Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN	: 2549-1999	No.	: 6	Month	: December
p-ISSN	: 1693-5462	Volume	: 23	Year	: 2025

Processing dates: received on 2025-5-02, reviewed on 2025-06-05, accepted on 2025-12-12 and online availability on 2025-12-31

Comparative time analysis of digital photogrammetry software using AI methods for design recovery in digital manufacturing

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Abstract

This research aimed to investigate the time efficiency of integrating traditional digital photogrammetry software compared to Artificial Intelligence (AI) in Reverse Engineering (RE). The investigation was conducted through a systematic comparison of the selected digital photogrammetry software and an AI-based method, using various objects for evaluation. Although high accuracy can be achieved with traditional photogrammetry software, the process is time-consuming, particularly for complex or large objects. Therefore, this research presents a timing analysis that demonstrates the efficiency advantages of AI-based methods over traditional digital photogrammetry software. The results showed that AI, by automating the reconstruction process, has the potential to reduce the time required for RE significantly. Moreover, the results of the 3D piston model using AI Google Colab™ were close to Agisoft Metashape, showing the potential use of alternative software as a solution in the RE process. These results suggested that AI-based methods could reshape the RE landscape, offering crucial efficiency gains for industries with rapid prototyping and just-in-time product Development.

Keywords:
Digital manufacturing, modeling, piston, photogrammetry, RE, AI

1 Introduction

The integration of digital photogrammetry and Artificial Intelligence (AI) is rapidly becoming prevalent, particularly in the domain of Reverse Engineering (RE) and Digital Manufacturing [1]. Therefore, this research aimed to comprehensively explore the comparative time analysis between digital photogrammetry software and AI-based method for RE applications [2,3]. The interaction between these technologies promises a revolution in speed and efficiency, enabling the reconstruction and analysis of complex objects [4]. As industries continue to demand faster and more accurate RE solutions, there is a need to explore the effect of integrating of AI on time efficiency in the RE process compared to traditional digital photogrammetry software [5,6]. RE is a crucial process in product Development, including the deconstruction and analysis of existing objects to understand design and functionality [7]. Digital photogrammetry is a traditional method that uses photography to create accurate 3D model [8]. Although the method is effective, traditional photogrammetry can be time-consuming, particularly when dealing with complex or large-scale objects [9]. The introduction of AI into this process enables faster, automated reconstructions, promising significant time savings without sacrificing accuracy [10,11]. The motivation behind this research originates from the increasing demand for efficiency and speed in RE practices. As industries race against time to bring products to market, traditional digital photogrammetry methods may struggle to meet tight deadlines. Therefore, the integration of AI offers a more responsive and adaptive approach to RE. The main objective is to conduct a time analysis, evaluating the efficiency gains provided by AI-based method compared to traditional digital photogrammetry software [12].

Digital photogrammetry plays a significant role in RE, providing a non-contact method for capturing object geometry through photography [13]. This process includes taking pictures from various angles to reconstruct detailed 3D model. Although the technique is accurate, traditional photogrammetry often requires manual intervention to identify and match key points, thereby making the process time-consuming, particularly for large datasets. Therefore, AI profound learning algorithms, offers a promising solution in image processing and pattern recognition [14]. In the context of RE, AI algorithms can automate the identification and matching of features in photographs, significantly reducing manual work [15,16]. Neural networks trained on extensive datasets quickly recognize patterns and establish correspondences, simplifying the reconstruction process [17]. In this research, the method used was a systematic comparison between selected digital photogrammetry software and AI-based method for RE tasks. Diverse objects, ranging from intricate mechanical components to complex organic forms, were also used to evaluate the performance of each method in various scenarios [18]. For the digital photogrammetry aspect, widely used software packages were selected, and the reconstruction process was documented [19]. Furthermore, the time required for essential steps, such as image capture, point identification, and model creation, was measured. On the AI-based side, a deep learning model trained on diverse datasets was implemented [20]. The time efficiency of AI-based method was assessed in the context of the same object set, focusing on the automatic identification and matching of features. Comparative analysis was conducted based on several metrics, including total processing time, accuracy of the reconstructed model, and adaptability to the complexity of different objects. This analysis was carried out to measure time savings and evaluate the reliability as well as robustness of each approach in various RE scenarios.

The results of this research have significant implications for various industrial applications. These include efficiency gains through AI-based method, which reshape the landscape of RE, particularly in industries with rapid prototyping and timely product Development. Additionally, there are opportunities for future exploration and transformation, as the integration of AI with continuous advancements in machine learning algorithms can further enhance efficiency and accuracy. The potential time savings and efficiency improvements offered by AI-based method can also transform the speed industries carry out RE tasks. Due to an increase in the demand for faster and more accurate solutions, the synergy between digital photogrammetry and AI offers a promising solution for transformative engineering practices. Therefore, this research provides quantitative insights, serving as fundamental for further innovation in optimizing neural network architectures, exploring real-time applications, and addressing potential challenges related to data privacy and security.

2 Research methodology

2.1 Close-range photogrammetry

Mills and Barber [24] provided an overview of the advancements in close-range photogrammetry within structural engineering, highlighting several key developments. Enhanced photogrammetry network designs, such as multi-station convergent networks, have significantly improved accuracy, precision, and reliability. The adoption of self-calibrating cameras and advanced analytical methods enables the use of non-metric cameras and simplifies calibration. A growing number of affordable software solutions are now accessible to users. Advances in internet technology have facilitated online photogrammetric measurements. Progress in digital technologies has streamlined workflows by eliminating the need for image digitization and enabling fully digital processes. Modern digital cameras, combined with improved analytical tools, offer greater flexibility and efficiency for photogrammetric measurements.

According to Jauregui and White [25] highlighted the key components and requirements for using close-range photogrammetry in bridge engineering applications. A measurement project typically involves a medium- to high-resolution digital camera, such as the Kodak DCS or Pro SLR series, along with 2-4 scale bars to establish network control. Uniformly distributed artificial or natural targets are essential; increasing the number of targets improves measurement accuracy. Specialized photogrammetry software, such as PhotoModeler or Australis, is used to process the data, and a total station is required for control-point measurements. To achieve high-accuracy results, flash photography and retroreflective targets are commonly employed.

