cloud modeling have relied on custom libraries of plants reconstructed using lidar. Landscape architects virtually reconstructing trees for point cloud libraries, however, face many of the same challenges as forest scientists reconstructing forests with lidar. Trees are hard to scan with lidar because of their structural complexity, the need for dense sampling, the cost of equipment, and the logistics of fieldwork. The cost alone of terrestrial laser scanners and uncrewed aerial systems, e.g. drones, with lidar sensors can be prohibitive. While a minimum of six scans per specimen is recommended for forest surveys (Wilkes et al. 2017), reconstructing a tree with enough detail for site scale design using terrestrial laser scanning often requires additional scans at greater height to capture the upper story of the specimen. Additional equipment such as a pneumatic mast, a crane, an articulated lift, or a scaffold is needed to scan the upper story, adding to the cost and further complicating the logistics of fieldwork. While trees are challenging to scan with lidar, herbaceous plants are even more challenging.

Herbaceous plant materials are challenging to scan in situ in the field with lidar because of their fine scale, low reflectance, and motion in the wind. Over distance, laser beams diverge and their footprint – the area illuminated by the beam – grows. Therefore, the footprint of a laser beam may be wider than the edge of a leaf or stem, resulting in only a partial hit. Partial hits with phase-based scanners can result in ghost points (Morsdorf et al. 2018), while wind causes plants to deform resulting in mis-registrations and thus noise (Vaaja et al. 2016). While image-based modeling techniques such as structure-from-motion photogrammetry have been used to reconstruct herbaceous plants in high fidelity in a lab setting, these techniques are even more sensitive to environmental conditions. Environmental factors like occlusions, wind, weather, sun angle, and changing illumination can result in incomplete reconstructions and noisy point clouds (Iglhaut et al. 2019).

Neural Rendering

Emerging techniques for neural rendering, however, can be used to rapidly reconstruct challenging scenes – such as trees and herbaceous plants in the landscape – in high fidelity. Neural radiance fields are a machine learning technique for novel view synthesis that can be used for high fidelity three dimensional reconstructions from a sparse set of images (Mildenhall et al. 2021). A neural radiance field is a continuous volumetric function representing a scene that is approximated and then optimized by a neural network trained on a set of images. Given camera poses for the input images, this volumetric function returns emitted radiance and density. The pose of the cameras – the spatial coordinates and viewing direction – can be calculated using structure from motion and multi-view stereo (Schönberger and Frahm 2016; Schönberger et al. 2016). The scene is rendered by casting camera rays through the radiance field. The radiance field is then optimized by minimizing the difference between the rendered view and the original photos. Novel views – views that were not captured in the original set of photographs – can be synthesized by casting rays from virtual cameras through the radiance field. While neural radiance fields were originally intended for rendering images or videos, they can also be modeled as point clouds. In this paper we demonstrate how neural renderings can be used to rapidly create high fidelity reconstructions of plants for point cloud modeling.

METHODS

We developed a computational design process for modeling landscapes as high fidelity point clouds. First neural rendering techniques are used to rapidly reconstruct challenging elements of the landscape. After the neural radiance fields are exported as point clouds, they are segmented, cleaned, and compiled into a point cloud library of landscape elements. The point clouds in the library can be transformed and composited together to create novel scenes. Scripting can be used to procedurally design complex landscapes. To demonstrate the potential of this approach, we compiled a point cloud library of landscape elements and then used visual programming to design a landscape structured by procedural noise.

Neural Radiance Fields

Neural rendering can be used to reconstruct landscape elements such as trees, herbaceous plants, groundcover, rocks, and deadwood in high fidelity from imagery rapidly collected in the wild. While terrestrial laser scanning requires expensive, bulky equipment, imagery for neural rendering can be captured using photography or videography. To build a library for landscape modeling, we collected imagery in the field of plants and other landscape elements for reconstruction as neural radiance fields. For comparison, we also laser scanned specimens including trees (Figure 4) and herbaceous plants. We used handheld cameras to capture footage of small landscape elements such as young trees, shrubs, herbaceous plants, and groundcover. We also used drone videography to capture footage of a large tree, a mature specimen of Platanus occidentalis or American sycamore (Figure 5). To record

6 Point cloud from neural rendering of blanketflower (Gaillardia aristata).

7 Cloud Garden

each specimen, we orbited in a spiral path around the subject capturing hundreds to thousands of frames, while attempting to maintain a steady distance from it in order to keep a relatively fixed focal length. We used Nerfstudio (Tancik et al. 2023), an open source Python framework, with the Nerfacto model to process our neural radiance fields and export dense point clouds.

Point Cloud Modeling

To compile a point cloud library of landscape elements, specimens should be isolated by segmenting them out of their surroundings, cleaned, and color balanced. To isolate each specimen, we manually segmented the point clouds in Rhino. While isolated specimens of plants could often simply be segmented to a circular region, entangled specimens required careful virtual pruning to isolate. Reconstructions of ground cover – such as bark, pebbles, grass, and creeping jenny – which were often captured on irregular, sloping topography, were segmented into circular regions and levelled with the ground plane. Because point clouds generated from neural radiance fields can have significant noise, we cleaned them automatically using noise and statistical outlier removal filters in CloudCompare. Since our scans were captured in the wild under dynamic and heterogeneous lighting conditions, we used colorimetric segmentation to remove white points and applied color balancing. Once processed, specimens were added to our point cloud library. Once a point cloud library has been collected, a landscape can be modeled by copying elements from the library, translating them into position, and then scaling and rotating them. Our modeling process was implemented using our own collection of scanned specimens as assets for point cloud modeling, Grasshopper for visual programming, the Bitmap Plus plugin for procedural noise generation (Mans 2023) with the FastNoise Lite library (Peck 2021), and Potree for point cloud rendering (Schütz 2020).

