


Design and Fabrication of Low-Cost 3D Scanner Based on Photogrammetry for Mechanical Components

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Abstract:- Photogrammetry is a technique used to create a virtual 3D model of objects using photos of an object. A 3D scanner in photogrammetry employs a specific methodology to capture the necessary data and generate accurate 3D models by collecting points from images taken from different angles. Various techniques have been proposed for 3D scanning, which are not easy to use. These require expensive 3D scanners and much time for processing. Therefore, a new fabrication of 3D scanning is required to perform scanning very quickly and efficiently. The proposed photogrammetry approach can enable manufacturing industries to make 3D models of any object efficiently and rapidly. For demonstration, a case study of piston scanning was selected. For this purpose, a smartphone camera is used first to take pictures of the gear from multiple angles. These pictures were then uploaded to Agisoft Metashape Professional to create its 3D scan. The dimensions of this 3D scan were compared to the original part, which showed a deviation of only 0.021 mm, demonstrating its reasonable application for a mechanical component. Finally, using Geomagic Design X, this scan was used to create a one-to-one 3D model of the piston.

Keywords:- Photogrammetry, 3D scanning, Reverse Engineering, 3D models, 3D scanner.

I. INTRODUCTION

Reverse engineering 3D models entails taking measurements and capturing details of objects using sophisticated scanning technologies like laser or structured light scanning. Advanced software is then used to process these digital scans to produce precise 3D models. This method is essential for undertaking tasks like quality control, customer customization, and historical preservation in sectors like aerospace, medicine, and archaeology [1,2]. The processes required to design, produce, assemble, and maintain systems and products fall under the purview of engineering. Reverse engineering (RE), on the other hand, is the opposite of forward engineering in that it takes a physical product or system and turns it into a digital model that can be converted into a computer-aided design (CAD) file [3]. Traditional forward

engineering uses logical, mathematical, and abstract ideas and transforms them into physical products or systems [4]. In many cases, physical products without any technical information or data may exist. In these cases, RE may replicate the product, examine its features, or acquire as-built models [5].

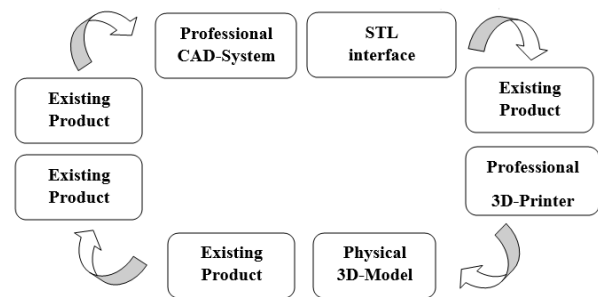


Figure 1. Reverse Engineering process

Photogrammetry pulls the principles of computer vision and image analysis to reconstruct or recreate 3D models of an object from a series of images or photographs taken from different angles and viewpoints [6]. By applying triangulation algorithms and extracting key visual features of an object, it becomes possible to recover the 3D geometry/model and texture of the 3D object being scanned [7]. Photogrammetry offers several advantages, including low equipment costs, greater accessibility, easily movable, and the ability to capture complex surface details with high accuracy [8].

Reverse engineering is an essential technique for most organizations but unfortunately, it requires expensive 3D scanners for proper operation and local industry cannot afford them. One of the other main issues with the scanning technique is scaling errors in the scanned model which can be removed by fabricating a 3D scanner in such a way that will scan objects from different angles and fixed distances by using the photogrammetry technique. This research aims to design and fabricate an economical 3D scanner based on the

photogrammetry technique with approximately the same level of functionality and accuracy.

Photogrammetry and its comparison with other professional 3D scanning.

Kanun et al. [9] attempts to use the photogrammetry technique to recover the damaged turbocharger of a car. He dismantled the turbocharger into two parts. Both parts were individually modeled and then assembled. Thus, the turbo wings under the covers were modeled in detail. However, he did not mention any setup or design for the photogrammetry technique. While the specific details of their photogrammetry setup were not provided, their approach likely encompassed standard photogrammetric processes such as feature extraction, camera calibration, and bundle adjustment to accurately reconstruct the turbocharger components and facilitate subsequent modeling and analysis.

In another study, Kanun et al. [10] described the process of photogrammetry technique to make 3D models of a car brake disc plate. They dismantled all the brake disc plates into pieces and used a proper photogrammetry setup and software (Agi soft Metashape) and create high-resolution 3D models of every individual part. Through precise feature extraction, camera calibration, and bundle adjustment processes facilitated by the software, they reconstructed high-resolution 3D models of each component. This approach allowed for detailed visualization and analysis of the brake disc plate parts, showcasing the effectiveness of photogrammetry in automotive component modeling.

