Original Article

# Recon-3D Measurement Accuracy Study for Small Scenes

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## Abstract

Recon-3D is an iOS mobile application dedicated to crash and crime scene documentation of small scenes, which fuses the Light Detection and Ranging (LiDAR) sensor and video frames to reconstruct 3D geometry as point clouds. In a recent training course, sixty students were asked to set up a mock scene with numbered measurement markers, scan the scene with their mobile devices, and provide 10 measurements between the numbered measurement markers in their scenes (n = 600). The results of these measurements were compiled and tabulated for accuracy. The average error of all participants was found to be approximately −2 mm with a standard deviation of 15 mm. The mean absolute error was found to be approximately 1 cm and the maximum error for any one participant was 10 cm. Expressing the errors in terms of percent, the average error for all participants was approximately −0.078% with a maximum percent error of 2.83%. Although these measurement exercises were uncontrolled, they show that the majority of errors (2σ), fell within 3 cm. Future studies using point-to-point measurements should include repeatability tests in a controlled environment as there were several variables which were unaccounted for in this study.

**Keywords:** LiDAR, crime scene investigation, crime scene reconstruction, forensic science

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## Introduction

Crime and crash scene documentation has benefited greatly by the use of total stations, terrestrial LiDAR scanners (TLS), and the use of photogrammetry. These technologies offer ways of documenting scenes in a highly detailed and efficient manner. Past studies have focused on LiDAR technology and photogrammetry in applications such as collision reconstruction, crime scene documentation, bloodstain pattern analysis, and bullet trajectory analysis. There has been great acceptance of the TLS and photogrammetry in the forensic field, especially the use of aerial imagery from drones in crash scene scenarios. These technologies all have their individual limitations whether it be cost, maintenance, portability, required level of training, or flexibility. Usually, the technology is available to a dedicated group of individuals who have access to the equipment and have been properly certified and trained.

One of the most limiting factors for smaller companies and police agencies is cost. Many investigators and private forensic engineering firms have been searching for low-cost tools which can provide 3D documentation capability within a reasonable margin of error and accuracy. In this regard, photogrammetry is a strong contender since it requires the use of a digital camera which can be found in mobile phones. In addition, there is software, which is required to process photographs taken from mobile phones, drones, and digital cameras to create 3D data. Photogrammetry software options range from free, to several thousands of dollars and can be available for PC and Mac, with some recent solutions now operating directly on mobile platforms. One advantage of photogrammetry is that the instrument used to document the scene (i.e., digital camera) is accessible to everyone, thus providing greater opportunities for 3D documentation. Of course, photogrammetry has its limitations as well, and objects such as vehicles with shiny, reflective surfaces cause problems for photogrammetry which requires stable and non-moving textures on a surface (Figure 1). In addition, not all scenes have the necessary lighting, weather, or environment suitable for photogrammetry.

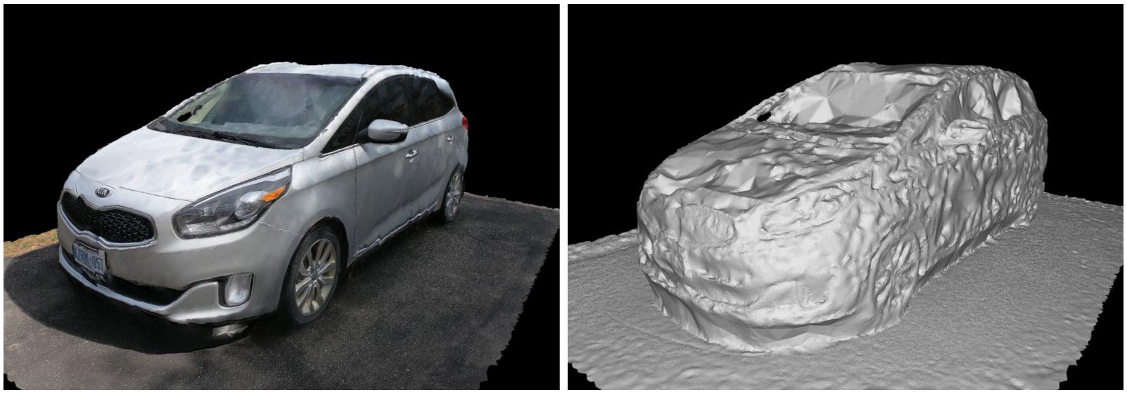
**Figure 1:** Photogrammetry model of a vehicle with texture (left) and same model with underlying mesh shown (right). The deformations on shiny, smooth textured surfaces are quite typical of what most photogrammetry software will produce.

