Architectural Scanning and Innovation in The Built Environment

Draft of Summary Masters Research Paper

By ELIJAH WILLIAMS

Cal Poly Architecture

Spring Quarter 2021

Introduction

Recently, a studio I was enrolled in received a donation from an alumnus: hundreds of boxes of unopened drawing lead and erasers. We couldn't help but think of Frank Lloyd Wright in his home and studio in the suburbs of Chicago, with lines of interns and junior designers posed before their drafting tables. Imagine the silent offices with only the sound of pencils being sharpened. The technology from that era is so obsolete that many students failed to understand what these products even were. But if you consider the outputs of these offices from the past and compare them to the present, they are not as wildly different as one might suspect. Even though entire rooms filled with people, vellum, brushes, and pencils have been replaced by computers, the results are not so different. The final outputs are line drawings, which are used as reference in representation, proposal, and fabrication of the built environment. But what would a future look like that forgoes the 2D output and exists solely in 3D, creating a digital workspace that a variety of designers can contribute to simultaneously?

This is, in some ways, the world of Building Information Management, of algorithmic project management and Xref file organization. Increasingly, there has been a need and call for accurate models of the built environment, within which these new digital models can be inserted. Using 3D scanners, designs can move from the physical to the digital in a matter of minutes, providing unprecedented accuracy for future designs. 3D scanning technology is used to create accurate 3D point clouds of the built environment and as a tool for the development of Architecture.

This places the current moment at an interesting meeting point of Architecture and Technology. This project aims to understand how 3D scanning technology might be made to perform better in an Architectural context, specifically using point cloud collection technology tailored to the scale of the built environment.

Literature Review

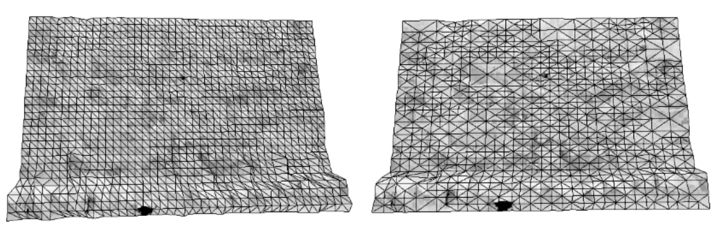
Architecture is a field that exists fundamentally as a duality, between the built work it produces and the theoretical field that discusses the merits of all work, built or unbuilt. 3D scanning threatens to exist only within the field of Technological research and not in the discipline of Architecture. 3D scanning Innovation has been driven by industries that do not have any specific interest in Architecture (Hoppe 2, Stamos 3). This premise is refuted through a range of speculative projects produced through a variety of methods in the article *Emergence in Architecture* (Castle 2004). Many of the techniques in 3D scanning that were developed for other industries find their way into the discipline of Architecture and serve as tools for exploration (Castle 2004). The relationship between Architecture and 3D scanning is established beyond simply the practical (Hadwad, et al.) to the point of the experimental (Castle). This has coincided with an increase in availability, using cell phones, which has brought an otherwise inaccessible field to the public realm (Takahashi).

When addressing and investigating what it is that technology might bring to the field of both architectural representation and building construction, it is worth looking at how drawings have changed throughout time. Focusing directly on one project in this regard, *Saint Clare in Santiago de Compostela Church,* it is possible to study the innovative methods that were used at the time to fabricate the façade of the church (Calvo-López et al.). By physically deconstructing the newer layers that have been added on top of existing components of the church since its initial construction, a survey team was able to study a set of representational drawings that were engraved in the stone floor of the project. The authors argue that these are full scale drawings, giving the design the ability to directly translate between the construction and the ideation phases of the project. Using modern photogrammetry techniques, the team, representing the Dept. of History, Representation and Restoration of Architecture at Sapienza University of Rome was able to create a set of accurate reference models to compare to the drawings found on site. The idea that drawings can be recreated based on digital imaging techniques resonates with the concerns of this project by presenting an alternative to conventional planar modeling techniques.

