Part Design and Evaluation through Reverse Engineering Approach

Fahraz Ali
University of the West Indies, St. Augustine
fidod7@gmail.com

B.V. Chowdary
University of the West Indies, St. Augustine
chowdary@eng.uwi.tt

C.A.C. Imbert
University of the West Indies, St. Augustine
csimbert@tstt.net.tt

Abstract

Most manufacturing enterprises focus on the delivery of increased productivity with high quality products through integration of computer aided design (CAD)/computer aided manufacturing (CAM) with computer aided engineering (CAE) tools. When this concept is applied to reverse engineering (RE), the challenge lies in quickly editing and modifying point cloud data collected from scanning the object to design of a three dimensional (3D) CAD model for rapid manufacturing purposes.

This paper presents an RE scenario to show how CAD and CAE systems are overlaid on product design to realize the goals of better quality and productivity of scanned CAD models used for inspection purposes. The primary objective of this paper is to outline, through a case study, how various scanning parameters will affect the data editing stage involved in the construction of the CAD model for the RE process. Geometric dimensioning and tolerancing (GD&T) is used as a validation tool for comparison of the CAD models generated from scanned data.

Introduction

A well-known definition of reverse engineering (RE) notes that it is a methodology that constructs computer aided design (CAD) models of physical parts by digitizing an existing object, creating a computer model, and then using it to manufacture the component [1]. Most studies have focused on how efficiently and accurately the point cloud data captured from RE systems can be altered through many developed data editing and data fitting algorithms to construct a CAD model of some accuracy. The data editing algorithms mainly involved point cloud data reduction [2–7] and data fitting algorithms involved surface reconstruction

[8–13]. However, these point cloud data were captured at some predetermined parameter settings that influence the accuracy of the data retrieved and, thus, the CAD model produced.

Bradley and Vickers [14] stated that there is an inherent trade-off between accuracy of measurement and width and depth of field with scanners operational through laser triangulation methods. Furthermore, it is important for validation of the scanned CAD models when RE is used for inspection purposes. Geometric dimensioning and tolerancing (GD&T) is applied as a tool for such validation. It is of particular importance to RE tasks related to industrial production, as well as product development, equipment upgrading, and maintenance [15].

No work has focused yet on determining the effect that initial three dimensional (3D) laser scanner parameters have throughout the data editing stage and on the accuracy of the resultant CAD model through inspection by GD&T. We present a case study, in this regard, involving the ShapeGrabber® AI310 3D laser scanner system, which functions on the principle of laser-based triangulation. This RE equipment was employed on an electrical socket cover for identification of issues resulting from variation of certain scanning parameters. In this study, the effect of the variation of the scanning parameters on the data editing stage of scanned CAD model will also be reported, along with GD&T testing function.

Methodology

The proposed methodology comprehensively addresses the various issues associated with the design and testing stages for industrial inspection of products through the RE process. Design issues were categorized under data capture, data editing, data fitting, and CAD model generation, in that particular sequence. Scanning parameters such as orientation, indexing, trajectory length, depth of field, resolution, and laser power were the issues related with data capture. Data editing involved issues associated with the creation of the point cloud model, such as point cloud reduction and data registration. Subsequent to creation of the point cloud model, and also included in data editing, was the creation of the polygonal model under which the issues of filling holes, relaxing, and sharpening edges were taken into account. Data fitting grouped together the issues of patch creation and generation of the non-uniform rational B-splines (NURBS) model. Under CAD model generation, issues associated with CAD model creation from the NURBS model and accommodation for further editing of the CAD model necessary for testing and manufacturing functions were addressed. Testing included GD&T inspection, materials testing, and structural analysis.

In this study, the main focus can be seen on all the elements involved in the design stage by first varying the parameters associated with the data capture stage of the scanned object, observing their effect on the accuracy of the models developed in the data editing stage, performing data fitting to generate the NURBS models, producing the scanned CAD models, and finally, validation of the scanned CAD models through GD&T inspection.

