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Original research article

Non-Scanning Acquisition Technique for Extracting Small Depth Difference on the Area of Interest

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ABSTRACT

The guidelines for selecting the appropriate surface acquisition method are created for capturing the geometric shape of small objects (less than 5 cm height) that contains minor details such as small depth difference on the area of interest. Scanning (3D laser scanner) and non-scanning (a mobile phone camera) techniques were applied in this study. The results are compared using both qualitative and quantitative measurements. The non-scanning technique by a mobile phone camera is almost 80 times less expensive than the 3D laser scan while generating similar 3D models with acceptable accuracy within 1.5 mm of the master object and within 1 mm error between the two methods. The average total time used in the non-scanning is less than half of the scanning one. Detail of small depth differences on the area of interest is better captured by non-scanning one with the application of the proposed guidelines. General capabilities and limitations of both techniques, such as the object surface types, color, surface preparation and symmetry that can affect the resulting 3D model of both acquisition methods are also discussed and tabulated.

Keywords: Non-scanning technique; Optical data acquisition; Reverse engineer (RE); Scanning technique; Surface reconstruction

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1. Introduction

Reverse engineering (RE) is the technology that allows a 3D CAD model to be constructed quickly and directly from an existing object [1-3]. It is also known as back engineering and is one of many crucial components required for concept development of products. Fig. 1 shows a diagram for concept development process which involves RE, voice of customer (VoCs), and Customer requirement with brand personality. RE consists of three main steps which are data acquisition, surface reconstruction, and surface fitting [4].

The result of the data acquisition will be constructed as a surface consisting of triangular facets during surface reconstruction, and will be formed in a virtual model in the surface fitting step. The accuracy of the final 3D model depends upon the pattern of the point cloud data which represents the geometric shapes of the master object. Applying the appropriate data acquisition method can help the design engineer to reduce some errors and time spent in modifying and correcting the constructed surfaces.

Data acquisition methods can be separated into contact and non-contact types [5]. Contact methods use a direct touch between the probe and the surface of the objects. The coordinated measuring machine (CMMs), and mechanic or robot arm with a touch probe sensing device are the two most popular types of the contact technique [6]. On the other hand, non-contact methods collect the data without touching the surface of the objects. The non-contact techniques can be divided into transmissive [7] and reflective [8]. The reflective technique can be further divided into optical and non-optical. The optical techniques are the focus of this research. Optical techniques are categorized into scanning and non-scanning.

The scanning technique often uses a 3D scanner to capture the surface of the object via point, stripe, or area sensors [9]. Early 3D scanners that were used to capture human head and body were large, expensive and also required an extensive amount of calibration time. Nowadays, hand-held 3D laser scanners offer a more compact, faster scanning solution [10]. However, the price of the equipment and maintenance are still posing a barrier to incorporate 3D scanning into small-scaled product design companies and the hobbyist market. An alternative approach of using Automated Selective Acquisition System (ASAS) was introduced [11] having substantial accuracy at considerably lower price than 3D laser scanners. ASAS requires set-up time with a fixed displacement sensor and a turntable.

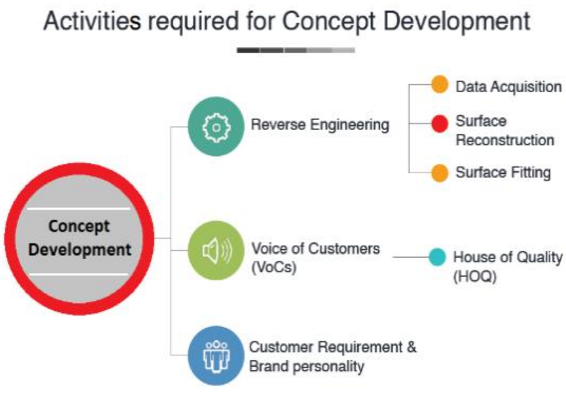


Fig. 1. Concept Development Process with RE.

A non-scanning technique called photogrammetry was introduced to create a 3D model from the merging of multiple images. Due to the image matching algorithm behind the photogrammetry, the color contrast of the object is used as matching reference during the merging process whereas the 3D laser scanner often needs referencing stickers placed on the object body. Therefore, for colorful, distinctive feature objects, the non-scanning technique requires less acquisition time and is more suitable for obtaining the model.