In 2020, Intel released their first RealSense sensor which relied on structured, infrared light. The cost of these sensors was less than $300 USD and could be used in conjunction with a laptop, mobile phone, and software to gather 3D data. In 2019, Intel released a true LiDAR sensor in the form of their L515 sensor. This device had some promise but did not perform well in outdoor conditions, which effectively limited its use. The sensor has since been discontinued. Companies such as DotProduct have made excellent use of the RealSense sensors. By combining the sensor and a tablet (or a mobile phone), a small and portable 3D scanning system is available, which can scan indoors and outdoors with an accuracy of a few centimeters [1].

## Apple LiDAR

Apple's first device capable of scanning depth data using LiDAR was the 2020 iPad Pro. The iPhone 12 Pro and Pro Max, which came later the same year, brought these sensors into the mobile phone. In 2021, both M1 iPad Pro models, as well as the iPhone 13 Pro and Pro Max, were fitted with LiDAR. Although not specifically for 3D documentation, the LiDAR sensor was intended for use with the camera to determine focus range and also to aid in depth sensing for virtual reality and augmented reality applications. However, since Apple's release of the LiDAR sensor, there have been several apps such as Polycam, Scaniverse, and 3D Scanner App, all of which take advantage of the LiDAR sensor and can provide realistic-looking textured mesh models. These apps are quick and simple to deploy and provide visually accurate results However, none of these apps are dedicated to forensics which has some stringent requirements regarding known accuracy and error [2].

The LiDAR sensor works by emitting small pulses of light, which are timed based on the known speed of light. The laser light is projected in the infrared range and uses a rapidly shifting pattern with a 12 × 12 grid of dots (see Figure 2). A complete cycle of the grid pattern results in a larger, interlaced 24 × 24 grid of dots. The range of the sensor is reported to be approximately 5 m but is reduced in outdoor environments where there is strong sunlight. The greatest benefit of the Apple LiDAR sensor is that it is small, with a 5 mm circular opening near the camera lenses.

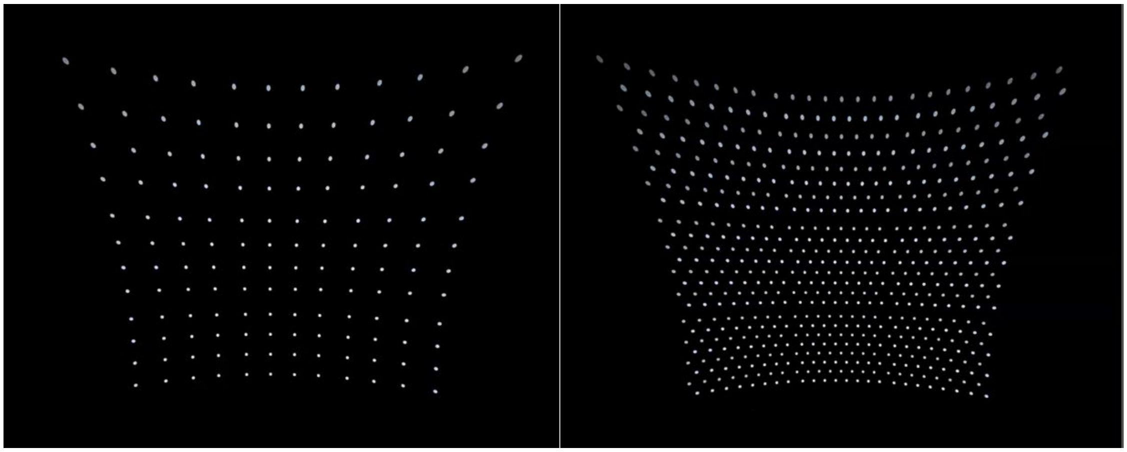

**Figure 2:** A single 12 × 12 grid of projected LiDAR dots (left). All shifting 12 × 12 grid patterns combined to produce an overall, interlaced 24 × 24 grid of dots (right).

The LiDAR sensor creates a depth map which is a static image providing estimates of distance to objects in a scene. Apple combines the LiDAR depth values with imagery from the main wide-angle camera. This combined data is passed through a machine learning method, which scales up the depth values and attempts to correct for artifacts. The resulting LiDAR depths are exposed to a software developer as a depth map (a 2D grid of depth values), where the depth map has a resolution of 256 × 192 pixels and has the same field-of-view as the main wide-angle camera (67° × 53° on an iPhone 12 Pro).