2.2 Single-camera measurement

Fig. 1 show illustrates the fundamental principle of photogrammetry, which states that when the camera's image plane and the object's plane are parallel, the actual dimensions of the object are proportional to the dimensions measured in the image. In this scenario, any deformation observed in the image plane, represented by ΔxΔx and ΔyΔy, corresponds to the deformation of the actual object, denoted by ΔXΔX and ΔYΔY.

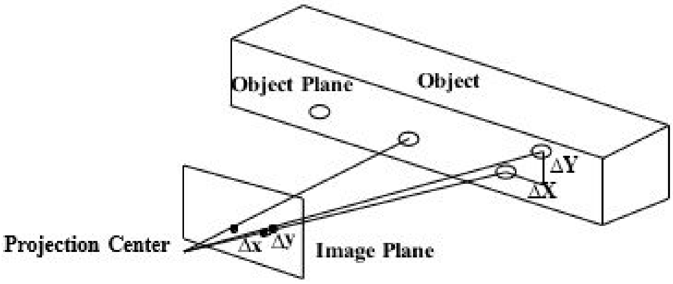


Fig. 1. Single-camera measurement [26]

The relationship between these deformations is governed by Eq. 1, in which b is the scale factor, determined from control points or scale bars. This scale factor establishes the proportionality between measurements in the image and those of the actual object, enabling accurate computation of real-world deformations.

$$\Delta X = b\ \Delta x, \text{ and } \Delta Y = b\Delta y \qquad (1)$$

2.3 Object photogrammetry

The selection of the object is based on various design considerations, such as size, dimensional complexity, detail, and depth, thereby yielding a range of dimensional measurements in the results [31]. Piston in Fig. 2 is selected due to its intricate geometric dimensions, which require high precision to achieve low errors.

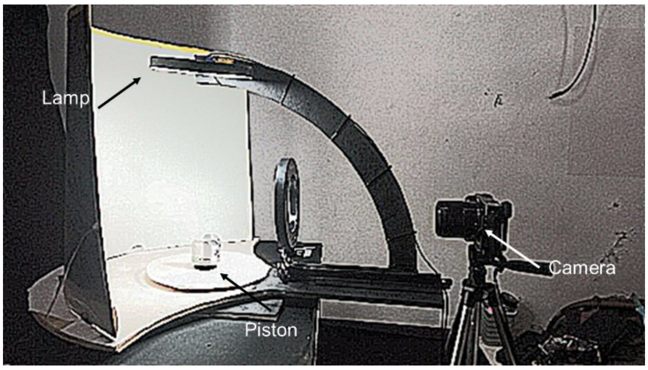


Fig. 2. Position of the object research

Moreover, photogrammetry is a method for acquiring 3D data on the form and dimensions of objects or environments by analyzing photographs [21,22,23]. This method involves analyzing traditional pictures or digital images to derive measurements and produce precise, intricate 3D representations [28]. The foundation of photogrammetry is triangulation, in which the spatial coordinates of points are determined by measuring the angles formed by lines extending to established reference points in multiple overlapping images

2.4 Camera settings

During the photo-capture process, several camera settings were used to ensure that the resulting images met the required specifications. The camera settings used in this research were adjusted based on the shooting environment, such as the lighting conditions in an enclosed space [29]. The Sony A6000 camera is configured manually: shutter speed 1/160 s, aperture f/1.8, ISO 400. The camera settings were adjusted to match the existing lighting conditions, enabling appropriate adjustments to ISO and aperture.

2.5 Camera calibration

Camera calibration plays a critical role in photogrammetric systems used for industrial applications, as measurement accuracy heavily depends on sensor quality and accurate modeling of the camera's internal orientation. Standard calibration models include parameters such as the 3D position of the perspective center in image space (principal distance and principal point), corrections for radial and decentering distortion, and adjustments for affine and shear within the sensor. These parameters are typically determined through a self-calibrating bundle adjustment using a network of convergent images captured from multiple stations. Comprehensive discussions of this topic can be found in [3]. Calibration becomes more challenging under specific conditions, such as: instability in camera geometry during image capture (e.g., due to gravitational effects); an insufficient number of images for self-calibration (e.g., in stereo online systems); unsuitable geometric configurations of the photos, making bundle adjustment with self-calibration infeasible (e.g., weak intersection angles or lack of orthogonal camera rotations around the optical axis); and insufficient calibration information provided by the object (e.g., lack of identifiable points or measurable distances).

Photogrammetric metrology systems often incorporate integrated bundle adjustment software, which may not always be accessible to standard users. Examples of such systems include Agisoft Metashape and Meshroom.

The camera calibration process uses features available in Agisoft Metashape. It employs the analytical computation of internal camera parameters via the Self-calibration bundle adjustment method, based on target points on the calibration plane [30]. In this research, a circular calibration plane with a diameter of 30 cm and a distance of 5 cm between target points was used, as depicted in Fig. 3. After photographing the calibration board, the photos were imported into Agisoft Metashape. Subsequently, the software was used to detect the distance between target points as 5 cm, as shown in Fig. 3. The results were compared with the software tolerance in the reference tolerance menu, with an error of 0.1 mm. The calibration results showed an average error of less than 0.01 mm, indicating successful calibration and suitability for the object-photography process.

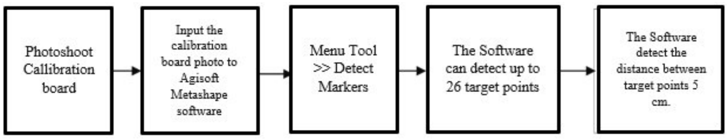


Fig. 3. Stages of the camera calibration process

2.6 Set up the photogrammetry studio

The photo studio setup includes configuring the environment for photography by arranging lighting, backdrops, and other essential elements to ensure optimal conditions for capturing high-quality images. This is carried out to create an environment that enhances the clarity, color accuracy, and overall visual appeal of the photographs. Essential elements such as lighting angles, background, and equipment placement play crucial roles in achieving the desired photographic results. Furthermore, the studio setup is a significant aspect of the overall photographic process, influencing the quality and effectiveness of the captured images in Fig. 4.

