Experimenting with 3D Digitization of Architectural Physical Models using Laser Scanning Technology

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This paper assesses the use of 3D Digitization techniques by carrying out laser scanning of typical physical models produced by architecture students. The aim was to examine the product of laser scanning with respect to scanning and 3D modeling processes, and the effects of variables such as characteristics of the models, materials used, and design complexity. In order to assess the similarities and accuracies achieved by the scanning and 3D modeling processes, the research investigated human perception of differences between analogue and digital models. This enabled an assessment of the degree to which digital models were accurate representations of the real ones, and whether laser scanning can successfully be used as a medium to recreate and represent complex architectural physical models. The study presents a potential direction for digital translation in architectural education.

1. INTRODUCTION

The advance of technology in the areas of building, environmental control and computing, meant that architectural teaching processes needed to adapt to the increasing use of modern digital tools. However, in many schools of architecture, computer technology is not adequately integrated into the curriculum, because first, its introduction means that there is a need for an important change in the way architectural design is taught particularly in studios, and second, the learning outcomes of digital modeling are not known or understood. Not surprisingly, digital technology is allowing students and designers to explore new areas without restraining their imagination in order to produce buildable complex designs. The process by which this is achieved relies primarily on the use of hybrid design techniques; that is the making of scaled physical models, and then 3D modeling. Traditionally, students produce very accurate scaled physical models as part of their design development, but struggle to recreate them digitally for further analysis and improvement.

Computers have revolutionized architecture, but at the same time they have created strong divisions amongst architects and scholars, primarily due to concerns about how Computer Aided Design - CAD - may be affecting designers' identities and the expression of their creative work. [1] Some designers have revolutionized the design process by letting computers lead the way, particularly when it comes to resolving complicated geometries. Others rely on free-hand sketches and physical cardboard models as important conventional tools that are combined with digital ones during their design process. [2]

The need to record and edit the design proposals within a digital environment and to improve information processing of architectural designs brings about the issue of whether the design process should rely on manual or digital tools, or both. This paper presents an approach where digital design development can easily complement manual one, through the use of physical models that are later digitized. Thus, suggesting a new educational approach to architectural computing and digital reconstruction.

The need for such experiment came about in answer to questions raised by indiscriminate use of CAD in architecture schools. This paper therefore focuses on assessing the use of 3D digitization in architectural design studios. It purports to explore ways of creating accurate digital models from precise physical models. In addition, this experience aims to encourage the use of digital tools in the design process by providing new ideas and opportunities rather than a mere representational medium. Generally, undergraduate students do not have prior knowledge of CAD, have to learn CAD applications on their own, and therefore struggle with creation of simple 3D models. It was thus hypothesized that if intricate physical models of well developed projects can be digitally recreated, students can then concentrate on exploring their design using digital tools instead of constructing them from scratch inaccurately and only for representational purposes. This is why an attempt was made to create facsimile translations of physical models. The aim was to examine the ease by which 3D digitization technology can quickly recreate digital models that could not otherwise be produced manually. This would offer more freedom in design development and exploration of the analogue interface knowing that unusual and complex forms can be effectively captured digitally. Schnabel et al. [3] pointed out a similar aspect in their experiment on 3D Crossover exploring whether the two representations had informed one another.

There are many ways of digitizing a physical model, but these generally fall into seven categories: mechanical tracking technology, laser scanners, magnetic tracking, ultrasonic scanning, photogrammetry, interferometry technology, and optical 3D scanners. These methods were reviewed, and mechanical tracking and laser scanning are the only techniques accurate enough to meet the requirements of architectural design. Photogrammetry and optical 3D scanners are not very accurate when using small-scale objects like physical models. However, airborne laser scanning (ASL) is not yet a substitute to photogrammetry which uses high resolution imaging particularly for digital terrain modeling. In fact, the two methods currently complement each other, with ASL having more potential for development and enhancement of data capture and processing. [4]

The development in non-contact recording technology, and particularly laser scanning, has enabled professionals in many expert fields such as engineering and heritage conservation to document and reproduce reality based models accurately and efficiently. There is an increasing need for introducing these methods to educational institutions. It would help better prepare students for a challenging professional life and enhance and modernize existing teaching methods that tend to rely excessively on traditional learning tools, particularly in architectural design studios.

