REPRESENTING COMPLEX SITES: EXPLORING MOBILE LIDAR AND THERMAL IMAGING AS METHODS FOR DOCUMENTING AND ANALYZING LANDSCAPES

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ABSTRACT
Understanding shifting site conditions is critical for describing and designing complex landscapes in landscape architecture. However, there is currently a large gap between the textures and conditions documented by students on site through analogue measures and the remote data used to construct the 3D model through most advanced design workflows. Over the last decade, point cloud models, such as those created by terrestrial laser scanning (TLS), have allowed the creation of site models generated from the site itself. The use of this technology in an academic setting has until recently been limited by accessibility, high learning curves, and high cost. This paper explores the use of new, low-cost terrestrial laser scanning (TLS) and novel heat mapping attachments as innovative, affordable, and accessible tools to investigate, represent, and model site conditions critical to facilitating design within landscape architecture, leading to a more democratic workflow between site study, design, and visualization. Weighing only a few pounds, these tools are highly portable and can scan conditions in only a few minutes, allowing students to document a range of conditions over the course of a single site visit or easily return to document change over time. This project explores the potential for novel TLS and thermal scanners in landscape architectural fieldwork and teaching through an advanced representation course. Workflows are reviewed for documenting site, processing data, and integrating scans into existing 3D site models in Rhino, as well as tips and limitations of the tools for landscape application. Finally, resulting student drawings are explored that query the analytical and creative potential of these tools. Despite limitations for documenting some site conditions, the resulting tools and workflows have the potential to democratize access to sites for both students and public partners and create an affordable, hybrid model for fieldwork within the field of landscape architecture.

Keywords
Point Cloud Modeling, LiDAR, Terrestrial Laser Scanning, Fieldwork, Thermal Imaging

1 INTRODUCTION

Understanding shifting site conditions, such as light, vegetation, and temperature, is critical for describing complex landscapes in landscape architecture. Representation of these conditions are not simply descriptions of site, but essential tools for generating design. Designers use a range of methods, both digital and analogue, to document these conditions, from hand sketching and photography to remote sensing and GIS analysis. Until recently, the methods for documenting sites through fieldwork have been quite separate from those used to construct three-dimensional digital site models. Fieldwork methods, such as site sketching and photography, often lack the resolution of information needed for design, can be time intensive, and are quite difficult to integrate with digital models. However, almost all source geometry used for constructing digital models—such as roads or topography, or planting—are collected from remote sources such as GIS shapefiles and digital elevation models (DEM) derived from satellite data. As shown in the work of Karen M'Closky and Keith VanDerSys, remote data is limited in its resolution, its strict (and sometimes incorrect) categorization, and its ability to only show a snapshot in time, which can be especially problematic in the context of rapidly changing sits or conditions, such as coastlines or flood extents (M'Closky and Van der Sys, 2022). Remote data cannot describe elements of site that are changing, such as light and shadow, density of height of vegetation, tidal shifts, the temperature at various times of day, or even, in erosion-prone areas, topography, and slope. As such, it is increasingly important to have tools for documenting site conditions that are mobile and easy to use, as well as methods that can be integrated with existing digital programs, such as Rhino or AutoCAD.

More recently, point cloud models, such as those created by terrestrial laser scanning (TLS) and aerial laser scanning, have allowed the creation of digital models generated from the site itself, and have recently become more ubiquitous in design practice. One of the most compelling tools for recording complex site conditions is LiDAR, which stands for Light Detection and Ranging (Murtha, 2018). LiDAR sensors emit pulses of light that record two critical elements. Firstly, they record the direction they are sent and, secondly, the time it takes for the pulse to return to the sensor after being reflected off an object. With this data, along with the position of the sensor, a geo-referenced three-dimensional point cloud of site can be constructed. These point cloud models are highly detailed, with point densities typically ranging between 1 to 30 ppsm (points per square meter), creating a remarkably rich visualization of materiality, texture, vegetation, structures, and terrain (Urech, 2020). Aerial LiDAR is compiled using drones or satellite data. While ideal for large scale sites, aerial LiDAR is often obscured by tree canopy, making microtopography, sub-canopy, and the ground plane below difficult to record. Terrestrial laser scanning uses the same technology, but instead mounts the LiDAR scanner at ground level on a tripod, providing accurate point cloud models of all the elements obscured by aerial LiDAR. Terrestrial LiDAR has recently been explored as a tool for recording site conditions in landscape architecture. Recently, the landscape architecture program at ETH Zurich at the Landscape Visualization and Modeling Lab has adopted TLS as a method for creating high-resolution 3-dimensional point-cloud models of landscapes and site conditions, as well as a tool for designing and iterating within more accurate base digital models (Girot, 2022; Urech, 2020; Urech, 2022). However, these tools have been limited in their application to landscape architectural practice and teaching due to cost and access. Scanners such as those used at ETH cost over $100,000, and even lower cost models, such as Leica Black, cost over $25,000, offering robust tools for professionals or research projects, but offering limited applicability within classroom settings. In professional practice, the cost of TLS systems means that point cloud models are often outsourced to outside engineering or surveying contractors. Other forms of generating point cloud models, such as photogrammetry using drones, are likewise limited in academic settings by needs for licensure to fly them, creating a bottleneck in fieldwork where the professor alone can make the scan. Bradley Cantrell and Justine Holzman have explored how responsive technologies can be used to monitor landscape conditions, but these tools typically have a high learning curve, making use in a typical landscape architectural studio or one-time fieldwork difficult (Cantrell and Holzman, 2015). The limitations of these technologies means that few landscape architecture programs can use them in fieldwork. In practice, this creates a large gap between the textures and conditions documented by students on site through typically analogue measures, and the remote data used to construct the 3D model, which becomes the basis for most advanced design workflows.

