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OPTIMIZING 3D LASER SCANNING PARAMETERS FOR GEOMETRIC PRIMITIVE IDENTIFICATION USING THE TAGUCHI METHOD

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Abstract: *As 3D scanning technology becomes integral to reverse engineering and quality control, the ability to accurately identify geometric primitives—such as planes, cylinders, and spheres—from point clouds is critical. This study investigates the influence of environmental and process parameters on the dimensional accuracy of 3D scanned mechanical parts. Using the Taguchi L9 orthogonal array method, nine experimental configurations were tested to evaluate the impact of three key factors: lighting conditions (Natural, Neon, LED), surface preparation (original, white matte, and white matte with markers), and scanning brightness parameters (10%, 40%, 80%). A mechanical test plate containing varied geometric features was scanned using a handheld laser scanner (Artec Leo), and the resulting models were processed to extract geometric primitives for comparison against nominal CAD dimensions. The statistical analysis, including Signal-to-Noise (S/N) ratios and Analysis of Means, revealed that surface preparation is the most statistically significant factor influencing both the geometric accuracy and the efficiency of the data file size. The results demonstrate that treating the object surface with a matte coating and reference markers drastically reduces noise and improves the precision of primitive identification, significantly outweighing the effects of ambient lighting or software scanning parameters. These findings provide a practical framework for optimizing 3D scanning workflows in industrial metrology.*

Key words: 3D Laser Scanning, Geometric Primitives, Taguchi Method, Reverse Engineering, Dimensional Accuracy, Surface Preparation

1. INTRODUCTION

3D scanning technology has become a cornerstone in modern manufacturing, playing a pivotal role in reverse engineering, quality control, and rapid prototyping. By capturing the physical dimensions of an object and converting them into a digital format, these technologies allow for the precise reconstruction of complex geometries that are otherwise difficult to measure. The availability of affordable digital scanning devices, such as laser scanners and structured light systems, has made point cloud representation one of the most common methods for digitizing object surfaces.

However, raw point cloud data is often unstructured and noisy, containing outliers or redundant data that limit its immediate utility in Computer-Aided Design (CAD) systems. To bridge the gap between physical objects and digital CAD models, it is essential to extract high-level geometric primitives—such as planes, cylinders, and spheres—from the scanned data[1]. Identifying these primitives allows for the reconstruction of a model based on basic components that are easily manipulated by CAD software.

The accuracy of this identification process is heavily influenced by the quality of the scan, which in turn depends on environmental and process parameters[2]. Factors such as ambient lighting[3], surface reflectivity[4], and scanner settings can introduce defects or noise, complicating the segmentation and fitting of geometric primitives. While many approaches exist for detecting primitives, they often struggle with robustness against noise or tend to over-segment the model[5]. Consequently, optimizing the scanning process to minimize these errors is crucial for applications requiring high precision, such as industrial inspection and reverse engineering[6].

This study aims to determine the optimal configuration of scanning parameters to maximize the geometric accuracy of identified primitives. Using the Taguchi L9 orthogonal array method, we analyze the influence of three key factors: lighting conditions, surface preparation, and scanning brightness parameters. By isolating

