A Cost-Effective Arduino-Based 3D Scanner Featuring PID-Controlled Adaptive Scanning Speed

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I. Introduction

Three-dimensional (3D) scanning technology has revolutionized fields from manufacturing to cultural heritage preservation. While commercial 3D scanners offer high precision, their cost often limits accessibility for education and small-scale applications. This paper presents a cost-effective Arduino-based 3D scanner for basic object digitization.

Our project utilizes an interrupt-driven design with an infrared (IR) sensor and a rotating platform to capture point cloud data. Constructed for approximately ₱2,756 (see Table I), the system demonstrates how affordable components can create a functional 3D scanner suitable for educational and introductory applications.

The scanner systematically acquires data by combining vertical IR sensor movement with platform rotation for comprehensive object coverage. This basic methodology captures essential geometric information, processable with software like MeshLab for 3D model generation. Key features include an interrupt-driven architecture, SD card storage for point cloud data, and automated platform rotation and height adjustment.

This paper details the system's design, implementation, and performance, focusing on scanning simple geometric objects. While limited in capturing fine details, the scanner is an effective educational tool, showcasing the potential of accessible 3D scanning solutions using readily available components.

II. Literature Review

The rise of 3D printing has increased the relevance of 3D scanning systems, especially for small-scale object replication. Many scanning technologies remain prohibitively expensive due to complexity [1]. Approaches are broadly contact or non-contact.

Non-contact active systems using triangulation have shown promise. Common reflective-optical scanning methods are triangulation and time-of-flight (ToF). Triangulation offers greater precision but limited range, while ToF provides greater range at the cost of precision [1]. Triangulation involves projecting a laser, capturing its reflection with a camera, and using trigonometry to calculate distance based on known camera-laser separation [1].

Recent developments focus on affordable scanning solutions. Li et al. [2] developed a system for civil structure detection using an elevating platform and a 2D laser sensor, achieving higher accuracy at lower cost. Reyes et al. [3] proposed a system with a 1D industrial photoelectric sensor. Athira et al. [4] used two IR sensors and motors, a more complex and costly configuration than single-sensor solutions.

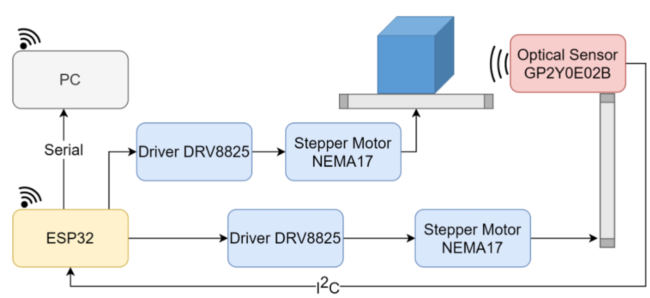

Fig. 1. Global architecture of a comparable 3D scanning system [1]

A key challenge in low-cost systems is balancing scanning speed with accuracy; higher speeds often reduce accuracy, especially with inexpensive range finders. Environmental factors like light interference, data acquisition noise, and beam incidence angles impact scan quality. Even in controlled environments, quality scans require high-quality sensors and circuits [1].

III. Methodology

A. Conceptual Framework

The system (Fig. 3 and Fig. 4) provides low-cost 3D scanning using IR sensor-based distance detection and automated platform rotation. Hardware includes an Arduino Uno, analog IR distance sensor, NEMA-17 stepper motor for platform rotation, A4988 stepper driver, a linear motion system for vertical scanning, and an SD card module for data storage.