Schulze-Buxloh et al. [11] attempted to make the prototype of a 3D scanner. They use the technique of two stepper motors and use photogrammetry software to take data from the prototype of a 3D scanner. However they did not propose a specific mechanism for the 3D scanning technique, they just made a prototype. Despite not proposing a specific mechanism for the 3D scanning technique, their prototype showcased the potential of combining stepper motors with photogrammetry software for data acquisition. By utilizing this setup, they laid the foundation for future developments in 3D scanning technology, emphasizing practical experimentation over theoretical proposals.

Setiyadi et al. [12] described in their paper the comparative Study of affordable Photogrammetry Software for reconstructing a 3D Model of a Human Foot. They use three software which are Agi soft Meta shape, 3DF Zephyr, and Regard 3D. The Agi soft Meta shape software has good results as compared to others. Despite not detailing specific mechanisms for 3D reconstruction, Setiyadi et al.'s study provided valuable insights into the comparative capabilities of different photogrammetry software packages, highlighting Agisoft Metashape as particularly effective for reconstructing 3D models of human feet.

Bogdan et al. [13] applied the technique of Reverse Engineering using photogrammetry on a Francis runner geometry which has a diameter of 1160 mm and 19 blades, which is a complex part. They use two software Agi soft Photo Scan and Geomagic Design X. They get results but do not discuss the method of capturing data in the form of pictures.

Their research contributes valuable insights into the application of photogrammetry in reverse engineering complex parts such as the Francis runner, showcasing the potential of software solutions like Agisoft Photoscan and Geomagic Design X in this field.

Khan et al., [14] proposed a technique for photogrammetry setup. They scan gear for the purpose and get almost good results in 3D models. But the proposed 3D scanner is manual not automated. The scanner needs at least two persons to operate it. Khan et al. obtained promising results in generating 3D models, showcasing the feasibility of their manual scanning method. However, details regarding the specific procedures for capturing data and operating the manual scanner were not provided in their study.

Asadpour et al. [15] described in his paper the process of photogrammetry technique to make 3D models of the tileworks plate. He used a mobile phone (Samsung Galaxy A720F) and a monopod for data collection (picture). He used eighty-four camera stations (photos) for the scanning of the tilework plate, 39 camera stations for west tiles, and 45 stations for east tiles. their photogrammetry setup and data collection methodology, Asadpour et al. successfully generated detailed 3D models of the tileworks plates. However, further details regarding the photogrammetry process and the specific procedures for capturing data with the mobile phone and monopod were not provided in their study.

Woloszyk et al. [16] developed a photogrammetry image-based approach for modeling imperfect structures and conducting Finite Element (FE) analysis. By capturing and processing images of the structure, they created a high-resolution 3D model that accounted for imperfections and irregularities. While the specific details of their photogrammetry setup and image processing techniques were not provided, Woloszyk et al. demonstrated the effectiveness of their approach in capturing the intricate details of imperfect structures for subsequent FE analysis.

Deane et al. [17] used historical aerial photos and digital photogrammetry techniques to investigate landslides. They accessed old aerial images, georeferenced them, and created orthorectified versions. By comparing these with modern imagery, they identified past landslide areas, analyzed terrain using DEMs, and assessed landslide susceptibility for practical geohazard management. Through this process, they identified areas affected by past landslides and conducted terrain analysis using Digital Elevation Models (DEMs) to assess landslide susceptibility. Their study aimed to provide valuable insights for practical geohazard management, demonstrating the effectiveness of integrating historical data and photogrammetry in landslide research and mitigation efforts.

Marín-Buzón et al. [18] explored how photogrammetry has emerged as a new scientific tool in archaeology, gaining popularity as a research trend worldwide. They state that photogrammetry involves capturing and processing images to create highly detailed 3D models of archaeological sites and artifacts, revolutionizing documentation, analysis, and preservation efforts in the field of archaeology. They emphasized photogrammetry's capacity for capturing and

processing images to produce highly detailed 3D models of archaeological sites and artifacts, consequently revolutionizing documentation, analysis, and preservation endeavors within the field of archaeology. Though specific methodologies and techniques were not detailed, their study underscored the transformative impact of photogrammetry on archaeological practices worldwide.