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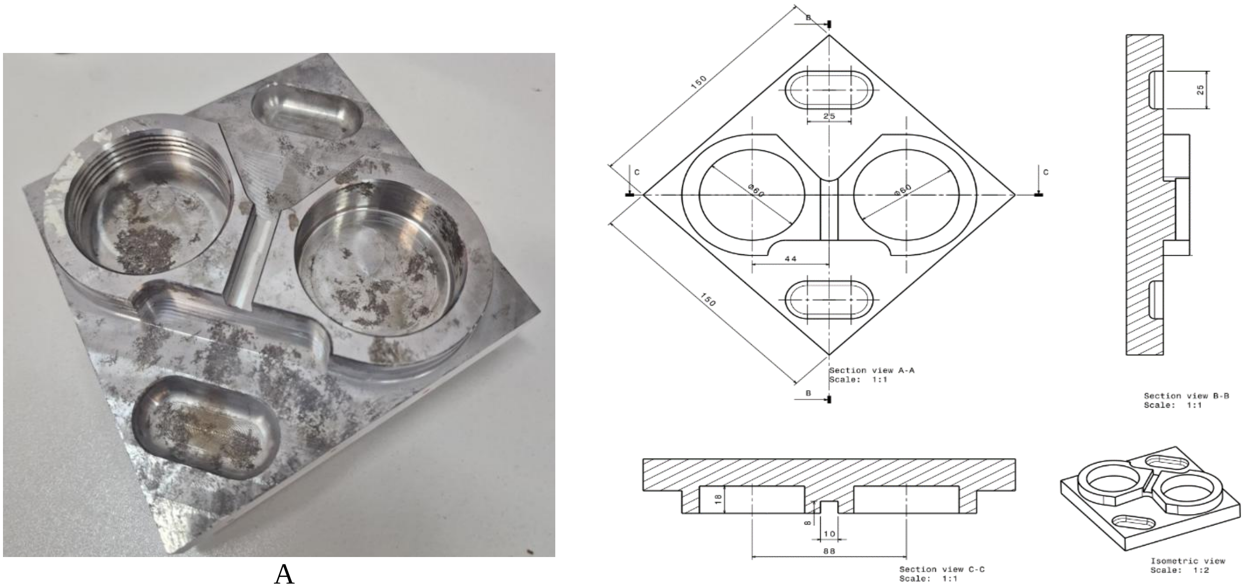
these variables, this research provides a quantitative assessment of how each factor affects the fidelity of the resulting 3D model, offering a pathway to improve efficiency and precision in industrial 3D scanning workflows.

2. MATERIALS AND METHODS

The primary instrument employed for data acquisition in this study was the Artec Leo, a wireless, handheld 3D laser scanner designed for independent operation without the need for a tethered workstation. This device is driven by an internal NVIDIA Jetson TX2 processor and features a built-in HD display for real-time monitoring of the scanning progress. The scanner operates using a hybrid geometry and texture tracking algorithm, utilizing a VCSEL 3D light source alongside a 12-LED white 2D light array to capture surface details. The technical specifications of the device include a 3D point accuracy of up to 0.1 mm and a 3D resolution of up to 0.2 mm, with a data acquisition speed capable of reaching 35 million points per second.

To ensure a comprehensive analysis, a suite of specialized software was utilized for processing, engineering, and measurement. Initial scan processing, including noise removal and primitive identification, was conducted using Artec Studio 15 Professional. Subsequent reverse engineering tasks, specifically the conversion of point cloud data into CAD-compatible formats, were performed in Geomagic Design X . Finally, CATIA V5 was employed for the precise dimensional measurements of the reconstructed models and for comparison against the nominal values of the physical part.

The subject of the investigation was a mechanical plate-type component, specifically chosen to represent a variety of common geometric features encountered in industrial inspections. The specimen integrates diverse geometric primitives, including internal and external cylinders, spheres, and slots, offering a robust baseline for testing the scanner's ability to capture complex topologies .



A

B

Figure 1 A - The physical test specimen (plate) B - Technical execution drawing of the specimen with nominal dimensions

Crucially, the physical state of the component provided varying surface conditions ranging from smooth, machined areas to sections exhibiting rust and high reflectivity. This variation was essential for evaluating how surface quality impacts the identification of geometric primitives during the scanning process.

2.1 Design of Experiments (Taguchi Method)

To systematically evaluate the influence of process parameters on scanning accuracy while minimizing the number of required experimental runs, the Taguchi L9 orthogonal array method was employed. This experimental design methodology focuses on optimizing processes by identifying the influence of specific control factors and their interactions.