With the rapid technological advancement of mobile camera resolution, along with the ability to auto-focus [12], the use of mobile cameras in 3D scanning applications has the potential to offer a more compact and inexpensive alternative to 3D laser scanners. The in-plane and depth accuracy of mobile phone cameras were found to be acceptable after calibration. Several software programs [14-15] were developed to aid in the 3D surface reconstruction process with a mobile phone. A notable photogrammetry program is *Autodesk 123Dcatch* [15]. However, the acquired accuracy has been said to be distorted, especially for complicated models with many small features. Therefore, the use of non-scanning mobile photogrammetry was limited to relatively large models so that the distortion and errors became negligible.

This research proposes a guideline for an accurate 3D model creation process of small models (less than 5 cm height) using a mobile phone camera (iPhone). The models are chosen to have small details that are normally difficult to capture using 3D laser scan such as minor slots, curvatures and undercuts. Fig. 2 shows the area of research interest within the scope of data acquisition techniques.

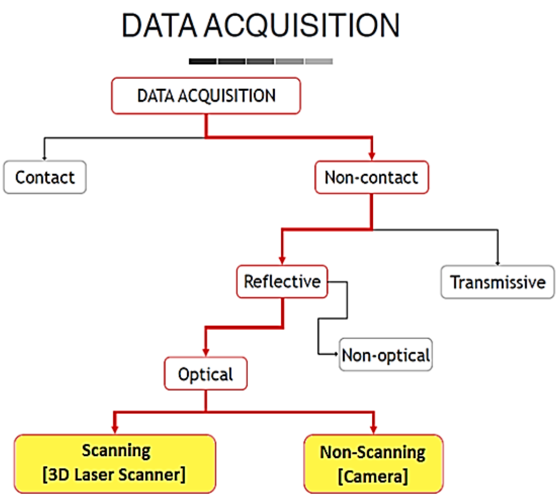


Fig. 2. Research areas - scanning and non-scanning techniques.

Scanning technique by 3D laser scanner and Non-scanning technique by mobile phone camera are considered. First the accuracy of both techniques will be compared with simple master reference models created from CAD for calibration. Then the performance of the proposed non-scanning technique is compared to a full 3D laser scanner with a set of small and complicated models.

2. Research background

2.1 Research objective

To specify the characteristics and important parameters of the acquisition devices required for detecting and capturing surface detail of the object. To make a comparison of the reconstruction phase between the scanning and non-scanning acquisition techniques. To consider and analyze the advantages and disadvantage of these two processes when scanning small objects. Proposed in this research is a guideline for non-scanning technique using mobile phone photogrammetry to create relatively accurate model for small and complicated objects.

2.2 Reverse engineering

Reverse Engineering (RE) is the technology that allows a 3D CAD model to be constructed quickly and directly from the existing object. RE consist of three main steps: data acquisition, surface reconstruction, and surface fitting.

2.3 Scanning (3D laser scanner)

The National Research Council of Canada was among the first institutes to develop the triangulation based laser scanning technology in 1978 [16]. Laser scanning uses the reflection of the laser beam to record arrays of points on the object surface. The scanner is typically hand-held and therefore requires background preparation and surface preparation prior to the scan [17]. The background preparation involves using the predetermined patterns, such as stickers, as the reference points in order to enhance the combination of each scanning region. The surface preparation involves using a powder spray to coat transparent, fluorescent and shiny surfaces, reducing error in data collection during the scan. Factors influencing the quality of scanning results are reference points, light intensity, and type of the object surfaces.

2.4 Non-scanning (mobile camera)

The non-scanning data acquisition technique uses a digital camera to capture an image or snapshot of the entire surface view. Next, the captured images are processed and combined to create a 3D model of the object surface. The noise and distortion of the images are kept within an acceptable level using image processing techniques [17-21].

Using the camera to capture the image is simple and user-friendly. However, the difficulty of the non-scanning technique lies in the surface registration and 3D reconstruction steps because there are no clear reference points to merge multiple images from the snapshots. Therefore, the processing time and the model accuracy generally depend on the image quality and the traces or clues of references.

Factors influencing the quality of non-scanning results are type of camera, focus length, contrast, aperture size, shutter speed, resolution, and type of object.