Three-Dimensional digitization is a process that captures the data with a 3D digitizer, such as a mechanical tracking device or laser scanner. However, in order to achieve this, one needs an accurate physical model. Three-Dimensional digitization serves to reproduce a surface model. This enables digital exploration and visualization and helps develop architecture entirely on the basis of its surfaceness. As a result, there presently is a proliferation of expressive skins as architectural forms. Architects such as Frank Gehry use a mechanical arm to digitise large physical models in the NURBS-based Rhino software. The result is then exported to CATIA for analysis, surface optimization, structural design, production of working drawings, and manufacturing. [5, 6]

Three-Dimensional digitization, whether contact or non-contact, allows the user to recreate physical objects quickly and efficiently in 3D computer space. This technique is crucial to the effective reproduction of an accurate digital copy of virtually any 3D object.

The use of contact 3D digitization was previously explored as part of this experiment within an architectural studio. A Microscribe 3D digitizer was used to digitally recreate the analogue models, following an approach similar to that used in Fran Gehry's firm. With this method, however, it was found that models needed to be of a large scale for more precision, there was considerable time spent digitizing, and the accuracy of the captured data was lacking [7, 8]. Therefore, another approach was taken, experimenting with non-contact 3D digitization, and laser scanning in particular, using smaller physical models.

The move towards non-contact 3D digitization is a logical one owing to the development in scanning technology and needs in terms of CAD and design knowledge. Laser scanning is a technique that is more accurate yet more expensive than conventional 3D Digitization processes. This technique is a very quick procedure that scans any opaque physical object. A 3D dense surface mesh or points cloud are produced as a result. In addition, software developments have enabled many scanners to effectively process the captured data and achieve an acceptable digital model. However, this technology has some drawbacks since reflective or transparent surfaces are not digitized very efficiently. [9, 10]

There are currently two types of scanners, close range and long range, with different methods for distance measurement. One group uses Time-of-Flight and the other uses Triangulation. In the case of this research, given the size (35x10x10cm) and type of objects to be scanned and the accuracy needed (<1mm), a close range scanner using Time-of-Flight was used [11]. This technique is increasingly being used to record reality-based cultural heritage objects, as well as larger objects and urban environments. Other applications of laser scanning include plant, civil, building and survey needs. [12]

The advantage of laser scanning is the quick collection of a large number of 3D surface points. It is highly productive and can result in an overwhelming amount of information that needs to be processed in 3D software [13]. As stated earlier, using a contact 3D digitizer proved to be complicated and time consuming and generated accuracy problems. An experiment is needed to test laser scanning in order to compare it to mechanical tracking technology, and to assess its effectiveness as part of the architectural design workflow.

The experiment explores physical representation, shape grabbing, and digital representation and modification, but does not deal with rapid prototyping as explored by Schnabel et al. [3] and Tamke [14], or by visually comparing 2D images of 3D objects using algorithms or software such as Geomagic Qualify. It is also not concerned by the measurement of point density accuracy or precision of the scanned objects. The main concern of the study is to effectively translate the analogue design to a digital environment for 3D visualization, design improvement, and representation, and to assess future users' response to the accuracy of scanned models in the context of education. The digital result is not intended for use in the production of detailed working drawings or for reverse engineering purposes.

2. THE PROCESS

As part of a design development exercise within an intermediate design studio, accurate physical models were made using the department's model-making laboratory. Three different models were selected; two solid models and one surface model. The first model was made of solid wood and displayed very simple geometric properties. The second model was constructed using strong 5mm thick white foam with paper coating. This sketch model was based on a rather complex conceptual idea and contained sharp angles. The third model was a simple sketch model with some fine details made using solid wood composite. These models were built using materials that had laser-friendly surface properties (non-reflective and opaque). In addition, Model 1, although a simple geometric shape, had curvature and some surface texture to help assess physical objects issues and the accuracy of their measurement.

The dimensions of the models were as follows:

- Model 1: 10 cm base radius, by 36 cm height.
- Model 2: 34 by 11cm base, by 32 cm height.
- Model 3: 20 by 10 cm base, by 6 cm height.