## Recon-3D

Recon-3D was released in May of 2022 and is an iOS app that uses depth map data from Apple's LiDAR sensor and fuses it with still video frames extracted from captured video. The captured data can be processed offline, on the device or uploaded and processed on the cloud. Recon-3D uses the EveryPoint engine to process and render the resulting 3D point cloud data. In contrast to other apps which provide textured meshed models, Recon-3D only provides colorized point cloud data as an output in the form of an e57 file. Part of the reasoning for this is that point clouds provide the raw, underlying points which show all errors and any gaps in the captured geometry. Meshed models (which are visually appealing, often have hidden anomalies associated with the meshing process. These meshed models try to balance out any noise in the underlying point data along with trying to bridge gaps where no data exists. In this regard, point clouds are better from a forensic perspective since they show the raw data, noise, missing areas, and other defects which may be hidden or interpolated in a textured mesh. Effectively, point clouds provide the most forensically accurate data from a given sensor for later visualization, interpretation, and reconstruction.

The workflow with Recon-3D begins by launching the app, choosing to create a new scan, naming the scan, choosing the scan settings, recording the scene, and processing the data. The main option for the scan settings is the resolution, which allows the user to choose an approximate point spacing between 1 and 30 mm. For most small scenes or for vehicle documentation, a resolution between 3 and 7 mm is usually acceptable. A smaller point spacing will provide greater detail with more points (i.e., higher resolution), while a larger point spacing will provide less points which will appear with less detail over the same area. In addition, processing time is increased with a higher resolution as more points are required to be reconstructed from the source data.

An important feature in Recon-3D is the ability to scale the scene based on AprilTags [3] which are open-source computer vision targets (see Figure 3). AprilTags have a "family" of unique targets which can be recognized in the captured video frames and are made up of black and white checkered squares. Different families of AprilTags have different grid configurations. When the reference target option is enabled in Recon-3D, the user is required to enter the center-to-center spacing between two similar

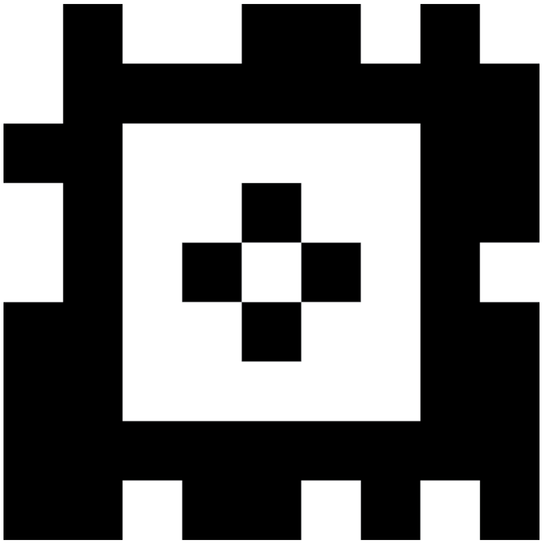

**Figure 3:** AprilTag used in Recon-3D.

AprilTags which have been placed in the scene. As a best practice, the larger the spacing between the AprilTags, the improved error reduction. Once the data is finished processing, the distance between AprilTags is automatically adjusted for scale based on the user's input reference distance. In cases where a reference distance is not available, the scaling of the object is approximated by the distance measurements recorded with the LiDAR sensor, where the accuracy and repeatability are not defined.

## Method

In June 2022, a Recon-3D training class was held through an online platform and students were given instruction on how the LiDAR sensor works, the use of the app, settings, scanning in varying situations, and how to take measurements using CloudCompare software. Students were also required to complete an assignment as part of the class certification with instructions as follows:

1. Choose an indoor or outdoor area to scan using Recon-3D.
2. Place 10 numbered measurement markers (provided in a PDF and printed on paper) throughout the scene in random positions to include horizontal and vertical measurements. Markers were to be secured using tape or placed on a surface where they would not move during the measurement exercise. Example layout of targets shown in Figure 4.
3. Place two AprilTags in the scene as far apart as possible.
4. Manually measure the distance between the two AprilTags and 10 of the measurement markers with a tape measure (or other instrument).
5. Using Recon-3D, create a new scan and use at least a 5 mm resolution.
6. Enter the reference distance between the two AprilTags.
7. Process the data on the cloud.
8. Once data is processed, download the data, and import into CloudCompare.
9. In CloudCompare, record measurements between the previously manually measured

**Figure 4:** Recon-3D data in CloudCompare software showing an example scene with measurement markers and AprilTags.

numbered measurement markers in an Excel file.
10. Provide Excel file and CloudCompare file to the instructor.