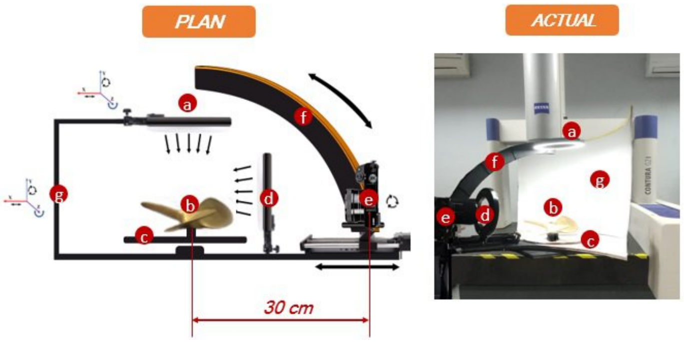


Fig. 4. Set up photogrammetry studio [27]

As shown in Fig. 3. Illustrates a well-organized setup for photographing objects in a controlled environment, showcasing a photo studio designed for precision and consistency. The studio includes:

- Lighting Configuration: Two strategically placed light sources; One in front of the camera, directly illuminating the object. One positioned above the object, providing overhead lighting to eliminate shadows and ensure uniform illumination. The lighting uses an LED Inbex Ring Light, which delivers a consistent brightness of 200 lux and is positioned at a 10 cm distance from the object to optimize lighting conditions.
- Object Positioning: The object (e.g., a piston in the image) is placed on a static table or stand, ensuring it remains stationary throughout the photography process.
- Rotational Lighting System: A 360° rotating lighting mechanism allows for precise control over the light angles, enabling consistent illumination for capturing high-quality images.
- Camera Setup: The camera is mounted on a tripod for stability. The tripod's adjustable height allows the photographer to capture images at three different levels, providing flexibility for various perspectives and details.
- Laptop Connection: The camera is connected to a laptop, which functions as a control system for capturing, viewing, and storing images. This integration ensures seamless workflow management and immediate evaluation of results.

In controlled environments where object photography requires precision and consistency, the setup of a photo studio becomes a critical factor in achieving desired results. The photo studio depicted in this example has been meticulously designed with dimensions of 55 cm × 45 cm × 55 cm, ensuring that it accommodates small to medium-sized objects. This studio setup enables systematic image capture, with a focus on eliminating shadows and maintaining uniform illumination across the object's surface. One of the most notable features of this photo studio is its lighting system, which has been carefully configured to provide even illumination from all sides. The studio is equipped with two primary lighting positions. The first light source is positioned directly in front of the camera, aimed at the object to ensure consistent frontal illumination. The second light source is placed above the object, providing overhead illumination. This dual-light arrangement minimizes shadows and enhances the visibility of fine details on the object's surface. Such a setup is crucial for applications that demand high-quality visual data, such as technical documentation, 3D modeling, or quality inspection. To achieve optimal lighting, the studio utilizes the LED Inbex Ring Light, a specialized lighting tool with a diameter of 16 cm. The LED ring light was selected for its ability to provide uniform illumination, reducing the risk of overexposure or uneven illumination. The light operates at an intensity of 200 lux, a level that ensures the object is sufficiently illuminated without creating harsh reflections or glare.

Furthermore, the light is positioned 10 cm from the object. This precise placement strikes a balance between brightness and shadow reduction, producing a soft, diffused light that effectively highlights the object's features. The static Table or stand within the studio provides a stable platform for the object being photographed. This ensures that the object remains stationary throughout the image acquisition process, maintaining a consistent position and orientation across all images. This is crucial for projects that require multiple images of the same object, such as photogrammetric modeling or documenting intricate details. A 360° rotating lighting mechanism enhances the studio's functionality. This feature allows the light source to rotate around the object, ensuring that all angles are evenly illuminated. This eliminates the need to manually reposition the object, reducing the risk of inconsistencies in the image series. The rotating light also facilitates capturing comprehensive views of the object, which is particularly useful for creating accurate 3D representations. The camera setup in this studio is equally well-thought-out. The camera is mounted on a tripod, which stabilizes the device and prevents motion blur during image capture. The tripod is designed with adjustable height settings, enabling the photographer to position the camera at three different levels. This flexibility allows the capture of images from multiple perspectives, accommodating objects of various shapes and sizes. It also ensures that critical details, such as intricate textures or small components, are photographed with clarity. To streamline the workflow, the camera is connected to a laptop, which serves as the central control system for the photography process. The computer is used to manage camera settings, trigger the shutter, and store the captured images.

This integration enables immediate image review, allowing the user to adjust lighting, focus, or composition as needed. The ability to view and evaluate images in real-time is particularly valuable in professional settings, where accuracy and efficiency are paramount.

The combination of these elements-strategic lighting, a stable object platform, a rotating illumination system, and an integrated camera setup-ensures that the studio is capable of producing high-quality images with consistent lighting and sharp detail. This level of precision is essential in various fields, including industrial inspections, product photography, and scientific research, where visual accuracy can significantly impact the outcomes. Beyond the technical aspects, the design of this photo studio also emphasizes user convenience. The compact dimensions make it suitable for small workspaces, while the straightforward setup ensures that users of varying levels of expertise can operate the equipment effectively. The inclusion of adjustable components, such as the tripod and rotating lighting system, further enhances its versatility, enabling it to adapt to diverse objects and photographic requirements. In practice, this setup is particularly beneficial for capturing images of objects with complex geometries or detailed textures. For example, in the case of the piston shown in the picture, the uniform lighting helps to highlight its surface finish, curvature, and other intricate features. The rotating light ensures that every piston area is evenly illuminated, providing a complete and accurate visual representation.

