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ORIGINAL ARTICLE

Sustainable Restoration and Remanufacturing Solution of Obsolete Spare by Advanced Reverse Engineering Technology: A Three-Dimensional Digitization Approach

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ABSTRACT - Substantial increase of e-waste in global has raised sustainability issue whereby rapid obsolescence of electrical and electronic products are noticed. Restoration and remanufacturing of obsolete spares is difficult as they are mostly unavailable and traditional reverse engineering technique by physical measurement is inaccurate. To tackle the problem, this research has adopted a three-dimensional (3D) digitization approach for capturing dimensional data accurately and then remanufactured the spare by 3D printing. In this research, the front panel cover of an obsolete printer is taken as case study. Firstly, the part was scanned with a 3D laser scanner to obtain dimensional data for generation of mesh model. The mesh model was then polished and segmented to serve as fundamental reference for reconstruction of solid model in Geomagic Design X (GDX), the computer-aided-design (CAD) software dedicated for reverse engineering. The accuracy of solid model was checked by comparing dimensional deviations between the mesh and solid models. The following step was to input the file to a slicing software for generating g-codes. By feeding those g-codes to a 3D printer, the part was successfully remanufactured. To ensure accuracy and consistency of 3D printing results, three prototypes were produced and measured on certain significant parameters. The result of actual dimensional deviations has shown that the remanufactured prototypes are very accurate (with mean accuracy of 98-99%). At the end of this research, the 3D-printed prototypes were sent to the part provider for conducting assembling compatibility test. Successful assembling of the remanufactured prototypes has complemented the research outcomes.

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INTRODUCTION

The tremendous increase of waste electrical and electronic equipment (WEEE) or e-waste generated annually has raised an alarming concern due to its highly toxic metal and chemical compositions which have been proven detrimental to environment and human health [1]. In Malaysia, the generation of e-waste is rising at an annual increment rate of 14% and the amount is envisaged as 1.1 million tonnes in 2020 [2]. Substantial increase of e-waste generation is one of the most prominent drawbacks of accelerating pace of technology advancement. This is especially sensible for the current electronic industry, whereby the ever-evolving trend of electronic and electrical gadgets has caused their rapid obsolescence and greatly reduced lifespans.

It has been discovered that the replacement of broken or damaged parts is difficult due to high cost and most often the spare parts for obsolete products are unavailable in market. Most original manufacturers only emphasize on new products' development to remain competitive instead of

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considering product maintenance and sustainable product life cycle [3]. Thus, it is crucial to develop a sustainable restoration and remanufacturing solution of obsolete spare to prolong the lifespan of electrical and electronic equipment for significant reduction of WEEE generated from electronic industry.

According to Bagci [4], reverse engineering is defined as "Systematic evaluation of a product with the purpose of replication which includes design of a new part, copy of an existing part, recovery of a damaged or broken part, improvement of model precision and inspection of a numerical model". Basically, reverse engineering is the only viable solution to duplicate a physical part when its technical details like drawings, engineering data, geometrical documentation and CAD files are unavailable [5]. However, traditional reverse engineering techniques are insufficient to capture and reconstruct intricate geometry of replacement parts accurately. Conventional dimensional data collection method utilised for reverse engineering refers to direct physical measurement on the spare part by using manual measuring tools like metre rule or even subjective approximation by visual inspection, which has been proven inaccurate and infeasible on replacement parts with complicated topology [6].

In contradictory to the ineffective traditional reverse engineering technique, the researcher has deployed advanced laser scanning technology for accurate 3D point data acquisition of an obsolete spare part in this research. The method, particularly known as 3D laser scanning has enabled 3D digitization of spare part in the sense that physical geometries are represented by 3D-scanned point cloud data. 3D laser scanning technology is based on physical principle of triangulation. In this context, a light beam produced by a laser is directed onto the scanned object and a charged couple device (CCD) camera is used to capture the reflected light. As the laser source and CCD detector are arranged specifically in relative orientations, the measurement spot on the scanned object is able to be triangulated. Hence, three-dimensional coordinates, (x, y, z) of a point on the scanned object surface can be calculated or computed by a simple triangle geometry based on previously calibrated positions which serve as constant base value. The key advantage of this 3D scanning technology is that a substantial amount of point data can be captured in a comparatively short period with favourable accuracy tolerance range of ±0.025 and 0.2mm [5].