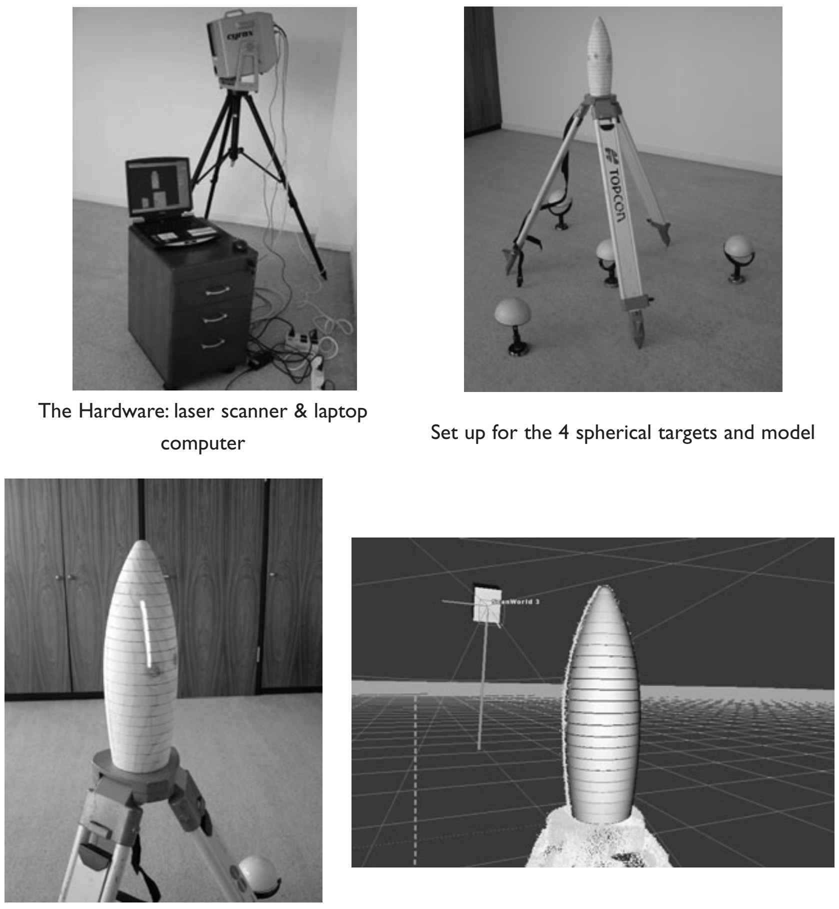
A Cyrax HDS2500 scanner system developed by Leica Geosystems was used. The components of this system include the Laser Scanner, tripod, battery, targets, and a laptop computer. In addition, four spherical targets were used for registration purposes. A digital camera was used for capturing the scanning region. The scanner's operation was controlled from the laptop by means of a cross-over cable.

Cyrax Laser Scanner uses the Class 2 Pulsed Green Laser that is safe for the eyes except for direct or long term exposure. The ranges are derived via measuring the Time of Flight (i.e. forward and backward) of the pulse. The scanner observes the Range (ρ), Direction (θ), Elevation Angle (Z or α) and the Return Signal Intensity (E) with respect to the Scanner Space, and deliver the spherical co-ordinates of the scanned point clouds of the object. The Laser Scanner needs not to be set up over any known position; instead, special scanning targets (≥ 3) were placed in the scanner's FOV (Field of View). Targets were surveyed and coordinated in the traditional way or set up on known positions. [15]

The scanner software Cyclone 5.1.1 was used for controlling the scanner, and to view and manipulate the 3D data. It is a 3D point cloud processing software; the software interface for the HDS laser scanner. It is also a tool that aligns point clouds captured from the different scanning positions. It has the ability to align overlapping areas of point clouds even without the use of targets. Captured data can be modeled in this software for export to CAD packages. Editing point clouds in any other CAD software would be extremely complex and time-consuming, which was the case for contact 3D digitization.

The Cyrax HDS2500 Laser Scanner was set-up at four selected positions and was manually pointed to the direction of the required scans. Targets were then positioned within the FOV of the scanner just below the model/tripod. Four spheres were used as target points for registration purposes as seen in Figure 1.

► Figure 1. The Hardware, scanning setup, and scanning of Model 1.



The Hardware: laser scanner & laptop computer

Set up for the 4 spherical targets and model

Model 1 being scanned

Model 1 viewed in Cyclone

The noise within the scanned point clouds was removed by either manual point selection, intensity or by trimming edges. The different scans were joined together to form a true 3D representation by matching up the name IDs of the scanned targets. The scanned point clouds were then directly transferred to the connected laptop and modeled using basic Cyclone modeling tools and later on exported to MicroStation for further modeling purposes.