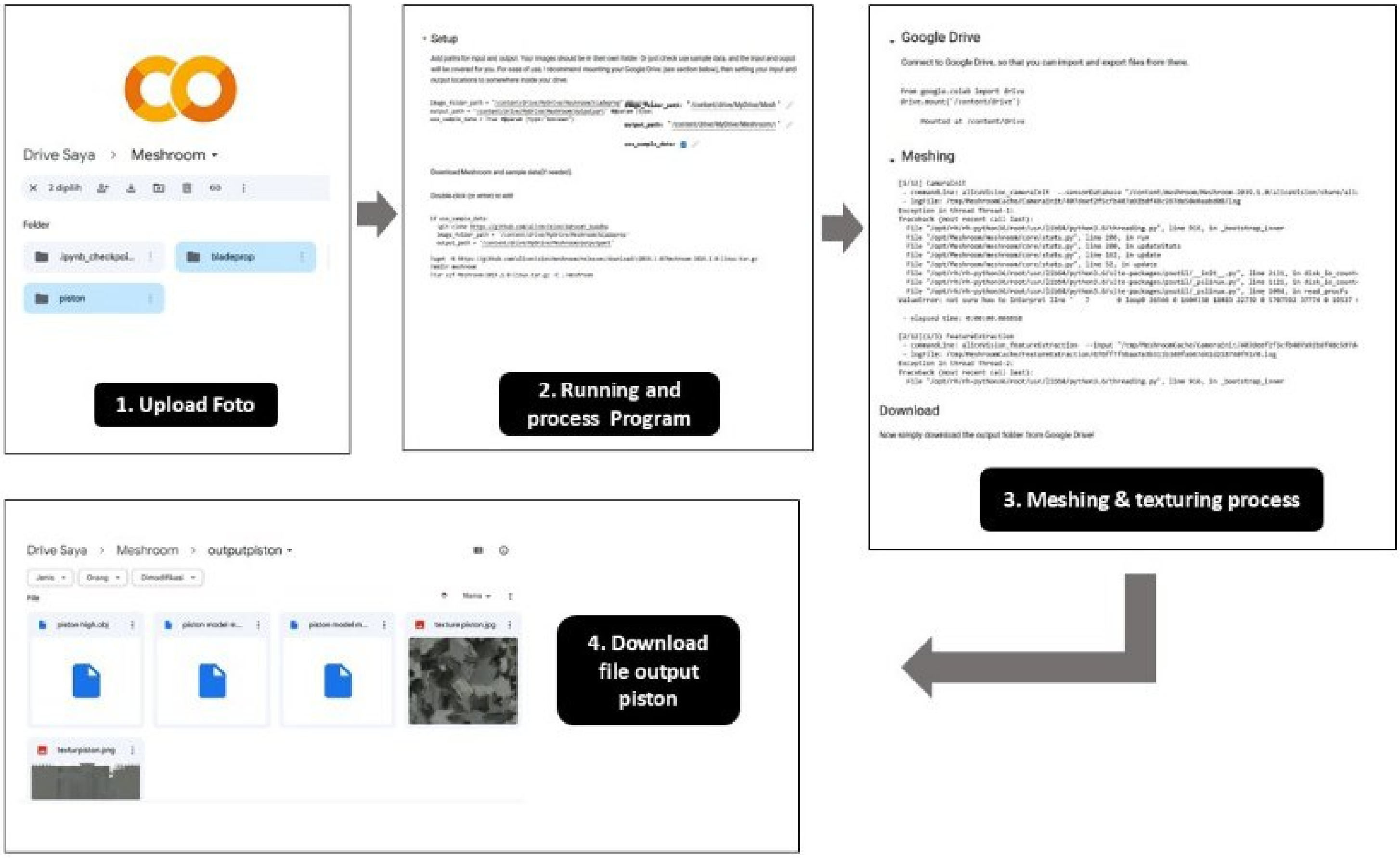
The choice of lighting equipment, specifically the LED Inbex Ring Light, also reflects a commitment to quality and reliability. The ring light's design ensures that the light is evenly distributed around the object, eliminating harsh shadows and creating a soft, professional-grade illumination. The intensity of 200 lux is carefully calibrated to suit most small to medium-sized objects, making it a versatile choice for a wide range of applications. Additionally, integrating a laptop as a control hub adds a layer of sophistication to the setup. By enabling real-time image capture and review, the computer reduces the need for repetitive adjustments, saving time and effort. This feature is handy for professionals working on tight deadlines or large-scale projects, where efficiency is key.

2.7 AI-assisted and conventional photogrammetry software

A conventional photogrammetric approach was employed, using two well-established software platforms, Agisoft Metashape and Meshroom, which are widely known for generating accurate 3D models via Structure-from-Motion (SfM) techniques. These tools follow a multistep, systematic process: aligning photographs from different angles to identify and match key features, followed by creating a sparse point cloud via triangulation to determine spatial positions. This cloud is then refined into a dense point cloud, capturing finer geometric details of the object's surface. Subsequently, the data is converted into a polygonal mesh comprising interconnected triangles to represent the object's three-dimensional form, with texture mapping applied in the final stage to enhance the model's visual realism. While both Metashape and Meshroom deliver robust outputs, they differ in terms of processing efficiency and usability. Metashape, a commercial software package, offers advanced automation and optimization tools suited to large datasets. In contrast, Meshroom, an open-source application that relies on the AliceVision libraries and a visual, node-based interface, offers greater flexibility but requires more manual adjustments.

Alongside these traditional tools, the study also explored a more contemporary AI-assisted 3D reconstruction method implemented on Google Colab™. This method used a Python environment integrated with machine learning libraries, including TensorFlow, OpenCV, NumPy, Matplotlib, and Open3D. The core innovation lies in the use of pre-trained Convolutional Neural Networks (CNNs) to automate key photogrammetric tasks, including feature detection, pose estimation, and depth map generation from monocular 2D images. This automation streamlines the reconstruction process by minimizing manual input and enabling neural networks to infer missing spatial data, thereby enhancing surface continuity. The workflow begins by uploading image datasets to Google Drive, authenticating with Colab™, and executing a Python script that processes the images into dense point clouds and mesh models. The outputs, stored on the Drive, enable efficient file management and scalability. The AI-assisted method demonstrated significant advantages in time efficiency, as shown in Fig. 9 of the study, requiring less time overall compared to Agisoft Metashape and Meshroom due to its fully automated pipeline. Despite generating denser point clouds (over 9.4 million points) and more mesh triangles (14.4 million), the AI models occasionally introduced visual noise, necessitating minor post-processing. Nonetheless, this approach's ability to perform on cloud infrastructure without high-end local hardware makes it especially valuable for researchers and small teams with limited computational resources. Its applicability extends to scenarios requiring rapid prototyping, large-scale object scanning, and digital preservation, reinforcing its potential as a transformative tool in RE and digital manufacturing workflows.

