Development Of 3D Scanner- Reverse Engineering Approach

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ABSTRACT

Advancements in 3D scanning have significantly influenced fields such as reverse engineering, prototyping, and digital preservation. However, commercial scanning systems' high cost and complexity continue to limit their adoption in small-scale industrial and academic environments. Addressing this gap, the present work introduces a cost-effective and automated 3D scanning solution focused on capturing the external geometry of physical objects with high accuracy and repeatability. The system integrates a depth-sensing module based on Time-of-Flight (ToF) technology, coordinated with a programmable ESP32-WROOM-32 microcontroller and motorized rotation mechanism to enable 360° surface acquisition. A fixed-angle rotational scan approach is employed, and depth data from multiple perspectives is fused using the Iterative Closest Point (ICP) algorithm to reconstruct a complete point cloud. Through a comparative review of existing methods such as structured light, LiDAR, infrared sensing, and RGBD cameras, this study identifies key challenges, including limited accessibility, calibration sensitivity, and point cloud inconsistency. The developed prototype offers a simplified yet scalable alternative, capable of exporting 3D models in formats like STL, OBJ, and PLY for seamless integration with CAD and reverse engineering workflows. Experimental results demonstrate reliable performance for non-industrial applications, validating the system's potential as a modular and replicable platform for affordable 3D digitization.

Keywords – 3D Scanning, Reverse Engineering, Time of Flight Sensor, Point Cloud, ESP32-WROOM-32

1. INTRODUCTION

Three-dimensional (3D) scanning has become an essential tool in modern engineering, enabling the accurate digitization of physical objects for applications such as reverse engineering, quality inspection, rapid prototyping, and digital archiving. Despite significant technological advancements, the accessibility of 3D scanning systems remains limited, primarily due to the high cost, complexity, and calibration requirements of commercial-grade solutions. These limitations challenge small-scale industries, educational institutions, and independent developers seeking affordable and reliable scanning tools. In response to this need, the present study explores the development of a low-cost, automated 3D scanner capable of capturing the external geometry of objects with reasonable precision. By employing a structured scanning process using programmable motion control and a Time-of-Flight (ToF) sensor, the system aims to deliver a practical solution that balances cost, functionality, and ease of use. The proposed design emphasizes modularity, making it adaptable for future enhancements, and supports standard output formats compatible with CAD software, thus serving as a bridge between high-end industrial systems and accessible engineering tools.

2. LITERATURE REVIEW

Ahsan Waqarn et al. "Complexities for adopting 3D laser scanners in the AEC industry: Structural equation modeling" (2023): Adoption of 3D laser scanning in the AEC sector is hindered by workflow incompatibility, limited awareness, and high investment costs. Structural Equation Modelling reveals how resistance to change and lack of standardization further delay integration across construction practices.[1].

Ridan Lukita, et al. “Development of 3D Scanner Application with Stereo Camera for 3D Object Reconstruction”(2023): A structured 3D scanning method using stereo vision and a checkered calibration box enables precise object reconstruction. The setup minimizes RMSE by optimizing camera parameters and completes high-accuracy model generation within minutes, proving effective for low-cost applications.[2]

Abid Haleem, et al. “Exploring the potential of 3D scanning in Industry 4.0”(2022): 3D scanning plays a vital role in enabling reverse engineering, digital twins, and smart manufacturing workflows. Its integration with AI, CAD, and IoT enhances automation, though challenges like surface reflectivity and large dataset handling remain relevant.[3]

Mayuri Gawade, et al. “3D Scanner”(2020): Integration of an IR Sharp sensor with onboard data storage enables multi-angle 3D scanning for consumer-facing applications. Enhanced usability in e-commerce and simulation environments is achieved through real-time model viewing and compatibility with rendering platforms.[4]