Data Capture

Orientation

The orientation of the object within the scanner is crucial for the optimization of the retrieval of data [16]. By positioning the electrical socket cover at various angles to the scan head, it was observed that a lot of time can be saved by using the position that allows for maximum data capture, since this would require only a minimum number of scans to completely define the object. For objects with steep surfaces, such as the electrical socket cover (steep surfaces located along the perimeter), scans from different orientations must be merged to fully represent all geometrical data. This is because the laser does not reach awkward inclines to capture sufficient data at one particular position, and as a result, the electrical socket cover required scans to be merged from a vertical and horizontal orientation to the scan head.

Indexing

It is important to scan around 3D shaped objects, and this requires repositioning of the laser scanner with respect to the prototype model [14]. However, the scanner used in this study repositioned the object, with respect to the scan head, through the use of an indexing table. The object (electrical socket cover) placed on the scanner table was automatically rotated through preset scan positions defined by angular distances and number of scans. A reasonable number of indexed scans were set for the electrical socket cover (six scans at an interval of 60°) after trial and error and using the orientation that allowed for maximum data capture. Dependent upon the object's size and complexity of geometry, the number of scans should be increased at closer scanning angular intervals to capture all variations in the surface [16]. Although this is required for greater accuracy, it occurs at the expense of time.

Trajectory Length

The trajectory length is the vertical distance through which the laser passes across the object's surface that is facing the scan head. This parameter is dependent on the object's size [16]. Testing was done by adjusting the movement of the laser from a suitable starting location to a desired end point to find the appropriate trajectory length for the electrical socket cover. If the scan head emitting the laser travels an unnecessary distance over or beneath the object, lengthy scan times would result due to useless data being processed. This, in turn, complicates editing of the scanned images because of the presence of unwanted data, thus further lengthening the design stage of the RE process.

Depth of Field

The depth of field is also known as the depth to which the scan head can capture data and is adjusted to suit the object's size [16]. Scan tests were performed on the electrical socket cover by varying the depth of field with the automated controlled slider tabs on the ShapeGrabber® AI310 software interface, to ensure all the data points are within the scanning volume and optimize the scanning time. From these tests, it was observed that smaller depth of fields yielded shorter scanning times. This occurs because the scanning volume decreases, thereby reducing the surveillance required by the scan head. Also, narrowing the depth of field to only contain the object eliminates the need to read unnecessary data, keeping the focus on the object.