The collection of data points has increased with the growth of digital technology but the way that points are being turned into 3D models has not advanced at the same speed (L. Carnevali). The applications investigated concerning the preservation and detailed colored scans of existing buildings using small scale drones presents a situation where photogrammetry would be preferable over a point cloud-based system (L. Carnevali).

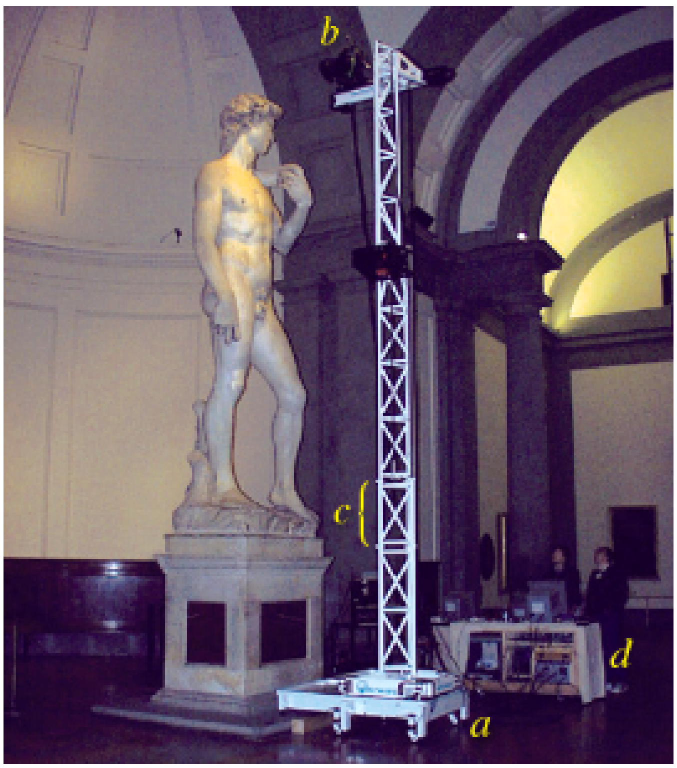
Cellular phones with high Megapixel cameras have proved an increasingly popular technique for photogrammetry because of built-in movement tracking systems (Takahashi). While Photogrammetry can provide accurate reference models, the editable nature of Point clouds, as well as the ease of collection, makes a data-point based model system a superior choice for integrating into a typical Architectural design workflow.

Point clouds, which are collected from 360 scanners and used in the creation of the 3D objects, become usable for various purposes. Point clouds are easy to store and translate compared to the meshes that can be made in photogrammetry or that point clouds can be converted to. Because point clouds are the file type that scanners collect data in, it is important to understand different methods for converting point clouds to meshes. The comparisons of Regular Meshing to Adaptive Meshing illustrate the value of using a LOD (Level of Detail) algorithm to create a mesh that varies in densities depending on necessary complexity (Hoppe). A graphical example from the paper is given below:



Example of Regular Mesh (Left) vs Adaptive Mesh (Right) (Hoppe)

In the article *“The Digital Michelangelo Project: 3D scanning of Large Statues”,* many of the issues concerning objects that exist outside the human scale are addressed (Levoy). An increase in size and complexity requires innovative solutions to the issues, such as creating multiple scans and merging scans (Levoy). The issues addressed in this paper concerning large and mobile scanning provide valuable insight into future technologies because many of the issues about size are relevant in the scanning of architecture as well. Small Drones can also be used for large elevations of buildings for instances when mounted scanners are not feasible, although this example specifically is related to photogrammetry (L. Carnevali)



Scanning System used to capture full scan of Michelangelo’s *David* (Levoy)

The conclusion drawn from this paper is that while photogrammetry could be useful in a specific instance, such as preservation, the ability to integrate multiple sets of point clouds makes a cloud-based system preferable for the architectural scanning project at hand. This distinction is important in understanding how these methods might differ between a preservation and a new construction project.