Robin H, et al. “A case study on the use of 3D scanning for reverse engineering and quality control”(2021): Reverse engineering and inspection processes benefit from 3D scanning by recreating accurate geometry in the absence of original documentation. The study outlines a systematic approach using point cloud data to replicate and analyze physical components.[5]

Kristijan Bartol, et al. “A Review of Body Measurement using 3D Scanning”(2021): Modern 3D scanning techniques like passive stereo, structured light, and time-of-flight imaging offer diverse solutions for accurate body measurements across fields. The proposed five-stage framework guides the process from body marking to measurement extraction, optimizing 3D scan quality and precision for varied applications.[6]

Leihui Li, et al. “A robust assessment method of point cloud quality for enhancing 3D robotic scanning”(2025): A novel Point Cloud Quality Assessment (PCQA) method enhances robotic 3D scanning by evaluating local and global scan quality through geometric analysis. The approach improves scan consistency and enables real-time rescanning of deficient regions, significantly boosting accuracy and reducing manual corrections in industrial and digital manufacturing applications.[7]

Maximilian Vogt, et al. “Comparison of iPad Pro’s LiDAR and True Depth Capabilities with an Industrial 3D Scanning Solution”(2021): While the iPad Pro’s LiDAR struggles with small object scanning due to limited resolution, the True Depth sensor provides acceptable accuracy (within 0.5 mm) for simpler shapes, although deviations increase with complex geometries. Despite limitations, the research demonstrates the potential for consumer grade devices to enable accessible 3D scanning for educational and prototyping purposes.[8]

Huiying Li, et al. “Design A DIY 3D Scanner for Scanning a 3D Object Using Arduino”(2023): A low-cost Arduino-based 3D scanner, built for small object surface capture, employs triangulation and infrared sensors.

Though suitable for regular geometries with minimal errors, its accuracy drops with complex shapes. The project demonstrates an affordable, scalable approach for educational settings and small-scale research, with potential for further enhancement in sensor precision.[9]

Caio César, et al. “Influence of operator experience, scanner type, and scan size on 3D scans”(2020): Operator experience, scanner type, and scan size significantly influence intraoral scan accuracy. More experienced operators yielded better results, especially for smaller regions, while the TRIOS 3 scanner outperformed the CEREC Omnicom in full-arch scans. The study highlights the importance of training, equipment selection, and technique for optimal scanning outcomes in dental treatments.[10]

Miroslav Kohut, et al. “Low-cost 3D Scanning Table for Educational Purpose”(2021): A cost-effective 3D scanner with Arduino and LiDAR provides hands-on experience in 3D data acquisition and point cloud processing. Built with ROS, it offers an affordable solution for education, costing around $150.[11]

Francesco Di Stefano, et al. “Mobile 3D scan LiDAR: a literature review”(2021): The review covers Mobile Laser Scanning (MLS) applications in urban planning, archaeology, and agriculture, focusing on deployment platforms and accuracy challenges. It suggests improvements in automation and precision for broader use.[12]

Hengyi, Zang, et al. “Precision Calibration of Industrial 3D Scanners: An AI-Enhanced Approach for Improved Measurement Accuracy”(2024): AI-enhanced calibration improves 3D scanner accuracy in industrial settings. Machine learning integrates with traditional methods, increasing precision and efficiency while reducing time and costs.[13]

Ikhwan Taufik, et al. “Prototype of an Arduino-Based 3D Scanner Printed Using 3D Printing”(2024): An affordable Arduino-based 3D scanner, utilizing infrared sensors and 3D-printed parts, captures data for model reconstruction. It provides a customizable, easy-to-assemble solution for non-expert users.[14]

Yi Liu, et al. “Processing curved surface with a high-speed triple galvanometer laser 3D scanning system”(2025): A high-speed triple galvanometer laser system optimizes scanning of curved surfaces by adjusting speed for varying angles, ensuring uniform ablation and precision for aerospace and automotive applications.[15]