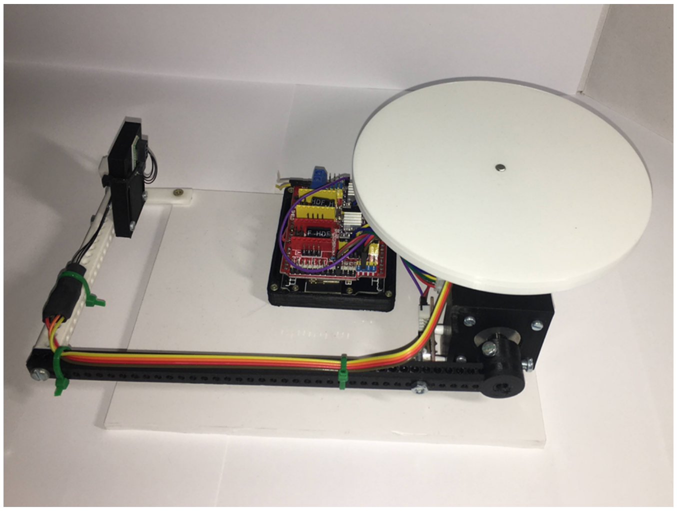

Fig. 2. Implementation of a real scanning system prototype [1]

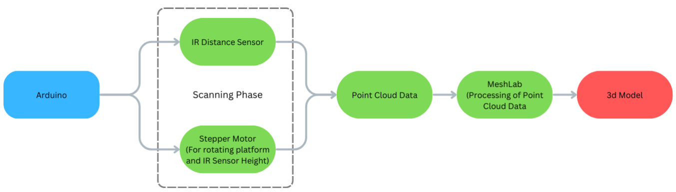

Fig. 3. Block diagram of the Arduino-based 3D scanning system

Operation involves placing an object on the NEMA-17 powered rotating platform. The IR sensor, on a vertical rail, measures distances at different heights. The Arduino processes sensor data, controls motors via the A4988 driver, and stores point cloud data on the SD card. MeshLab processes this data for 3D model generation. This integrated approach ensures coordinated sensor/motor control, efficient data handling, and simplified 3D model creation. The physical design (Fig. 4) features a robust mechanical structure for accurate scanning.

B. Program flow

The system's operation, illustrated in Fig. 5, commences with the initialization of essential peripherals, including the SD card interface, input/output pins for motors and sensors, and the calculation of critical scan parameters such as step-to-angle conversions and Z-axis layer increments. Following initialization, the scanner enters a standby state, awaiting a button press to initiate the scanning sequence.

Upon a debounced button press, the system first performs a Z-axis homing procedure, utilizing a limit switch to establish a precise starting vertical position. Concurrently, a unique filename (e.g., SCANxxx.TXT, where xxx is an incrementing number) is generated for the current scan session, and a header containing scan parameters is written to this file on the SD card. The main scanning loop then begins. The user can press the button again at any time during the scan; this action will immediately halt all motor activity, terminate the current scanning process, and re-home the Z-axis.

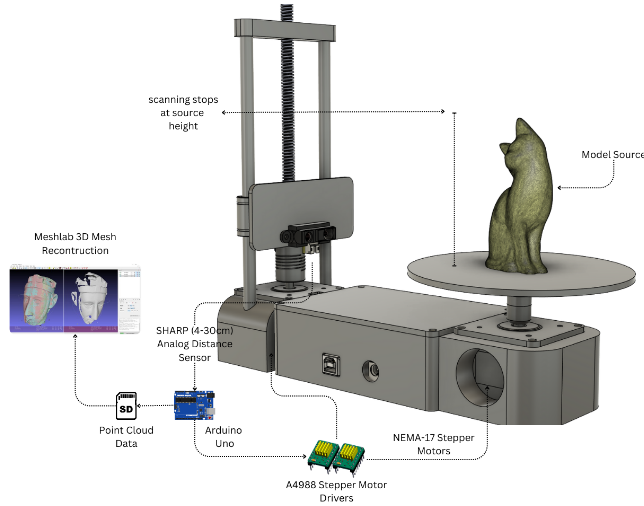

Fig. 4. Conceptual diagram: physical implementation and data flow

The scanning process is executed layer by layer. At the commencement of each new horizontal layer, an initial object detection routine (`checkForObject()`) is performed. This routine involves a quick rotational sweep to ascertain if any part of an object is within the sensor's range at the current height. If no object is detected for a predefined number of consecutive layers (determined by `empty_scan_threshold`), the system concludes that the object's vertical extent has been fully scanned, and the process is terminated automatically.