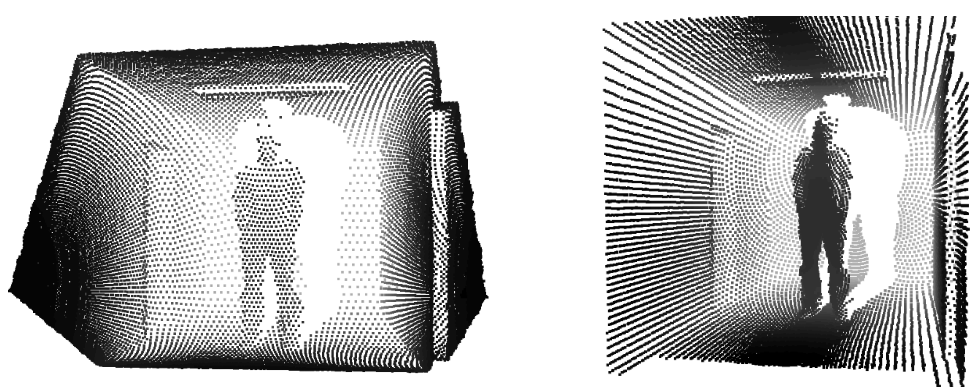
Methodology Plan

The methods for this project involve learning about the existing technology and understanding how the implementation of these technologies could be improved in the Architectural context. The outcome of the project will be a piece of scanning hardware that improves the relationship between scanning and Architecture. In order to achieve this, the methods for the project are divided into three sections, each aimed at a different part of the project. Through the literature review, the use of 3D point scanning, compared to Photogrammetry, appears to be preferable for this project. The development of both business plans and positioning will be given as well.

These three distinct techniques aim to create a framework within which to focus the tools that will be used to complete this project. The first is to understand, within point-based scanning, which tools and methods would be best to test in an Architectural context. The second technique is the survey of the industry, which aims to understand, as a supplement to the literature review, how technology is being used in the professional field. The third section examines techniques and technology needed to create a working prototype of this device and the other technology needed to complete a large-scale improvement for small firms **t**o help understand the technology used in the field of 3D scanning, a survey of existing technology is required.

Summary and Understanding of Existing Technology

The second is to understand, within point based scanning, which tools and methods would be best to test in an Architectural context. Many of the projects in this field, covered in the Literature review, create in-depth tests for existing technology that can be used to create a rubric of how and why different techniques are used in different situations. These Topics have been subdivided into sections labelled based on their specific functions: Techniques for Working with Point Clouds, Techniques for Collecting Point Clouds, Applications and Methods for Specifically Architectural Point Cloud Data.



Pitching Scan vs Rolling Scan (Wulf and Wagner)

The scans above show how different mechanical methods create point clouds of different densities and accuracies. Although these are two of the simpler examples, it illustrates how the scanner only collects data that is picked up from the optical sensor, independent of the scanning techniques (Wolf and Wagner). While this may suggest that increased accuracy could potentially increase the resolution to the point of realism, there have been no such developments. In the field of Survey Architecture, processing this data “has not improved significantly in the last decade…” (L. Carnevali). Recreating surfaces from collected data points has been computationally complex in the past but is increasingly possible due to developments in small scale computing. The storage and "remeshing" of points is increasingly possible, although this misunderstands the relationship between scanning and architecture. This review does not focus on Integrating Complex Scanning Systems (Levoy & Remondino) as the meaningful developments and progress in this field do not relate as directly to Architecture as initially believed. Instead, the development of a novel piece of technology to hit at the fundamental difference between these two sections better understands the needs of Architects.Testing the merits and drawbacks of the current ecosystem of design is important to understand the point of what we are working on here.

While there are many limits to the applications of LiDAR technology into Architecture, a considerable amount of work and research was done in this project to design a system, formerly referred to in this paper as "the ecosystem", that integrates Machine Learning technology. While the explanation of the business implications are visible in the "Experimental Pitch Plan" section of this paper, the development of a key part of this system does pertain to the way space is imagined and perceived within Architecture. The above section refers to the limits in computational power, but does not propose a solution to help improve accuracy or meaningfully disrupt the existing system. One possible exploration, through complex sorting algorithms, may be possible but does not allow for a visual and Architectural study of the techniques needed within the scope of this paper. The approach considered in the coming section is for a tool to create a database of floor plans, especially tailored in their design for Machine learning applications.