A recent breakthrough happened in 2020 when new models of the iPad and iPhone offered integrated LiDAR, making the tools available for the first time at a far lower price-point (Hallereau, 2020). The integrated LiDAR in these tools allows scanning of color, light, vegetation, and topography accurate to +/-1 inch (Hallereau, 2020). These tools, however, are limited in scale, with a scanning distance of up to 5 meters, which can be slightly expanded with the use of a selfie-stick (Teo, 2023). The maximum scan possible with this technology remains approximately 500 sq ft— ideal for small architectural sites, such as a room or perhaps a small patio, but not large enough for most landscape architectural projects. However, in the past two years, new software has allowed this technology to be applied to larger sites. SiteScape Pro, a professional-level app designed for the construction and architecture fields, allows multiple high-resolution scans to be tiled together in the cloud to form highly accurate point cloud models of larger sites, up to 5000 square feet. These tools allow 3D models of landscapes to be constructed affordably and with ease, creating accurate scanning of color, light, vegetation, and topography.In addition to allowing the tiling of multiple scans, the professional level subscription to SiteScape Pro allows a seamless workflow with Adobe programs such as ReCap Pro and Autocad, improving the use of current programs used by students in other design courses. SiteScape is not the only recent digital tool offering great potential for the use of iPad and smartphone-based fieldwork in landscape architecture. Additional low-cost accessories allow iPads and mobile devices to be used for thermal imaging, allowing students to also document non-visible phenomena such as the effects of urban heat islands or explore the impacts of lack of tree cover in underserved communities. FLIR One is a handheld thermal imaging scanner that can connect to both tablets and smartphones and costs around $500 per unit, making it relatively affordable for departmental acquisition. All of these tools weigh only a few pounds, can be carried into remote locations, and can scan conditions in only a few minutes, allowing multiple students to document a range of sites and conditions over the course of a single site visit. These tools offer great potential for fieldwork in studio settings, where students often can only visit the site for a short period of time and need to have quick methods for documenting information to inform their design. In addition, these tools allow students to return to sites to document conditions that change over the course of the semester, from canopy cover to temperature, providing the ability to update models quickly and easily.

1.1 Research objectives

While iPad and iPhone-based LiDAR has recently been explored for BIM architectural applications and the geosciences (Luetzenburg, 2021; Teo, 2023), there has been no analysis of the applicability of these novel tools for landscape architectural practice and teaching. Scanning a building or an interior space is vastly different from documenting the complexities of a living landscape, so understanding how well these tools fare for documenting light, shadow, microtopography, and vegetation is critical for understanding their applicability to our field. In addition, no study of SiteScape Pro and its multi-tiling capabilities has been conducted in a fieldwork setting at a landscape scale. Both LiDAR and thermal scanning workflows need to be tested in the field to understand their potential strengths and weaknesses for landscape architectural education and practice.

This project fills this gap in knowledge by exploring the potential for terrestrial laser scanning (TLS), typically used by engineers or surveyors, as well as novel thermal scanning attachments for the current generation of iPads, to investigate, represent, and model site conditions critical to facilitating design within landscape architecture. In particular, this research sought to test the fieldwork potential of two novel tools and workflows for landscape architectural design and teaching and assess their strengths and weaknesses. As technical studies of iPad-based LiDAR have been conducted in the past to test their accuracy, the focus of this study was not on measuring points per square meters or fall-off distances, but in analyzing its overall applicability and use for documenting landscape conditions in the context of actual class fieldwork (Teo, 2023). First, the project explores iPad-based LiDAR scanning using SiteScape Pro at a landscape scale and explores its strengths and weaknesses in documenting site-specific elements, such as vegetation, hardscape, and structures. Next, the project tests the thermal imaging workflows using the same iPad setup to understand the viability of thermal imaging for field work. Finally, the project creates a replicable, low-cost workflow for these tools that can be adopted by landscape architectural programs and professionals. In summation, the goal of this study was to test and create a more democratic workflow between site study, design, and visualization using novel digital tools that is more affordable, accessible, mobile, and flexible than current professional-level workflows. In addition, through exploring the workflows through student work, the project offers alternative methods that these tools might be applied, offering not only objective methods of modeling a site through LiDAR but also human-centered methods of recording movement through and perception of a site.