Based on the captured point cloud, a series of point data processing techniques like merging, meshing by triangulation, regional segmentation, surface fitting, and reconstruction of geometrical primitives can be conducted to generate an accurate solid model of spare part in CAD software. For sustainable remanufacturing of spare part, fused deposition modelling (FDM) technology, also known as 3D printing is utilised as it is one of the most widely used and affordable additive manufacturing technology.

MATERIALS AND METHODOLOGY

The front panel cover of Brother MFC-240C colour inkjet all-in-one printer (Figure 1) is adopted as the reverse engineering case study in this research. The part is provided by Mega Computing Centre, a small enterprise from Bintulu which is engaged in repair and refurbishment of old printers' business. As acknowledged by the company manager, replacement parts of old printers are extremely hard to find in current market due to rapid product obsolescence in electronic industry. Even sometimes certain spare parts are available online, it is costly to purchase and great inconvenience encountered with localization issue. Likewise in this case study, the spare of front panel cover no longer exists in market for replacement since the printer model is old and obsolete. Thus, the researcher has helped to restore the part in CAD by 3D laser scanning and then remanufacture it by 3D printing. Basically, the operational framework of reverse engineering process consists of three milestones: i) digitization phase, ii) CAD reconstruction phase and iii) production phase.

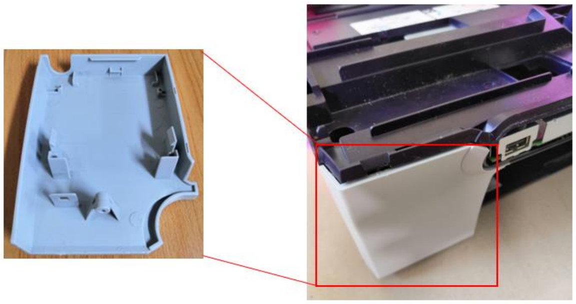


Figure 1. Front Panel Cover of Brother MFC-240C Colour Inkjet All-In-One Printer

Digitization Phase

The main purpose of digitization is to collect 3D topology data of the object and generate a mesh model based on the 3D-scanned point cloud. Before 3D data collection, the object's surface needs to be cleaned to remove any dirt or stain on its surfaces, as shown in Figure 2(a). This is important to ensure accuracy in 3D data capture process later by getting rid of unnecessary scanning inhibitor. In addition, the scanned object needs to be examined visually to determine if any reflective, shiny or dark surface exists. Such surface types will hinder the reflection and obstruct the 3D laser scanning process [5]. It is necessary to coat the object with white spray before scanning if the object is in dark colour or consists of shinny surface.

For 3D data collection, EinScan Pro 3D laser scanner is applied together with a turntable, as portrayed in Figure 2(b). The equipment set, as well as its corresponding EXScan Pro scanning software are developed by Shining 3D Technology Corporation. Different with other ordinary handheld 3D scanners, the coupling between EinScan Pro 3D laser scanner and turntable have enabled the feasibility of automatic fixed scan, rather than handheld scanning. 3D data can be collected through multiple scan views by fixing the 3D scanner stationary and rotating the part. Comparatively, automatic fixed scan mode with consistent stability offers higher scanning accuracy due to the fact that handheld scanning exhibits more noise and outliers due to inconsistent and error-prone human intervention.

