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Evaluation of the applicability of low-cost 3D scanning methods for reverse engineering: a case study of a motorcycle engine chrome valve cover

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The chrome-plated valve cover of a motorcycle engine features a complex shape and a shiny surface, making it a difficult element to reverse-engineer. This paper explores the use of low-cost scanning methods and compares their accuracy. Scans were performed using a low-cost 3D scanner, as well as LIDAR and TrueDepth sensors in iPhones. The paper also discusses the method of object preparation and assesses its applicability to reconstructing parts of vehicles, such as the valve cover. The results of testing the 3D Revopoint MetroX scanner and the TrueDepth sensor on the iPhone 12 Pro were promising. Point cloud data were obtained for both an object coated with a scanning spray and a chromed one.

Key words: *reverse engineering, TrueDepth, iPhone LIDAR, 3D scanning, engine component*

1. Introduction

The 3D scanning technologies began to emerge in the 1960s. They were continuously developed, but a breakthrough occurred in the 1990s. Several companies launch 3D scanners in forms similar to those we know today [10].

Due to its cost, 3D scanners were initially available only to a narrow group of companies or researchers. The further development of the technology and its increasing adoption across various industries have contributed to the widespread adoption of 3D scanning. At the current stage of technological development, a significant democratization of 3D scanning technology is observable. Manual scanners such as the Revopoint MetroX or the Creality Raptor are now available to individual customers. As manufacturers state, these scanners enable data acquisition with metrological accuracy while remaining affordable [9, 17].

Moreover, the development of mobile technologies in recent years has brought a revolutionary change to the field of 3D scanning. It has enabled the integration of sensors and technologies into smartphones.

In 2017, Apple introduced the TrueDepth facial recognition technology in iPhone X. The principle of operation is that the dot projector emits over 30,000 dots onto the surface in front of the device. The infrared camera captures reflections from these light points, enabling the creation of a surface model from the resulting pattern. To ensure accurate detection even under low-light conditions, the system is equipped with an infrared radiator that also illuminates the area in front of the camera [3, 6].

In 2020, Apple introduced a LiDAR (Light Detection and Ranging) sensor into its mobile devices, starting with the iPad Pro 2020 and then the iPhone 12 Pro and newer models. The principle of operation is that LiDAR uses Time-of-Flight (ToF) measurements, which determine the time it takes a light signal to travel a given distance. Therefore, LiDAR emits a pulse or modulated light signal and measures the time difference between the emitted signal and the returning wavefront. This innovation has opened new possibilities in mobile 3D scanning, particularly in research applications and in industrial settings, where traditional measurement methods require expensive equipment and specialized personnel training [1, 12, 23].

The 3D scanning is widely used across various industrial sectors. It ranges from scanning large geographic areas for map creation, to applications in medicine, reverse engineering and the design of production workstations [8, 13, 19].

A wide range of research is available on the application of iPhone sensors as an alternative to traditional scanners. The iPhone LIDAR has been widely used for reconstructing buildings, detecting cracks and architectural details, and documenting cultural heritage [2, 4, 7, 25].

There are also highly specialized applications of this technology for inspection and measurement during the sinking of mineshafts or for monitoring underground pipe installation sites [15, 18].

An interesting application is its use in reconstructing accidents for virtual recreation of the accident site, as well as in vibration measurement and modal analysis [21, 22].

Regarding TrueDepth technology, research primarily focuses on typical medical applications. Examples include studies on facial registration in individuals with facial nerve palsy, orthodontics, or ear reconstruction [5, 8, 14, 20].

A review reveals a very limited number of publications addressing smartphone-based scanning of regular shapes common in mechanical engineering, and there is no reference to such applications in the context of the potential application of iPhone sensors in mechanical engineering for reconstructing engine components and other vehicle parts. In the study on hydrogen injection simulation, reverse engineering methods were used to map the engine's geometry [24]. The exact scanning technique is not described, however this represents a potential application area for iPhone sensors.