2 METHODS

In the Spring of 2023, the author received a grant from the Center for Teaching Innovation at Cornell to test out these novel tools for documenting site conditions for landscape architecture, using an advanced representation class to test both the technologies and the workflow. Prior to the grant application, multiple scanning apps were downloaded and tested, including SiteScape as well as free apps such as Polycam, 3dScanner App, Scaniverse, SeeingAI, and LiDAR Scanner 3D. The free apps were of varying ease of use and quality, but only the professional SiteScape app allowed multiple tiles to be stitched together, meaning it was the only app able to make scans at a landscape scale at the time of the study. The innovation grant funded the purchase of three iPads, one FLIR One thermal scanner, and an annual license for SiteScape Pro to develop the new workflow, test it over the summer, and incorporate the tools into the Fall 2023 course. During July and August, the author tested the tools in a range of conditions, including a wooded backyard, a complex meadow, and a creekside gorge trail. A range of scans were made to explore how these tools could work for field work to document existing landscape conditions, including both visible (light, ground, materiality, microtopography, vegetation) and invisible (thermal conditions) using novel iPad-based applications. Using trial and error across these sites, a scanning methodology was refined, scans were processed, and a workflow was created from SiteScape (scanning) to Autodesk ReCap (processing) to Rhino (compiling) to integrate scans with GIS data in a 3-D model. Figure 1 shows the overall workflow for both iPad-based TLS and FLIR One thermal scanning developed during this time.

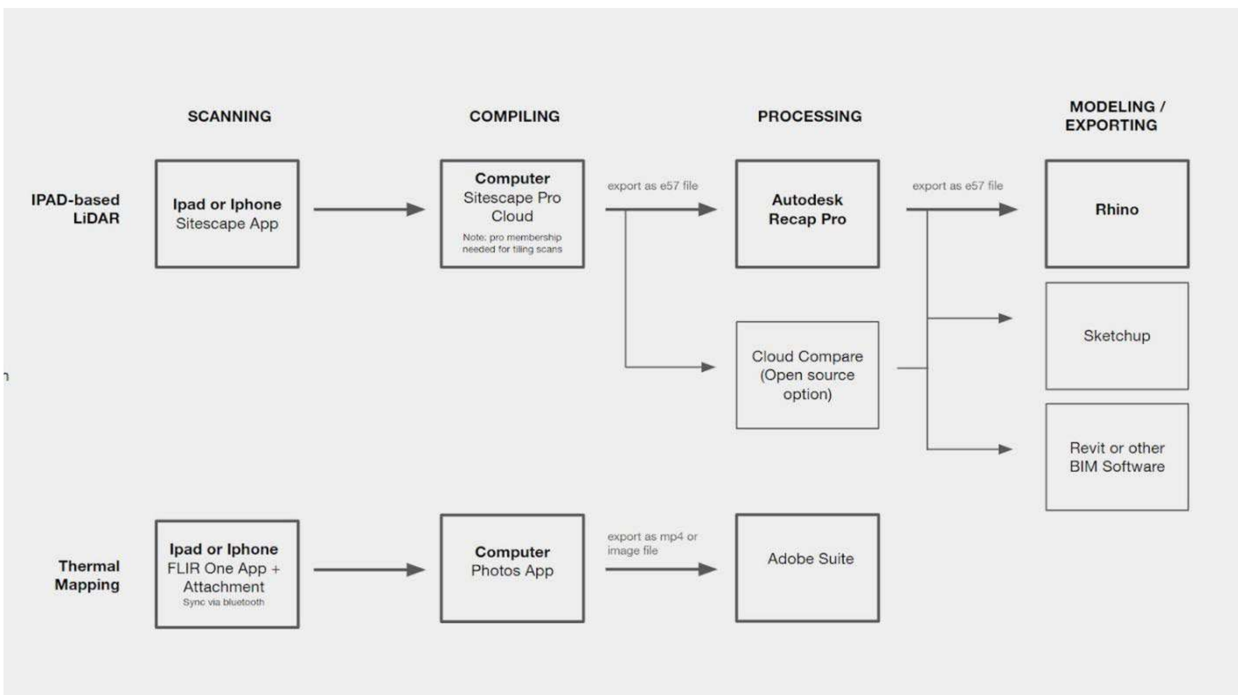

Figure 1. Workflow used for iPad-based terrestrial laser scanning and thermal mapping using FLR One. Bold arrows show workflow used in the course, while light arrow shows alternative workflows for use with different programs. Diagram by the author.

2.1 Scanning

After an initial introduction to the tools in class, scanning techniques were demonstrated and tested in the field with the students. On the workshop day, students were taught how to successfully operate the equipment, how to create and compile multiple scans to construct an accurate 3D point cloud model, and discussed possible applications of TLS and thermal scanning for analyzing specific site conditions (i.e. light, shade, thermal conditions, etc). First, students conducted a TLS scan using the SiteScape app on the iPad. The tools are very intuitive. On the iPad, the student opens the app, clicks a button, and begins scanning. The progress of the scan and the point cloud model constructed is visible on the iPad during the process, allowing the student to see what has been scanned and what still needs to be scanned in real time. Each individual scan can capture up to 12 million points. As one scans, a bar at the bottom of the program updates to show how many points have been captured in each scan and how close you are to the end of it. With SiteScape, this process can be continued for up to 10 scans—for a total of 120 million points. The students can also specify the resolution of the point cloud, that is how dense the 'spray' of points will be for a given scan. Smaller sites with complex geometry or condition benefit from a 'tighter' spray, while larger scans that cover a greater region benefit from a lower density so the 10 scans can cover a broader region. Preparation for scans became particularly important. Students were instructed to find structures or objects that could be aligned with aerial data or GIS data sets, to make combining scans with 3D models more seamless. For example, a student scanning a coffee shop was instructed to include the outside curb at the street corner, which could be used to match existing curb data from city GIS data in the Rhino model.