Based on the above instructions, students were able to complete the assignment. Each project was inspected prior to tabulating the results and in some cases, students had notable errors such as:

1. Incorrect scaling: The measured scale between AprilTags was not entered properly in Recon-3D, or the AprilTags were not correctly detected in the scan which defaulted to the sensor scaling.
2. Incorrect point measured in CloudCompare: The student intended to measure between two specific evidence markers but mistakenly clicked on a different point.
3. Transcription Error: The recorded measurement in the Excel file did not agree with the measurement in the CloudCompare file.
4. Incomplete Measurements: Not all of the required measurements were completed.

In cases where the assignment was either incomplete, clearly incorrect, where the instructions were not followed, or where errors exceeded 10 cm, the student was notified and allowed to either correct their entries or attempt a new assignment. For example, one participant had errors in excess of 1 m on one measurement. When checked in CloudCompare software, it was clear there was a typographical error or incorrect value entered in the Excel data sheet. This person was then excluded from the overall data set. In another example, a participant misunderstood the use of April Tags and instead of two April Tags for scaling the project, they used four. As a result, the Recon-3D algorithm detects more than two targets and defaults to not using any scaling in the project since it cannot determine which two targets to use for a reference scale. Thus, the default sensor scale is used and accuracy cannot be guaranteed. This data set and similar data sets were excluded. In another example, a person incorrectly picked a point such that instead of choosing the center of the evidence marker, the point picked through to a point farther away. Upon inspection, it was clear there was an error in measurement greater than 10 cm and the participant was asked to correct their measurement by choosing the correct point at the center of the evidence marker.

## Results

A total of sixty students completed the assignments and the tabulated data is in Table 1.

The distribution of errors for all the data is shown in Figure 5 while the absolute errors are a more conservative approach and focuses only on the magnitude of errors as shown in Figure 6. In some cases, it is useful to look at the errors in terms of percentage to the overall measurements and thus, the percent error and percent of the absolute errors are shown in Figure 7 and Figure 8, respectively.

In addition, the errors were plotted by distance (i.e., how large the measurements were) to see if there was any correlation to larger distances having larger errors. There were many measurements in the range of 1 to 6 m but then only few measurements between 6 and 11 m. The results are shown in Figure 9.

## Discussion

The results of this study show that on average, there does not appear to be any large bias in either the positive or negative direction. The mean value for all errors was found to be −2 mm and as such, is a relatively small error which equates to −0.08% of the average error values.

**Table 1:** Summary of results with 60 students and 10 measurements each, n = 600.

| | Error (mm) | Absolute Error (mm) | % Error | % Absolute Error |
|---|---|---|---|---|
| **Average** | −2 | 10 | −0.078 | 0.422 |
| **Standard Deviation** | 15 | 12 | 0.688 | 0.549 |
| **Maximum** | 100 | 100 | 2.830 | 7.920 |
| **Median** | −1 | 6 | −0.050 | 0.250 |
| **Mode** | −1 | 1 | 0.000 | 0.000 |