Shusheng Bi, et al. “A Survey of Low-Cost 3D Laser Scanning Technology” (2021): Mobile 2D LiDAR systems, when mechanically maneuvered, enable budget-friendly 3D data acquisition. The paper classifies six motion patterns and highlights accuracy and real-time challenges from mechanical and sensor limitations.[16]

Curzio Pagliari ,et al. “Enhancing ergonomic comfort: A study on customized cushion design using 3D scanning and additive manufacturing” (2025): 3D scanning and TPU-based additive manufacturing enable personalized office chair backrests tailored to spinal contours. Integrated lattice structures enhance support, posture, and comfort for prolonged sitting. [17]

FangzhouMu, et al. “Towards 3D Vision with Low-Cost Single-Photon Cameras” (2020):By leveraging temporal light transport data from miniature single-photon sensors, the method reconstructs 3D shapes using neural SDF and differentiable transient modeling. It achieves detailed geometry from sparse, low-cost inputs.[18]

Mohamed Abdelmomen, et al. “Survey on 3D Technologies: Case Study on 3D Scanning, Processing and Printing with a Model” (2020): The study compares structured light and laser scanning, followed by additive manufacturing of a rubber duck model. It links 3D digitization to production, highlighting practical challenges and Industry 4.0 relevance.[19]

3. LITERATURE SUMMARY

The reviewed literature emphasizes the growing relevance and diverse applications of 3D scanning across industries, particularly within the context of Industry 4.0. Key insights highlight advancements in low-cost and DIY scanner development using Arduino and infrared sensors, as well as the integration of AI for calibration and precision enhancement in industrial settings. Studies show that factors like operator skill, scanner type, and object geometry significantly affect scan accuracy. Emerging techniques such as stereo vision, mobile LiDAR, and neural networks expand the capabilities of 3D reconstruction. Despite challenges like high investment costs, data handling, and surface reflectivity, 3D scanning proves invaluable in reverse engineering, digital twin creation, ergonomics, and education, marking it as a pivotal technology for future manufacturing and customization.

4. PROBLEM IDENTIFICATION

Despite significant advancements in 3D scanning technology, challenges persist in achieving high-precision, cost-effective, and user-friendly solutions for small-scale and educational applications. Many existing systems either demand expensive hardware or lack the adaptability to scan complex geometries with consistent accuracy. Additionally, issues such as sensor limitations, workflow integration, calibration complexity, and real-time data processing hinder widespread adoption, particularly among non-expert users and resource-constrained environments. These limitations highlight the need for a low-cost, accurate, and scalable 3D scanning system that balances performance with accessibility.

5. OBJECTIVES

The primary objective of this research is to design and develop a cost-effective, portable 3D scanning system capable of accurately capturing the geometry of small to medium-sized objects. The study aims to enhance scanning precision using affordable components and optimize the process for ease of use, making it suitable for educational, prototyping, and small-scale industrial applications. Additionally, the project seeks to integrate efficient data processing methods for reliable 3D model reconstruction.

6. METHODOLOGY

To realize a cost-effective and automated 3D scanning solution, the proposed methodology is structured around a series of sequential operations designed to acquire comprehensive surface data. The process begins by positioning the target object on a stepper motor-driven turntable, enabling precise rotational increments. A VL53L5CX Time-of-Flight (ToF) sensor, fixed at a known distance from the object, measures depth information using an 8×8 grid of infrared laser pulses, with each frame capturing real-time spatial data. For vertically extended or concave objects, the sensor is mounted on a linear rail system that allows vertical actuation using an additional stepper motor, thereby collecting depth data at multiple heights and uncovering internal geometries. The ESP32-WROOM-32 microcontroller communicates with the sensor via I2C to acquire and buffer the depth matrices. As the object rotates—typically in 5° increments—depth frames are sequentially captured from different viewpoints. These are then converted into Cartesian coordinates using trigonometric transformations that account for the sensor’s angular field of view, enabling point cloud generation from each scan slice. After full rotation, all point sets are aligned and merged using rotation matrices, facilitating the reconstruction of a complete 3D dataset.