The value of this proposal, to create a new tool for creating Architectural floor plans, is positioned against the traditional methods, which require depending on a somewhat meaningless definition of accuracy. By abstracting accuracy into a few sorted measurements and leveraging the power of a pretrained network, the potential here is a new paradigm not just in the practical sense but in the abstract notion of accuracy as it pertains to Architecture. Buildings are instead rendered as a set of disparate points, collected during the Architecture As-Build and Measured Drawing Process, much as Architects are currently making measured drawings using existing tools.

Meetings with Ellipsis Drive, a company out of the Netherlands, suggest that it is possible to both store and deliver this data in a web interface, allowing for non software delivery of data. Their product offers a web interface to display geolocated drawings, allowing for non-technical users to interact with and map data. This tool would be helpful in delivering Machine Learning Based Technologies to users with no ability to run software locally or implement said technology integrated with their local machines. The increasing power of pretrained neural networks means that it may not be necessary to have a large data set of existing data but that a general theory of sorts may be arrived at through the use of machine learning and a limited set of training data.

In an effort to create a system to automate the creation of training data, the following experiment was completed. Starting with the basic square patterns in Figure 1, offering a matrix of sizes of rooms, first starting with 1 room of small proportion and extending 1 room at a time in each direction. The towers in Figure 2 represent the technique for starting from these simple extended 2D drawings and creating a tool for interpolating floor plans through a contour. Visible in Figure 3, a red contour is added at a preset and regular height through automation creating a set of floor plan shapes that, although visibly similar and geometrically varied. Figure 4 shows the outcome of 1 of these curves, visible in 2D and annotated. Relevant here is that this technique allows for the creation of highly productive machine learning data, as opposed to finished architectural drawings. Although the results may be similar, this system prioritizes the development of data to train a machine learning model, not the output of finished drawings. Through extrusion and lofted distribution, in which a finely differentiated set of floor plan drawings are generated, the link between machine learning and architecture can be established.

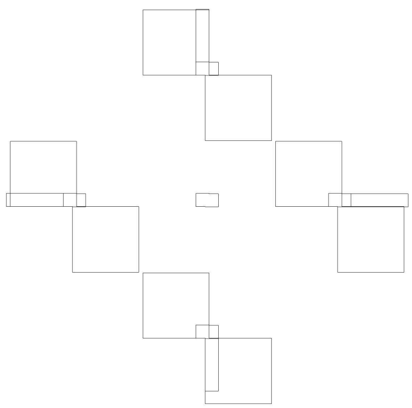


Figure 1

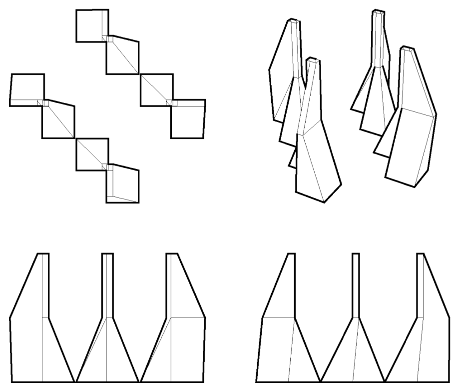


Figure 2

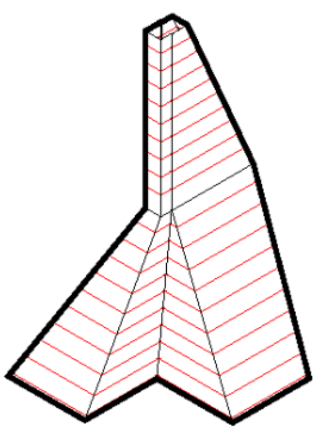


Figure 4

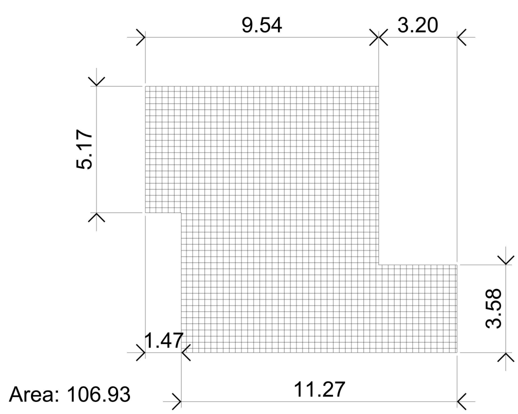


Figure 5

Survey of the Industry:

In an attempt to establish a strong understanding of 3D scanning it is necessary to go beyond what is being done in an academic context. This is an industry in development, and it is fundamental to learn what is happening at the cutting edge. Because many of the applications of 3D scanning in Architecture happen behind closed doors at firms, interviews will help to learn how and why these technologies are being used. This paper initially focused on understanding if and how these technologies were being used in typical Architecture firms. Although the central coast is a small area geographically, the implications are wider, assuming that firms will behave similarly throughout the United States and likely farther. Outreach to more than 70 firms in the greater San Luis Obispo area, with a response rate of 21.4%, generated in depth responses for 15 small firms in the area and more than 10 interviews, which are significantly representative of the more than 72,000 firms represented in the AIA Firm Survey Report 2020. This represents a framework and surveying ecosystem that could be used to collect data on a significantly larger portion of the small firms in the country. While this data is not complete, it frames an argument for the introduction of such a technology as it is being proposed here to this particular community of Architects and Construction Professionals. See Figure 5, Figure 6 and Table 1 below.

Figure 5:

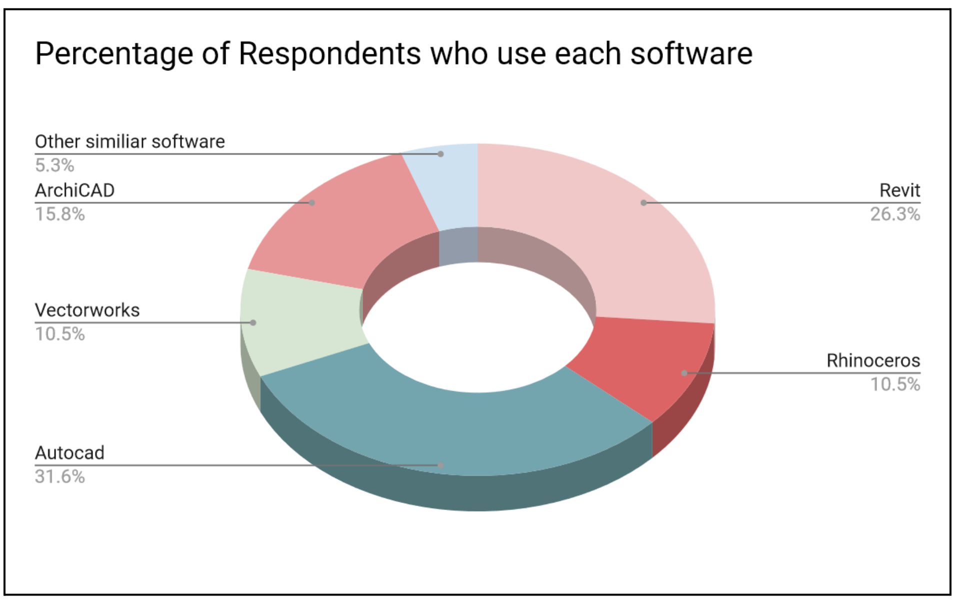


Figure 6:

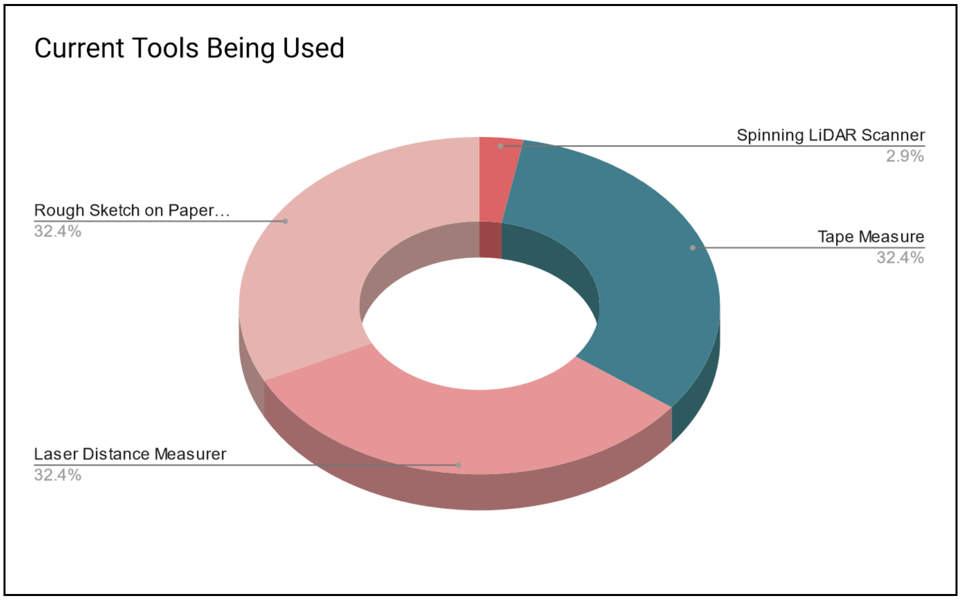


Figure 7:

A typical set of measured drawings for a renovation on a small <2000 sq/ft house takes on average 13 hours.
On average, it takes 2 employees to create drawings for a single project.
On average, 78% of employees at architecture and construction firms work on drawings.

Figure 5 is a clear representation of the wide use 2D drawing software and popularity of the Autodesk software suite, shown here through AutoCAD and Revit (BIM) softwares. The ability to see this data in this form allows a clear understanding of how any output from a new device would enter existing workflows and software ecosystems. All of the listed softwares and many others, function through a mix of plug-ins and SaaS software models that portend to lock a firm into a single ecosystem. While the ability to integrate directly through a software solution is appealing, the variety of softwares used, despite their similar functions, means that this is practically impossible within the scope of this project. This understanding was key, opting instead to create drawings in an open source vector based format, in this case OBJ, making it operable in all software shown in our survey shown in Figure 2. For more information on the choice and functionality of this ecosystem see the format exploration section.

In the AIAS Firm Survey 2020, the growth of integrated BIM software solutions, such as REVIT, is well documented as these practices are often encouraged to save time and money by integrating their 2D and 3D workflows within these software products. Due to our focus on measured and as-built drawings, the project drawings output by the ecosystem proposed in this paper would undergo serious editing and processing before entering a more complex ecosystem. Because there has historically been no reason for most as-built and measured drawings to enter 3D space, many firms in the central coast use only 2D software products in their workflows, software products that lack many of the complex features available in these high-end solutions. By understanding that firms may not be able to spend the time or money upgrading to the highest end software solutions, the ecosystem can integrate equally well

Figure 6 shows which tools are commonly used for the creation of measured and as built drawings. This data is from firms with fewer than 20 employees, offering a window into the otherwise lone-wolf portion of the industry that drives a majority of the small-scale renovations across the country. This data was collected in a multi-select format, suggesting that an average firm would be using all 3 of the most common results from our survey with only a single firm using Spinning LIDAR, on top of the other tools. The low level of adoption of LIDAR solutions is suggestive of a disconnect between the technologies in this multibillion dollar industry and the small scale firms that might benefit from the time saving effects that these technologies claim. In interviews, local firms stated that the two main reasons for not using these solutions were the inaccessible price point and the lack of actual time saved.

"We tried a Spinning LIDAR Scanner service and could have measured the entire project 3 times in the time it took to fix the broken file format. Way too detailed and didn't help at all, took us forever to try to clean up the file."