The study isolated three critical control factors, each tested at three distinct levels to determine the optimal configuration for geometric precision. The first factor, Lighting Conditions, varied the ambient environment between natural light, neon light, and LED light to assess the scanner's sensitivity to external illumination. The second factor, Surface Preparation, tested the object in its original metallic state, coated with a white matte

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spray to reduce reflectivity, and finally coated with matte spray with the addition of reference markers to aid alignment. The third factor, Scanning Brightness, adjusted the scanner's texture brightness parameter to 10%, 40%, and 80%. The combination of these factors resulted in nine distinct experimental configurations (C1 through C9) as dictated by the L9 matrix.

Table 1: The L9 Orthogonal Array showing the 9 experimental configurations]

Configuration	Light	Surface of the part	Scan Parameters (Surface Brightness)
1	Natural	Original	10%
2	Natural	Matte White	40%
3	Natural	Matte White + marker	80%
4	Neon	Original	40%
5	Neon	Matte White	80%
6	Neon	Matte White + marker	10%
7	LED	Original	80%
8	LED	Matte White	10%
9	LED	Matte White + marker	40%

A standardized scanning protocol was established to ensure consistency across all trials. The test specimen was positioned on a flat concrete surface, which provided a consistent texture background for all configurations, minimizing external variables. For each configuration, the specific parameters were input into the scanner, and the device was moved around the object to capture the geometry from all necessary angles, ensuring complete coverage of the features. Following data acquisition, the project files were imported into Artec Studio 15 for post-processing. The raw data, often containing artifacts and background noise (such as the floor), required cleaning and registration. The floor data was manually removed using the software's eraser tool to isolate the specimen (figure 2).

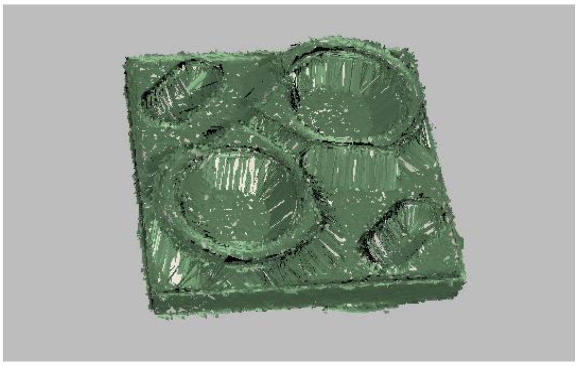

Figure 2 The model during the editing phase with background removal

The scan data was then processed using the "Global Registration" and "Outlier Removal" algorithms. A mesh was generated using settings optimized for geometry preservation: "Good" scan quality, "Small" object size, and the hole-filling method set to "Don't fill" to prevent artificial interpolation of missing data, which could skew accuracy results.

Once the 3D mesh was finalized, geometric primitives were identified directly on the model. Using the software's "Construct" menu, specific surfaces—such as the walls of a cylinder or the curvature of a sphere—were selected ("brushed") to guide the fitting algorithms. For example, to identify a cylinder, the user highlighted the base and lateral walls, allowing the software to mathematically fit the optimal cylinder primitive to the selected mesh data (figure 3). These identified primitives were then exported to Geomagic Design X and subsequently to CATIA V5 for dimensional verification.

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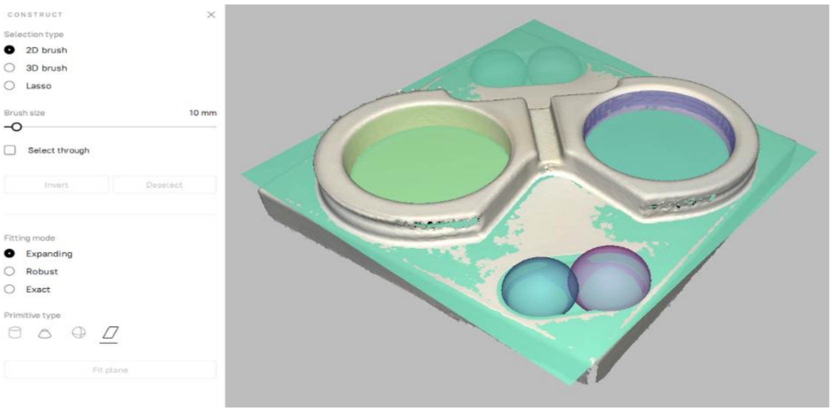

Figure 3. Identification of a cylindrical primitive on the scanned mesh

3. RESULTS

The nine experimental configurations yielded varying degrees of geometric accuracy when compared to the nominal dimensions of the physical specimen. Table 2 presents the measured values for critical features, including cylinder diameters, sphere diameters, and distances between axes, alongside the resulting file sizes for each scan.