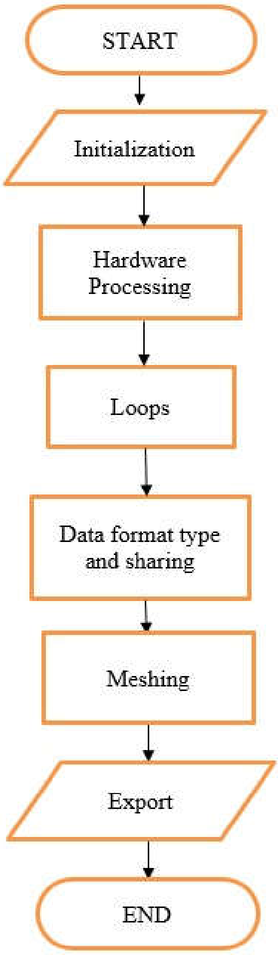

Figure 1: Flowchart of the 3D scanner's automated scanning workflow.

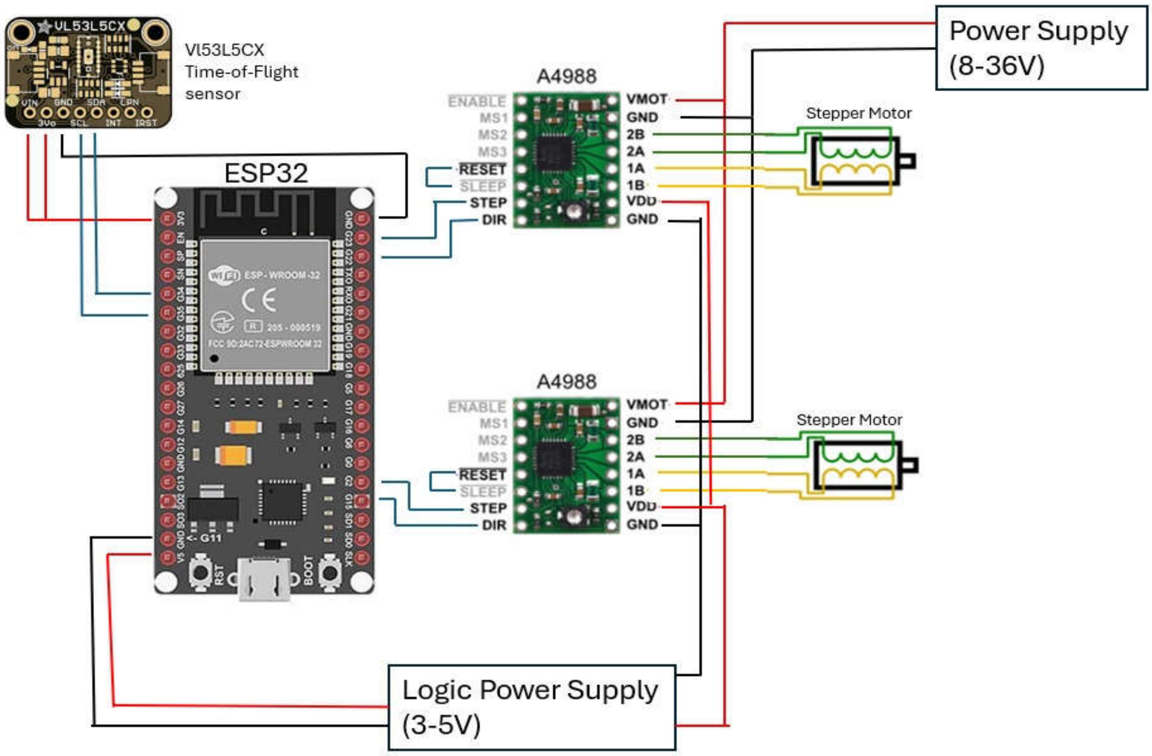

Figure 2:ESP32-WROOM-32 interfaced with A4988 drivers and VL53L5CX ToF sensor for dual-stepper motor control.