Fig. 5 illustrates a streamlined workflow for AI-assisted photogrammetry using Google Colab™, comprising four main steps that enable users to reconstruct 3D models efficiently without requiring high-performance local hardware. The process begins with uploading a series of photographs captured from multiple angles into a designated Google Drive folder (e.g., Meshroom > piston), which serves as the input dataset for 3D reconstruction. These images are then accessed via a Python program executed in the Google Colab™ environment, where libraries and software, such as Meshroom, are configured and linked to the Drive. The script initializes the reconstruction process, which comprises key stages: feature extraction, camera pose estimation, depth map generation, dense point cloud creation, meshing, and texture mapping. These automated tasks are executed through Meshroom's pipeline, with real-time outputs logged within the notebook interface.



Google Drive

Connect to Google Drive, so that you can import and export files from there.

```
from google.colab import drive
drive.mount('/content/drive')

    Mounted at /content/drive
```

Meshing

Download

Now simply download the output folder from Google Drive!

Fig. 5. Workflow for AI-assisted using Google Colab™

Once processing is complete, the resulting 3D model files (e.g., .obj, .mtl) and associated texture images are saved to an output folder in Google Drive (e.g., Meshroom > outputpiston) for easy download and further use in digital manufacturing, design validation, or visualization. This end-to-end method demonstrates the effectiveness of cloud-based tools in democratizing access to advanced 3D reconstruction techniques, making them suitable for rapid prototyping and RE applications across educational and industrial contexts.

2.8 Algorithms for 3D reconstruction

According to Fig. 6. The process of 3D modeling follows a systematic series of steps designed to create a detailed and accurate 3D representation. It begins with the crucial task of collecting images and objects that will serve as the model's foundation. Once the pictures have been gathered, the next step is to upload them to Google Drive, where they are organized in a single folder. This organization is critical to ensuring that data is easily accessible and efficiently processed. Google Drive serves as the storage platform, allowing seamless integration with Google Colab™ for further processing. The images stored in Google Drive are then accessed and processed in Google Colab™, a cloud-based platform that facilitates the modeling workflow. At this stage, the images are carefully rearranged and processed to create a point cloud. This point cloud serves as the fundamental framework for the 3D object, providing the basis for the final model. Point cloud generation is a key step in the process, as it defines the object's overall structure and spatial arrangement. To increase precision and detail in the model, polyline meshes are applied to the point cloud. These meshes play an essential role in enhancing the accuracy and visual clarity of the 3D representation.

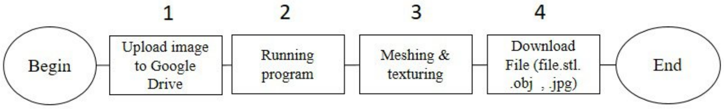


Fig. 6. The Google Colab™ standard workflow for 3D model reconstruction [27]

By incorporating polyline meshes, the model achieves sufficient refinement and detail to resemble the real-world object on which it is based closely. This step ensures that the final 3D model is both geometrically accurate and visually detailed, making it suitable for a wide range of applications, including RE, digital preservation, and scientific research. The entire process, from image collection to the application of polyline meshes, is designed to be efficient and user-friendly. By leveraging Google Drive and Google Colab™, the workflow eliminates the need for complex hardware setups or extensive manual intervention. Instead, the cloud-based tools streamline the process, making it accessible to users with varying levels of expertise. Additionally, integrating these tools enables scalability, allowing the processing of large datasets without significant delays or computational constraints.

According to Fig. 7, the 3D modeling workflow depicted in the diagram consists of six essential steps, forming a structured and detailed process to generate high-quality 3D models. The process begins with the addition of images, which are necessary for reconstructing the object in three dimensions. These images are collected and uploaded into the software, serving as the foundational input data. Proper selection of these images ensures the accuracy and quality of the resulting model. Once the photos have been added, the next step is to align them. This phase is critical because it establishes the spatial relationships among images by identifying and matching standard features. The alignment process lays the groundwork for a cohesive model by ensuring that all photos are properly oriented relative to one another. By accurately aligning the images, the process ensures consistency and prevents errors in subsequent stages. Following alignment, the software calculates the dense point cloud. This step is vital to constructing the 3D object framework, as it generates a dense point cloud representing the object's surface [32]. Each point in the cloud corresponds to a specific feature captured in the input images, forming the basis for detailed 3D reconstruction. The dense point cloud acts as a bridge between the raw image data and the final 3D model [33].

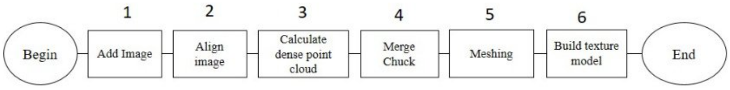


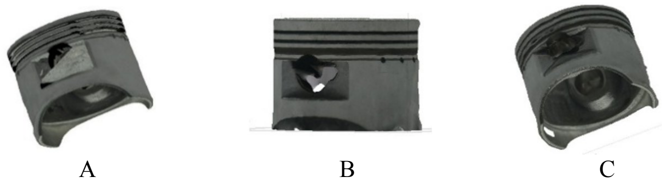
Fig. 7. Schematic workflow for 3D model reconstruction with software

The fourth step involves merging chunks. In cases where the 3D model comprises multiple sections or components, this phase integrates these components into a unified structure. The merging process ensures continuity and seamless transitions between different parts of the model, maintaining its geometric integrity. This step is crucial for complex objects or models constructed from large datasets. The fifth step, meshing, transforms the dense point cloud into a continuous surface. During this phase, the points are connected to form polygons, creating a mesh that outlines the object's shape. This step enhances the model's structural representation, enabling further refinement and the addition of surface details. The resulting mesh forms the core framework of the 3D object, providing a clear depiction of its geometry. Finally, the sixth step involves building the texture model. This phase applies detailed surface textures to the mesh, adding color and fine details to the object. Applying textures enhances the visual realism of the 3D model, making it more representative of the original object. By combining geometric accuracy with visual detail, this step completes the modeling process, producing a high-quality 3D representation.

3 Results and discussion

3.1 3D reconstruction process

Figs. 8 and 9 present various 3D reconstructions of the piston, demonstrating the exceptional quality achieved by the imaging system. The models are characterized by their true-to-life natural colors and high resolution, which enhance the clarity and detail of the resulting outputs. These results are made possible by an effective acquisition setup and a carefully planned 3D reconstruction process.