2.5 Surface reconstruction and fitting

According to the scanning technique, "*VXelement*" software is used to scan an object and generate a 3D CAD model with a selected resolution. After the CAD model has been constructed, a reconstruction process provides a better surface of the model by deleting unwanted points and enclosing the bottom part. To complete those steps mentioned earlier, "*Geomagic Studio*" software is being used. The last reverse engineering software used for this technique is "*CloudCompare*" which provides a mean distance between points which can be used to indicate an error in the object.

For the non-scanning technique, after capturing multiple view photographs of the object, a cloud-based program called "*123D Catch*" [15] is used to create a digital mesh of the surface model. The detailed description of the algorithms and procedures of image processing of the software are not publicly available. However, processing undoubtedly involves the use of Structure-from-Motion (SfM) method [22] after detection of common image feature with algorithm similar to Sift image matching algorithm [23]. The sift-based image matching process has three main steps: Sift feature extraction, feature matching, and homographic transformation. The feature extraction step detects common stable feature points from both the reference and the sensed image that are invariant to scaling and rotation by the Sift method described in [24]. Then, feature points that represent the same point on the object are matched in the feature matching step. Lastly, homographic transformation is applied to both images using the relative image coordinates known from the feature points pairs. The cycle of these three steps is repeatedly done through a series of multiple images to create the final 3D model of the object.

3. Method of Approach

In this research, a quantitative measure of performance was conducted for both scanning and non-scanning data acquisition techniques by comparing the acquired surfaces with the master model. Fig. 3 illustrates the general workflow of this research.

Firstly, the geometric shapes of the existing object are extracted and revealed through point cloud data that will be used for constructing triangular facets in the subsequent process. The surface reconstruction process starts mapping the points according to the references and creates a net of triangles which covers a given surface partly or totally. Then, the surfaces are merged together with a process called surface fitting to generate the final 3D model of the master object. The acquired 3D model is then compared to the CAD model of the object sharing the same center of reference.

The Euclidean distance [25] between the nearest neighbor points can be computed by Eq. (1), with a program called "*CloudCompare*" [26].

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (1)$$

where x_1, y_1, z_1 and x_2, y_2, z_2 are the Cartesian coordinates describing nearest neighbor points, respectively.

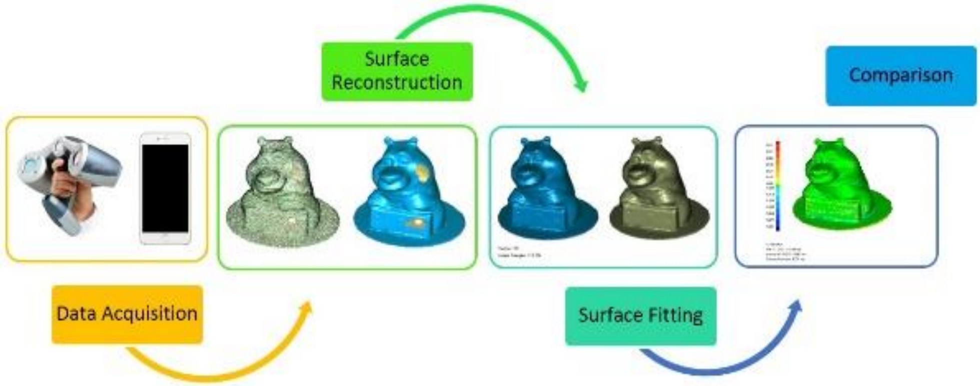


Fig.3. Overall process of the research.

In order to compare the performance between the scanning and non-scanning techniques, several types of objects will be used as the master pieces. The choice of the master object for performance assessment should have possible difficulties in acquisition such as undercut, shiny surfaces and curved edges.

Small objects (less than 5 cm high) will be used to test the accuracy of the data acquisition techniques. Fig. 4 and Fig. 5 illustrate the overall process of both data acquisition methods.