Table 2 The values obtained following measurements for each configuration

Config.	C1	C2	C3	C4	C5	C6	C7	C8	C9	Nominal Part Dimension
Diam. cil. 1	58,289	60,606	61,111	60,637	60,461	61,409	58,095	60,628	60,539	60
Diam. cil. 2	58,987	59,797	60,697	59,617	59,577	60,454	61,018	59,502	59,595	60
Distance cil 1&2 axes	90,039	88,520	88,179	88,784	88,455	88,406	89,303	88,336	88,343	88
L Piece	151,468	150,437	148,79	150,624	150,57	149,573	149,383	150,462	149,76	150
l piece	151,224	150,342	149,635	150,910	150,088	149,689	151,578	150,615	150,438	150
h cil. 1	16,038	12,327	15,426	16,336	14,172	12,586	13,107	12,924	12,82	18
h cil. 2	17,494	15,488	16,429	17,199	15,756	16,287	17,370	15,66	15,767	18
Sphere 1	22,269	24,957	25,882	31,185	25,153	25,477	23,103	24,385	25,585	25
Sphere 2	29,587	24,604	26,031	32,704	25,009	25,319	25,297	24,52	25,833	25
Sphere 3	25,374	24,888	25,344	26,772	28,896	25,524	32,311	24,732	24,928	25
Sphere 4	32,604	25,546	26,829	26,772	26,070	25,622	22,942	25,192	25,506	25
h grove	8,126	8,556	7,902	7,548	8,071	7,809	8,021	8,071	8,015	8
l grove	9,121	8,669	10,151	8,804	8,667	10,134	8,352	9,236	9,152	10
Planes height	0,049	0,274	0	0,098	0	0	0,253	0	0	0
File size (MB)	447,28	152,49	172,970	313,61	261,45	155,80	464,92	118,41	253,63	-
Defined plane angle (º)	0,228	0,104	0,002	0,313	0	0,007	0,119	0,001	0	0

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The data reveals significant deviations across configurations. For instance, Configuration 1 (Natural Light, Original Surface) resulted in a file size of 447.28 MB and notable dimensional errors, such as a measured diameter of 58.289 mm for Cylinder 1 against a nominal 60 mm. In contrast, Configuration 5 (Neon Light, White Matte Surface, 80% Brightness) yielded a significantly smaller file size of 261.45 MB and much higher precision, with Cylinder 1 measuring 60.461 mm.

Visual inspection of the processed meshes corroborates the quantitative data. Scans performed on the original, reflective surface (Configurations 1, 4, 7) exhibited high levels of noise and artifacts, particularly around the edges of the cylinders and spheres. Conversely, configurations utilizing the white matte spray (Configurations 2, 5, 8) and markers (Configurations 3, 6, 9) produced cleaner, more continuous meshes. As shown in the comparison below, the application of matte spray effectively eliminated the scattering and reflection issues caused by the metallic surface, preventing the formation of "holes" in the mesh data.