If an object is detected, or if the empty scan threshold has not yet been reached, the system proceeds with a detailed 360-degree rotational scan of the current layer. For each discrete angular step in this rotation:

1) The infrared distance sensor acquires distance data. To enhance measurement stability and reduce noise, multiple raw readings (`scan_amount`) are taken and averaged.
2) A Proportional-Integral-Derivative (PID) controller (`calculatePID()`) dynamically adjusts the turntable's rotational speed. The step delay for the stepper motor is varied based on the rate of change in the measured distance from the previous step. This adaptive speed control allows the scanner to slow down when encountering complex surface details (large distance changes) and speed up over simpler, flatter regions (small distance changes), thereby optimizing both scan time and the potential for detail capture.
3) The acquired distance, along with the current rotation angle and Z-height, is converted into Cartesian (X, Y, Z) coordinates. These coordinates are then written as a new data point to the open file on the SD card.

After the completion of a full rotational scan for the current layer, the Z-axis mechanism moves the sensor platform upwards by a defined layer height (`z_layer_height`). This entire layer-scanning sequence (object check, rotational scan with PID control, data logging, Z-axis increment) repeats until

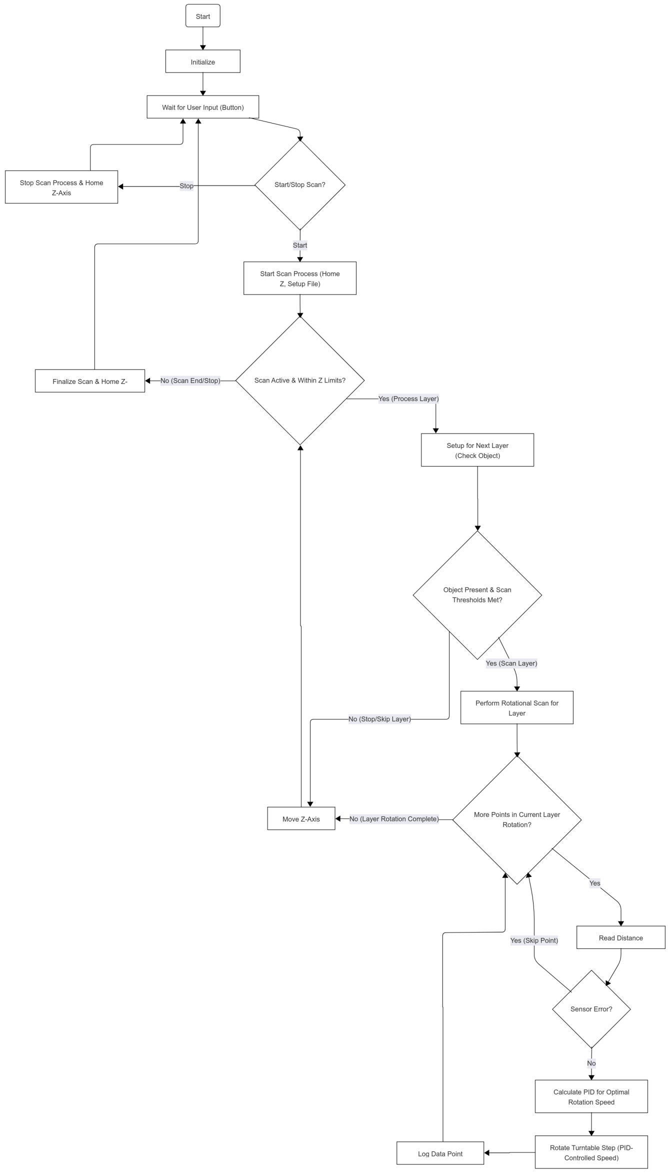

Fig. 5. Program Flow Chart

the predefined maximum scan height (`z_axis_height`) is reached, the scan is manually stopped by the user, or it is automatically terminated due to the `empty_scan_threshold` being met. Upon any form of completion or termination, the Z-axis is homed to its starting position.