RESULTS

As a proof of concept to demonstrate the potential of point clouds as a medium for the computational design of landscapes, we designed the Cloud Garden– a garden generated by procedural noise (Figure 1). We used gradient noise to procedurally model this woodland garden using the Cloud Forest Library – our point cloud library of plants (Figure 6). Our plant palette included Japanese maple, Japanese cedar, saucer magnolia, bay laurel, cherry laurel, plum yew, autumn fern, and lamb's ear, while our ground cover included creeping jenny, mulch, and gravel. To model the garden, we generated a gradient noise map and translated the intensity gradient of noise into plant communities with the highest range dominated by overstory plants, the mid-ranges by understory plants, and the lowest by groundcover (Figure 7).

DISCUSSION

Point clouds have a pointillist aesthetic that can be precise, detailed, and yet abstract. While they can be precise and are often treated as authoritative data, scanned point clouds are inherently incomplete, discontinuous representations of space, capturing only scattered points on the surface of things. While rendered point clouds may cohere into continuous images if they are dense enough, their pointillist aesthetic still evokes their inherent incompleteness and thus a sense of contingency. As an inherently abstract medium, point clouds resist the pitfalls of hyperrealism; incompleteness and thus contingency and imperfection are expected. Given the abstraction of this medium, point clouds of varying density and detail can be combined into coherent scenes. By nesting massive point clouds of varying scale within each other, landscapes can be visualized across scales. Multiscale scenes can be constructed at planetary scale with space-borne lidar, at regional scale with airborne lidar, at landscape with drone lidar, and now at the scale of a leaf with neural rendering. Now that fine-scale landscape elements like herbaceous plants can be reconstructed rapidly with neural rendering, point cloud modeling can be used to model across multiple scales of landscape.

The adoption of point cloud modeling in landscape architecture has been slow due to the cost and logistics of laser scanning, the hardware requirements for working with large point clouds, the lack of robust support for point clouds in design software, and the dearth of libraries of point cloud assets. With advances in software and scanning, however, it is growing easier to work with point clouds. Software for point clouds – including programming libraries (Rusu and Cousins 2011; Zhou, Park, and Koltun 2018; Butler et al. 2021), render engines (Schütz 2020), and design tools (Girardeau-Montaut et al. 2005; Evers and Zwierzycki 2016; Settimi et al. 2022) – is being developed rapidly. With level-of-detail data structures like octrees, massive point clouds with billions of points can be visualized efficiently by render engines like Potree. With emerging techniques for neural rendering, challenging elements of the landscape like trees and understory plants can be reconstructed in high fidelity from footage captured by drones or handheld cameras. With the publication of the free and open source Cloud Forest Library, designers have access to detailed point cloud assets for landscape modeling. Furthermore, now that designers can easily scan local plants, they can begin to build their own point cloud collections of local species. They can work digitally with specific specimens, whether those existing on site or available in nearby nurseries. With high fidelity point clouds of specific plants, designers can computationally experiment with management regimes and thus aesthetics of care (Sutton 2022) using techniques such as virtual pruning (Reckziegel et al. 2022).

CONCLUSION

With the Cloud Garden we demonstrate how point clouds from neural renderings can be used to model landscapes in immersive detail. While laser scanning has been used to model landscapes at scales from the forest to the tree, neural renderings from imagery captured in the wild can record details down to the branch. Now, with point cloud modeling, landscape architects can design not only with site specific trees, but also understory planting and groundcover. With scans of decaying deadwood or plants in bloom (Figure 7c & s), dormancy, or senescence, landscape architects can model aspects of the ephemera of landscape. With scans of found objects like Hodge Podge (Figure 8), they can work with the idiosyncrasies of vernacular landscapes. With techniques like virtual pruning, they can explore strategies for management and care.

DATA

Our datasets are released under Creative Common Zero public domain dedication and are archived on Zenodo. Cloud Garden can be explored online in full resolution in an interactive point viewer powered by the Potree render engine at xyz.cct.lsu.edu or in low resolution on Sketchfab.

Cloud Garden: https://doi.org/10.5281/zenodo.15670829
Cloud Forest Library: https://doi.org/10.5281/zenodo.8194066
Potree: https://xyz.cct.lsu.edu
Sketchfab: https://skfb.ly/pyp9U

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8 Point cloud from neural rendering of Hodge Podge.

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IMAGE CREDITS

All images by the authors.

Brendan Harmon is Associate Professor of Landscape Architecture at Louisiana State University. His research programs include geospatial software development, computational ecology, and heritage conservation.

Hye Yeon Nam is Associate Professor of Art and Design at the New Jersey Institute of Technology. Her work as a new media artist explores the entanglement of humans, technology, and nature.