A B C

Fig. 8. Images of 3D model solids, object views of different SfM software

Fig. 9. Images of 3D model wireframe object views of different SfM software

The imaging and scanning parameters, such as the X-axis sliding distance, are tailored to match the object's size and structural complexity. For intricate objects such as pistons, which exhibit detailed, multifaceted geometries, a considerable X-axis sliding distance of 33 mm is employed. This enables the scanning system to cover the object and capture its minute details comprehensively. The images are saved in JPG format with a resolution of 2,240 x 3,360 pixels, ensuring high-quality visual data. Each image typically requires 500 KB to 1.5 MB of storage and is captured in approximately 4 seconds. To enhance image sharpness and depth of field, the system employs autofocus combined with focus stacking. This is configured using Method B (depth map) for rendering, with parameters including a radius of 8, a smoothing factor of 4, and a split-stack parameter aligned with the X-axis sliding distance. The images are stored in JPEG format with a quality setting of 100%, ensuring the preservation of visual detail. On average, the focus-stacking process takes approximately 0.22 seconds per image, underscoring the system's efficiency.

Once the images are captured and processed, the 3D model is constructed using Google Colab™, an online platform that facilitates advanced computational workflows. The reconstruction process follows a systematic sequence of steps:

- Uploading images of the object to Google Drive, where an output folder is created to store the meshing and texturing results automatically.
- Establishing a connection between the Google Colab™ program and the files in Google Drive, achieved through Python programming.
- Executing the program, which processes the input files to perform meshing and texturing operations automatically.
- Downloading the completed 3D mesh file to the designated output folder, ensuring seamless integration and accessibility.

The duration required to construct a 3D mesh model is influenced by the number of Extended Depth of Field (EDOF) images involved in the process. On average, the meshing phase takes between 40 to 60 minutes (Fig. 10), depending on the number of images and object complexity. To calculate the total time required to complete the 3D model, one must consider the cumulative time for image acquisition, focus stacking, and mesh construction. This holistic approach ensures that each phase of the process contributes to the model's overall quality. Using this methodology to build a 3D piston model offers several distinct advantages. First, it eliminates the need to reposition physical specimens during scanning. This not only reduces the risk of damaging delicate objects but also simplifies the workflow, making it more suitable for intricate or fragile specimens. Additionally, the system integrates synchronous imaging and EDOF calculations, enabling full automation of the entire process. This is particularly advantageous for large-scale RE projects, where efficiency and accuracy are paramount. The integration of AI-powered techniques further enhances the capabilities of this 3D reconstruction process. Specifically, a Python program running on Google Colab™ is used to manage and optimize the image acquisition and processing stages. This innovative use of AI enables the system to handle complex tasks with minimal human intervention, making it a suitable solution for industrial and scientific applications.

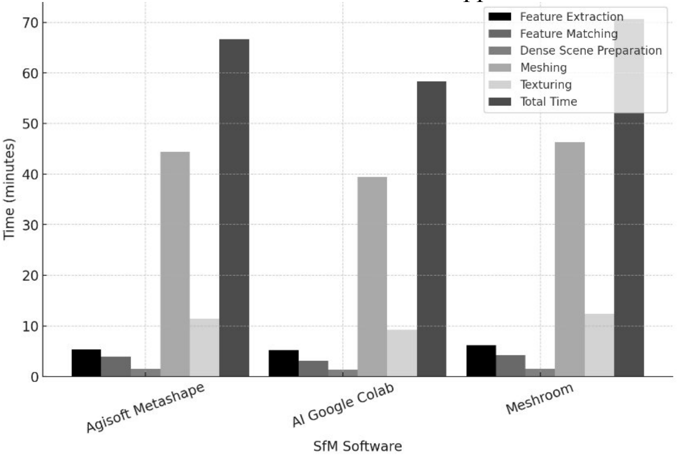


Fig. 10. Comparison of 3D reconstruction time

The focus stacking and photogrammetry techniques employed in this setup are particularly well-suited to capturing objects with significant depth. By combining multiple images captured at different focus planes, the system produces a composite image with EDOF, ensuring that all parts of the object are in sharp focus. This approach not only improves image quality but also enhances the accuracy of the 3D model. In practice, the photogrammetry studio scheme employed here can capture detailed and accurate representations of objects. The combination of high-resolution imaging, advanced focus stacking, and AI-driven 3D reconstruction ensures that the resulting models are both visually and structurally precise. This makes the system a valuable tool for a wide range of applications, from industrial design and manufacturing to scientific research and education. For example, in the case of a piston, the system's ability to capture intricate details and complex geometries is particularly beneficial. The use of a large X-axis sliding distance ensures that every part of the piston is thoroughly scanned, while the focus stacking process highlights its surface features and structural nuances. This level of detail is crucial for RE, where accurate digital models are needed to analyze and replicate physical objects.

The efficiency of the workflow is another key advantage of this system. By automating the acquisition, stacking, and reconstruction processes, the system minimizes the time and effort required to create high-quality 3D models. This is particularly important for large projects, where the ability to handle a high volume of images and objects is essential. Furthermore, the use of Google Colab™ for 3D reconstruction offers several practical benefits. As an online platform, Google Colab™ provides access to powerful computational resources, enabling users to process large datasets and complex models without the need for high-end local hardware. The integration with Google Drive also simplifies file management, making it easy to store, organize, and retrieve images and model files. The Python-based program used in this setup is another highlight of the system. By leveraging the flexibility and power of Python, the program can be easily customized to meet specific project requirements. This makes it a versatile tool for a wide range of applications, from academic research to industrial design. Method described here represents a state-of-the-art approach to 3D modeling, combining advanced imaging techniques, AI-driven processing, and a streamlined workflow. By eliminating the need for manual repositioning and integrating automation at every stage, the system ensures that even complex objects like pistons can be accurately and efficiently reconstructed in 3D. This not only enhances the quality and precision of the models but also makes the process more accessible and scalable for a variety of applications.