The research objective was to verify the possibility of using augmented reality scanners originally employed in iPhones to reconstruct a representative engine component in a virtual environment. The studies focused on whether obtaining an accurate scan of shiny surfaces is challenging and whether this depends on the scanning technology. The potential of using iPhone sensors for scanning an engine component approximately 230 × 160 × 70 mm in size was also validated. Based on the reviewed literature, it was expected to achieve greater accuracy with the TrueDepth sensor compared to LiDAR. These studies also aimed to verify whether the acquired data were sufficiently accurate for applications in mechanical engineering.

2. Materials and methods

2.1. Research approach description

To address the formulated hypotheses, a dedicated research setup was prepared. It was established from the ground up by the authors of this study. It consisted of the following elements: a scanning device, a Mac Mini computer with an M4 processor, a portable external monitor, input devices in the form of a mouse and keyboard, a rotating table with markers applied and a device for recording illumination intensity. During scanning, a set of formers with markers was also used to support tracking.

In the context of scanning devices, the Revopoint MetroX scanner was used as the reference device. This model was chosen because it is highly suitable for scientific research, combining two scanning technologies in a single device: structured light and laser scanning. According to the manufacturer, the single-frame accuracy is as low as 0.02 mm, and the volumetric accuracy is 0.025 mm + 0.05 mm × L (m), where L is the measurement length in meters [17].

In this study, three modes of the Revopoint MetroX scanner were used. The first mode is structured-light-based marker tracking, and its variant relies on tracking characteristic features of the scanned objects. The other two scanning modes are the 14 crosslines mode and the 7 parallel lines mode. Both are based on laser technology and use marker-based tracking.

The research setup is presented in Fig. 1. The Revopoint MetroX 3D scanner is located on the rotating table. The Revopoint MetroX is a scanning device used as a benchmark for iPhone sensors.

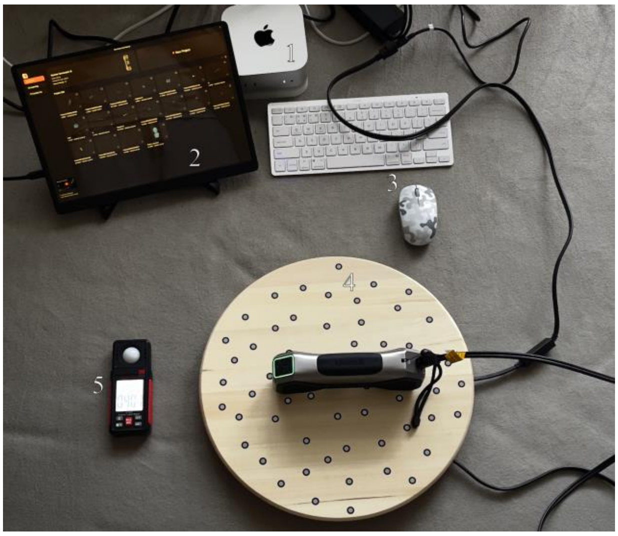

Fig. 1. Research setup equipped with a Mac mini (1), a portable external monitor (2), input devices (3), a rotating table with markers applied (4) and an environment meter Habotest HT 603 (5)

The validated devices used for research were the TrueDepth and LIDAR sensors in the iPhone 12 Pro. The iPhone 12 Pro was selected because it is the first device available to include both TrueDepth and LIDAR [3].

The environmental conditions were maintained at constant levels and recorded using the Habotest HT 603 device, as shown in Fig. 1. Throughout the study, the temperature was 21°C and the humidity was 60%. The controlled parameter rarely considered in other studies was illumination intensity, set at 40 lx.