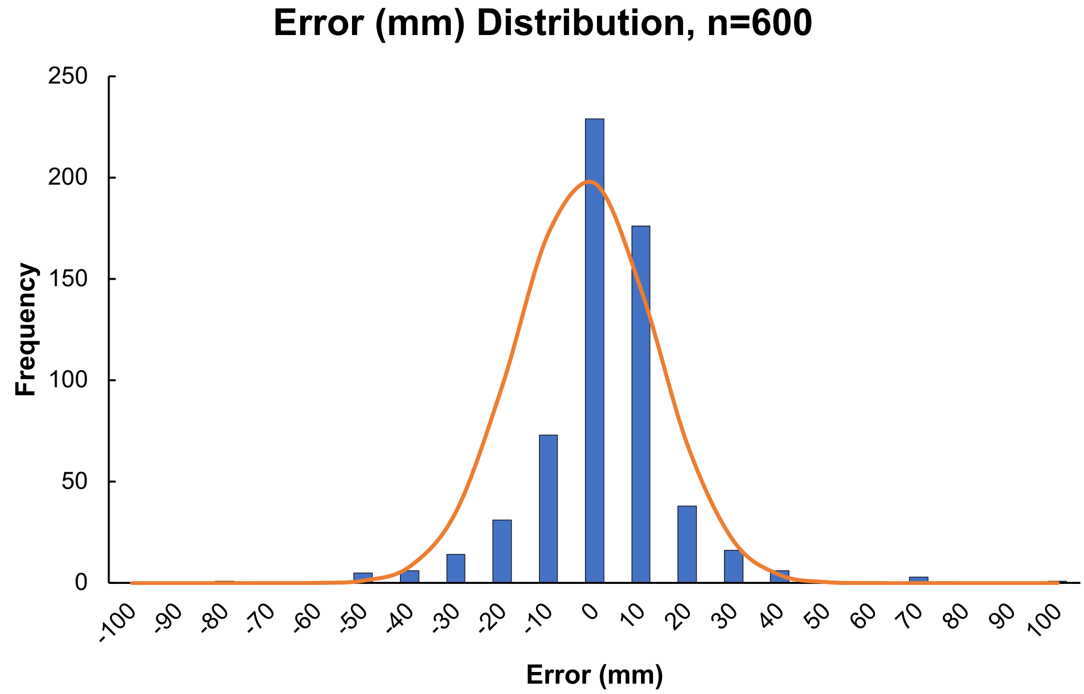

**Figure 5:** Histogram with a normal curve showing distribution of errors from student assignments, n = 600.

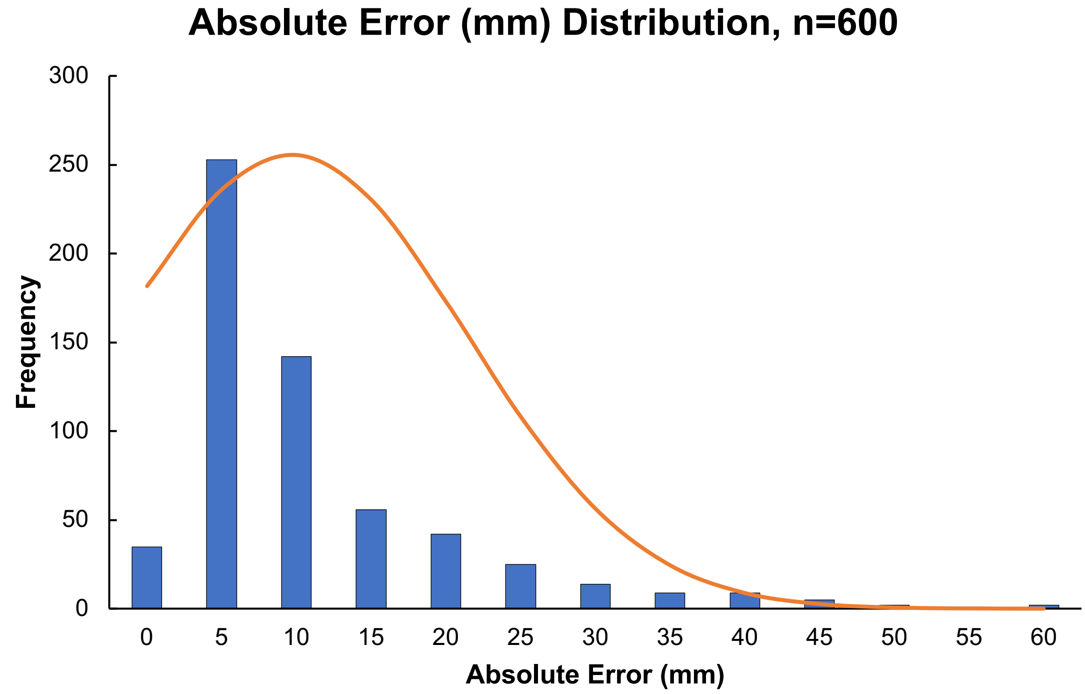

**Figure 5:** Histogram with a normal curve showing absolute errors which is a measure of the magnitude of errors n = 600.