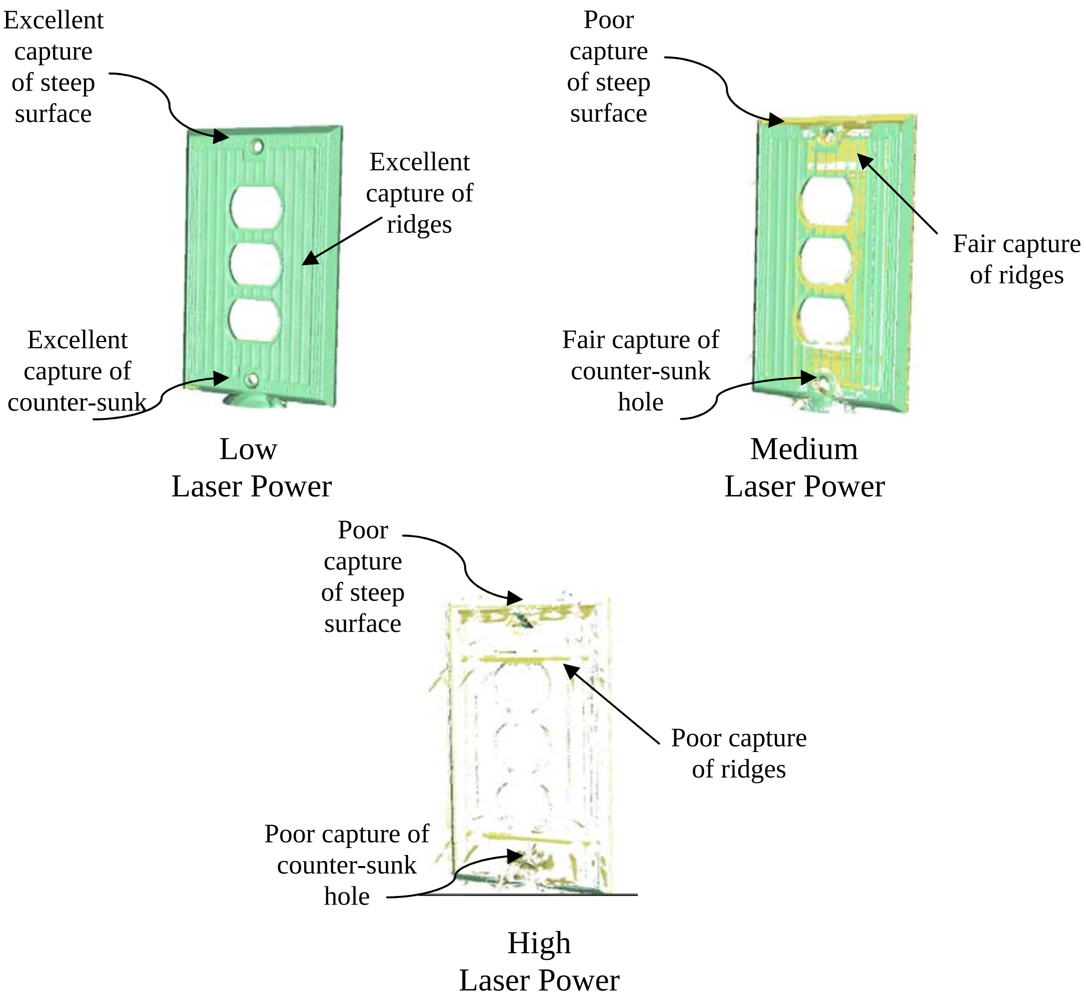
Resolution

When the object is being scanned, the trajectory length must be defined. This vertical distance, however, is divided into numerous intervals at which the laser passes horizontally across the object from the bottom upwards until the entire surface at that particular position is scanned. The distance between these intervals is known as the scanning resolution [16]. For the electrical socket cover, the scanning resolution was varied between 0.05 mm and 0.1 mm. This had significant impact on time and accuracy because a lower scanning resolution (0.05 mm) resulted in greater number of intervals, which the laser had to pass across the object's surface, thus increasing accuracy (by capturing more data) and scanning time. Small objects, as well as those with intricate designs, demand high accuracy for proper surface definition, and therefore, low scanning resolutions should be applied.

Laser Power

Laser power (the intensity of the laser beam emitted by the scan head) is another parameter crucial in data capture. The laser power varied in intensity from one to eight, with one being the lowest intensity. The color and reflective nature of the material of the object greatly influenced the quality of the point cloud data obtained through the laser power setting [16]. It was noted after trial and error that objects of a lighter color, such as that of the electrical socket cover, produced excellent quality scans at a lower laser power (intensity = 2), fair quality scans at a medium laser power (intensity = 6), and poor quality scans at a high laser power (intensity = 8). The results for these intensities are shown in Figure 1.

Also, objects made of a reflective/shiny material or glossy finishes tend to complicate data capture, since no laser power could produce satisfactory scans. These shiny or glossy surfaces introduce additional reflections that interfere with relevant data being processed and result in noise [17]. Additionally, an object that is not very reflective, such as the electrical socket cover, was easily scanned. Variation of laser power had no effect on scanning time but certainly yielded results that show how accuracy can be affected.