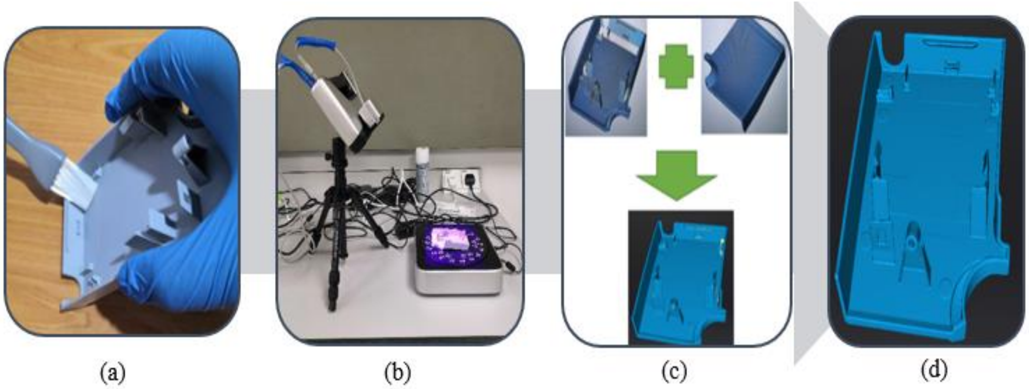


Figure 2. 3D Data Collection and Processing Steps of Digitization Phase

The 3D scanning process is repeated with different orientations of the object on the turntable like front-view and back-view in order to increase the accuracy of 3D laser scanning. The primary advantage of such scanning method is to minimise the occluded surfaces which tend to be missed at single scan from fixed angle. After obtaining a few clusters of point cloud from multiple orientations of 3D laser scanning, combination of the point clouds is performed by point data merging program embedded in EXScan Pro scanning software (Figure 2(c)) to obtain an accurate set of 3D data. The end of digitization phase involves the conversion of the point cloud to a mesh model by triangulation function in the scanning software. Then the mesh model is further corrected and polished by hole-filling and sharpening functions to produce an accurate stereolithography (STL) file (Figure 2(d)) with 'stl' extension.

CAD Reconstruction Phase

After the STL file is ready, it is imported into CAD reverse engineering software for reconstruction of CAD model. In this research, Geomagic Design X software is selected as it is the most powerful software tool dedicated for reverse engineering, as recommended by Buonamici et al. [7] after performing comparison study among various CAD reconstruction software.

The first step of CAD reconstruction is mesh segmentation whereby the mesh model is distinguished into several subsets based on each geometrical criterion (Figure 3(a)). The main objective of segmentation is to subdivide the scanned data into closely related and organised regions comprising significant geometrical features or surfaces. Once the pointer is dragged towards classified region, significant geometric primitives like planes, natural quadrics and tori (surface generated by revolving a circle about an axis three-dimensionally) will be recognised and indicated immediately. For accurate features classification, it is a good rule of thumb to keep a low sensitivity threshold of segmentation (between 20% and 30%) to avoid faulty segmentation result caused by scattered or over-defined regions.