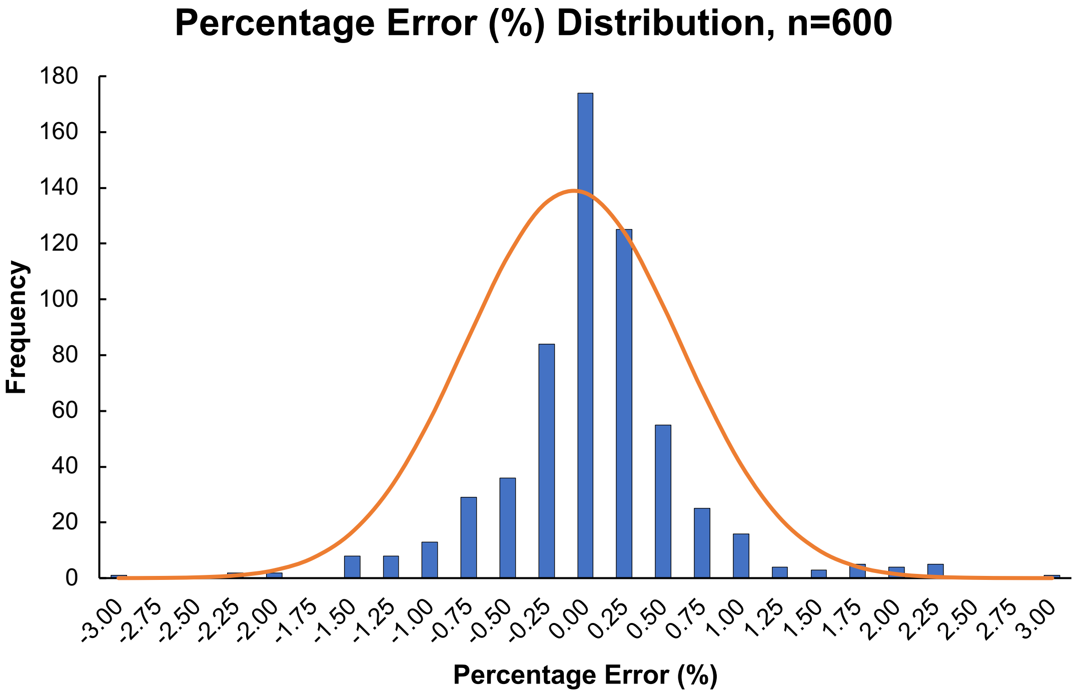

**Figure 7:** Histogram with a normal curve showing the percentage of error distribution, n = 600.

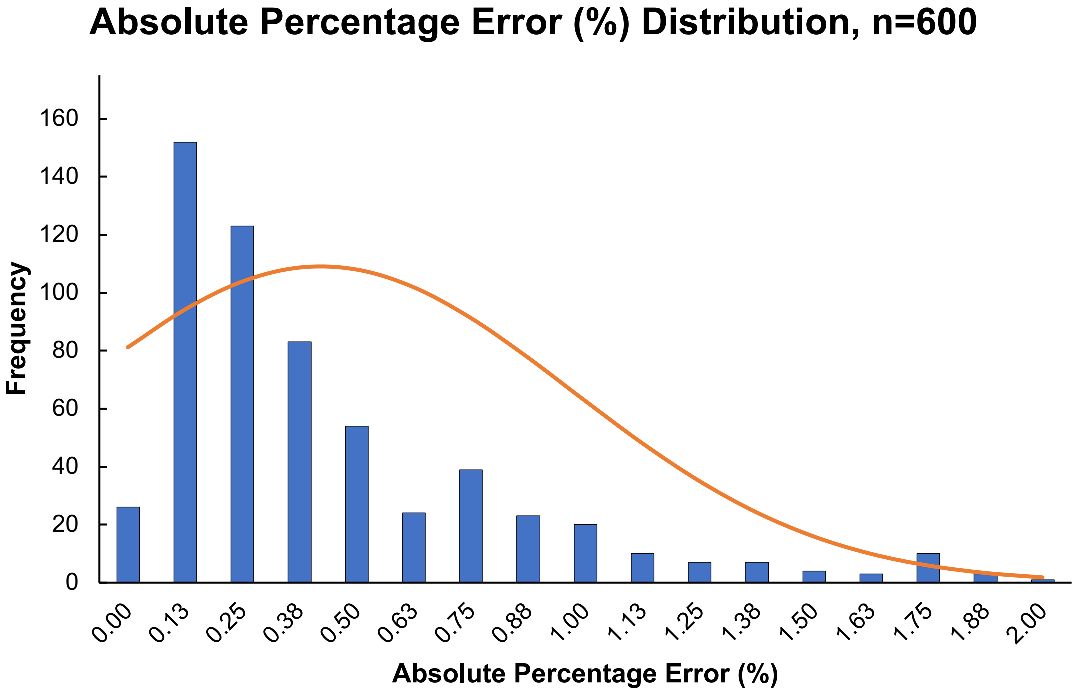

**Figure 8:** Histogram with a normal curve showing the absolute percentage error distribution, n = 600.

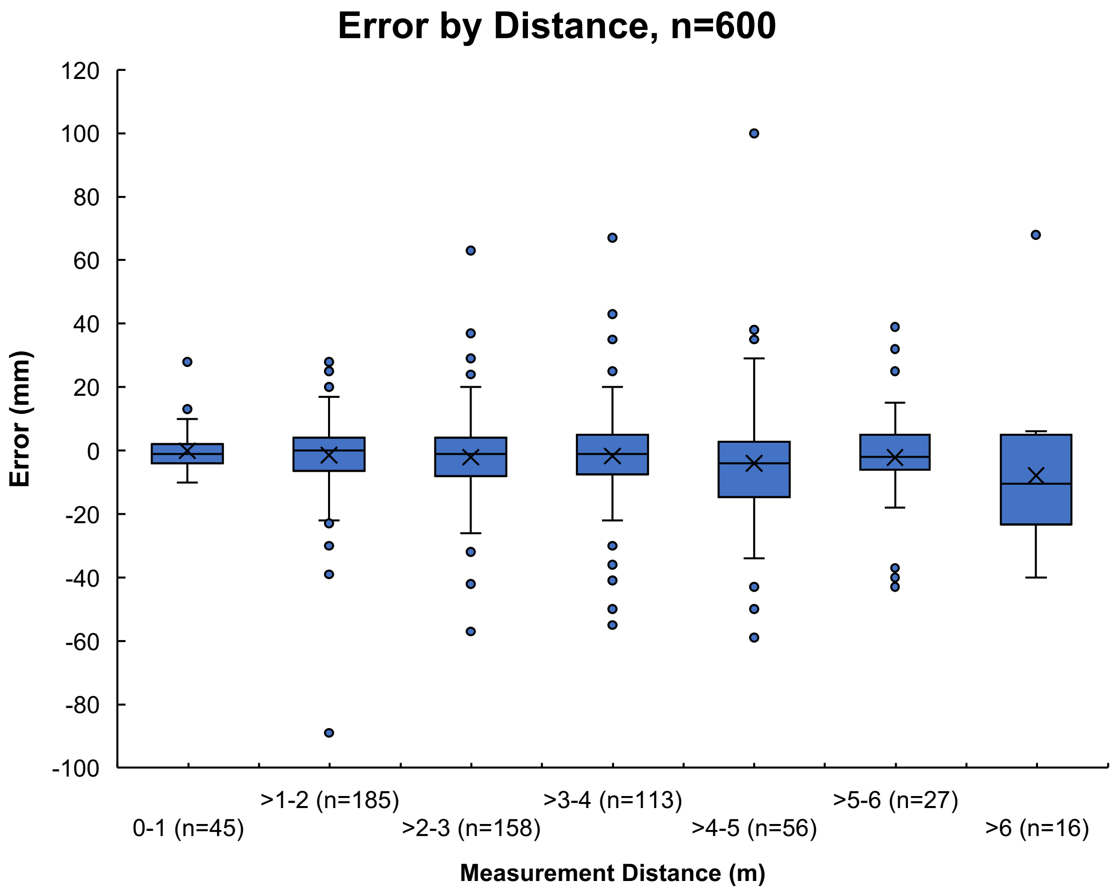

**Figure 9:** Box plot showing errors (n = 600) classified in distance ranges up to 6 m and then all measurements greater than 6 m. The 'X' represents the mean value, and the points represent outliers. The number of data points at each distance range has been shown.

However, when looking at the distribution of errors (Figure 5), there does appear to be a greater number of errors at the +0.01 m mark. Otherwise, the errors appear to be relatively well centered around the zero-error position.

The absolute errors are a good indication of the magnitude of errors made on average and thus they do not have the benefit of "zeroing" and are a worst-case scenario. In this study, the mean absolute error was found to be 0.01 m and is another way of saying that on average, the magnitude of errors that students made in their measurement exercise was approximately 1 cm.

Since this was an uncontrolled experiment, it is important to note some of the limitations which may have affected the results of this study. Students were allowed to create their own scenarios for the measurement exercise and some chose small spaces, indoors, while others chose larger spaces, outdoors. The scale of the project is important since it could have caused difficulties when manually measuring between the evidence markers. This is especially so when measurements included an elevation change over a longer distance. Many students worked alone and had some difficulty in holding the tape measure directly over the evidence markers or keeping the measuring tape from sagging across a larger distance. These types of errors would have contributed to some of the errors in this paper, but not all. Another limitation and/or source of error was the accuracy of the manual measurements themselves and/or the device used to conduct the manual measurements. Some students used a standard tape measure and others used a laser measuring device. The accuracy to which each student measured and recorded their manual measurements must be considered.