Actual scanning times took an average of approximately 2 hours per model, with four scans/positions approximately 30 minutes per scan per model. Scans were all done using the same high resolution (1mm point spacing / 999 x 999 pixels) at a distance of 2 meters for a better defined image. [15]

The laser scanning process resulted in the capture of dense point clouds for the three models as follows: Model 1 = 2,684,960 points; Model 2 = 2,956,245 points; Model 3 = 3,725,509 points.

3D models were developed and created from the point cloud data, converting point clouds to CAD object-based line and surface models using 3D modeling tools available in Cyclone.

Models 2 and 3 proved to be more time-consuming in creating an accurate as-built model from their point clouds. Geometric objects such as lines and shapes needed to be physically drawn into the point cloud images. Unnecessary point clouds or noises partly due to surface reflectivity, range and scale were deleted. It was difficult at times to identify and determine the edges of objects in order to fit and draw the lines or shapes of the point cloud data because of the scale of the models.

The 3D modeling of the scanned data took approximately six times longer than the scanning process. This is a very important aspect that should be taken into consideration when planning a scanning job, particularly when the design process has to follow a tight schedule of submissions. The 3D modeling process also comes with its complications and problems associated with the software or the level of detail required. Adequate time should be available for the post laser scanning process.

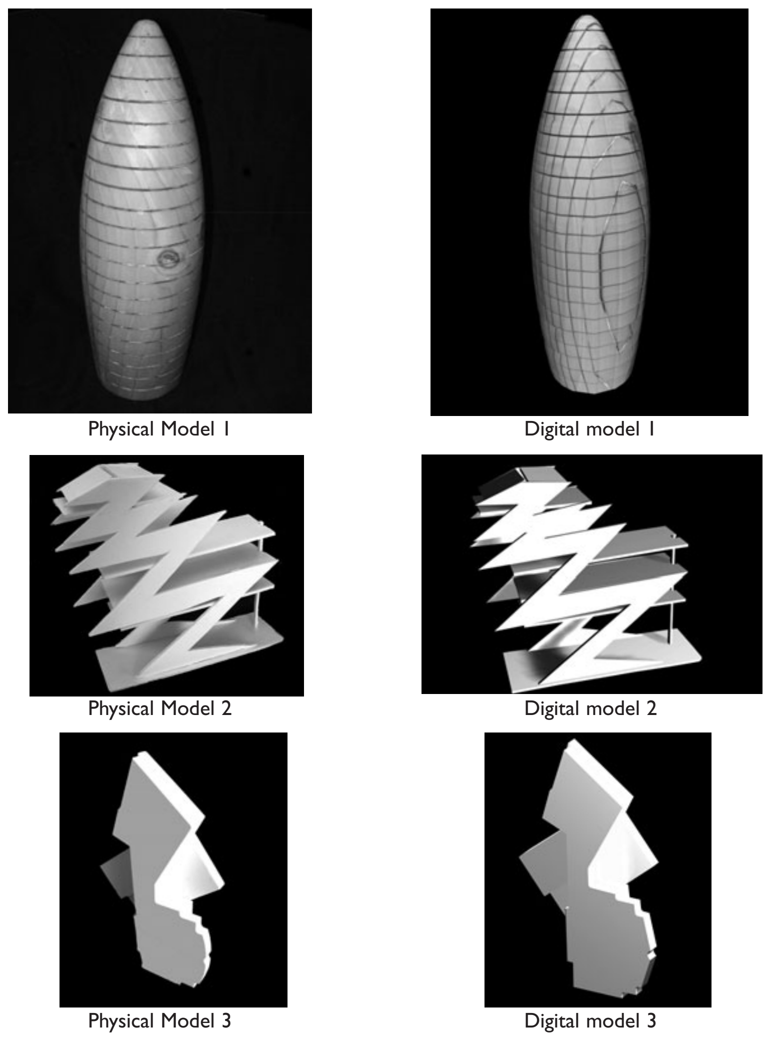
3. THE RESULTS

The fact that a large amount of point clouds are generated in an hour or so, offers many opportunities for 3D modeling. As a result, this technology can speed the design process and allow architectural students to express their ideas efficiently without conceptual or physical limitations, and to explore them effectively within a digital environment. However, with more complex objects, 3D modeling of the captured point clouds can be difficult and time-consuming.

Model 1 was the least problematic and had the least number of scanned points. Model 2 had sharp angles and proved complicated in 3D modeling. Model 3, being of a smaller size compared to the other two, was also challenging in 3D modeling and needed the most scanned points. Careful consideration should be given to these aspects in order to achieve optimum results.