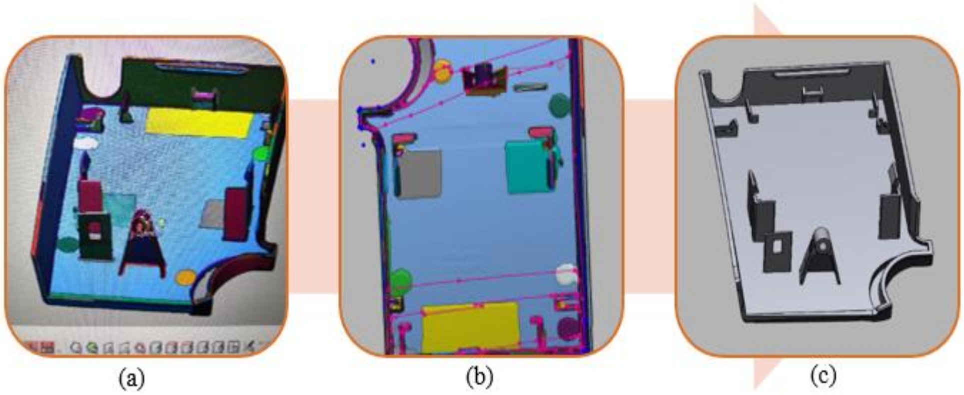


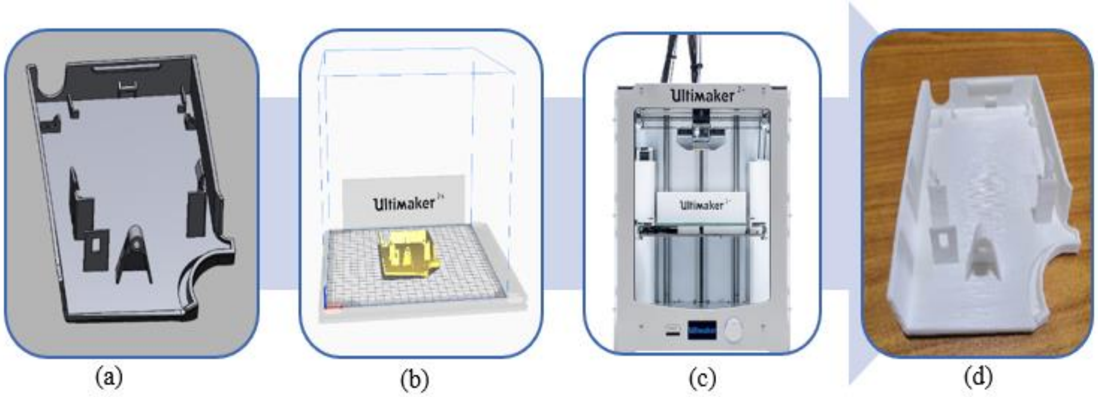
Figure 3. CAD Reconstruction Steps in Geomagic Design X

Based on the classified regions, two-dimensional (2D) mesh sketches (Figure 3(b)) can be generated by tracing the boundary lines or edges comprising the topology features. Hence, 2D drawings of geometric primitives are easily generated by using the mesh sketches as fundamental guides and significant reference. In this context, multiple drawing tools like spline, line, and arc are used optimally.

Solid modelling operation is carried out to generate 3D CAD model from the 2D drawings on plenty drawing planes. Various solid modelling operations like extrusion, cut extrusion, revolution, sweep and loft et cetera are performed to form distinct solid parts. By merging all those sold parts lead to the creation of a complete solid model (Figure 3(c)). In order to ensure the accuracy of reconstructed solid model, the deviation between the mesh model and solid model can be checked and measured by deviation analysis tool in GDX based on the tolerance set by user.

Production Phase

In this research, FDM additive manufacturing technology has been selected for rapid prototyping of the front panel cover, as illustrated in Figure 4. The primary reason of selecting FDM is due to the fact that it offers high sustainability whereby product manufacturing cycle is shortened significantly along with the manufacturing cost, especially for small batch production. Besides FDM, several additive manufacturing technologies like stereolithography (SLA), selective laser sintering (SLS) and electron beam melting (EBM) et cetera have been developed over the past few decades. Among them, FDM is particularly well known as 3D printing which joins material layer-by-layer to construct a 3D model in real life [8]. On top of that, FDM is the most conventional and low-cost additive manufacturing technology [9; 10; 11] because FDM process is relatively simpler and more convenient as compared to SLA, SLS and EBM which requires the utilisation of a laser or electron beam. Therefore, FDM is the best matched rapid prototyping method with 3D scanning which suits the need of repair and restoration work the most in order to remodel and remanufacture spare parts at affordable cost.



(a) (b) (c) (d)