C. System Architecture

The primary design principle is cost-effective 3D scanning for simple geometric shapes.

1) System Design: Table I lists components. The total cost, approximately ₱2,756, makes it an economical alternative to commercial scanners for its scope.

The scanner's component layout and dimensions are shown in Fig. 6, Fig. 7, and Fig. 8. The design integrates mechanical and electronic components compactly. The vertical scan mechanism uses an 8mm×200mm T8 threaded rod, supported

TABLE I
COMPONENT LIST WITH COSTS

Component	Quantity	Cost (₱)
8mm×200mm Threaded Rod (2mm Pitch)	1	250
8mm Nut (2mm Pitch)	1	34
8mm×8mm Coupling	1	30
8mm×200mm Linear Rod	2	230
LM8UU Linear Bearing	2	88
NEMA-17 Stepper Motor	2	998
TMC2208 Stepper Motor Driver	2	316
SHARP IR GP2Y0A41SK0F (4-30cm)	1	295
Arduino Uno R3	1	250
Micro SD Card Module	1	65
PLA Filament (Approx. 200-250g)		200
	Total	**2756 ($47)**

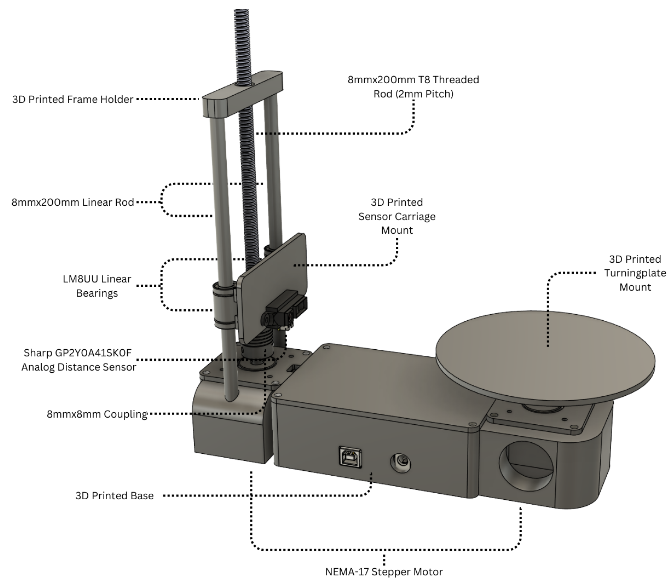

Fig. 6. Assembly view of the 3D scanner showing major components

by two 8mm×200mm linear rods and LM8UU bushings for smooth motion. The 3D-printed sensor carriage mount (Sharp GP2Y0A41SK0F) reduces weight while maintaining rigidity. The NEMA-17 driven turntable enables precise rotation. Electronic components are housed in a 3D-printed circuit box, and a custom base ensures stability.

The mechanical structure has two motion axes: a vertical axis (NEMA-17 motor, T8 threaded rod) for height adjustment, and a rotational axis (NEMA-17 motor) for the scanning platform. A4988 stepper motor drivers were chosen for suitable full-step operation, current limiting, simple interface, and protective features. The Sharp GP2Y0A41SK0F analog distance sensor was selected for its 4-30cm detection range, ±1mm accuracy, 16.5ms response time, and resilience to ambient light. The Arduino Uno R3 controls motors, sensor readings, data processing, and SD card storage. PLA filament was used for 3D printing the base and brackets due to its stability, printability, strength, and cost.