2.2. Object

The object scanned was the valve cover of a BMW motorcycle engine. This valve cover was selected because it has a challenging surface form from a reverse-engineering point of view. A significant characteristic of this valve cover was its chrome plating. To verify the impact of the chrome-plated surface on scan quality, a scan was also performed on the object coated with AESUB scanning spray. This procedure resulted in a matte, white coating surface, whose thickness may be negligible in the analysis [11, 16].

Fig. 2. Chromed valve cover lying on a rotating table

Fig. 3. Spray-coated valve cover lying on a rotating table

Figure 2 shows the valve cover in its natural state, i.e. chromed. The cover was placed on a rotating table, and around it, shape guides equipped with markers were positioned. Figure 3 presents a similar setup, but the valve cover was coated with a scanning spray.The pyramid- and dome-shaped templates, covered with markers, shown in the figures are extremely important in the scanning process, as they allow the scanner to determine the spatial positions of objects.

2.3. Methodology

The object scanned was the valve cover of a BMW motorcycle engine. This valve cover was selected for its numerous slots, holes, and grooves. A significant feature of this valve cover was its complex surface geometry. The Revo Scan 5 MetroX software version V5.6.9 was used to aggregate data from the reference scanner. This software was provided by the manufacturer together with the scanner. The scanning was performed manually, meaning the scanner was moved slowly through space without imposing any mechanical constraints. The software controlled the distance between the scanner and the object through a quality scale display. The distance between the scanner and the object always remained within the "good" or "excellent" range. As the number of frames increased, the number of acquired cloud points also increased, and the points changed color from red to orange to green. Achieving all points in the cloud with a green color indicated a successful scan of the object. All software settings were configured for maximum accuracy at the expense of performance. The goal was to achieve the highest possible data-acquisition quality under the given conditions.

Fig. 4. Scanning of the valve cover using True Depth technology. The iPhone was held in hand with the display facing the object being scanned, while the portable external monitor displayed image from the RGB camera and the TrueDepth sensor

For data acquisition from TrueDepth and LIDAR sensors, the 3D Scanner App version 2.3.6 was used. In this case, the scanning was also performed manually with the phone being moved through space without imposing any specific mechanical constraints. The application parameters were also set to maximum point cloud quality, at the expense of performance. It should be noted that the 3D Scanner App records only 15 seconds of data from the TrueDepth sensor. A photograph of the TrueDepth technology scanning process on a smartphone is presented in Fig. 4.

The four scans of the external surface of the object were performed using the Revopoint scanner (in the crosslines mode, parallel lines mode, fullfield mode – marker and feature tracking mode). The same scanning procedure was applied to the object coated with a scanning spray.

Data acquisition was also carried out using the TrueDepth and LIDAR sensors for both the naturally chromed and spray-coated surfaces for each technology.

It should be noted that during scanning, points are not only recorded from the object itself but also from the background. This situation occurs both when using a 3D scanner and when using iPhone sensors. To eliminate unwanted background points, all point clouds were processed in Revo Scan 5 MetroX. Figure 5 and Fig. 7 show examples of scans before and after the removal of background elements.

Comparisons of the point clouds were conducted using CloudCompare version 2.14 Alpha. All point clouds were compared against a reference cloud generated using the Revopoint scanner in crosslines mode, with the object coated with spray for scanning. CloudCompare is a program equipped with specialized functions enabling such comparisons and is available under an open-source license. Relative positioning of the point clouds was performed using the built-in function in CloudCompare, which minimized the positional error between points of the two compared point clouds. Automatic, software-based scale correction was also possible. It was observed that scans from the iPhone, using both the TrueDepth and LIDAR sensors, are approximately 1000 times smaller than those from MetroX. The scans from Revopoint MetroX do not require scale modification.