This quote, from a small firm that had hired out a spinning LIDAR from an As-Built Service, articulates how the result of the Spinning LIDAR Scanner service failed to save them any time or money. After a single effort, the use of this service was abandoned and the conventional methods were taken up again. This is represented in our larger data pool, as these devices and services were rare and when they had been used, the users felt like they had wasted both their own time and their clients money and that they were getting a LOD (Level of Detail) that did not align with the goal of the drawing overall.

Figure 7 represents a finding from our Survey of small Architecture firms in the central coast that were better represented as figures for clarity. Key here is the admission that the measured or as-built process for a small home (less than 2000 sq/ft) takes approximately 13 hours, as an average across all inputs. From our interviews, it became clear that the number of hours and time spent translating on site measurements into CAD software products (as shown in Figure 5) is about 1:4, or about 2 hours of drawings on site for every 8 hours entering drawings.

In many ways, this report concerns itself with understanding how and why small Architecture firms are not using and benefiting from technological progress shared by other industries. At this juncture, it is worth considering how the fee structure is designed for this process, as these firms fundamentally are businesses that are considered with their bottom line and not as directly with the generally conception or fascination with Architecture as an art.

These firms, although not the most numerically significant employers, do represent a meaningful portion of the Architecture industry (AIAS Firm Survey 2020).

For an individual or homeowner looking to have a set of measured drawings done for any reason they should expect to pay between $50 and $150 per hour, scaling along with the size of the project and the expected time. Some practices give a flat fee, of say $1200 for all "small residential" projects and make up the difference on projects that take longer, resulting in approximately the same time spent. Architecture firms typically bill on the higher end of the scale, closer to $150/hr and speciality contractors or drawing services can hit price points closer to $50/hr, with a fair amount of variety. Importantly, this part of the process is not meaningfully profitable for Architecture firms. Consider that for a major renovation or addition, in the range of $100,000-$300,000 USD, estimating the total cost of Architects fees at about 10%, an Architect could make from $10,000 to $30,000 USD on such a project. The as-built process represents a small portion of that process from both a time and money perspective, suggesting that it is not a meaningful project to pursue, but this misunderstands the functioning and process of Architecture firms more generally. Although this process is not the most profitable, it is required to start any renovation or addition process.

Importantly this process is a major pain point for these firms. Multiple firms reported in interviews that they often found themselves in a position to debate and argue with clients over the bill for a set of measured or as-built services. They describe the origin of this as the fact that the client only sees them on site for a small portion of the time it takes to make the drawings, creating a misunderstanding that the hourly billing rate is being violated or manipulated to make the practice money. A single firm gave details, including that they spent a good portion of the beginning of each project arguing with homeowners who wanted to try to avoid the as-built or measured drawing fee by doing it themselves or providing an alternate source of drawings. This can pose a complex legal problem that is not at the core of this project, concerning the need for architects to see the site of their proposed renovations. In order to avoid this, multiple firms choose instead to outsource these drawings themselves to small drawing-only firms that repeat the same service that they would perform, but remove the headache. According to reviews of receipts provided for viewing, there is no substantial financial difference between the various ways of having these drawings done for the client, but the Architects often choose to lose out on this potential revenue source due to the amount of coordination and debate required. Architecture firms will find a service they can trust and require that any client interested in working with them must first use this service to create an accurate and detailed set of measure drawings that they Architect can work with going forward. Note the Experimental

Lines 2 and 3 in Figure 7 illustrate the potential business loss due to time spent creating measured and as-built drawings, with small firms using 78% of their workforce to create drawings. The survey included many solo practitioners, leading to an average of 2 employees working on drawings at any given point, although it typically could be 100% of an office working on these drawings. This result is meaningful here, as it means that the as-built and measured drawing process, that which we are primarily concerned with in this paper, could create a complete blockage of a firm's day to day operations. This finding suggests that the process of creating the above-mentioned drawings, although meaningfully accurate and successful in leading to thousands of renovations every year, fails to meet the needs of Architects.

After collecting and understanding the data represented in the above figures, it is relevant to consider the effects that a more complex understanding of how existing solutions have failed to meaningfully disrupt the Architecture ecosystem here in the central coast could contribute to the larger argument.