Zhou et al. [19] experimented with mesoscopic (mm-scale height variation) photogrammetry, a technique that involves using an un-stabilized phone camera for capturing images. They faced the challenge of the lack of stabilization but successfully applied photogrammetry methods to create detailed 3D models of small objects and surfaces. The study demonstrates the potential of using common, portable devices for accurate and cost-effective 3D data acquisition in various fields, including archaeology, cultural heritage documentation, and engineering applications. Their study showcased the potential of utilizing common, portable devices for accurate and cost-effective 3D data acquisition across diverse fields, such as archaeology, cultural heritage documentation, and engineering applications. While specific techniques for image capture and processing were not elaborated, Zhou et al.'s research underscored the versatility and accessibility of photogrammetry for various scientific and practical endeavors.

From the literature survey, it was discovered that a considerable measure of work has been performed on the 3D scanning technique using the photogrammetry technique. Various methods have been developed for 3D scanning techniques by different researchers. However, these techniques often come with limitations in terms of the angle used for capturing images, calibration of the camera, compatibility with the software, and safety concerns such as laser scanners, etc. In light of these challenges, we are designing and fabricating a 3D scanner that will overcome these limitations.

II. RESEARCH METHODOLOGY:

In the present study, mechanical components namely the piston and bevel gear are selected for analyzing the scanning performance of photogrammetry using an indigenously developed setup.



Figure 2. Piston and Bevel Gear

For scanning indigenously-developed photogrammetry setup is used as shown in Figure. The setup comprises of the following items: smartphone camera, turntable, solid colored background, diffused lighting setup, camera stand, and printed mark points for scale accuracy. The rotatory table rotates in the steps of 10 degrees up to 360 degrees. So, it becomes 36 steps. In each rotation of 10 degrees, the camera of a scanner takes 1/one picture per rotation so, a total are 36 pictures captured in one rotation of a rotatory table by the camera. However, we need to cover all angles and sides of the objects, for that we take pictures 3 times hence $(36 \times 3 = 108)$ picture So, 108 pictures are needed to create a perfect mesh and 3D model from pictures through the photogrammetric technique. The 3D scanner has been designed in such a way that fulfills the mesh requirements. The Infinix smart 5 camera setup with a 13-megapixel primary camera and a depth sensor has been used for taking pictures of the objects. Two stepper motors are used one is for rotation of the rotatory table and another is for rotating camera/ mobile phone ring. A Stepper motor of NEMA 17 1.8 degree 200 steps-per-revolution four-phase has been used for the purpose. Arduino nano is used which is reliable and cost-effective as compared with other types. And Diffused light is used for clear pictures.

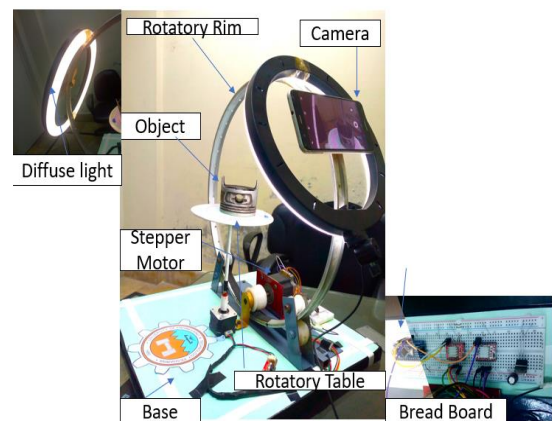
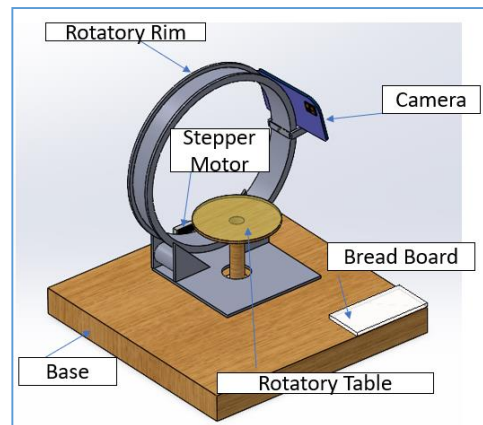


Figure 3. Design of 3D Scanner in SOLIDWORKS

After taking pictures of a piston with the 3D scanner, the next step is to develop a 3D mesh in a photogrammetry software which has multiple tools for the development of mesh models such as Photo scan, Reality Capture, 3DF Zephyr, Mesh room, and c Meta shape.