The second part of the experiment focuses on the comparative analysis of analogue and digital models. It should be noted that considerable amounts of research dealing with the comparison of analogue and digital environments is on going. Different methodologies are used for this comparison: some use human psychophysical experiments and others use computer models. For this paper, human perception of visual difference was used by asking several groups of people (architectural students of different years, and non-architectural students), to distinguish between the analogue and the digital models and to assess their similarities [16, 17]. This survey focused on photo and functional realism or the 3D realism of the overall geometry accuracy (shape, size, proportions, and materials) and the overall similarities between the physical models and the digital models at a quick glance. [18]

Other evaluation methodologies involve the use of computers or the use of Virtual Reality (VR) to look at the images. The problem with those is that color perception varies due to ambient illumination and the type of monitors used [19]. As a result, there was no attempt made here to experiment with different means of display such as monitors or VR. Instead, high quality color prints and a questionnaire with a number of options to choose from for some groups, and pictures displayed with a LCD projector and paper questionnaires for large groups were used. The users were encouraged to express their response by means of quick recognition and detection of the required variables.



► Figure 2. Comparison of 3D models

The survey was delivered to 117 participants as follows; 57 architectural students and 60 non-architectural students; 72 were male and 45 were female. Students came from different levels of the specialization, and as a whole there were 97 from first and second year, 13 from third year, and 7 from final year. Students were shown the survey on either color prints or LCD projector; 42 students were given color prints and 75 the LCD projector.

As mentioned above, participants were asked to identify which model is the computer or digital model compared to a picture of a real model, then to measure the accuracy of their lighting/shadows, 3D geometry and material, followed by the measurement of their similarity using a scale 0 to 5. This was done for the three models. A 5-point scale was not used in order to avoid middle scale choices commonly chosen when the participant is unsure. The '0' option was used in order to stress that this value meant no comparative features were present. The 'Don't Know' option was also given. As noted above, six degrees of evaluation were given as follows:

- Accuracy: 0-very inaccurate; 1-inaccurate; 2-closer to inaccurate; 3-closer to accurate; 4-accurate; 5-very accurate;
- Similarity: 0-very dissimilar; 1-dissimilar; 2-closer to dissimilar; 3-closer to similar; 4- similar; 5-very similar.

Overall, the method of visualization had direct effect on the way participants responded to the identification process. Although the LCD projector offered large and clear images, the clarity and resolution of the images was not comparable to the high quality color prints. Another variable considered was the type of model. Model 3 was difficult to identify for both modes of visualization, maybe due to its fine details and smaller scale.

Participants from upper years were able to easily identify the computer model. Models 1 and 2 received similar results, but Model 3 caused confusion for the lower and middle years' students. Digital models 1 and 2 were most often correctly identified (overall percentages of recognition of digital models were: Model 1 (77.8%), Model 2 (73.5%), and Model 3 (47.9%)). This supports the view that some respondents were unable to clearly and confidently identify the computer models, particularly for Model 3, thus supporting the fact that the physical and digital models appeared quite similar.

Having reviewed the basic factors used in the experiment, there is now a need to examine the answers respective to the three models with respect to accuracies and similarities between the analogue and digital models. The 3D modeling aspects are crucial to this research, and in particular how an object is recreated in a digital environment. With respect to 3D geometry, Models 1 and 2 scored higher rates for "accurate" followed by "very accurate" then "closer to accurate". The following figures show the percentages for "closer to accurate", "accurate" and "very accurate" respectively for the three models; Model 1 (24.8; 30.8; 29.1 %), Model 2

(22.2; 34.2; 35 %), and Model 3 (21.4; 37.6; 23.9 %).

Unlike the 3D geometry, the Similarity question between the analogue and digital models show higher rates for "similar", followed by "closer to similar" then "very similar", The following figures show the percentages for "closer to similar", "similar" and "very similar" respectively for the three models; Model 1 (31.6; 34.2; 11.1%), Model 2 (26.5; 42.7; 18.8%), and Model 3 (27.4; 35.9; 18.8%). Model 2 scored the highest rate for "similar" and has the highest combined percentage for the three ratings (88%) given its complex form. The resulting differences between the evaluation of the 3D geometry and the similarity need further investigation in order to pinpoint the reasons behind these discrepancies.