The hardware implementation supporting this workflow integrates key components for precise motion control and data acquisition. The ESP32-WROOM-32 serves as the central control unit, interfacing with two A4988 stepper motor drivers that control rotational and vertical movements through NEMA 17 motors. The drivers are fed logic signals from the ESP32's GPIO pins, while power is supplied via a dual setup—12V for motor operation and 3.3–5V for microcontroller and sensor logic. The VL53L5CX sensor connects to the ESP32 through dedicated I2C lines, while micro limit switches are incorporated to establish motion boundaries and ensure accuracy. This integrated system ensures that each scanning cycle is executed with high mechanical precision and synchronized data capture. The captured point clouds undergo post-processing steps such as noise filtering, triangulation, and mesh refinement using tools like MeshLab, resulting in a clean, watertight 3D model ready for applications in CAD, additive manufacturing, or virtual analysis environments.

7. DESIGN AND FABRICATION PROCESS

The design and fabrication process followed a structured approach aimed at achieving dimensional precision, modularity, ease of assembly, and reliable operation of the scanning system. Each mechanical component was modelled using CAD tools and subsequently fabricated through Fused Deposition Modelling (FDM) 3D printing using PLA material. The subsections below elaborate on the stages involved.

7.1 Design Methodology

7.1.1 Requirement Analysis

The system was conceptualized with the following key objectives:

- Enable controlled vertical and rotational movements.
- Integrate sensing and actuation modules.
- Maintain high dimensional accuracy and mechanical stability.
- Ensure modularity and manufacturability using 3D printing.

7.1.2 Component Design Strategy

Base Plate:

The base functions as the primary structural platform. Designed with 10 mm thickness for rigidity, it includes mounts for dual stepper motors, a central cavity to accommodate a timing belt-pulley system, and an unperforated area for flexible electronics installation. Additional features include gussets and chamfers to enhance mechanical strength and user safety.

Carriage Plate:

Responsible for vertical motion, the carriage features slots to support linear motion rods and a mounting interface for the lead screw nut. A rear cutout reduces mass and provides clearance, while strategically positioned holes facilitate mounting to the brass holder.

Constrain Plate:

This component constrains the linear rods, ensuring accurate vertical alignment. Ø22 mm and Ø8 mm holes are provided for rod clamping and attachment, respectively. The thickened profile minimizes vibrations and maintains structural integrity.

Rectangular Brass Holder:

Serving as the nut holder for the lead screw, this component was modelled for brass fabrication. It includes a threaded Ø10 mm hole and Ø3 mm mounting holes, providing a secure interface with the carriage while enabling precise linear translation.

Rotating Plate:

A Ø200 mm circular plate is attached directly to the shaft of a stepper motor, enabling controlled rotation of the part under inspection. A central boss and smooth transitional fillets improve balance and surface finish.

All parts were modelled in Autodesk Fusion 360 and assembled virtually to verify fit, interference, and functionality. Design refinements were carried out iteratively to address issues related to manufacturability, structural loads, and ease of assembly.