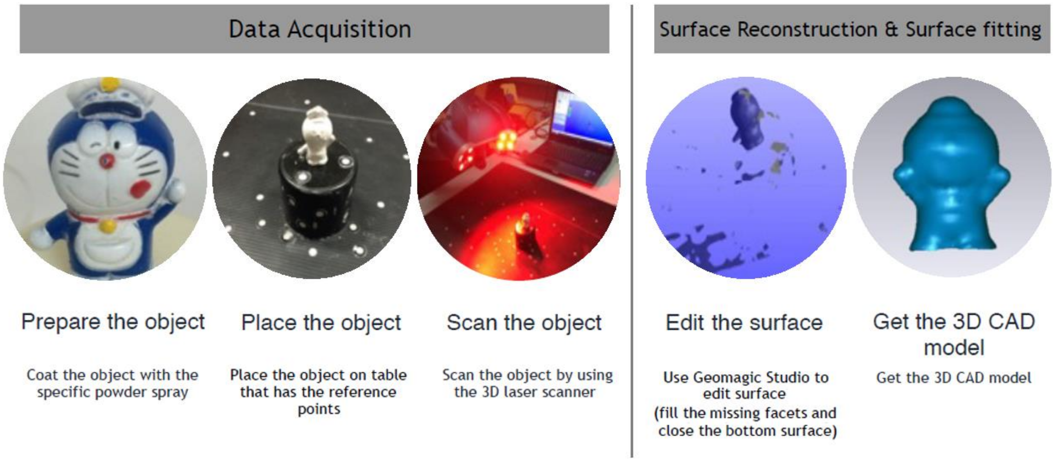


Fig. 4. Scanning Method using 3D laser scan.

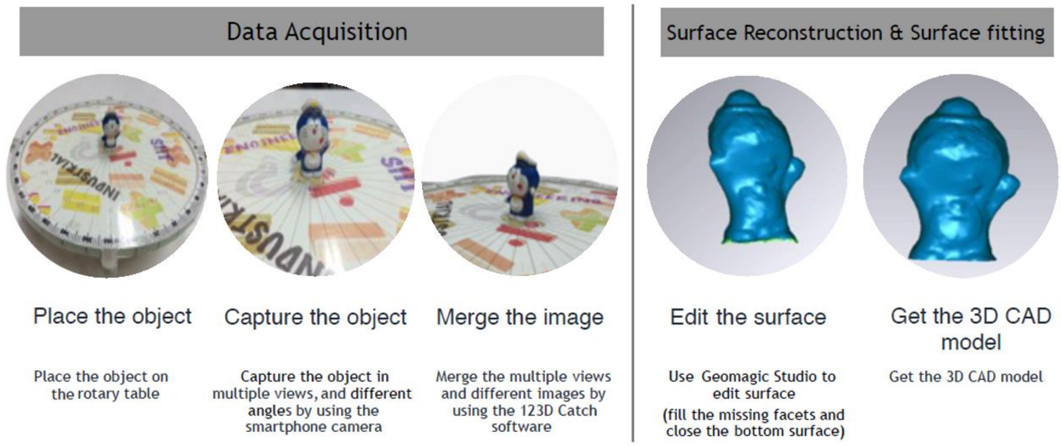


Fig. 5. Non-scanning Method using phone camera.

3.1 Scanning data acquisition method

A 3D laser scanner [10] was used with the following specification as shown in Fig. 6.

- *Model:* The REV scan™serial 11191
- *Laser type*: Laser Class II (eye-safe)
- *Resolution in z axis*: 0.1 mm (0.004 in)
- *Accuracy*: Up to 50 µm (0.002 in)
- *Volumetric Accuracy:* 20µm + 0.2 L/1000

Firstly, shiny surfaces of the object are powder- coated in the surface preparation step. Next, the object is placed on a reference table. Small objects with height less than 5 cm have to be placed on top of a cylinder with attached references. After the object is placed on the reference table, the object is scanned using *"VXelement*" software with its scanning resolution set as 1 mm. The 3D CAD Model that generated from this software contains noise and unwanted points. After the data acquisition step has been completed, the 3D CAD model will be passed on to the surface reconstruction and surface fitting steps. For this step, *"Geomagic Studio*" software will be used to fix, decorate, and repair any particular CAD model. The missing facets and filling of the bottom surfaces are done during this step. The 3D CAD model of the object is completed after this software has been used.

Fig. 6. 3D laser scanner application.

3.2 Non-scanning data acquisition method

A mobile phone camera was used in the experiment. The camera was chosen because it is portable and easy to find.