These tools have their capabilities according to the file size, resolution, etc. Photo scan and 3DF Zephyr create the best results regarding the model resolution (point number), model file size (MB), and total 3D model reconstruction time (seconds). Agi soft Meta Shape Professional is chosen as the most accurate and reliable software for 3D mesh construction [20]. In this research, Agi soft Meta shape has been used which involves the following steps for 3D mesh generation.

Step 1: Upload all pictures of the object to the software.

Step 2: Align all the photos which determines the position of the camera in each picture and creates the initial shape from the pictures as shown in Figure 4, the total time taken by these steps was approximately 11 minutes.

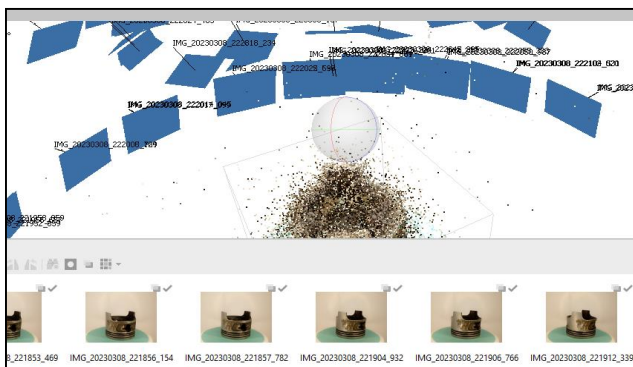


Figure 4. Initial shape after picture alignment

Step 3: The next step is to create a point cloud object from the aligned photos. This step takes a very long time and requires a fairly powerful computer to work efficiently. This process takes approximately 2-5 hours depending upon the computer used.

Step 4: The next step is to generate a 3D mesh. Agi soft Metashape is efficient in this regard which creates a fast and accurate mesh model. The process takes time up to 4 minutes.

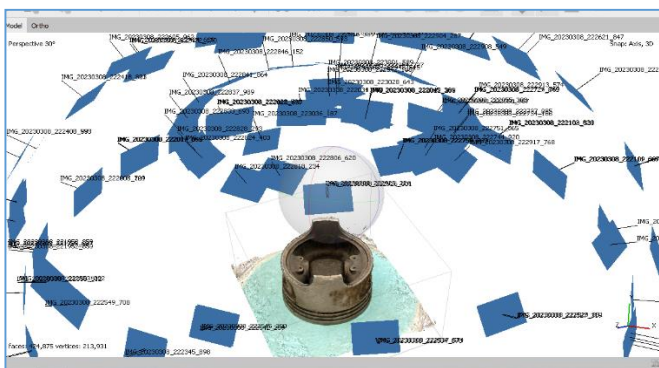


Figure 5. 3D Mesh of the object

Below is the resulting solid mesh model of the scan object (Piston).



Figure 6. Resulted Solid Mesh Model using Photogrammetry

For comparison purposes, Wiiboox Reeyee SP Desktop 3D scanner (supplied by Wiiboox, Nanjing, China) is used. It uses structured light scanning, which involves projecting a pattern of light onto the subject and measuring the distortions in the pattern caused by the surface of the object. This allows the scanner to capture detailed and accurate measurements of the object's shape and size, as well as its surface texture and color. It has a scanning accuracy of 0.1 mm. The light source is LED and the camera is 3×106 CMOS (complementary metal oxide semiconductor).

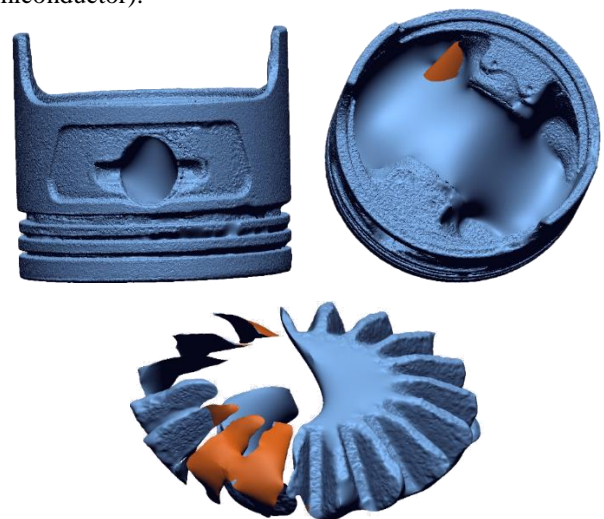


Figure 7. Resulted Solid Mesh Model using Wiiboox Reeyee SP Desktop 3D scanner

III. RESULTS AND DISCUSSION

Figure 6 represents the level of detail present in a scan made through the technique of Photogrammetry, the internal geometry even though having some minor bumps and rough surface is captured completely and can be reverse-engineered without any issues. The holes present in this scan also show the lack of problems present in many entry-level professional 3D scanners where the holes are filled in. Overall, the results have

very high levels of detail and surfaces are smooth, making it a much easier model for reverse engineering.