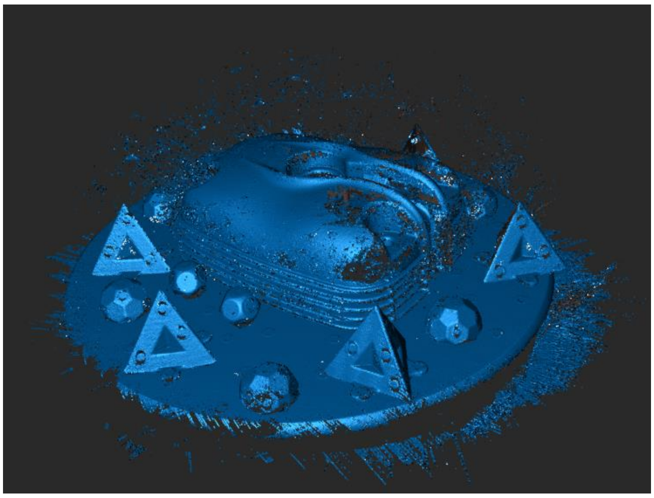

Fig. 5. Example of raw data obtained using the Revopoint MetroX scanner

3. Results

A total of 12 scans were performed. Point cloud data were successfully obtained in only 9 cases. The LiDAR mode on the iPhone and the full-field mode on the Revopoint scanner failed to capture point clouds of the chrome coating on valve components. A test was also conducted using the iPhone's sensors to scan an object rotated on a turntable. During this test, the smartphone was held stationary. The result of this test showed a fused point cloud that bore no resemblance to the original object. This suggests that tracking on the iPhone uses the device's gyroscopes. It should be noted that a similar issue was not observed in scans performed using a 3D scanner. Example scanning results are presented in the following figures.

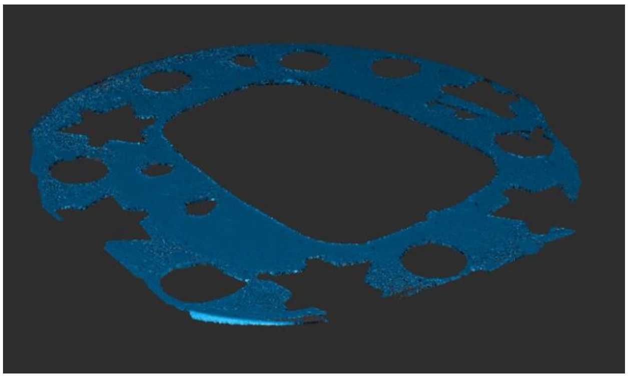

Fig. 6. The result of aggregation data using the RevoPoint MetroX scanner in full-field mode for the chromed part

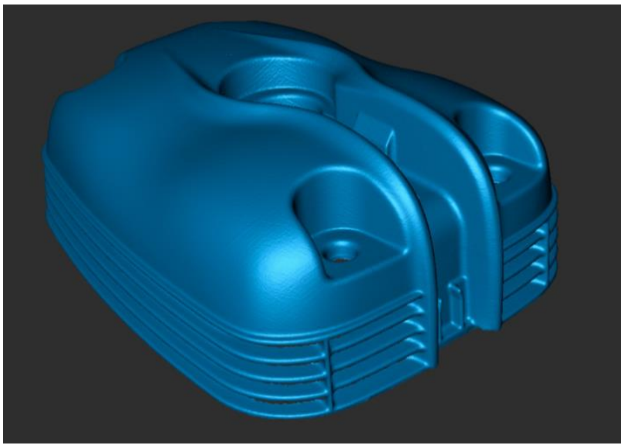

Fig. 7. The result of aggregation data using the RevoPoint MetroX scanner in crosslines mode for the spray-coated part. The point cloud shown in the figure has already been cleaned

In Figure 6, it is clear that only background data were acquired, and practically no points from the scanned object were captured. In contrast, Fig. 7 shows the point cloud obtained using the Crosslines mode on an object coated with spray. A very dense point cloud, in which the points visually merge into a single surface, was observed.

Meanwhile, in Fig. 8 and Fig. 9, an object coated with sprayisd is scanned using a smartphone equipped with TrueDepth and LIDAR sensors. It is immediately evident that the point cloud is significantly sparser, especially with the LIDAR sensor. Detailed results are presented in Table 1 and Table 2.