2) Circuit Design: The circuit schematic (Fig. 9) and internal layout (Fig. 8) detail the interconnections:

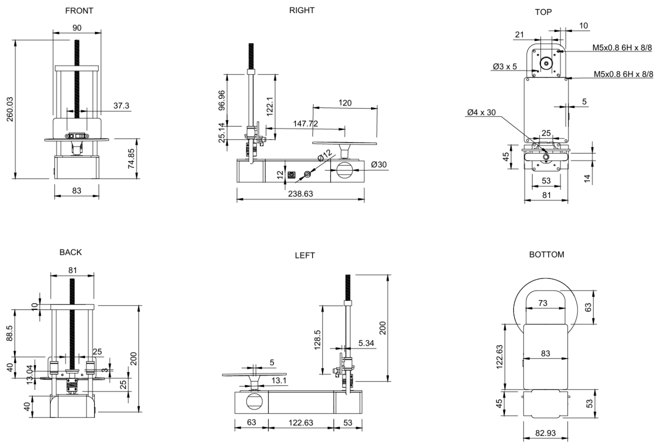

Fig. 7. Orthographic views of the 3D scanner model showing dimensions

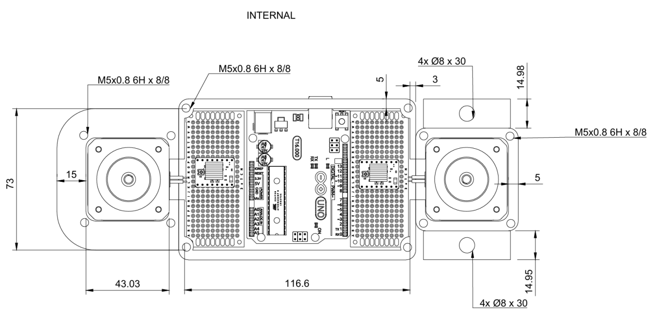

Fig. 8. Orthographic view of the 3D scanner's internal layout

a) Microcontroller Configuration: The Arduino Uno R3 (A1) is the central controller, using digital pins for control/communication, analog pins for sensor input, AREF for reference voltage, and standard power pins.

b) Motor Control Circuitry: Two A4988 drivers (U1, U2) control NEMA-17 motors M1 (turning plate) and M2 (Z-axis). Each driver uses ENABLE, STEP/DIR signals, grounded MS1/MS2/MS3 pins (full-step operation), 12V VMOT, and 5V VDD.

c) Sensor Integration: The Sharp GP2Y0A41SK0F sensor (U3) connects via VCC (5V), GND, and VOUT (analog output to Arduino).

d) Storage Interface: The Micro SD card module (J1) uses SPI (MOSI, MISO, SCK, D4 for CS) and standard power.

e) Control Elements: An OMRON SS-5GL limit switch (SW1) for Z-axis homing and a push button (SW2) for manual control.

f) Power Distribution: A dual-voltage scheme provides 12V for motor drivers and 5V (regulated) for logic and sensors.

g) Protection Features: Protection includes 47μF decoupling capacitors (C1, C2) for motor drivers and A4988 current limiting.

3) Performance Characteristics:

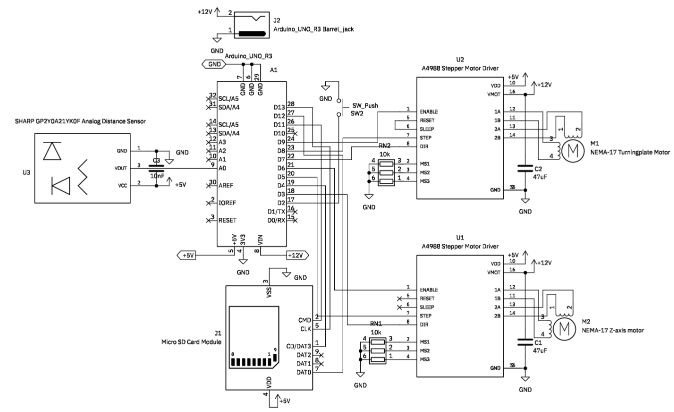

Fig. 9. Circuit schematics of the 3D scanner

a) Scanning Resolution: Vertical resolution is defined by the T8 rod's 2mm pitch and motor's 1.8° step angle, yielding a theoretical minimum vertical step of $0.01\,\text{mm}$ ($\frac{2\,\text{mm}}{360°} \times 1.8°$). Rotational resolution is $1.8°$ per step (200 steps/360°). Distance measurement resolution (Sharp GP2Y0A41SK0F) is approximately ±1mm.