3.2 3D model evaluation

Fig. 8 shows a present a visual representation of a 3D solid model of a piston, displaying various perspectives of the object. This illustration emphasizes the complex geometry of the piston, reconstructed without the application of textures. The absence of texture allows for a focused analysis of the model’s structural accuracy, particularly in evaluating how well the scanning system captured the intricate cylindrical form, grooves, and cutouts. The reconstruction primarily reflects the effectiveness of the photogrammetry-based approach in preserving the physical characteristics of the piston, including its ring grooves, skirt contours, and internal cavity. The modeling process demonstrates the system's capability to capture the precise geometry of the piston’s surface features, which are critical for its performance in an internal combustion engine. The piston head, ring lands, and skirt sections are essential components that influence the efficiency of combustion and mechanical motion. Since pistons interact with extreme temperatures and pressures, achieving high accuracy in their 3D modeling is crucial for wear analysis, RE, and manufacturing applications. Despite the system’s overall success, certain limitations become evident when assessing the finer structural details, particularly around the oil control ring grooves and skirt edges. These areas, due to their small dimensions and intricate designs, pose a challenge for accurate reconstruction. Minor distortions or missing details in these regions indicate opportunities to improve the scanning methodology. These discrepancies may result from various factors, including insufficient image resolution, suboptimal lighting conditions, or the limitations of the photogrammetry software in interpolating fine geometries [34].

One of the key factors influencing the accuracy of the 3D reconstruction is the number of EDOF images used during scanning. The quantity of images directly affects the final quality of the solid model. A greater number of EDOF images generally improves detail resolution and geometric accuracy by providing additional data points, enabling the software to construct a more precise 3D wireframe representation. Conversely, fewer images can yield less accurate models, with visible errors and missing details, particularly in complex regions such as the piston crown and cooling channels. The success of the reconstruction also depends on the alignment and overlap of the captured images. Proper alignment ensures that all piston components are accurately represented in the final model. Misalignment or insufficient image overlap can cause gaps or distortions in the reconstruction. Because pistons exhibit cylindrical, symmetric features, achieving optimal image alignment and coverage is critical for capturing the full contours and dimensional details of the component.

To enhance reconstruction accuracy, a structured workflow was implemented, including precise control over the X-axis sliding distance during image acquisition. The X-axis sliding distance determines the spacing between successive image captures, thereby influencing image overlap. A well-adjusted sliding distance ensures that all sections of the piston are sufficiently covered, minimizing the risk of missing fine features. Lighting conditions also play a crucial role in the quality of the reconstruction. Consistent, uniform lighting reduces shadows and reflections, ensuring more reliable capture of surface details. Uneven lighting can introduce artifacts or distortions, particularly in areas with high reflectivity, such as polished piston surfaces. In this study, the lighting setup was optimized to ensure uniform illumination, thereby enabling the system to reconstruct the piston's intricate details accurately. The reconstruction process further benefited from the application of advanced photogrammetry techniques. Photogrammetry, which reconstructs 3D models from 2D images, relies on precise feature matching across multiple images to generate an accurate 3D structure.

In this case, the photogrammetry software effectively reconstructed the piston's overall shape and features, despite challenges in capturing more minor, intricate details, such as the ring-groove edges and oil holes. Variations in reconstruction quality across different regions of the piston highlight both the strengths and limitations of the scanning system. While the system performed well in capturing the general geometry, including the cylindrical shape and major structural features, it encountered challenges in modeling finer details such as small internal cavities and intricate grooves. These observations suggest that further refinement in scanning techniques and software algorithms could enhance the accuracy of piston 3D modeling.

Several improvements can be implemented to optimize the reconstruction process. One of the most effective solutions is the use of higher-resolution images, which provide more detailed data and allow the software to capture small geometric features with greater precision. Additionally, refining the focus-stacking technique could enhance depth of field, ensuring that all regions of the piston are captured in sharp detail. This is particularly important for objects with varying depths, such as pistons with complex internal cavities and multiple ring grooves. Another key area for improvement is the optimization of the photogrammetry software's algorithms. Implementing machine learning or AI-based techniques could improve the software's ability to interpolate missing details, correct distortions, and refine delicate structures. These advanced technologies could also enhance the reconstruction of complex, reflective surfaces, which often pose challenges in traditional SfM-based 3D modeling.

Fig. 8 shows and illustrates the wireframe visualizations of a 3D model generated using three different SfM software tools: Agisoft Metashape (A), AI Google Colab™ (B), and Meshroom (C). Each wireframe represents the reconstructed 3D object using distinct algorithms and processing techniques, highlighting the variations in output quality and structure among these tools. SfM is a computer vision technique that reconstructs 3D models from a set of 2D images acquired from multiple viewpoints. The process involves feature detection and matching, camera pose estimation, and both sparse and dense reconstruction to build a 3D point cloud and generate a mesh.

Different SfM software packages employ distinct algorithms, resulting in differences in the quality, resolution, and overall appearance of the final 3D model. Agisoft Metashape, depicted in image (A), is a widely used commercial software known for producing high-quality 3D models. The wireframe depicts a smooth, well-formed mesh with fine detail, effectively capturing the object's geometry. Its strengths lie in delivering detailed texture mapping and efficient processing, but it requires a paid license, which can be a barrier for casual users. Image (B) showcases a model generated using AI-based SfM processing in Google Colab™. Unlike traditional SfM tools, this approach leverages cloud-based deep learning techniques for 3D reconstruction. While the model retains significant details, it appears rougher and less structured than the output from Agisoft Metashape, possibly due to estimation errors inherent in AI methods. Despite these challenges, Google Colab™ provides substantial computational power without requiring a high-performance local machine, making it accessible for research and academic purposes. Meshroom, illustrated in image (C), is an open-source SfM software developed by AliceVision. It is popular for being free while providing robust photogrammetry capabilities. The wireframe exhibits a complex triangulation pattern, though it appears less smooth and contains incomplete areas compared to the other software. Meshroom's advantages include its open-source nature, GPU-accelerated processing, and detailed control over the reconstruction pipeline. However, it may produce less polished outputs and require high-quality images for optimal results. The analysis and comparison of different SfM software tools for reconstructing 3D models provide valuable insights into their performance and suitability for various applications. Specifically, as shown in Table 1, Agisoft Metashape consistently delivers superior results with fewer errors when compared to alternative software such as AI Google Colab™ and Meshroom. This distinction is evident in the reconstruction of a 3D piston model, where Metashape demonstrates higher-definition outputs, more precise details, more natural color reproduction, and smoother textures. As shown in Figs. 8 and 9, illustrate this comparison vividly, emphasizing Metashape's capability to produce models with exceptional visual and geometric quality. The output from Metashape outshines that of AI Google Colab™ and Meshroom, which often generate noisier point clouds and fail to maintain a refined level of detail. Despite these limitations, AI Google Colab™'s results are notable, as its dense cloud and mesh models approach the quality of Metashape's output, indicating its potential as an alternative software for RE tasks.