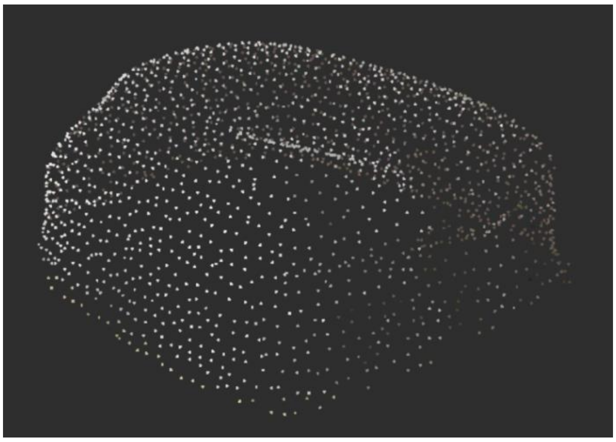

Fig. 8. The result of aggregating data using the iPhone LIDAR for the spray-coated part

Fig. 9. The result of aggregating data using the iPhone TrueDepth for the spray-coated part

Table 1. Detailed results of research for Revopoint MetroX

	CL mode (spray)	CL mode (chrome)	PL mode (chrome)	PL mode (spray)	Fullfield mode mark. trac.	Fullfield mode feat. trac.
Frames	11602	18793	20359	13878	732	766
Points	4592885	4715804	2170745	4275369	10581396	6126736
Points for cover	2297315	1659049	600244	2618915	4759835	3684869
C2C distance < 0.2 mm	N/A	92%	6%	86%	51%	80%
C2C distance < 0.5 mm	N/A	98%	14%	98%	74%	97%
C2C distance < 1 mm	N/A	99%	32%	98%	95%	98%
C2C distance < 2 mm	N/A	100%	68%	99%	100%	99%
C2C distance < 5 mm	N/A	100%	98%	99%	100%	100%

Table 2. Detailed results of research for iPhone sensors

	Crosslines (CL) mode (spray)	Iphone TrueDepth (sparay)	Iphone TrueDepth (chrome)	Iphone LIDAR (spray)
Frames	11602	–	–	–
Points	4592885	4350681	3378698	8920
Points for cover	2297315	140772	169048	1964
C2C distance < 0.2 mm	N/A	9%	9%	5%
C2C distance < 0.5 mm	N/A	22%	25%	9%
C2C distance < 1 mm	N/A	49%	50%	23%
C2C distance < 2 mm	N/A	79%	70%	40%
C2C distance < 5 mm	N/A	97%	88%	82%

The first row of the table presents the number of frames in each mode. The second row shows the number of points after performing a fusion operation, i.e. the removal of duplicate points in space. The third row displays the number of points related only to the valve cover, meaning after eliminating background point cloud data.

A key pattern observed here is that approximately 38% more frames are required to achieve sufficient scanning results for objects with shiny, reflective surfaces. Additionally, the point cloud density for the shiny surface version is about 31% less dense. This can be explained by the fact that a chromed surface scatters light, making it difficult for the 3D scanner to capture the reflected signal.

Importantly, the number of points obtained using TrueDepth technology is comparable to that of laser-based 3D scanner modes. However, after removing the background, the final number of points representing the actual geometry is several orders of magnitude smaller. This indicates that the TrueDepth sensor has a wide field of view and captures significantly more background points than a 3D laser scanner.

Furthermore, the point cloud generated by the iPhone LiDAR sensor is 3 orders of magnitude sparser than the reference point cloud, indicating that the iPhone LiDAR has significantly lower resolution.

Rows four through six of Table 1 show the percentage of point-to-point measurements between two point clouds that fall within specified error margins – 0.2 mm, 0.5 mm, and 1 mm. In Table 2, the LiDAR and TrueDepth sensor results are presented.