b) Scanning Speed: Scanning speed depends on motor speed (200 full steps/sec without PID, variable with PID), sensor response (16.5ms per raw reading, multiplied by `scan_amount`), and data processing/storage (est. 5-10ms/point). With PID control, speed varies dynamically. A typical scan (200 rotational steps, 100 vertical layers) might take 10-25 minutes, depending on object complexity and PID response.

c) Point Cloud Density: Density varies with settings. A 360° scan (1.8° rotational steps, 1mm vertical steps) can generate up to 19,400 points (200 × 97). Actual count depends on object geometry and sensor accuracy. Coarser 1.8° angular resolution yields fewer points but faster scans.

d) Power Consumption: NEMA-17 motors draw 0.5-1A at 12V each; Arduino Uno 50mA at 5V. Other components have negligible draw. Total active scanning power is estimated at 12-24W.

e) Accuracy and Precision: Overall system accuracy is influenced by sensor accuracy (±1mm), mechanical precision (est. ±0.1mm), and motor positioning repeatability (typically within ±5% of a step, ±0.09°). This results in an estimated system performance with an angular step of 1.8°, a practical vertical step of 0.1mm (or as set by `z_layer_height`), and radial accuracy of approximately ±1mm (dominated by sensor limitations).

f) Environmental Factors: Performance can be affected by ambient light (IR sensor influence), temperature (motor/sensor effects), and vibration (scan accuracy). Optimal performance is in a controlled indoor environment.

TABLE II
SURFACE PERFORMANCE OF GP2Y0A41SK0F ANALOG DISTANCE SENSOR

Surface	**Rating**	**Notes**
White paper/card	Excellent	High reflectivity provides reliable readings
Light paper	Good	Consistent detection and measurement
Wood (light)	Good	Works well on most wooden surfaces
Cardboard	Good	Reliable detection on standard cardboard
PLA (light)	Good	Most 3D printed objects work well if not glossy
PETG	Good	Works well with matte finish
ABS	Good	Reliable with standard surface finish
Black surfaces	Poor	Low reflectivity leads to inaccurate measurements
Glossy surfaces	Poor	Specular reflection causes erratic readings
Transparent	Poor	IR passes through, causing inconsistent detection

IV. RESULTS

A. Prototype

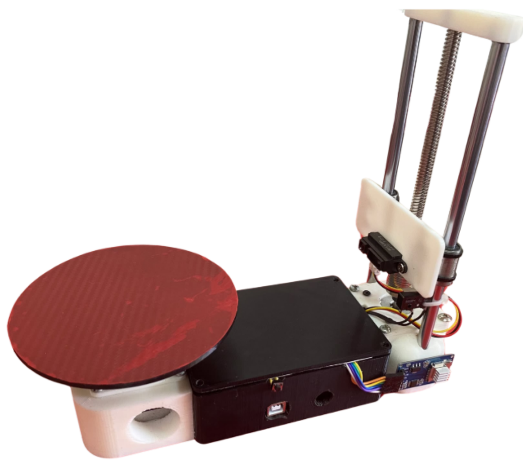

Fig. 10. Prototype Implementation

The finalized prototype (Fig. 10) integrates the described mechanical and electronic components. During testing, it successfully scanned simple objects like cylinders and rectangles, capturing essential geometry. Generated point cloud data, imported into MeshLab, produced 3D models reflecting the scanned objects' general dimensions and shapes. The system's simplicity and effective design highlight its potential as an educational tool.

B. Scanning Performance

The scanner was successfully tested with simple geometric objects, demonstrating its capability for basic 3D digitization. The scanning resolution (e.g., 0.5 mm layer height as per typical `z_layer_height`, and 1.8° angular step) was consistent with design parameters. Observed scanning speed, now influenced by the PID controller for adaptive rotational speed, varied depending on object complexity. For a typical scan, times ranged from 10 to 25 minutes. Point cloud density could reach up to 19,400 points for a full 360° scan with 1mm layers, varying with object geometry and sensor limitations.