Excellent capture of steep surface

Excellent capture of ridges

Excellent capture of counter-sunk

Low Laser Power

Poor capture of steep surface

Fair capture of ridges

Fair capture of counter-sunk hole

Medium Laser Power

Poor capture of steep surface

Poor capture of ridges

Poor capture of counter-sunk hole

High Laser Power

Figure 1: Screen Shots of Point Clouds for Varying Laser Power for the Electrical Socket Cover

The scans produced from the two combinations of scanning parameters, laser power = 2, scanning resolution = 0.05mm, and laser power = 2, scanning resolution = 0.10 mm, were then carried forward for editing to produce CAD models of the electrical socket cover. These combinations of scanning parameters were selected because they yielded better quality scans. Geomagic® Studio 9 was the software used for editing the data captured from the ShapeGrabber® AI310 3D laser scanner system by transforming the scans in its initial point cloud form to a CAD model through different transition phases. These phases included point cloud data to polygonal model, polygonal model to NURBS model, and NURBS model to CAD model. This can be seen in Figure 2.

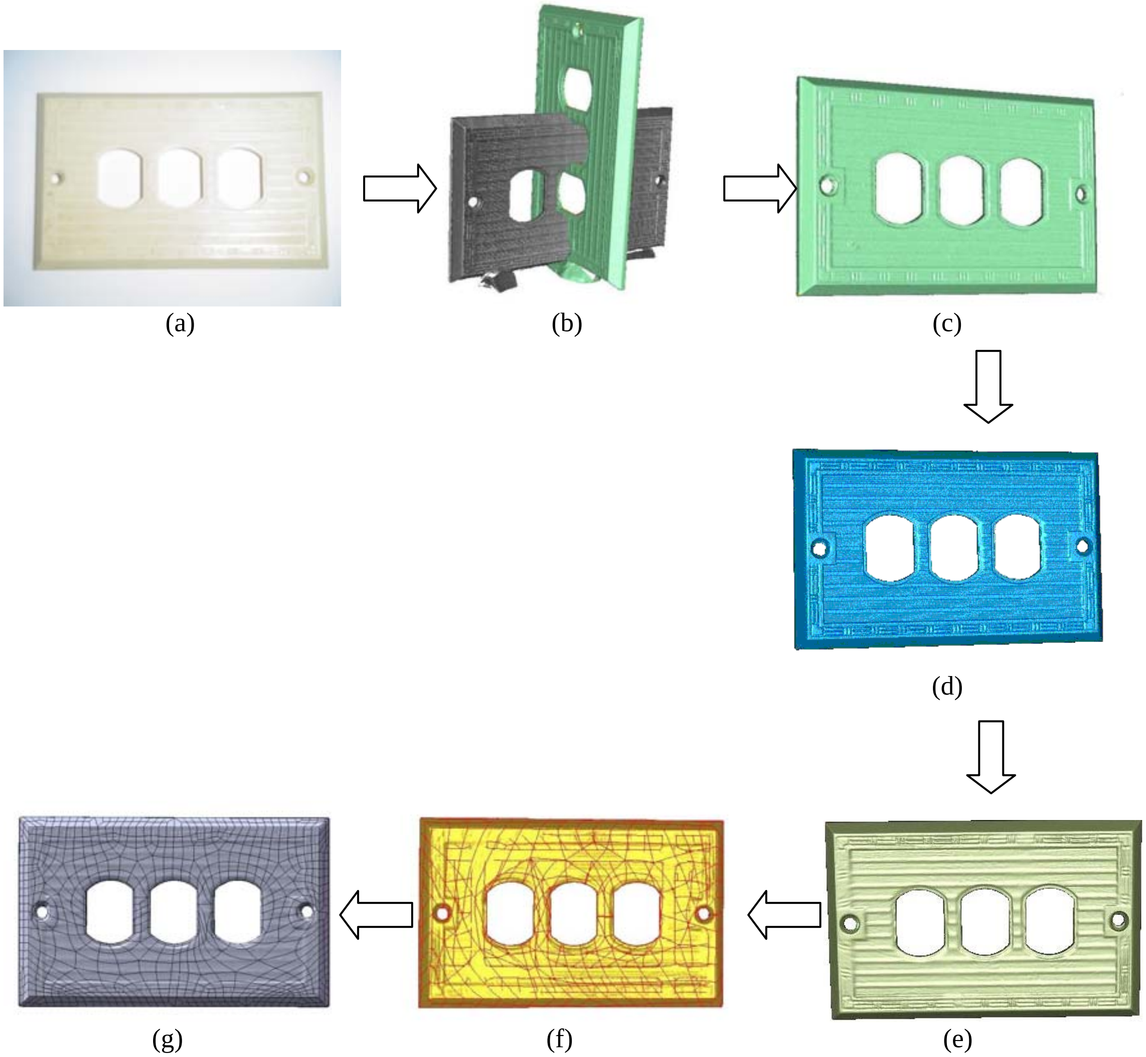

(a) (b) (c) (d) (e) (f) (g)

Figure 2: RE Process Flow Chart for Design Stage

(a) Physical model of electrical socket cover; (b) Point cloud data collected; (c) Registered point cloud model; (d) Polygonal model; (e) NURBS model; (f) CAD model generated in Geomagic® Studio 9 for GD&T inspection; (g) CAD model in SolidWorks® 2006 to be used for testing

Data Editing

Point Cloud Model

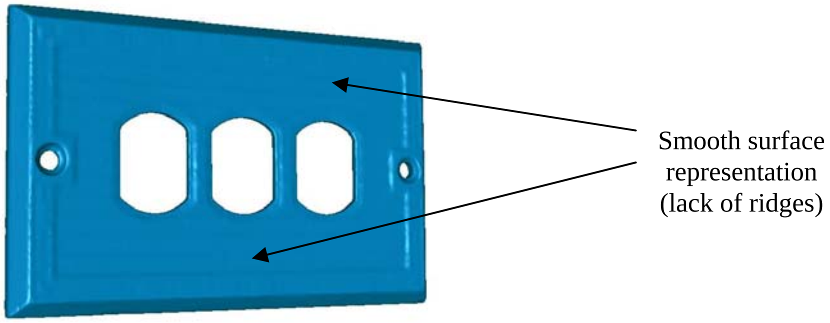
The scans from the two parameter combinations saved by the ShapeGrabber® AI310 software were imported into Geomagic® Studio 9, using the compatible .gpd file format. Scans of each face of the electrical socket cover were saved individually, and all scans for the same orientation were opened collectively. Point cloud data reduction ensued, which involved cleaning up unnecessary data known as outliers captured from the fixture (used to support the electrical socket cover during scanning.) This was required to ensure only relevant data would be processed in the later phases.