Conclusion

A variety of different techniques for collecting point cloud data and converting it into 3D objects have been reviewed in this paper, as laid out in *Summary and Understanding of Existing Technology* Section, revealing that the existing meshing software offers a variety of different options for converting point clouds into 3D objects, as well as a variety of hardware options for conducting scans. The aim of this project, by completing the process laid out in the Methodology Plan, is to create a piece of 3D scanning technology that could adapt 3D scanning hardware and software to better serve Architecture as a field.

Within the literature review, it is laid out how the existing technologies have had a variety of results in the context of Architecture projects. The limitations of this project are in the ability for it to successfully report on the technical aspects of 3D scanning. Another limitation that influences this project is the ability to store and work with large and complex files. This issue is common across all projects in this field and might find its solution in cloud storage.

The next step would be to develop a piece of Architectural Technology that remotely surveys the built environment, an area where the bridge has not yet been made between the industries of 3D scanning and Architecture. Elements of this might include feasibility studies for small firms to implement 3D scanning into their workflow, mechanicalization of the collection of information at a variety of points and testing specific software and scanners.

References

Calvo-López, José, et al. “The Eighteenth-Century Full-Scale Tracings in the Church of Saint Clare in Santiago de Compostela: Execution Drawings or Design Sketches?” *Construction History*, vol. 31, no. 2, 2016, pp. 81–106. JSTOR

Hadwan, MK, et al. “Photogrammetry as an Aid to Lighting Design for Complex Obstructed Interiors.” *Lighting Research & Technology*, vol. 34, no. 3, Sept. 2002, pp. 221–28. *SAGE Journals*, doi:10.1191/1365782802lt049oa.

Hoppe, Christoph, and Susanne Krömker. *ADAPTIVE MESHING AND DETAIL-REDUCTION OF 3D-POINT CLOUDS FROM LASER SCANS*. p. 7.

L. Carnevali, et al. “CLOSE-RANGE MINI-UAVS PHOTOGRAMMETRY FOR ARCHITECTURE SURVEY.” *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLII–2, no. 2, 2018, pp. 217–224. *cpslo-primo.com*, doi:10.5194/isprs-archives-XLII-2-217-2018.

Levoy, Marc, et al. “The Digital Michelangelo Project: 3D Scanning of Large Statues.” *Proceedings of the 27th Annual Conference on Computer Graphics and Interactive Techniques*, ACM Press/Addison-Wesley Publishing Co., 2000, pp. 131–144. *ACM Digital Library*, doi:10.1145/344779.344849

Liu, L., and I. Stamos. “A Systematic Approach for 2D-Image to 3D-Range Registration in Urban Environments.” *2007 IEEE 11th International Conference on Computer Vision*, 2007, pp. 1–8. *IEEE Xplore*, doi:10.1109/ICCV.2007.4409215.

Shapiro, Aaron. “Street-Level: Google Street View’s Abstraction by Datafication.” *New Media & Society*, vol. 20, no. 3, Mar. 2018, pp. 1201–19. *SAGE Journals*, doi:10.1177/1461444816687293.

Takahashi, Y., and H. Chikatsu. *3D MODELLING AND VISUALIZATION OF CULTURAL HERITAGE USING MOBILE PHONE CAMERAS*. p. 5.

Y. Guo, H. Wang, Q. Hu, H. Liu, L. Liu and M. Bennamoun, "Deep Learning for 3D Point Clouds: A Survey," in IEEE Transactions on Pattern Analysis and Machine Intelligence, doi: 10.1109/TPAMI.2020.3005434.

LIMITATIONS Many of the limitations are in the understanding of the elements of Computer science, Electrical Engineering and Coding that are at the base of this field. Without being able to fully understand what principles are being used in the varying technology, it would be incorrect to draw any strict conclusions about how the field might best adapt to Architecture. At the same time, Architecture exists as an interdisciplinary field, where it is more relevant that the technology is applied successfully than the understanding is complete.