FLIR One consists of a thermal camera integrated into a small hand-held device that can either be hand held or attached by a clip to a mobile device, giving flexibility in the field. The device is similarly intuitive and easy to use. An app is downloaded onto the device, which allows the thermal image from the scanner to synch via Bluetooth to the remote device, where it appears live on the screen (see Figure 2).

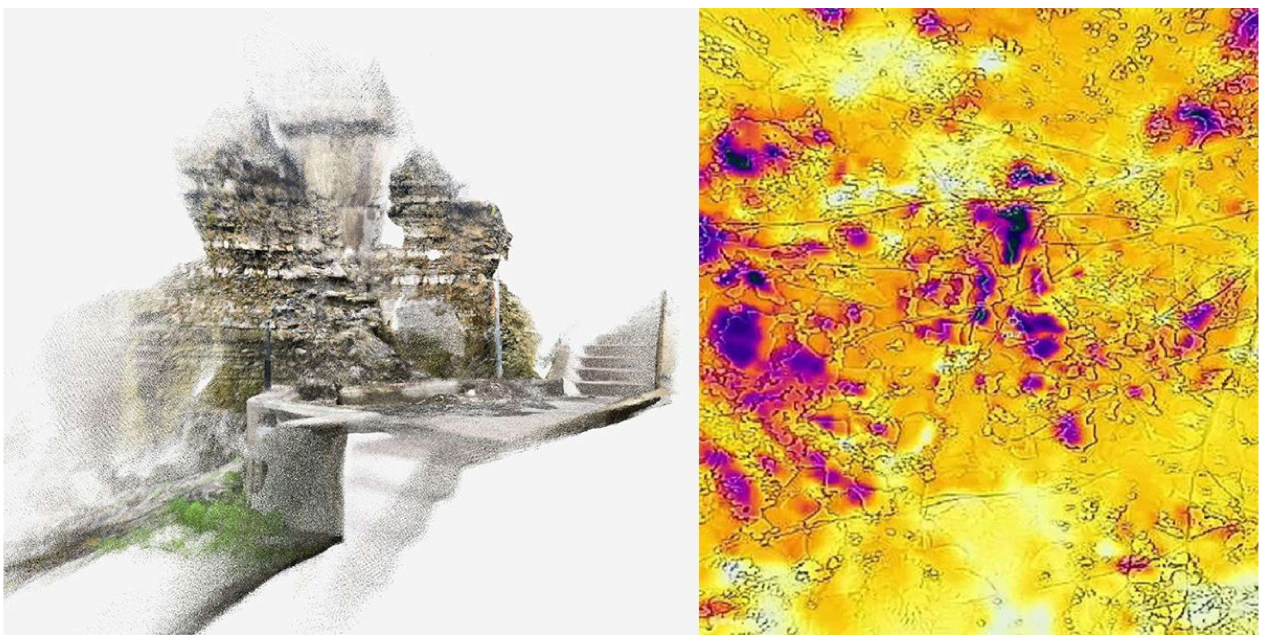

Figure 2. (Left) Terrestrial LiDAR scan of Cascadilla Gorge using iPad, illustrating the maximum scan distance of 5 meters, which is often more limited in practice. (Right) Thermal scan using FLIR One attachment with iPad showing temperature difference in dappled tree canopy. In addition to the ramp showing cold (purple) to hot (white), the tool can take spot temperature readings at chosen locations. Images by the author.

The thermal image is displayed as a color ramp from cool to hot, which can be set to change as the scanner moves, or set at a consistent, programmable temperature range so that one site can be clearly compared to another. The program also allows one to add spot-points to take specific temperature readings of key locations, which can be displayed in degrees Celsius or Fahrenheit. These spot points can also be easily moved by touching the screen of the mobile device and dragging spot points to alternative locations. Spot points were particularly helpful for taking temperature readings of different materials and conditions, such as concrete in full sun versus shade. Finally, the scan can also be automatically labeled with high and low temperatures in each area, providing key information for quick temperature monitoring. The app allows thermal scans with any temperature spot points or ranges to be saved either as still images or as videos, both of which are sent to the device's photo folder. Students were given instructions on how to use the FLIR One on the class iPads or on their own mobile device, having downloaded the app ahead of time. Students were instructed to plan ahead in how they hoped to use the scanner, specifically in setting maximum and minimum temperatures for a set color ramps using spot points from multiple readings, so that they could take either a video or series of photos that allowed them to compare multiple conditions along their chosen transects.