By using the appropriate selection tools facilitated by Geomagic® Studio 9, all the unwanted points were deleted. It was noticed that cleaning the individual scans of faces of the electrical socket cover was faster than cleaning the combined file with all the scans merged for that particular orientation. This occurred since the individual scans had fewer points to manipulate as opposed to the combined file. However, after cleaning, the set of scans representing each orientation were merged separately, resulting in two combined files (one for each orientation) for both parameter combinations.

Another task needed to be performed before generating the polygonal models. Since scans were taken with the electrical socket cover at two different orientations, the point cloud data appeared in the respective positions as they were scanned; scans of the electrical socket cover in the vertical position and another set of scans in the horizontal (refer to Figure 2 (b)). Therefore re-arrangement of the two merged sets of scans to fit into each other was crucial for the development of the scanned point cloud models (for both parameter combinations) to be further edited in the other phases. This was achieved through the feature of registration, which could be done manually or globally. Both were implemented. Manual registration was performed by the user in which one merged scan set was approximated to the other by mapping similar points on each scan set to one another. This roughly aligned the scan sets. Following this, global registration was executed in which the program performed a more precise alignment by calculating a best-fit solution for combining the two scan sets. At this stage, all scans were merged into one best-fit point cloud model for each parameter combination, resulting in two point cloud models for further editing.