Figure 4. 3D Printing Process of the Front Panel Cover

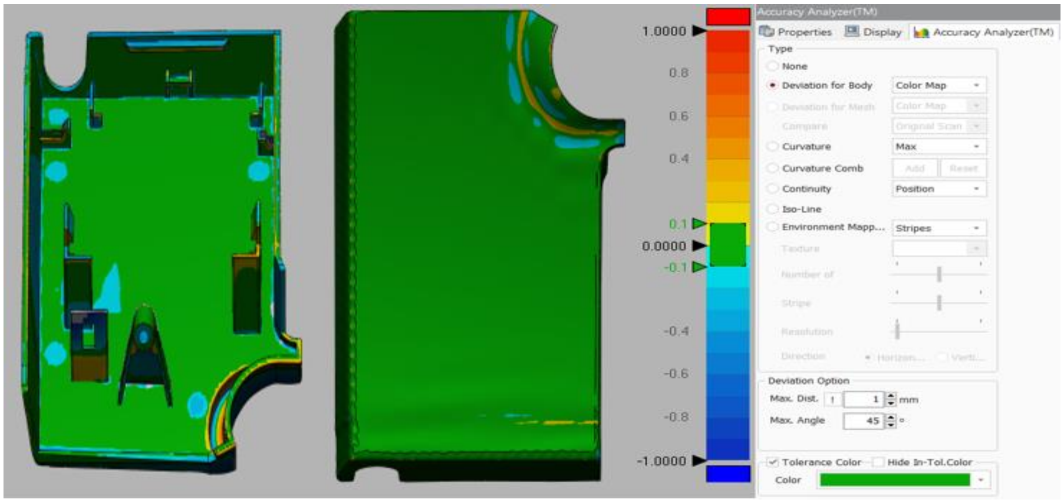
The first step of 3D printing is to convert the CAD model into STL file by CAD software. Then it is input into a STL model slicing software to generate g-codes. In this research, Ultimaker 2+ 3D printer bundled with corresponding STL model slicing software, Ultimaker Cura are applied. The STL model of remodelled front panel cover is input into Ultimaker Cura (Figure 4(b)) for being sliced into several 2D horizontal layers. There are various 3D printing parameters like infill pattern, infill density and 3D printing filament materials which need to be configured in Ultimaker Cura. In this research, the infill density of 3D printing is set to be 100% whereas polylactic acid (PLA) filament material is chosen.

For FDM, the most common and applicable 3D printing material is thermoplastics such as PLA and acrylonitrile butadiene styrene (ABS). In comparison, PLA has higher strength but ABS is more heat-resistant [9]. After the 3D printing configuration is done, the STL model is sliced to produce several lines of g-codes. G-codes comprise several lines of text which serve as the control language, similar in the case of CNC machining whereby it conveys sequential fabrication instructions to the machine. Apart from nozzle temperature and other 3D printing settings, the most important component in g-codes consists of X, Y and Z coordinates which enables the precise movement of the nozzle during material extrusion process. After that, the g-codes are input into Ultimaker 2+ 3D printer (Figure 4(c)) with the assistance of a microSD card for 3D printing operation. Post-processing step is required to remove the support material after 3D printing. By these, a prototype of the front panel cover is successfully restored and remanufactured, as shown in Figure 4(d).

RESULTS AND DISCUSSION

Accuracy of Reconstructed CAD Model

After a solid model is successfully reconstructed based on the classified regions, dimensional accuracy validation of the solid model will be performed by accuracy analyser tool in GDX (Figure 5). It is essential to assure geometrical accuracy of the solid model by comparing its deviation with the mesh model generated from 3D laser scanning previously. This is because inaccurate CAD model would result in larger dimensional error of remanufactured prototype since the generation of g-codes is based on the slicing of the STL model converted from the CAD model.



Type
- ○ None
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- ○ Deviation for Mesh: Color Map
- Compare: Original Scan
- ○ Curvature: Max
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- ○ Continuity: Position
- ○ Iso-Line
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- Stripe
- Resolution
- Direction: ● Horizon... ○ Verti...