Model 2 achieved the highest mean value (3.95) - close to rating 4 - for the 3D geometry and thus was judged most accurate. This could have been caused by the level of complexity displayed in the model. Models 1 and 3 were of a more regular shape and thus did not offer a perceived 3D modeling challenge; they had a mean value of 3.78 and 3.65, respectively for the 3D geometry. The mean values achieved for the evaluation of the similarity between analogue and digital models were slightly lower than those of the 3D geometry; in fact the three models scored less than 4 (3.38; 3.67; 3.56, respectively), thus being between "closer to similar" and "similar". Having said that, all models scored rates between "closer to accurate" and "accurate" for the 3D geometry, and "closer to similar" and "similar" for the Similarity evaluation, with Model 2 having high percentages for both "very accurate" and "similar".

To sum up, the answers of most students regarding which one is the digital model were close only for model 3, as 47.9% identified it and 49.6% did not. For models 1 and 2 these were very far apart since Model 1, 77.8% identified it and 21.4% did not, and Model 2, 73.5% identified it and 25.6% did not.

The type of visualization greatly influenced the identification of the digital model. Models 1 and 2 received similar results. Digital Model 3 was easily identified with color prints (78.6%), but could not be recognized by the majority when the LCD projector (30.7%) was used. These rates were respectively 95.2% against 68% for Model 1, and 90.5% against 64% for Model 2.

Architectural students were not as successful in identifying the digital model as it was expected. This is an unexpected result given that non-architectural students are attending their first year at the university and are not used to comparing imagery or have an understanding of 3D modeling. Further, research is needed in order to effectively study the visual difference using diverse visualization techniques and more advanced modeling studies. It should be noted that negative evaluation results could have been caused by unrealistic renderings (illumination model or surface textures), and not by errors of the manual CAD fitting process or the inaccurate point clouds as these were not perceivable due to the size of the models and the high rates scored by the accuracy of the Geometry responses.

4. CONCLUSION

This paper examined the potential of laser scanning technology for the facsimile translation of analogue physical models produced by architectural students. Three models were used for the experiment; two were solid models and one was a surface model.

The experiment showed that laser scanning is simple and very accurate, though editing point clouds can be time-consuming. Using laser scanning proved to be easier than using a contact mechanical digitizer (3D Microscribe). This is mainly explained by the amount of captured 3D data and the development of smart 3D editing software such as Cyclone. Cyclone enabled a quicker edition of the captured point clouds.

From an architectural design point of view, this technology can enhance the design process and allow architectural students to efficiently and freely express their design ideas, and to visualize them quickly, particularly if these are complex and difficult to represent using analogue means.

Further research could explore the process of transferring the digitized models to a Building Information Modeling application such as ArchiCAD, Autodesk Revit or Bentley Architecture, with an emphasis on the advanced modeling of scanned models to achieve highly similar models. This could serve to explore the impacts of design variations and to assess how to best generate accurate representational drawings from a comprehensive 3D model or a virtual building with detailed parametric information. Laser scanning technology can be further examined by investigating the calibration techniques and the material characteristics of the physical models. In the experiment presented in this paper, the geometric properties of the physical models did not pose a problem. In fact, the digital models displayed an accurate representation of the analogue ones.

This accuracy enhances the value of the digital tools when used for the architectural design process. These digital tools can also serve to support the process of digital reconstruction within the realm of architectural education. It promotes further experimentation of digital recreation as part of the design workflow within design studios. Models of different scales, geometric properties and materials could be used to establish guidelines for non-contact 3D digitization of architectural physical models. How objects are accurately recreated within a digital environment is a topic of growing interest.

Further study of the results obtained revealed that the method of visualization used to compare the digital versus the analogue models has a direct effect on the way participants responded to the identification process. Although the LCD projector offered larger images, results suggest that models were more difficult to recognize when projected with a LCD then when shown on a print. In addition, the type and scale of model impacted the visual perception as was the case with Model 3. Further research can focus on perceived visual difference as impacted by the use of different visualization techniques and by the complexity of the model used in the digitization process.

At a broader scale than that explored in this paper, other possible research areas could be the application of laser scanning in recording of urban areas and historic buildings [20, 21]. For instance, Tokyo was recreated using airborne laser scanning in order to boost tourism by providing the data on touch-screens at information points throughout the city [22]. Overall, the experiment presented here uncovered a range of results, setting the stage for more advanced study to take place in a variety of directions.

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