2.2 Compiling, processing, and final composite

After taking scans in the field, students were given a demo on a workflow to export, compile, and refine their point cloud models using Adobe ReCap. Once the scans were completed, they were compiled on SiteScape Pro's website and then downloaded as e57 files. Students were introduced to Autodesk ReCap, an Autodesk program made for working with large scale point cloud and LiDAR data. ReCap was used to combine multiple scans into a single point cloud, refine the model through deleting unnecessary points, reclassify points (for example, to separate trees and objects from the ground plane for accurate topography), as well as measuring and annotating. Once refined, Autodesk ReCap files can be exported into Rhino or BIM software, or as exported as high-resolution images for making drawings in Adobe Suite. Screenshots or exported jpegs were used for constructing initial transect drawings (see Figures 3 and 4). It should also be noted that this workflow used Autodesk ReCap since it was free with our department's academic Autodesk license. For those without a license, Cloud Compare is a free open-source program that offers similar tools. It should be noted the ReCap makes the process of working with e57 files particularly user friendly, so it is recommended for ease of use. After extracting data or high-resolution images of scans, students compiled their final transect drawing in Adobe Illustrator or Photoshop. For FLIR One thermal imaging of the site, students could use spot temperature data as needed to annotate drawings or bring video stills and photographs into Photoshop for compiling into drawings.

In later phases of the course, students created 3D models of the site using aerial LiDAR from NOAA datasets and GIS data, combined with TLS data from fieldwork to construct a more robust 3D model. First, students were taught to construct a Rhino 3D model of the site, using aerial LiDAR downloaded from NOAA, high-res aerial imagery, and local municipal GIS data exported from ArcGIS Pro. A high-resolution topographic mesh was constructed from site contours using the Bison Grasshopper plugin, which is a free plugin that can make a terrain from either point data or contours with a simple script. The municipal data included road edges and building footprints, which were particularly helpful as reference for inserting individual scans. For those taking scans not near buildings, students were able to estimate locations based on the aerial image and site topography. However, it should be noted that the inability to georeference scans is one of the major differences between low-cost mobile-TLS and more expensive options, such as drone and professional TLS systems.

3 RESULTS

This study led to several types of results, including those related to the tools and workflow and those related to the resulting student work from the workshop. First, in testing the tools on various topics, it was discovered that some aspects and types of site conditions translate well into TLS point clouds and others were less successful. Secondly, the student work from the workshop offered creative explorations of the tools, manifesting both the strengths and weaknesses, including limitations to using FLIR One for short-term field work. In addition, several major takeaways on how the tools can be best introduced and implemented in a course setting were discovered, which are included in the discussion section below.

First, though the workflow for scanning was remarkably intuitive and easy for students to adapt, TLS scanning was noticeably uneven based on the type of site and condition being documented. From test scans over the summer, it became clear that, though TLS tools worked well for topography, materiality, and patterns of light and shade. However, the tools were much more limited for vegetation. This was partly due to how the scanning process works. The process of TLS scanning can be compared to painting with spray paint: the iPad sprays out a series of lasers across the site that are visualized as points on the screen that are visualized in real time. With spray-paint, the more one sprays over a surface that has already been painted, the more paint drips result. Similarly, with LiDAR, if one rescans a region continually, the scan becomes more error-prone and full of anomalies. This meant that complex vegetation became particularly confusing for the scanner.   For example, to scan a single plant, scans need to be taken from multiple directions around a plant; for a shrub or a meadow; this process meant regions were rescanned multiple times which resulted in greater anomalies. Tree canopy also confused the scanner both due to distance (much of it is beyond the 5m range of the scanner), though trunks and various caliper sizes translated clearly into the file. This meant that the tools were less helpful for plant ID or modeling individual plants or trees. However, the tools remained accurate when documenting 'masses' and extents, or densities and dimensions of trunks (see Bobrowski, 2023 for best practices for urban forest scanning). Tiling of regions remained possible, but TLS using iPad-based LiDAR is less capable of creating immersive models of trees or complex forests as shown in the work of Girot and others (Girot, 2022). IPad-based TLS was ideal for documenting more constructed conditions of site. Hardscape and structures translated quite easily, as did geologic formations such as cliff faces in the gorge setting. Reflections in windows or water could confuse how the scanner registered distance, though more active hydrology such as the flow patterns of shallow creek beds were rendered accurately. For spatial accuracy, the best scans were conducted on cloudy days, especially for regions with water. However, scans in sunny conditions were ideal for documenting color, shade, and light patterns.

Both tools were implemented by students to conduct a site transect along a portion of Cascadilla Creek of their choosing, which moved between both naturalized and urbanized regions. Students were given leeway on how they would use the tools and what they would document, and the resulting student work showed the potential for the tools' application for fieldwork, as well as some unexpected and welcome alternative applications. The workflow from SiteScape to ReCap to Rhino shown in Figure 2 was easily adopted by students and resulted in a range of different types of applications. Some of the students used the tools to document the complex topography of the gorge. Xinyun used her scans as well as an audio recorder to track the complex patterns of riffles, runs, and pools along the creek, pairing it with sound, and annotating the types and scales of obstructions [see Figure 3].