Deviation Option
- Max. Dist. 1 mm
- Max. Angle 45 °

☑ Tolerance Color ☐ Hide In-Tol.Color
- Color 🟩

Figure 5. Deviation Analysis between the Mesh Model and Solid Model

From Figure 5, the deviation analysis between the mesh and solid models are represented by a colour map comprising different colour indicators of corresponding deviation ranging from -1.00mm to 1.00mm, as shown in the colour bar. It can be observed clearly most of the reconstructed solid model parts are depicted in green, which indicates that the average deviation is only ±0.1mm. Besides green colour, certain small portions of the solid model are spotted in light blue or yellow, indicating average deviation of ±0.2mm. This is within tolerance and understood since there are some excessive features on the surface of the original front cover. They might be over-designed features or imperfections caused by conventional manufacturing process. These features can be exempted from solid modelling as the assembling compatibility would not be affected without them. Furthermore, some curvatures and free-form surfaces (irregular surfaces) appear in light yellow which means perhaps more fillet or chamfer actions are needed. Since the deviation is not large, these light-yellow portions are tolerable as adding fillet or chamfer one by one on the small portions would be time-consuming and user-intensive. In overall, the accuracy of the reconstructed solid model is satisfactory with average deviation of 0.1-0.2mm.

Accuracy of Remanufactured Prototypes by 3D Printing

Despite accuracy checking for reconstructed solid model in GDX, dimensional validation of the remanufactured prototypes by 3D printing is important too. In this study, three prototypes of the front panel cover are remanufactured and then measured by an industrial certified digital vernier callipers (Figure 6).

CERTIFICATE OF INSPECTION / 検査成績書

発行No./Issue No.: 4152794283

Product name/品名	Digimatic Caliper/デジマチックキャリパ
Model No./符号	CD-8"ASX
Code No./コードNo.	500-197-30
Serial No./製造No.	14540021
Measuring range/測定範囲	0-200mm / 0-8inch
Minimum indication/最小表示量	0.01mm / 0.0005inch
Standard Temperature/標準温度	20°C
QC Manager T.Suzuki	T.Suzuki

Inspection standard : Mitutoyo standard
Based on : JIS B 7507 1993,DIN 862:1988
Traceable to : NMIJ/AIST by JCSS No.0030, NIST via No.683/283699-13, PTB via No.4937 PTB 08
NIST and PTB : Confirmation of technical capability by the transfer standard (ISO/IEC 17043)

Mitutoyo Corporation

(1) Result of inspection/検査結果

	Measuring length 測定長	Permissible values 許容値	errors/誤差 External/外側	errors/誤差 Internal/内側
Unit : mm 単位 : mm	φ4	0.01 -0.03	—	-0.02
	0	±0.02	0.00	—
	50		0.00	0.01
	100		0.00	0.01
	150		0.01	0.01
	200		0.01	0.02
Unit : inch 単位 : inch	φ0.16	0.0005 -0.0015	—	-0.0010
	0	±0.0010	0.0000	—
	2		0.0000	0.0005
	4		0.0000	0.0005
	6		0.0005	0.0005
	8		0.0005	0.0010

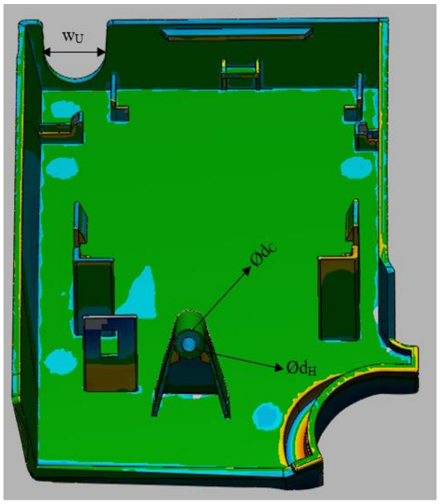
(2) Judgment/判定 : Passed/合格

※DIN 862:1988 : 0.03

Figure 6. Certified Digital Vernier Callipers from Mitutoyo Corporation in Japan

The digital vernier callipers, which is developed by Mitutoyo Corporation in Japan has an accuracy of 0.01mm. Three significant parameters, hole diameter for screw insert (denoted as d_H), external diameter of cylindrical screw holder (denoted as d_C) and width of U-slot (denoted as w_U) are chosen for dimensional measurement since these dimensional parameters are of high responsibility for correct matching of the prototypes with the printer. To ensure the consistency of result, each parameter measurement is taken three times to obtain the average. Comparison of parameter measurement between the original specimen and the other three remanufactured prototype samples is tabulated and shown in Table 1.