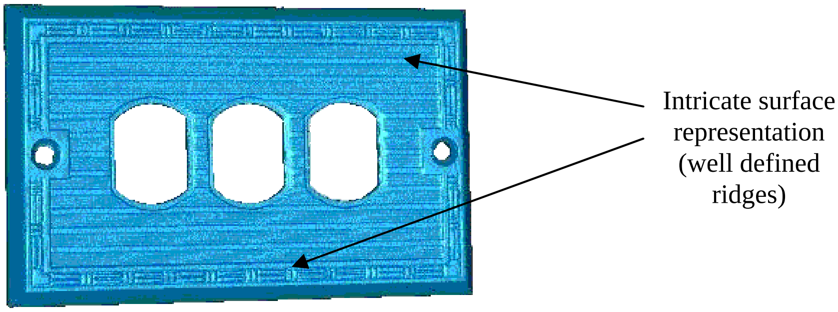
Polygonal Model

The point cloud models were then automatically formed into triangular meshed surface models known as polygonal models by implementing the wrap function, which initiates a meshing algorithm incorporated within the software. The number of triangles used to define the polygonal models needed to be set according to the intent of design restoration. The front face of the electrical socket model contained a lot of definition and, hence, required approximately 350,000 triangles for detailed representation. However, if only basic representation (general outlines of the major geometric entities) was of interest, approximately 150,000 triangles were necessary for generation of the polygonal model. Figure 3 shows this contrast. The detailed polygonal models for each parameter combination were selected for further editing since an accurate, high quality CAD model is the design intent for inspection purposes.



Smooth surface representation (lack of ridges)

(a) 150,000 triangular mesh



Intricate surface representation (well defined ridges)

(b) 350,000 triangular mesh

Figure 3: Variation of Definition in Polygonal Models of the Electrical Socket Cover

The polygonal model is subjected to most of the geometric and surface editing. This is because during the transition from point cloud data, areas of insufficient data or awkward regions resulted in holes, unwanted features, rough edges, and intersecting triangles in both polygonal models. These deficiencies must be resolved before they can be developed into accurate NURBS surface models because the polygonal model is used as a reference to produce the NURBS surface, hence, it should be sound and of a particular quality [17]. Surface editing algorithms integrated within the Geomagic® Studio 9 software were easily executed through editing tools such as “fill holes,” “repair intersections,” “relax,” and “sandpaper.” First, all faulty intersections were repaired with the “repair intersections” tool by scanning the mesh, highlighting the intersections, and readjusting the mesh to eliminate any errors. This was done at the expense of surface detail, usually noticed at the areas of complexity.

Areas of complexity on the electrical socket cover included the depth of the counter-sunk holes, as well as the edges of the inclined surfaces. There was insufficient data captured for the depth of the counter-sunk holes; as such, there were some gaps in the polygonal models that needed to be filled for proper definition. It was noted that there was a different number of holes in the polygonal electrical socket models dependent on the parameter combination. The parameter combination of laser power = 2, scanning resolution= 0.05 mm produced seven holes in the polygonal model, whilst the parameter combination of laser power = 2, scanning resolution = 0.1 mm produced eleven holes in the resultant polygonal model. As such, both polygonal models were selected, and the “fill holes” tool was implemented to fill the gaps. The edges of the inclined surfaces for both polygonal models were generated to be rough. The “relax” and “sandpaper” tools were used to sharpen the edges by defining the strengths to be applied, ranging from low to high on a slider tab. Following this, the polygonal models were decimated to decrease any redundant triangles so that the file sizes could be reduced and processing time increased. The polygonal models were now appropriate to be transformed into NURBS surface models.