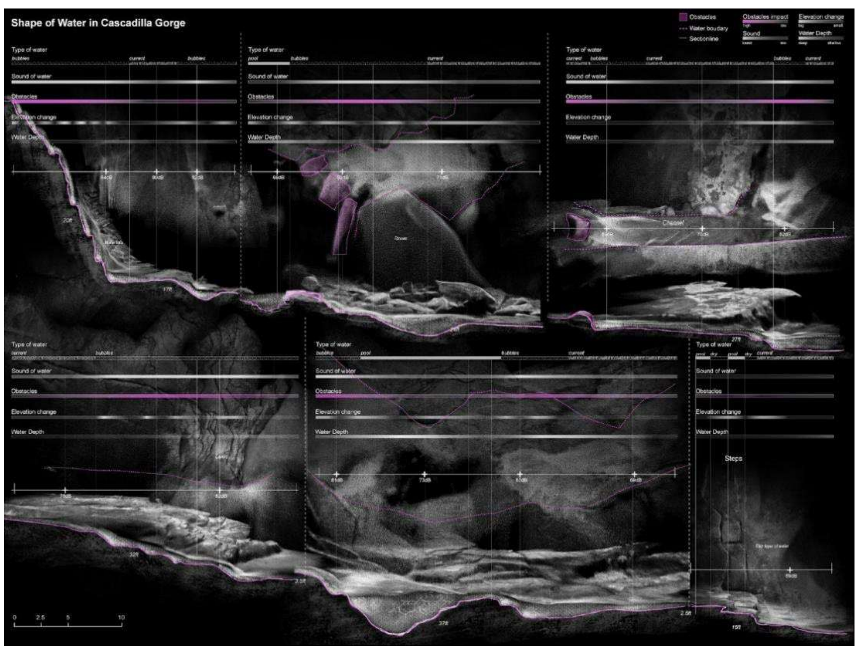

Figure 3. Final student transect study exploring complex patterns of riffles, runs and pools along Cascadilla Creek, using iPad-based LiDAR processed and compiled using class workflow. TLS scans were taken of different pools, and, after processing and importing into Rhino, sections were cut to allow comparison between the areas. Drawing by Xinyun Li.

Another student used TLS to document the microtopographies of Cascadilla Gorge and its creek bed, exploring where different mosses and algae could grow along a sectional transect. Another student used the colored point cloud to translate into a visual diagram of hydrologic patterns throughout the creek bed, showing a correlation between the speed of water and where vegetation could or could not take root.

Other students used TLS to document structures along the creek, including bridges, stormwater infrastructure, or even lost objects discovered along the path; these translated clearly into accurate 3D point cloud models and were easily integrated into Rhino models in later phases. Only one student ended up using FLIR One Thermal Scanning, and this was both due to student interest, as well as the limitations of using these tools on a single site visit when the temperature and conditions were not ideal. Martin Brice's transect explored microclimates throughout the gorge, using thermal scanning to map local temperature and visualize light and shadow conditions [see Figure 4]. The drawing integrated sections constructed from a 3D Rhino model after the workshop, along with plant species identification in the various microclimates. Occasionally, students explored how the tools offered unique methods of visualizing site conditions and histories beyond what the tools were originally designed to document. Peter Jenkins' work exploited the somewhat ghostly aspect of point cloud scans, in which the areas outside of the scan become just as potent as the limitations of the scan itself. Peter approached the transect through the lens of psychogeography, using TLS to scan locations of memory while using an EEG and ECG biosensor to monitor his brainwave activity (O'rourke, 2016). The resulting drawing combined point cloud renderings of key locations with brain wave data keyed to his drifting path along the creek, creating a drawing that became a complex meditation on memory and place.