Table 1. Dimensional Comparison between the Original Front Panel Cover and 3D Printed Prototype Samples



Parameters

$Ød_H$: Hole Diameter for Screw Insert
$Ød_C$: External Diameter of Cylindrical Screw Holder
w_U : Width of U-Slot

Para-meter	**Speci-men**	**Proto-type Sample I**	**Proto-type Sample II**	**Proto-type Sample III**	**Deviation of Sample I (%)**	**Deviation of Sample II (%)**	**Deviation of Sample III (%)**
d_H (mm)	2.43	2.45	2.48	2.45	0.684932	1.780822	0.821918
d_C (mm)	5.99	6.15	6.16	6.17	2.726767	2.893712	3.005008
w_U (mm)	12.72	12.70	12.71	12.71	0.157274	0.078637	0.078637
				Mean Accuracy (%)	98.810343	98.415610	98.698146

According to the tabulated results, the mean accuracy of the three prototype samples as compared to the original specimen are very high (above 98%) and similar which constitute 98.810343%, 98.415610% and 98.698146% for Sample I, Sample II and Sample III respectively. The consistency of dimensional accuracy of 3D-printed prototypes has proven that FDM technology is reliable and credible for remanufacturing the obsolete spare.

Apart from scientific measurement, assembling compatibility test has been conducted for the three prototypes whereby they are sent to the company in Bintulu to determine whether they can be well-fit with the Brother MFC-240C printer. As a result, the assembling process for the three 3D-printed prototypes went smooth and they were successfully fit onto the printer with a screw accurately tightened and inserted. (Figure 7). The accuracy of the remanufactured front panel cover has successfully gained satisfactory and recognition from the company.

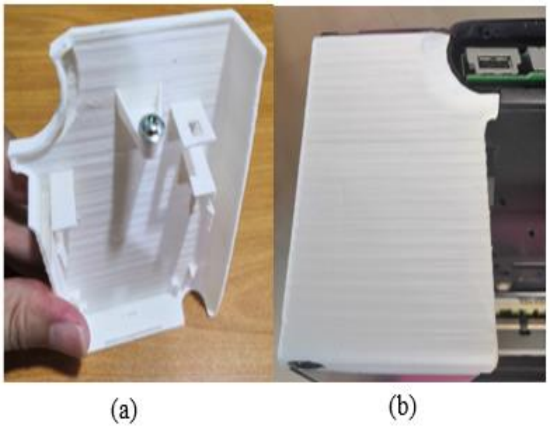


Figure 7. Successful Screw Insert and Assembling of the 3D-Printed Prototype of Front Panel Cover

CONCLUSION

This research has successfully provided a feasible solution to restore and remanufacture obsolete spare accurately and independently by advanced reverse engineering technology. The full-stack solution commences with 3D digitization by laser scanning, followed by CAD reconstruction or remodelling in GDX and finally 3D printing through a FDM printer. The utilisation of a 3D laser scanner to capture dimensional data has prominent strength in which the complex topology of specimen can be scanned and converted to point cloud data. Then the point cloud is meshed and polished to be fed into GDX for CAD reconstruction. During CAD reconstruction phase, this research has demonstrated how segmentation technique can ease the solid modelling process and also ensure high accuracy of solid model (average deviation of 0.1-0.2mm) by conducting deviation analysis between the mesh model and solid model. High accuracy of solid model reconstructed based on the mesh model indicates preliminary success of restoration and potential remanufacturing of the spare.

When it comes to production phase, three prototypes are produced by 3D printing for actual dimensional accuracy comparison. Three significant parameters of the specimen have been selected for measurement by an industrial certified vernier callipers and the results are tabulated to calculate the average accuracy of the 3D-printed prototypes. As a result, it can be observed that FDM technology is capable of remanufacturing the front panel cover with a very high mean accuracy (between 98% and 99%). The results are also being validated by conducting assembling compatibility test between the 3D-printed prototypes and the corresponding printer. Matching of the prototype with the printer is successful with accurate screw insert. In a nutshell, this research has shown how an obsolete spare can be restored and remanufactured successfully by 3D laser scanning and 3D printing.

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