Figure 7 represents the level of detail present in the scan produced using the professional scanner. The internal geometry is nonexistent below a certain level of depth and the holes are also filled in with extra mesh. The scan overall has high levels of detail with smooth surfaces but holes and internal geometry are filled with unnecessary mesh data which will make complete reverse engineering impossible.

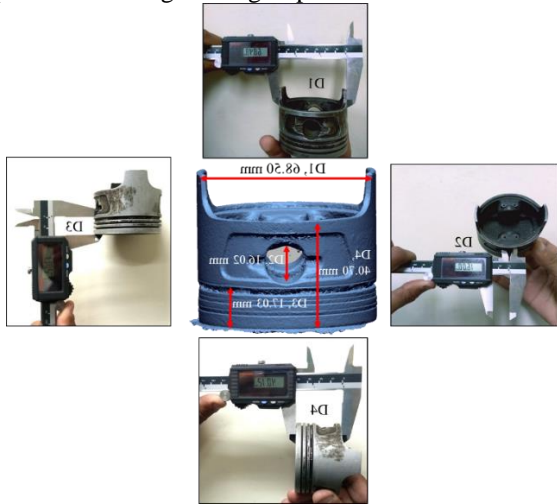


Figure 8. Actual measurement of piston vs Mesh model (D1)

Table 1 Resulted data of 3D scanner obtained from 5 replications

Actual Readings	D1	D2	D3	D4	D5
	68.48 mm	16.00 mm	40.12 mm	67.54 mm	17.02 mm
Results obtained through 3D Scanner					
Replications	1	2	3	4	5
D1 (mm)	68.50	68.52	68.47	68.51	68.49
D2 (mm)	16.02	16.04	16.08	16.03	16.02
D3 (mm)	40.70	40.69	40.72	40.71	40.70
D4 (mm)	67.59	67.56	67.57	67.51	67.52
D5 (mm)	17.03	17.01	17.00	16.99	17.00

The real value of the object in our testing was 50.55 mm, and the value measured in the scan was 50.5 mm. This difference of just 0.0357 mm demonstrates the high level of accuracy that can be achieved using photogrammetry with markers. The error in this measurement is just 0.07%, which is

a very small percentage considering the overall size of the object. The scanning result using professionals lacks sufficient details of bevel gear.

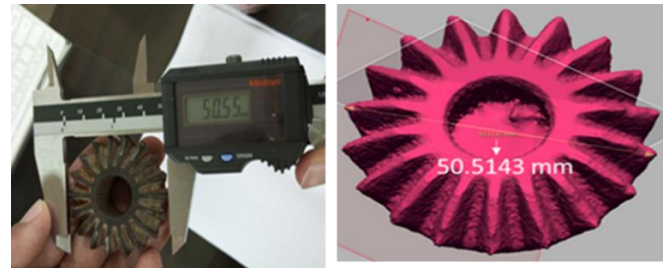


Figure. 9 Gear

CONCLUSION

The results of the 3D scanner were very clear and accurate according to the physical object. We take the piston head as an object for testing, it has a complex shape and contour geometry shape. The 3D scanner collects the images from different angles and covers all the sides and corners of a piston head. After collecting images of a piston through the 3D scanner, we use AGI-soft Meta shape for initial processing to get a solid mesh Model.

The resulting 3D scanner gives an optimal result for every object without investing in the expensive 3D scanner and giving much time, we can get good results through the photogrammetry technique. Various technique is used for Reverse Engineering but photogrammetry gives good results with accuracy in size, model, and processing time.

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I completed my graduate studies in Industrial Engineering and I am hardworking, self-motivated, and have a good attitude towards multi-tasking collaboratively. I am currently working as a Research Associate at UET Peshawar under the Pakistan Science Foundation-funded project "Design and Manufacturing of Assistive Devices Used in Physical Rehabilitation of Disable People using Additive Manufacturing Technology ". Along with position, we are doing publication in photogrammetry technique used for Reverse Engineering. My research direction is towards linking the Reverse Engineering technique with additive manufacturing.