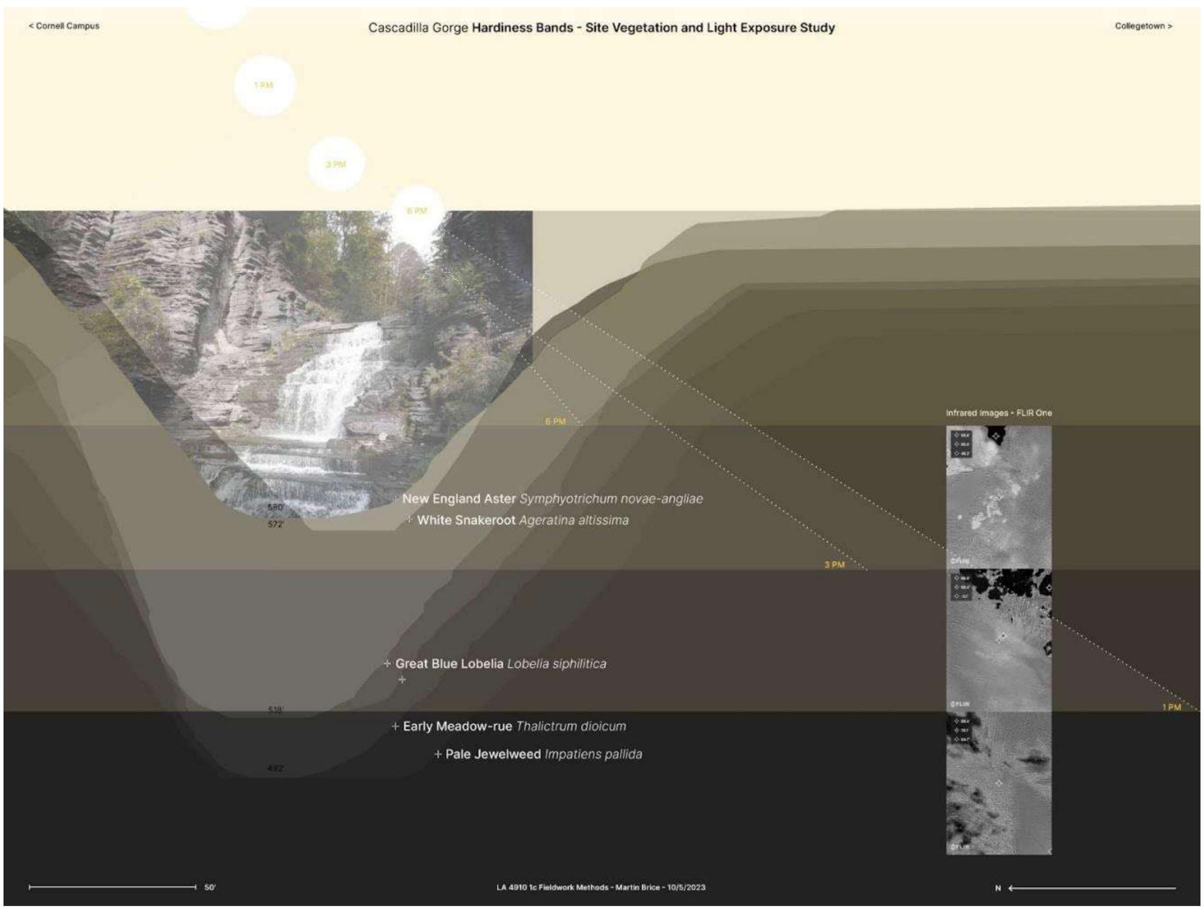

Figure 4. Transect of microclimates and ecological conditions along Cascadilla Creek, using thermal imaging to document light, shade, and temperature throughout the gorge. Thermal stills from the FLIR One, shown on the left side, recorded both light and shade patterns along the gorge, while spot temperatures tracked the high, low, and average temperatures in each location. Drawing by Martin Brice.

4 DISCUSSION

Several key takeaways became clear from the results of the workshop, including how best introduce the tools and conduct a scan, and how best to use these tools for both documentation and representation within landscape architecture. The first takeaway was that it is critical to test tools well before fieldwork and to have a clear plan for large scale scanning before you go into the field. Prepare your path before you go using Google Earth as a base map to test the regions that are scannable; in the field, it is critical to test your path and find key objects to make tiling multiple scans easier as well as aid in inserting it in future Rhino models. Be sure to create a path to understand how much you can cover with ten scans and create a clear walking path to follow. It is also critical to have some overlap in each of your scan regions, but too much will cause problems and anomalies in your file as discussed above. We discovered that there is a clear art form to the act of making a scan. The technique we discovered was to map out a path ahead of time, moving the scanner in an s-like shape to 'cover' the area of interest with an 'even' spray of points and have a very slight overlap to make sure the site is fully scanned. For large multi-scan files, it is critical to have a clear structural object for combining the files and aligning them. Objects such as bridges, pavers, buildings, or other geometric objects offer the best objects for aligning multiple scans. If a site doesn't have a clear object for aligning files, it is possible to bring your own, such as a cardboard box or something light, geometric, and mobile like a milk crate or a book to help register scans. In this case, when mapping out the path of multiple scans, you might place multiple boxes or key objects at strategic locations at the overlap of multiple scans; similarly, one could ask a partner to move a single box at key times during the scan, being careful not to scan the partner. Files larger than 10 scans are possible but require manually combining the files either in ReCap or in Rhino. Secondly, while it is tempting to use these tools only for site documentation, it became clear from student work that there are creative possibilities of the tools to document elements of time and memory. During testing, students created strangely beautiful results through embracing the fact that the scanner can capture people or objects moving, creating a Muybridge or ghost-like effect. One of the first projects students did in the course was make drawings to explore movement through space through chronophotography, and several students explored the potential for similar explorations in three-dimensions using LiDAR. By embracing the temporal aspect of the scan, the technology can capture paths or routes taken by an individual as well as limitations and blind spots embedded into scans.

These tools also offer great potential for studio trips in academic settings; however, their applicability is very much limited (especially thermal scanning) by the environmental conditions on the site. In addition, they require introduction and testing prior to the field trip for students to understand their utility. After the representation course workshop, I shared both the iPad-based LiDAR and thermal imaging tools with my advanced graduate studio during our field trip in late September. Only one student adopted the tools due to the limited introduction to the tools but to great effect. The student was exploring the interface of ditch ends to the Wallkill River in a complex agricultural region, and used TLS to make 3d models of various ditch typologies which informed her later design (see Figure 5).3D point cloud models allowed Xizi to quickly document dimensions, vegetation cover, and infrastructural elements of the ditch network, as well as the conditions of critical junctures with the Wallkill River. With thermal mapping, it is particularly important to think ahead. Our field trip in late September was too late and too cloudy to map elements of heat inequality in urban sites, something that would have been helpful to do for certain student projects. For example, to the urban heat island effect and impacts of lack of shade in communities, it would be critical to schedule field work during the summer and to visit on a sunny, hot day.