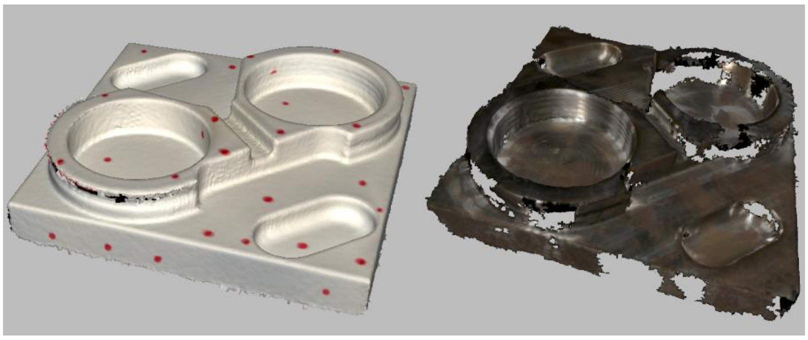

Figure 4 Differences in scan quality based on surface preparation

To isolate the impact of each variable, a Taguchi analysis was performed using the measured means and Signal-to-Noise (S/N) ratios. Impact on Dimensional Precision The "Response Table for Means" calculated for the cylinder diameters indicates the relative influence of each factor. The analysis assigned a Rank of 1 to Factor B (Surface Preparation), indicating it had the most significant Delta (1.19), followed by Lighting (Rank 2) and Scanning Parameters (Rank 3).

The Main Effects Plot for Means (figure 5) demonstrates a steep slope for Surface Preparation, confirming that the transition from the original surface to a treated surface (matte or matte + markers) result in the most substantial improvement in dimensional accuracy.

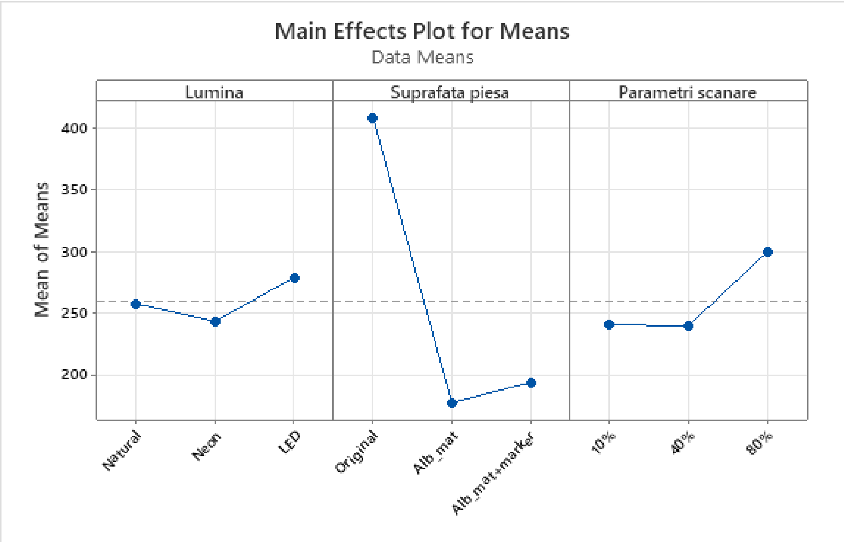

Figure 6 Main Effects Plot for Means (File Size

Efficiency was evaluated by analyzing the resulting file size of the scan; larger files typically indicate higher levels of noise and artifacts that require manual cleaning. The Taguchi analysis for file size confirmed that Surface Preparation is the dominant factor (Rank 1) with a massive Delta of 231.2, compared to 35.4 for Lighting and 59.9 for Scanning Parameters.

The data shows that scanning the original surface results in significantly larger files (mean > 400 MB) due to noise capture, whereas treated surfaces reduced the mean file size to under 200 MB.

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The Signal-to-Noise (S/N) ratio analysis, using the "Nominal is Best" criterion, further validated the robustness of the process. Factor B (Surface Preparation) again achieved the highest rank (Rank 1), with a Delta of 0.2004, indicating that surface treatment is the most critical variable for reducing process variability.