Table 1. Specifications comparison of different SfM software to reconstruct 3D piston model

SfM software	Arrange images	Dense cloud (number of points)	Mesh model (number of triangles)	Export model
Agisoft Metashape (Version 1.7.0)	206	4,312,144	376,621	.obj
AI Google Colab™	206	9,425,935	14,434,422	.obj
Meshroom (Version 2021.1.0)	206	256,341	525,224	.obj

Agisoft Metashape's ability to produce visually accurate, geometrically refined 3D models derives from its advanced algorithms and robust processing capabilities. In the context of 3D piston model reconstruction, as illustrated in Fig. 11, Metashape achieves a balanced trade-off between model complexity and quality. The dense cloud generated by Metashape contains approximately 4,312,144 points, while the corresponding mesh model comprises 376,621 triangles. These figures highlight the software's efficiency in processing and structuring data, ensuring a high level of detail without overburdening computational resources. Furthermore, Fig. 10. illustrates how Metashape maintains its output quality across different orientations of the piston model, underscoring its versatility and reliability in handling complex geometries. The models produced by Metashape exhibit smooth textures, natural colors, and minimal visual noise, making it the preferred choice for applications requiring precision and realism, such as RE and digital preservation.


A B C

Fig. 11. Images of 3D model texturing object views of different SfM software a. Agisoft Metashape, b. AI Google Colab™, and c. Meshroom

In contrast, AI Google Colab™, while offering impressive computational power and scalability, produces results that, though close to Metashape in quality, are hindered by certain limitations. As noted in Table 1, AI Google Colab™ generates a dense cloud with approximately 9,425,935 points, significantly higher than Metashape's output. The corresponding mesh model, comprising 14,434,422 triangles, demonstrates the software's ability to process dense datasets and generate highly detailed 3D models. However, this level of detail comes at a cost, as the resulting point clouds often exhibit noise and irregularities that degrade the model's visual and geometric quality. Fig. 11 illustrate these shortcomings, showing that while AI Google Colab™'s reconstructions are detailed, they lack the refinement and smoothness characteristic of Metashape's outputs. Nonetheless, the software's performance demonstrates significant promise, particularly in applications where processing time and scalability are critical factors. As indicated in Table 1, AI Google Colab™ exhibits the shortest cumulative processing time, making it a practical choice for time-sensitive projects or preliminary stages of RE.

Meshroom, an open-source photogrammetry software, occupies a different niche within the spectrum of SfM tools. Its accessibility and ease of use make it an attractive option for users with limited resources or those seeking a cost-effective solution for basic 3D reconstruction tasks. However, as illustrated in Table 1, Meshroom's output lags behind that of both Metashape and AI Google Colab™ in terms of density and detail. The dense cloud produced by Meshroom contains only 256,341 points, while the corresponding mesh model comprises 525,224 triangles. Fig. 10 further emphasize this point, showing that Meshroom's outputs are characterized by rough textures, less natural color reproduction, and a general lack of refinement. Despite these limitations, Meshroom remains a valuable tool for educational purposes, exploratory projects, or situations where high fidelity is not a primary requirement.

The findings from Table 1 and Fig. 10 underscore the importance of selecting the appropriate SfM software based on the specific requirements of the task at hand. For applications requiring high precision and visual accuracy, Agisoft Metashape is the clear choice, offering superior results with minimal errors. Its ability to produce high-quality 3D models with balanced complexity and computational efficiency makes it particularly well-suited for RE processes, where capturing fine object details is critical. In contrast, AI Google Colab™, while less refined in its outputs, provides a viable alternative for tasks that prioritize processing speed and scalability over visual quality. Its ability to handle large datasets efficiently positions it as a strong contender in scenarios where time constraints or resource limitations are significant considerations. Meshroom, though limited in its output quality, offers a practical solution for users seeking an accessible and cost-effective option for basic 3D reconstruction tasks. RE, which involves reconstructing physical objects into digital models, relies heavily on SfM software to capture intricate details and reproduce them accurately in a virtual environment. The results presented in Table 1 highlight the potential of these software tools to meet the diverse demands of this field. Agisoft Metashape's advanced processing algorithms enable it to achieve a level of detail and accuracy essential for RE applications, ensuring that reconstructed models faithfully represent the original objects. AI Google Colab™, with its dense point clouds and detailed mesh models, also shows promise in this domain, particularly for projects that can tolerate a degree of noise in exchange for faster processing times. Meshroom, while less suitable for high-precision tasks, may still find utility in exploratory or educational contexts, where the focus is on accessibility and ease of use rather than accuracy.

4 Conclusions

In conclusion, this research demonstrated the effectiveness of various SfM software in reconstructing high-quality 3D models, using a piston as the case object. Among the three tested tools, Agisoft Metashape produced the most refined results, exhibiting superior visual and geometric quality, fewer errors, smoother textures, and more precise surface details. However, the time analysis presented in Table 1 and Fig. 9 indicates that the AI-based method using Google Colab™ had the shortest total processing time, making it particularly suitable for time-sensitive applications in RE and digital manufacturing.

Although Agisoft Metashape produced the most visually accurate models, AI Google Colab™ generated a denser point cloud (9.4 million points vs. 4.3 million in Metashape) and a significantly higher number of mesh triangles, reflecting its potential to handle large datasets. This suggests that Google Colab™, despite some noise and irregularities, can serve as a viable alternative, particularly when computational resources are limited and rapid results are required. The integration of Python-based automation in Google Colab™ and the use of synchronized imaging with EDOF further contributed to workflow efficiency. Therefore, while Metashape remains the top choice for detailed reconstructions, AI-assisted approaches offer promising trade-offs between speed and model complexity for scalable RE processes.

Acknowledgments

The study was funded by the LPPM, Diponegoro University, under grant number 583/UN7.D.2/TU/III/2025, and by the LPDP/Kedaireka grants 33/IV/KS/06/2022 & 505/UN7.D2/KS/VI/2022.

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