Additionally, the results from Tables 1 and 2 regarding the percentage of point-to-point measurements between two point clouds that fall within a specified error margin were presented in Fig. 10 for better readability.

It should be noted that only the crosslines(CL) mode of the Revopoint scanner enabled a successful scan of both shiny and matte surfaces with comparable quality. This means that the number of data gaps or "holes" in the model are acceptable and nearly 100% of point-to-point measurements fall within 1 mm. Importantly, in all tested cases, the surface coverage achieved by scanning spray improved overall scan quality.

Figures 11 and 12 show the point clouds obtained in TrueDepth and LIDAR modes compared to the reference cloud. The point clouds are coloured according to the legend on the right side of the figures. Legend presents the nearest points between two point clouds (C2C). Value is in mm.

The analysis of the values obtained from measurements using the LIDAR and TrueDepth sensors indicates that approximately 80% of the measurements fall within 2 mm for the TrueDepth system and within 5 mm for the LIDAR sensor. This means that, assuming 80% of the points are sufficient to reconstruct the object (with missing data approximated digitally), a smartphone with TrueDepth technology could reconstruct it with an uncertainty of 2 mm. A similar conclusion can be drawn for the LIDAR sensor, with the difference being that the uncertainty would be 5 mm.

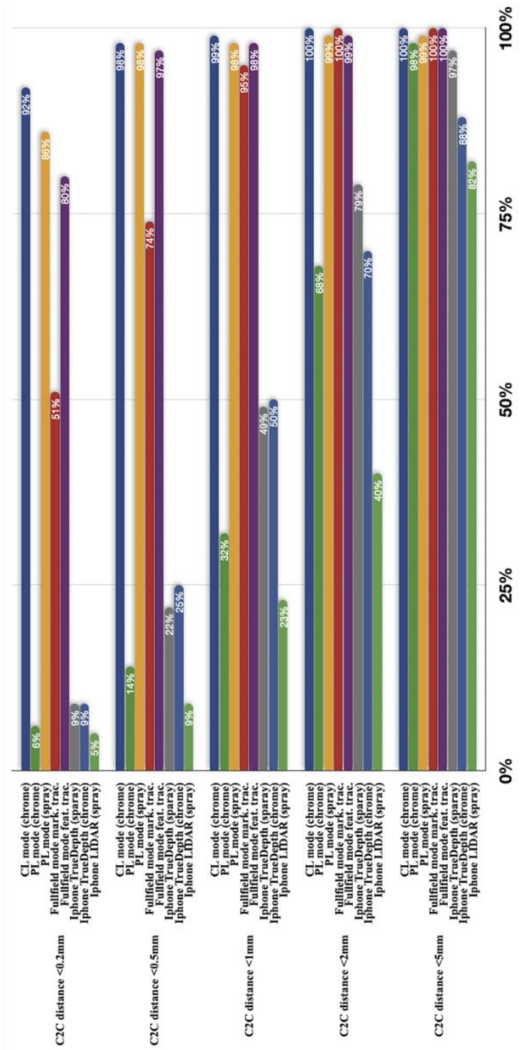

Fig. 10. The research results show cloud-to-cloud distances for each mode

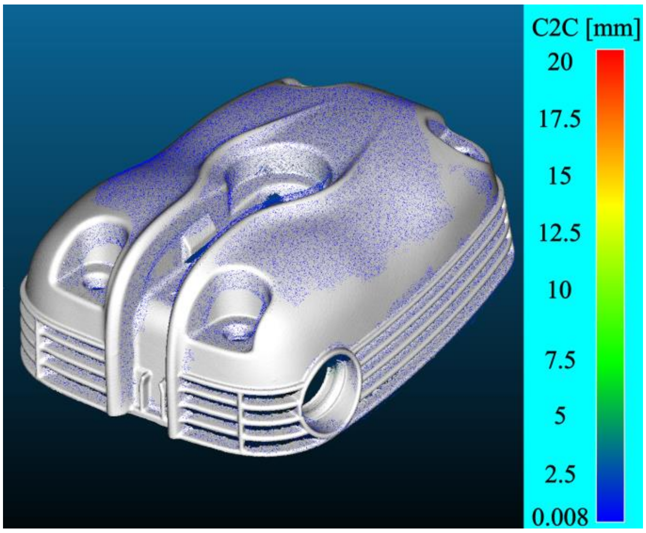

Fig. 11. Comparison of the results of scanning a sprayed-coated valve cover using the iPhone TrueDepth sensor against the reference scan obtained with the Revopoint MetroX scanner in crosslines mode

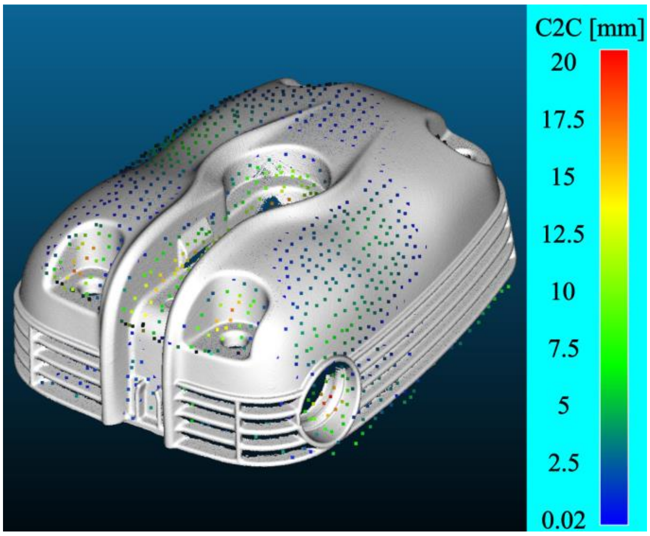

Fig. 12. Comparison of the results of scanning a sprayed-coated valve cover using the iPhone LIDAR sensor against the reference scan obtained with the Revopoint MetroX scanner in crosslines mode

However, this conclusion is not fully valid due to the low point cloud density, which will be used to mesh the model. In such a case, important features of the object may be lost – for example, the texturing on the side wall may be merged into a flat surface.