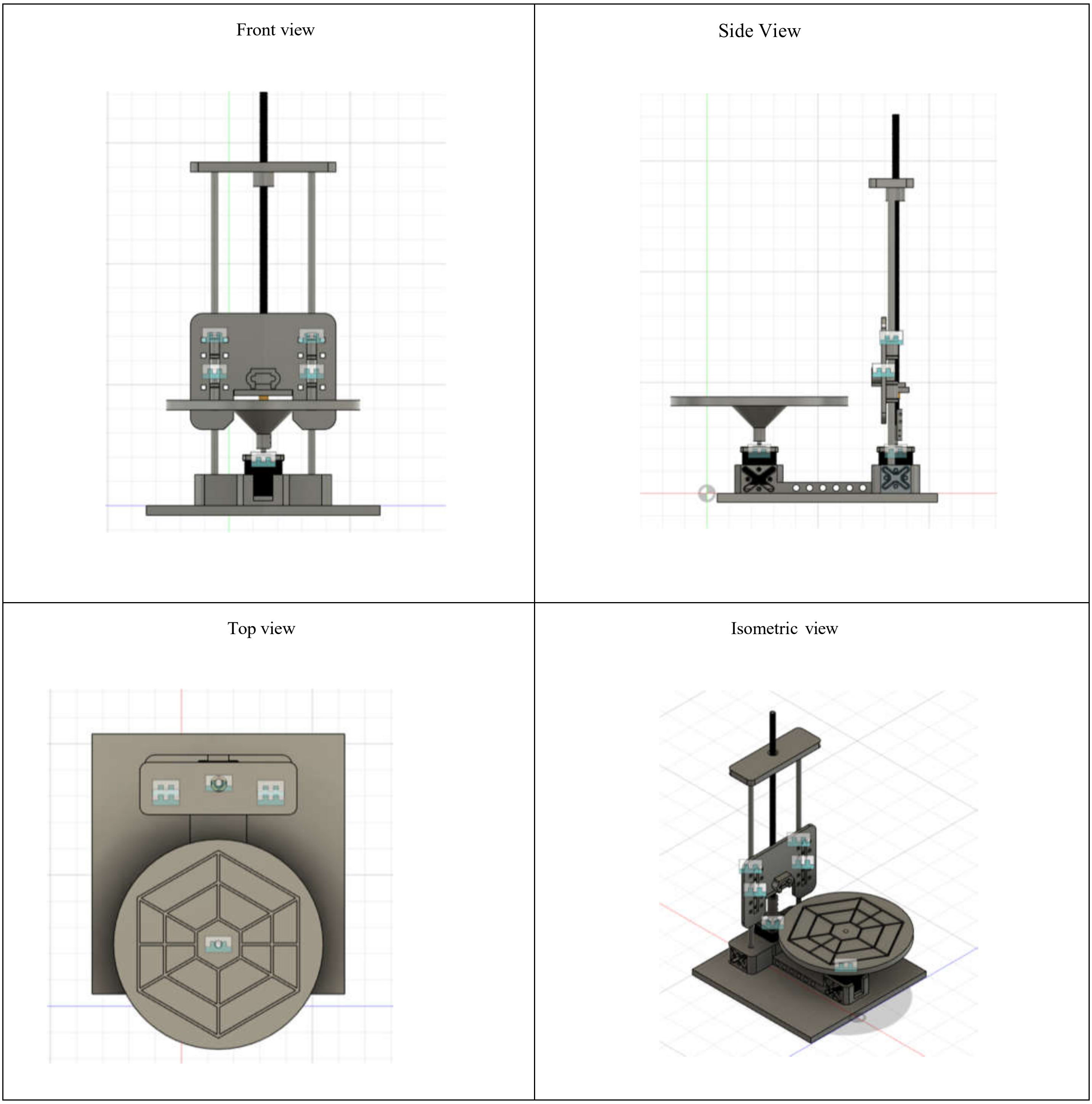

Figure 3: Project Model

7.2 Material Selection and Fabrication

7.2.1 Choice of PLA Material

Polylactic Acid (PLA) was chosen for its favorable properties in rapid prototyping and light-load mechanical applications. It is a biodegradable thermoplastic polymer derived from renewable resources such as corn starch and sugarcane. PLA is preferred in FDM 3D printing due to its low extrusion temperature (190–220 °C), minimal warping, and excellent dimensional accuracy. It also produces negligible fumes, making it safer for indoor fabrication environments.