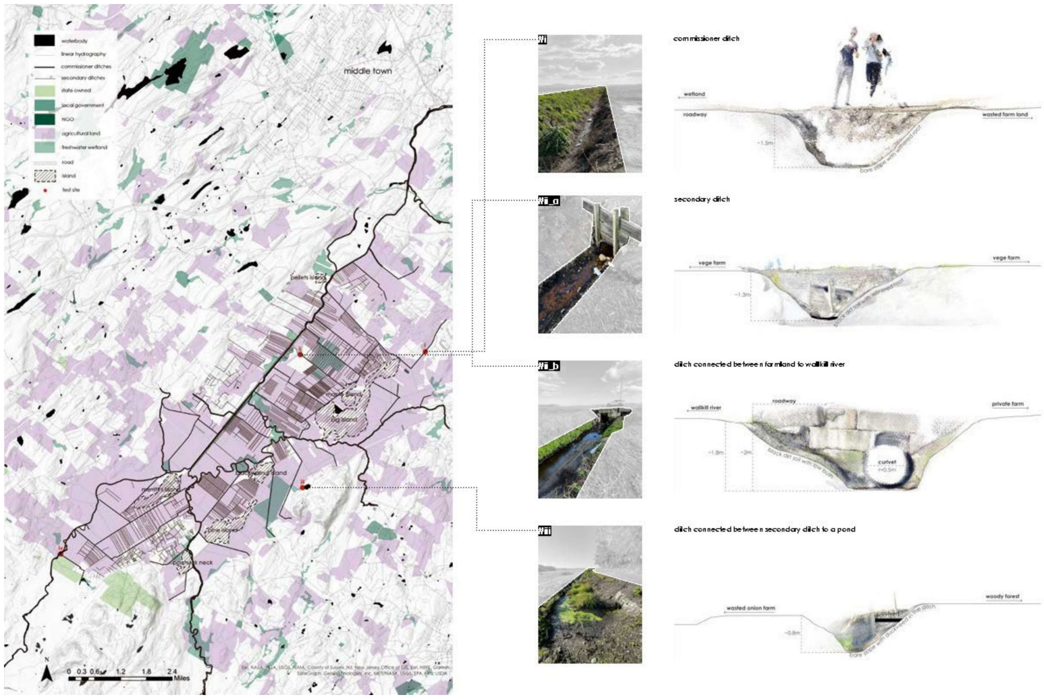

Figure 5. TLS scanning offers great potential for studio field trips, such as this study of ditch typologies. TLS scans were made of a series of ditch profiles in the field, and keyed into site mappings of ditch systems. Scans were imported into Rhino, and simple sections were cut to show microtopography, slope, and vegetation cover. Drawing by Xizi Yu.

Finally, this research supports the applicability of these tools beyond the context of this study. It became clear that these tools also offer the opportunity to democratize site access for students and project partners. All the tools are extremely light-weight, intuitive to use in the field, and can collect data extremely quickly, allowing multiple students to collect information during a single site visit, or to easily return to monitor change over time. In each semester in studio courses, there are often a few students who are unable to complete fieldwork at the project site during the field trip, either due to accessibility issues or absences for other reasons. The creation of a class-wise point-cloud model using TLS would be highly useful in democratizing access to the site for all students. If field trips to project sites are not possible for any reason, such as during COVID, instructors can create immersive models using TLS that would allow students to virtually experience them. The technology also has potential for engaged learning and studio courses, as all the results of scans are highly visual and legible to non-design audiences. By adding inexpensive Google glasses and basic VR, students could develop their designs in immersive virtual environments for community partners to experience their design proposals. IPad-based LiDAR and point-cloud mapping offer an unparalleled tool for students to analyze sites, develop designs, and share final projects with communities.

5 CONCLUSION

While conventional TLS systems and methodologies are either impractical or unaffordable for fieldwork in most academic settings, TLS through mobile LiDAR and thermal imaging using the FLIR One offer promising tools for fieldwork in landscape architecture. The proposed workflow for iPad-based TLS and thermal mapping offers an affordable, accessible, and quick method for constructing three-dimensional models of sites that is of great interest for academic programs and small-scale practitioners. The use of SiteScape to tile multiple scans together, and the possibility of using ReCap to combine even larger scans, allows scans to be quickly constructed of not only elements or conditions of site but of small to mid-size sites in their entirety. Limitations to TLS include its maximum 5 m scanning range (overcome with a ladder or a selfie stick), and its difficulty in scanning either single plants or complex vegetation, such as meadow conditions. Student explorations also revealed the tools' strengths in documenting site structures, hardscape and materiality, microclimates, complex geology, as well as more sensorial and subjective qualities of site. Limitations to thermal mapping were primarily due to the timing of fieldwork, though the tools themselves were intuitive and easy to share. For both tools, preparation in scanning methods and planning out scanning paths were critical to the creation of successful point cloud models. Based on student explorations, these tools also offer novel methods for documenting not only site conditions such as topography and materiality but also movement through space, as well as concepts of memory and place. Finally, TLS and thermal mapping offer accessible ways to visualize site conditions to share with non-design collaborators or stakeholders, making them particularly powerful tools for working with communities. In summation, TLS and novel heat mapping attachments like FLIR One offer innovative tools to investigate, represent, and model shifting site conditions critical to facilitating design within landscape architecture, and offer a more democratic workflow between site study, design, and visualization for fieldwork.

ACKNOWLEDGEMENTS

This research was made possible through generous funding from Cornell's Center for Teaching Innovation Innovative Teaching & Learning Grant. Thank you as well to my Fall 2023 Thick Description class for experimenting and embracing these new workflows in completely novel ways.

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