The Apple LiDAR sensor is known to have difficulty recording darker surfaces and, in many cases, can give "noisy" point data on black surfaces. In this study, the target markers were black and white and, in the future, the target markers should likely be changed to a lighter shade of grey to allow better reconstruction of darker surfaces. The LiDAR sensor also has issues with shiny surfaces and in some of the student projects, participants used targets with some shine, which may have affected the measurement results.

One important step in the exercise was to properly scale the project. Normally, a larger spacing between AprilTags helps to minimize errors but there is a practical limitation on how far one can measure between AprilTags using a tape measure. If the measurement between AprilTags is off by a small amount, this causes a global error bias in the results and all measurements are affected. Thus, controlling and measuring the AprilTag distance as best as possible is a very important step in the Recon-3D process and should be double-checked before entering a scaling value when scanning. The accuracy of the students' AprilTag measurements used in scaling the data sets is an additional potential source of error in this study.

Additional errors had to do with how accurately students could measure points in CloudCompare. This is also related to the resolution chosen in each of the scan projects. If, for example, a student decided to choose a resolution of 7 mm, there is a risk of being a maximum of 3.5 mm away from the actual point to be measured. In some cases, the point of interest may coincide with a scan data point, but the less dense the data, then the more difficult it is to choose a precise point for measurement. Thus, the greater the point spacing, the higher the risk of being less precise when taking measurements. The point picking process in CloudCompare uses the mouse pointer to hover over the area of interest while the user clicks the left mouse button. The closest point inferred to the mouse pointer position is selected. In some cases, it was difficult to discern the center of the AprilTags or the actual center point of the evidence markers and a slight error would have been made. In addition, sometimes students were viewing the point cloud from a particular perspective which had some overlapping data. Instead of choosing the intended point, a different point, closer or farther away from the intended point, was measured. This small oversight may have not been obvious unless a closer inspection was made and was left as is for the purposes of this study

When classifying the measurements based on distance, it is possible that larger measurements caused problems for students because they could not measure the evidence markers with sufficient accuracy. Figure 9 shows a distribution of errors for 1 m increments up to 6 m, and then measurements greater than 6 m. The graph shows that there is no obvious trend as outliers began to show from as little as 2 m and up. It should be noted that for the few measurements that were greater than 6 m, the average error was the largest, but only marginally with a value of approximately −0.01 m. With so few data points for distances greater than 6 m further work would be required to properly make any conclusions about the effect of distance on errors in these measurement ranges.

The majority of students in this study were relatively new to Recon-3D. However, there were some users who had previous experience since they were provided with early beta versions of the software for testing purposes. The experience level and familiarity of scanning techniques with Recon-3D was greater with these students and this was somewhat evident in their results. When isolated from the overall group and errors averaged, n = 9 experienced users had a similar overall average of −0.002 m when compared to the entire group, but had a lower maximum error of 0.029 m. A summary table of results is provided in Table 2.

**Table 2:** Summary of results with 60 students and 10 measurements each, n = 600.

| | Error (mm) | Absolute Error (mm) | % Error | % Absolute Error |
|---|---|---|---|---|
| **Average** | −2 | 7 | −0.063 | 0.266 |
| **Standard Deviation** | 12 | 9 | 0.393 | 0.295 |
| **Maximum** | 29 | 50 | 0.980 | 1.630 |
| **Median** | 0.000 | 5 | −0.010 | 0.175 |
| **Mode** | 3 | 3 | −0.030 | 0.070 |

## Conclusion

In this study, sixty students were assigned a task of setting up a small scene from which they were asked to measure 10 different distances each. Point-to-point measurements were taken manually with the majority of students using a standard tape measure to obtain distances between measurement markers. Overall, the results of this study show that Recon-3D can provide point-to-point measurements with centimeter-level accuracy. However, more experienced users who have some practice with scanning and familiarity with CloudCompare software were able to achieve improved results. For most smaller crime and crash scene scenarios up to 10 m, errors below 3 cm should be expected and would seem reasonable for general scene or evidence documentation. However, when measurements are required for more critical activities, it is up to the analyst to decide whether or not the measurement errors are suitable for their analysis. Future studies should provide a more controlled environment to eliminate unaccountable participant variables and the variability in repeated scans should be examined.

## Supplemental Materials

To allow for independent evaluation of the findings in this article, the author is providing all the raw data in Appendix A.

## Conflict of Interest

Eugene Liscio, P. Eng. is the CEO and Developer of Recon-3D. He has a financial stake in the company with full ownership. Participants in this study had no stake or financial gain in the outcome of the study.

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