Comparison with ABS:

- Ease of Printing: PLA is less prone to warping and does not require a heated bed or enclosure, unlike ABS.
- Precision: Better dimensional stability, suitable for tight-tolerance parts.
- Fume Safety: PLA emits a mild, non-toxic scent, while ABS produces potentially harmful styrene vapors.
- Surface Finish: PLA provides a smoother and glossier surface finish out of the printer.
- Hardware Requirements: PLA can be processed on standard desktop 3D printers without high-end features.

7.3 Fabrication via FDM 3D Printing

All components were fabricated using the Fused Deposition Modelling (FDM) method, ideal for PLA due to its predictable print behavior and low shrinkage.

Material Specifications:

- Type: Polylactic Acid (PLA)
- Filament Diameter: 1.75 mm
- Tolerances: ±0.02 mm
- Colour: As per requirement; colour has negligible impact on mechanical performance

Parameter	**Value**
Nozzle Temperature	200-210°C
Bed Temperature	50-60°C
Layer Height	0.2 mm
Infill Density	30-50%(varies by part)
Print Speed	40-50mm/s
Cooling Pan	ON after the initial few Layers
Support Structures	Enabled where necessary

Table 1: 3D Printer Settings

7.3.1 Fabrication Guidelines for Key Components

Components	Fabrication notes
Base Plate	50% infill, large brim for edge adhesion, precise bed leveling required
Carriage Plate	30–40% infill, clean bridging required for vertical slots
Constrain Plate	Printed flat, 50% infill, stable extrusion to avoid layer marks
Brass Holder	Printed in PLA for prototyping; central hole may need post-processing for press fit
Rotating Plate	Use concentric infill for circular finish, 30–40% infill for balance
Top Panel	High infill (50%), three outer perimeters, slower speed to avoid warping

Table 2: Fabrication Guidelines for Key Components

7.3.2 Post Processing

After printing, parts underwent the following steps to ensure dimensional and functional adequacy:

- Cleaning & Deburring: Support remnants removed; edges sanded (400–600 grit).
- Hole Finishing: Critical holes are refined using drills or reamers for accurate fits.
- Surface Treatment: Optionally painted or vapor-treated for improved aesthetics.
- Assembly: Components were assembled using standard fasteners, set screws, and adhesives as required.

8. RESULT AND DISCUSSION

The designed 3D scanning system effectively captured the outer geometry of small-sized objects with notable precision and reliability. By combining a Time-of-Flight (ToF) sensor with a motor-driven rotating base and an ESP32-WROOM-32 controller, the system ensured consistent surface coverage through fixed-angle scanning. The use of the Iterative Closest Point (ICP) algorithm allowed for accurate alignment and merging of multiple depth scans into a unified 3D point cloud. The final 3D models, available in STL, OBJ, and PLY formats, were compatible with standard CAD tools and suitable for reverse engineering purposes. When compared with similar low-cost alternatives, this system demonstrated greater consistency, simpler calibration, and quicker model generation without the need for expensive components. Minor challenges, such as surface noise and slight misalignment in intricate shapes, were noted, primarily due to the ToF sensor's resolution and ambient lighting effects. These could be addressed by optimizing the scan path, applying filtering techniques, or using controlled lighting. Overall, the system presents a practical and customizable approach to budget-friendly 3D scanning for educational and light industrial use.

9. CONCLUSION

The development of a low-cost, automated 3D scanning system outlined in this study demonstrates a viable alternative to high-end commercial solutions, particularly for educational, prototyping, and small-scale industrial applications. By integrating Time-of-Flight sensing, programmable motion control, and iterative point cloud reconstruction, the system successfully captures detailed external geometries with consistent accuracy. The methodology balances affordability with functionality, offering compatibility with standard 3D file formats and CAD tools. Supported by insights from extensive literature, the proposed scanner addresses key industry challenges related to cost, accessibility, and usability. The results validate the platform's reliability and scalability, positioning it as a practical tool for reverse engineering workflows and future expansions in modular 3D scanning technologies.

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