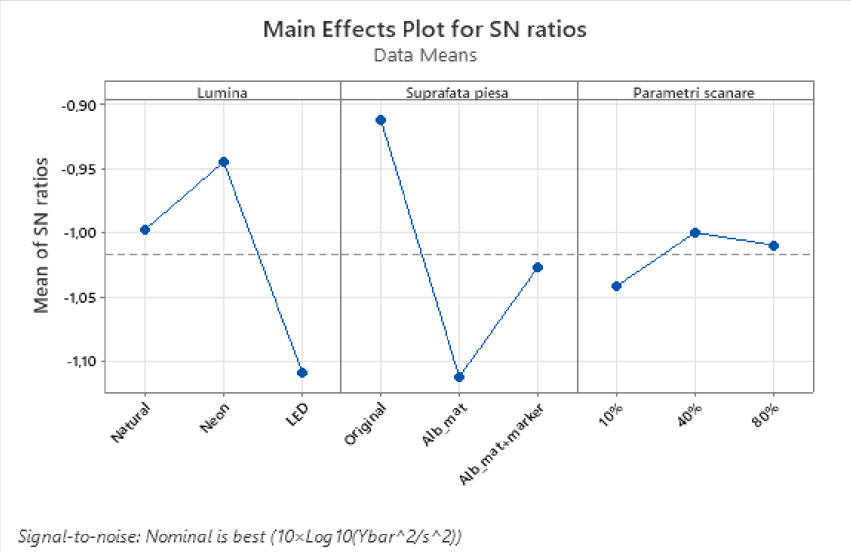

Figure 7 Main Effects Plot for S/N Ratios

The S/N plot (figure 7) reveals a clear peak at the second level of Surface Preparation (White Matte), suggesting that while markers aid alignment, the matte coating itself is the primary driver of geometric fidelity.

4. DISCUSSION

The most significant finding of this study is the overwhelming impact of surface preparation on both dimensional accuracy and process efficiency. The Taguchi analysis consistently ranked Surface Preparation as the primary factor (Rank 1) across all metrics: mean dimensional accuracy, signal-to-noise ratio, and file size. The physical specimen, in its original state, contained reflective metallic surfaces and areas of corrosion. These conditions introduce significant noise into the scanning process due to the scattering of the laser light, resulting in artifacts and "holes" in the 3D mesh. This noise is quantitatively visible in the file size analysis; scans of the original surface generated files averaging over 400 MB, whereas surfaces treated with matte spray averaged under 200 MB. The excessive data in the original scans represents noise rather than geometric detail, which complicates the software's ability to fit accurate primitives to the mesh. By applying a white matte spray, surface reflectivity was neutralized, creating a uniform texture that allowed the scanner to capture geometry without light interference.

Influence of Lighting and Brightness While less critical than surface preparation, lighting conditions and scanning brightness parameters still played a measurable role. The analysis indicated that Neon lighting generally provided better consistency than Natural or LED lighting for specific dimensions. This is likely due to the diffuse nature of neon tubes compared to the directional intensity of LEDs or the variability of natural light, which can create hard shadows and glare. However, the "Nominal is Best" S/N analysis revealed that once the surface is properly prepared (matte coated), the sensitivity to lighting variations decreases. This suggests that controlling the surface properties of the object acts as a buffer against suboptimal environmental lighting.

Based on the synthesis of dimensional accuracy and file efficiency, the optimal scanning configuration identified in this study is Configuration 4/5 parameters: Neon lighting, White Matte surface preparation, and a texture brightness setting of approximately 40%. This combination minimized the deviation from nominal dimensions while maintaining a manageable file size for post-processing.

5. CONCLUSION

This research utilized the Taguchi L9 orthogonal array method to optimize the 3D laser scanning process for the identification of geometric primitives. The study successfully demonstrated that while modern handheld scanners like the Artec Leo are capable of high-speed data acquisition, the fidelity of the resulting model is heavily dependent on process variables.

The statistical analysis confirmed that surface preparation is the single most critical factor in achieving high-precision scans of mechanical parts. The application of a matte coating to reflective or heterogeneous surfaces significantly reduces noise, improves the robustness of the signal-to-noise ratio, and facilitates the accurate algorithmic identification of planes, cylinders, and spheres. While environmental lighting and software brightness settings do influence the outcome, their impact is secondary to the physical condition of the object's surface.

For industrial applications involving reverse engineering or quality control, this study recommends prioritizing physical surface treatment over environmental adjustments. Future work could explore the automation of primitive identification using machine learning algorithms to further reduce the dependency on manual post-processing and enhance the efficiency of the "scan-to-CAD" workflow.

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