- *Camera type:* iPhone 6 plus
- *Resolution*: 8 Megapixel
- *Aperture size*: f/2.2, 29 mm (standard)
- *Sensor size*: 1/3", 1.5µm
- *Optical Image Stabilization (OIS)*
- *Phase Detection Auto Focus (PDAF)*

First, the object is placed on the reference table. Then the hand-held camera captures 15 to 40 images [27] of the object from various angles. The images are then merged by using "*123D Catch*" RE software to produce a set of surfaces representing the 3D model. Finally, "*Geomagic Studio*" is used to edit and trim the noise and unwanted surfaces during the surface reconstruction and surface fitting process.

The key concept of the non-scanning technique is merging common points of every image taken. The lens distortion and the number of different image views have the direct effects on the merging results. As the object of interest or common points appearing on every frame might be distorted or deformed, the image registration process used to combine surfaces and form a virtual model is quite challenging.

In order to easily extract the object out of the background, the colors of the background and the object are recommended to be in different tones, and various artworks or printings are required on the object's surface and background for use as references which are very important components for the surface registration process.

Fig. 7 presents the layout of the camera-based acquisition technique (non-scanning) where the different views of the object are taken.

Fig. 7. Taking images from different views.

- *Layout*: Object on the platform with reference patterns
- *Imaging*: Take images from different directions around the object.
- *Distance between object and camera*: 20~30 cm.
- *Capturing angle*: 30~60 degrees.
- *Recommendations*: The key point of this application is about "the auto-focus function of the mobile phone camera" to keep the object of interest in focus even if there are some changes in distance between camera and object. The designer should try to maintain the same camera distance between the two consecutive images. Camera angle can be changed to capture undercut or hidden feature(s) of the object.

3.3 Comparison approach

After the complete 3D models have been obtained, "*CloudCompare*" software will be applied. This software is used to compute the mean distance between two objects set at the same center.

4. Result and Discussion

In this research, the comparison between the 3D models can be separated into two sections: Comparison between the referencing 3D CAD model and the acquired 3D models, and comparison between the 3D models acquired from both scanning and non-scanning approaches.

Seven models (i.e., two cylinder parts, and five spherical-shaped parts with added features) and their specific geometric details are explained in the following sections.

4.1 Comparison with reference 3D CAD

The acquired 3D models of master objects from both scanning and non-scanning methods were compared with the reference model drawn by CAD software. Table 1 lists two cylindrical-shaped master models: *manufactured part*, and *consumer can with a lid*. These objects were chosen because they contained acquisition difficulties such as undercuts, curved edges, and shiny surfaces while being simple enough for the reference CAD model to be accurately drawn. This made them suitable for the accuracy assessment of the data acquisition methods. The comparisons between the acquired models and their reference CAD models were then conducted as shown in Fig 8.

Table 1. List of master models used in *Part I* of the experiment.

No.	Picture	Part Descriptions
1		**Model Name:** *Manufactured part* **Shape:** *Cylinder with rectangle slot* **Material:** *Brass*
2		**Model Name:** *Consumer can* **Shape:** *Cylindrical body with cap* **Material:** *Flat white plastic*