Tests on objects like cubes and cylinders (Fig. 11, Fig. 12) showed that while basic shapes were captured, point clouds were approximate. A scanned cube roughly represented edges and faces, but with slight distortions and unsharp edges. A cylinder's scan captured its curved surface and base, but with imperfect smoothness and flatness. These examples show its potential for introductory tasks while revealing limitations in capturing fine details.

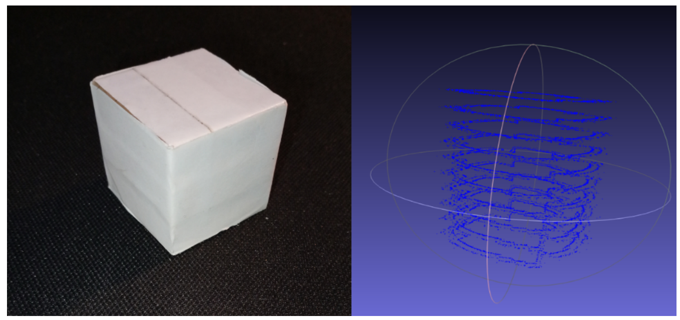

Fig. 11. Cube Shape Demonstration

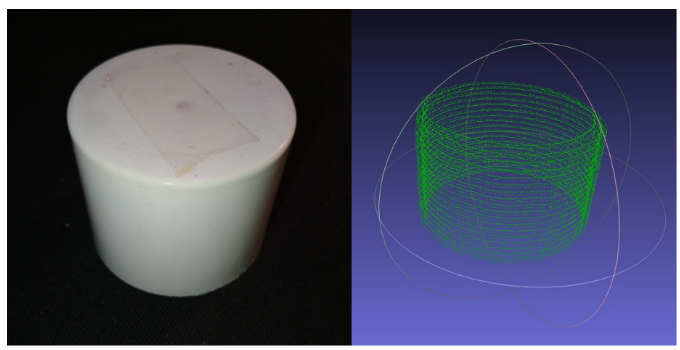

Fig. 12. Cylinder Shape Demonstration

C. Scanning Performance Limitations

Limitations in scanning objects with fine details or complex geometries were observed, primarily due to: Sensor accuracy (Sharp GP2Y0A41SK0F, ±1 mm), restricting fine detail capture. Motor operation, `steps_per_rotation_for_motor = 400` means half-stepping for our 1.8-degree motor), limiting precision for objects needing higher resolution. Scan volume, restricting object size. The PID-controlled speed helps optimize time but does not inherently increase the sensor's or motor's fundamental resolution.

Despite these, performance was sufficient for its intended educational and introductory purposes. The achieved precision enabled point cloud capture that, while not entirely accurate, could be processed into 3D models with MeshLab. Future improvements could include higher-resolution sensors, optimized mechanical design for stability, and exploring microstepping for finer motor control if not already maximized.

V. Conclusion

This Arduino-based 3D scanner demonstrates the feasibility of a cost-effective solution using readily available components. It captured point cloud data from simple geometric objects for 3D model generation. Costing approximately ₱2,756, it offers an affordable alternative for educational and small-scale applications.

The design balanced cost, simplicity, and functionality, featuring button-controlled operation with Z-axis homing, adaptive PID-controlled scanning speed, SD card data storage, and automated motion. 3D printed parts and off-the-shelf electronics contributed to low cost and ease of assembly.

While limited in resolution, accuracy, and scan volume, it is an effective educational tool, showing potential for accessible 3D scanning. Future work could improve performance by incorporating higher-resolution sensors, optimizing mechanical stability, and enhancing software for faster data processing or more sophisticated scan strategies.

This project highlights how low-cost solutions can democratize 3D scanning, making it accessible for education, hobbyists, and small-scale applications, inspiring innovation in 3D digitization.

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