4. Conclusions

Summarizing the conducted research on the iPhone LIDAR scanner, the authors observe problems with data acquisition of small objects due to the low point cloud resolution. This limitation, combined with higher uncertainty than other methods, may contribute to the restricted applicability of this technique for reverse engineering engine parts.

Spraying during scanning of highly reflective objects significantly improves results and scan quality. The iPhone TrueDepth sensor technology enables data acquisition of both standard matte and shiny surfaces.

The data obtained from the TrueDepth sensor appears promising. Both the resolution and the accuracy of the scans seem sufficient for specific engineering applications. It is also worth noting that position tracking in the iPhone is based on its built-in gyroscope, rather than on features of the scanned object or markers. Here, it should be noted that building a device to track the iPhone's movement in space may prove essential for further research.

The authors emphasize the need for further studies. For instance, validation of the TrueDepth sensor as a tool for scanning objects used in machine construction, particularly those with sharp edges, could be valuable.

Regarding future research directions, it would be worthwhile to investigate whether combining point clouds from multiple scans performed with the TrueDepth sensor yields more accurate results, higher point cloud density, and eliminates the limitation of a 15-second data acquisition period. Another area worth exploring is the application of polarizing lenses during the scanning of highly reflective objects.

The authors believe that the topic of scanning objects using iPhones deserves further development. Advancing this topic will help mitigate the limitations encountered and enable the application of this method to a broader range of objects in the automotive industry.

Nomenclature

CL crosslines (mode in Revopoint MetoX)
PL pallarellines (mode in Revopoint MetoX)
C2C cloud to cloud (distance)

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