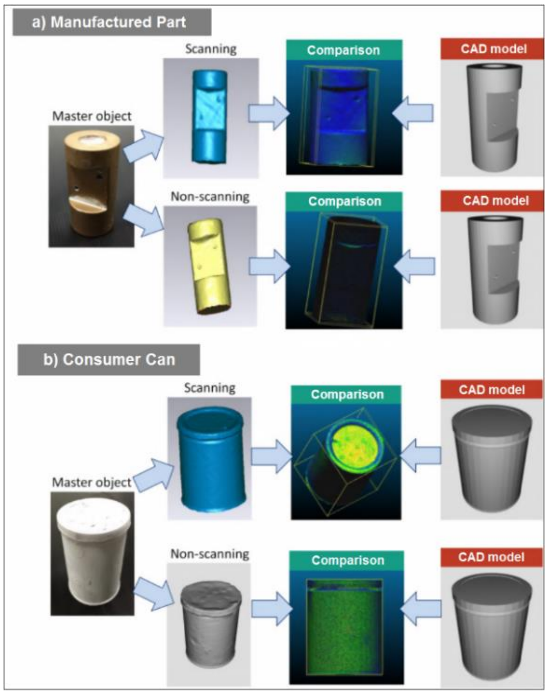


Fig. 8. Comparison between acquired models

Table 2 reports the mean distance error of the comparison. The values were calculated from three trials for each case. The results suggest that both the scanning and non-scanning methods were able to achieve less than 1.5 mm mean distance error. Considering the small-sized object of 5-cm height, the mean distance error amounted to less than 2% for the 3D laser scanning and less than 3% for the camera in the non-scanning method. Therefore, it could be said that both acquisition techniques were sufficiently accurate when compared to the master CAD model.

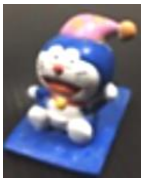
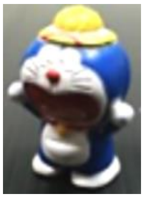
Table 2. Mean distance error with CAD references.

Acquisition Methods	Mean distance error [mm]			
	Manufactured Part		Consumer Can	
3D Laser Scan	0.77	SD 0.82	0.60	SD 0.43
Camera	1.01	SD 0.84	1.29	SD 0.83

4.2 Comparison between scanning and non-scanning methods

The second part of the experiment compared the final 3D models obtained from both methods. Five models of "*Doraemon*" with different postures were used for the comparison. The models were chosen because they contain complex shapes; that is the big spherical head, and two small spherical hands attached to cylindrical arms. Minor details such as facial expressions and clothing that contain small depth differences are also present. These features might have the direct effects on the acquired surface quality and thus are suitable choices for the comparison. A summary of the models is listed in Table 3. The results show that the round shape in the model presents some difficulties of laser reflection during the scanning process as shown in Fig. 9. The 3D laser scanner cannot preserve small differences in depth of the two connected-regions. As a result, from the sample model A, the area of the eyes was merged and blended to the head and face zones.

Table 3. List of sample models used in *Part II* of the experiment.

No.	Picture	Part Descriptions	Model Code
1		**Model name:** China **Special feature(s):** Round head, Bun hairstyles, and Curve bow in hand	A
2		**Model name:** Pirate **Special feature(s):** Pirate hat, and Long coat	B
3		**Model name:** Aladdin **Special feature(s):** Cone hat, and Rectangular mat	C
4		**Model name:** Hat **Special feature(s):** Round hat	D
5		**Model name:** Wizard **Special feature(s):** Cone hat, and Long coat	E

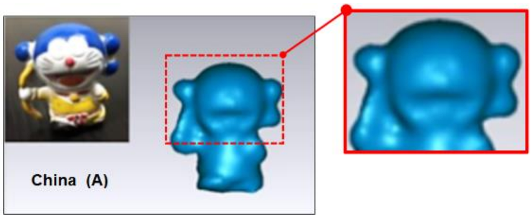


Fig. 9. 3D model from scanning method (Model A).

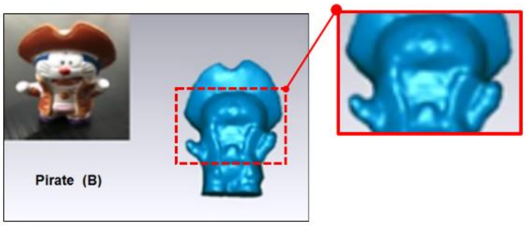


Fig. 10. 3D model from non-scanning method (Model B).

For the mobile phone camera, the small depth difference could be retrieved with better result as shown around the body area of the sample model B (i.e., shirt and bell around the neck). However, the distortion of the lens has direct effect on detection of the sharp edges such as the hem of the cloth as shown in Fig. 10.

Objects that contain symmetric features (i.e., a cylinder, sphere or cubic), sometimes present a difficulty for identifying the common reference points during surface registration. A pair of images taken in sequence could not clearly distinguish between the two consecutive regions shown on the two images; that causes an error in the acquired model. The mean distance errors between scanning and non-scanning methods were computed using the "*CloudCompare*" software.

Table 4. Mean distance error between scanning and non-scanning techniques.

Model No. (complex shape)	Mean distance error [mm] Scanning VS Non-scanning
Aladdin (*Model C*)	0.11
Hat (*Model D*)	1.00
Wizard (*Model E*)	0.81

Table 4 lists the mean distance errors from this experiment. The result shows that there were small deviations between the scanning and non-scanning techniques. The mean distance error reached the maximum value of 1 mm at model D which contained symmetrical geometric shapes. This was because of the limitation of the non-scanning acquisition, the phone camera. The comparisons between each acquisition technique and the actual 3D model was not reported because CAD models of the samples were not available.

Illustrated in Fig.11 were the images taken from different views for the non-scanning technique.

Fig. 12 shows some of the finalized 3D models from various master models with complex shape. The results shown in Fig. 13 were reported as the surface mapping between scanning and non-scanning models to provide the evidence that the results obtained from mobile camera have similar geometric shapes comparable to the results from 3D laser scanner even when used with small-sized model (5-cm height).

The aforementioned factors, such as surface types, and symmetry of the master objects posed some limitations on the surface quality of the acquired models. The surface outlines of the finalized models were visually confirmed to match the master objects. This means that both techniques could extract 3D models without much difference in the final model accuracy.

For the sphere or round shape, the scanning method generated a smoother surface of the finished model whereas the non-scanning method captured more details of peaks and troughs but contained some distortion especially with the object that contained symmetrical features.

The total time consumed was 77 minutes on average for the scanning method and 35 minutes on average for the non-scanning method, respectively. Furthermore, the equipment cost for the 3D laser scan was more than 80 times higher than that of the camera. Table 5 presents the general capability of the two acquisition methods, and Table 6 describes the details of the acquisition processes of model E.

Fig. 11. Taking different views (at least 15 images) for Non-scanning method.

Table 5. General capability of the two methods.

Object's characteristics	Acquisition Method	
	Laser Scanner	Camera
Shiny/Glossy	✗	✓
Flat/Matte	✓	✓
Transparent	✗	✗
Sharp edge	✗	✗
Symmetrical	✓	✗
Fine texture	✗	✓
Black color	✗	✓
Single color	✓	✗
Multi-color	✗	✓
Smooth surface	✓	✗

Table 6. Details of the acquisition processes.

	Process details	Acquisition Device	
		3D Laser Scanner	Camera
Time spent for Model E	Device setup	15 min	5 min
	Object's surface preparing	10 min	3 min
	Acquiring	20 min	5 min
	Reconstruction & Correction	30 min	20 min
	Surface Fitting	2 min	2 min
Others	Object size	3 cm x 2.5 cm x 5 cm	
	Technical skill required	Med-High	Low
	Preferred lighting condition	Dark	Normal
	Cost of the device	70,000 USD	850 USD

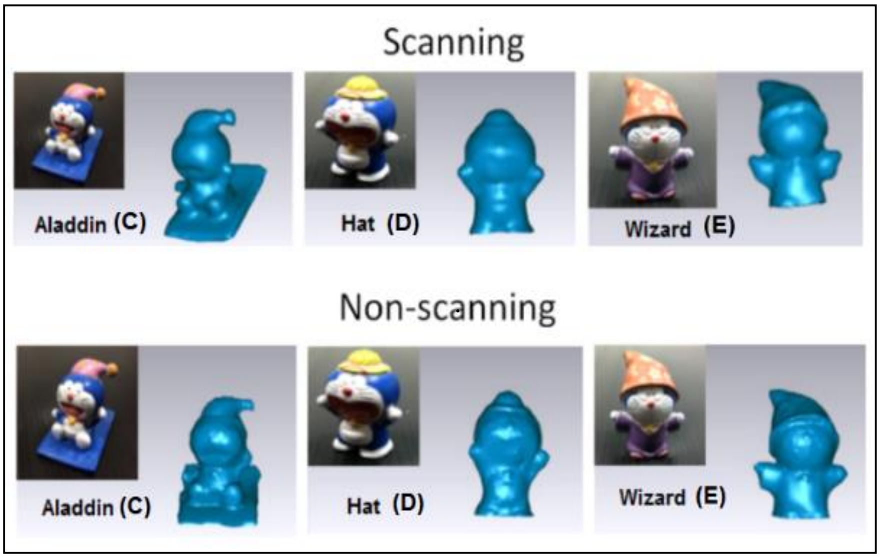


Fig. 12. Finalized 3D model from both methods with complex shapes.

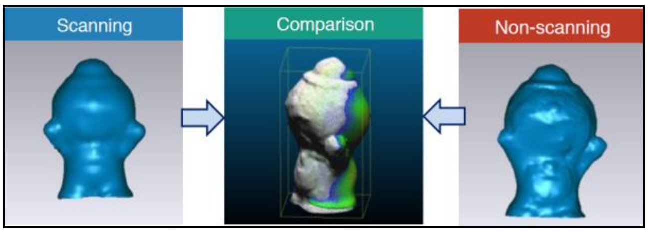


Fig. 13. Comparison between the acquired 3D models from both methods by using *CloudCompare*.

5. Conclusion

This research proposed a guideline for selecting the appropriate non- contact acquisition technique to support quickly detecting the geometric shapes of an existing object. An accurate 3D model creation process of small and complex models (less than 5-cm height) will be the key criteria for this study.

After observing the acquisition activities from camera-based, and 3D laser scanning techniques, the results showed that the proposed non-scanning technique using a mobile phone camera (iPhone) could produce an acceptable accuracy comparable to the model acquired from a 3D laser scanner.

The recommended information about the number of views taken is at least 15 images up to 40 images (which is a limitation of the image-registration software); however, if the object contains some details as shown in the following conditions, the number of taken views should be increased.

The criteria of object's complexity are considered in a qualitative manner. The designer can check the conditions of the object's surface by using these following guidelines.

- ☑ Sharp edges found?
- ☑ Indistinctive features (e.g., small-depth difference, shallow slots, and holes?
- ☑ Single color (monotone) features?
- ☑ Multi-color features?
- ☑ Curvature surfaces/features found on the main area?

Note that the designer needs to prepare multi-color stickers for attaching around the solid/plain color surface of the object since the contrast between two consecutive areas is required for surface registration and extraction in camera-based acquisition technique.

This research conducted the performance assessment of optical data acquisition techniques used in product development stage of reverse engineering. Two types of optical data acquisition: scanning and non-scanning were examined and compared using both qualitative and quantitative measurements. The conclusions of the research are presented in the following subsections.

5.1 Comparison

- **Scanning method:** A 3D laser scan was used to extract point cloud and then reconstruct and fit the triangular facets among the points to create a 3D model of master objects.
- **Non-scanning method:** A mobile phone camera was used to capture several images of the master object from different views and then combined into a 3D model using reverse engineering software.
- **Comparison:** First, the acquired 3D models from both methods were compared by calculating the mean distance error between them and the master CAD model. From the experiment with cylindrical master objects, both methods could produce a satisfying accuracy within 3% when compared to the master CAD model. Then, both acquisition methods were compared with each other for the small and complex objects. The generated 3D models presented the mean distance error less than 1 mm between the two methods. Therefore, both techniques could extract 3D models without much difference in accuracy between the finalized models.

5.2 Applications

- **Time:** The average total time used in the non-scanning technique is less than half of the scanning one.
- **Cost:** Non-scanning technique using a camera is almost 80 times less expensive than the 3D laser scan used in the scanning technique.
- **Overall:** The obtained results can support potential use of the non- scanning approach with camera as a practical and

inexpensive alternative to the commonly-used scanning method with a 3D laser scan.

5.3 Recommendations

- **Scanning method:** it requires surface preparation process, such as coating an object's surface with flat white color for shiny/transparent/fluorescent object and adding references, a lot of marker dot stickers that are used for shining 3D scanners.
- **Non-scanning method:** some limitations regarding the object surface types, color and symmetry that can affect the resulting 3D model of the non-scanning type were presented.
- **Contribution:** The target groups who might get the benefits from this study are: Designers who would like to get the "small-depth different details" or "curvature features" of the surface by using a non-contact acquisition method. The mould maker who would like to fix or repair the mould located on the machine's platform. Anyone who would like to apply easy-to-access camera phone or tablet for capturing things and turn them into a 3D virtual model where the surface quality of the final part can be noticed with the same level as the one obtained from a 3D laser scanner.
- **Future work**: more detailed investigation of broader types of objects and improvement on the current non-scanning technique as the automatic capturing function would be beneficial.

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