Data Fitting

NURBS Model

The NURBS surface is developed through the decomposition of the polygonal model into quadrangular patches [17]. The quadrilateral patches were arranged in a layout appropriate to represent the shape of the electrical socket cover for each polygonal model. A multiple resolution surface was then laid on each patch, and a NURBS surface was fitted to each patch. A satisfactory NURBS object for the electrical socket cover would be produced by constructing each patch approximately rectangular in shape, ensuring there were no severe or multiple curvature changes in the interior of the patch and preventing creation of unnecessary patches [17]. These objectives were achieved through automatic construction using the Geomagic® Studio 9 software.

First, detection of curvature and contours was performed to identify the contour lines on the electrical socket cover. The identified contour lines are then used to break the selected object into regions of low curvature change that could be easily represented by a set of smooth patches. Next, the patches were constructed, followed by a grid creation process that involved a grid placed within each of the defined boundary patches. The intersection points of this grid lie precisely on the polygonal surface model and were used to calculate the splines of the NURBS surface [17]. It was observed that the denser the grid, the greater the amount of detail captured from the polygonal surfaces and represented in the final NURBS surfaces. The “construct grids” command performs an automated parameterization of the triangular surface to a dense, quadrangular patchwork. Once this grid was calculated, the “construct NURBS” command automatically computes the final NURBS surface; as such, the two NURBS models were developed.

CAD Model Generation

With the NURBS models computed, they had to be converted to CAD models. This was necessary to support further inspection through GD&T, since geometric features embedded in the NURBS surface model must be recognized and properly parameterized [18]. Geomagic® Studio 9 allowed for this automatic conversion by allowing the user to activate the command, “to CAD phase.” The CAD models were then saved as IGES files and imported into the CAD package, SolidWorks® 2006. This was required since the CAD functions were limited in Geomagic® Studio 9, and SolidWorks® 2006 offered the necessary tools for the requirement of further editing, such as allocating the material of the electrical socket cover, which is crucial for other testing functions such as materials testing and structural analysis.

GD&T Inspection

Geomagic® Qualify 9 was used for the GD&T inspection of the scanned CAD models (for both parameter combinations) generated in Geomagic® Studio 9. This involved comparison between two CAD files; one file was to be loaded as the reference file (original CAD model of the electrical socket cover) and the other as a test file (one of the scanned CAD models). When loaded, neither of the two CAD models was aligned, and a best-fit alignment was performed on them to allow for comparison testing. After the best-fit alignment, GD&T was executed. The reference CAD model was used to define feature control frames, known as callouts, through the implementation of the "create callouts" command [19]. This is shown in Figure 4. These callouts were used to define geometric characteristics, such as flatness and cylindricity, off the reference CAD model for the electrical socket cover.

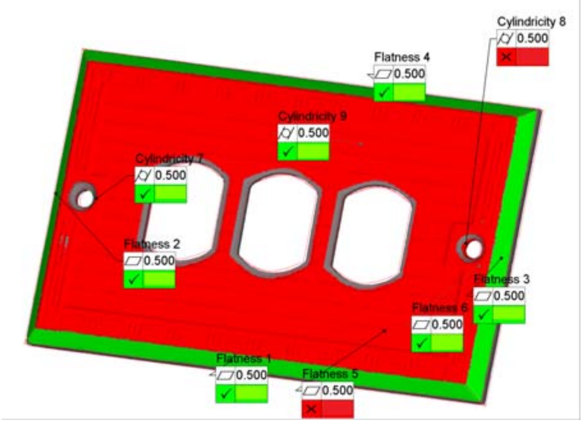


Figure 4: GD&T Callouts from the Original CAD Model of the Electrical Socket Cover

Cylindricity of the counter-sunk holes and flatness of the front face of the electrical socket cover were the two main geometric characteristics of interest because they were important for its functional requirement and useful for manufacturing operations. The callouts that were generated were then passed to the "evaluate callouts" command to generate a visual feedback on the form and fit of the scanned data within a specified tolerance of 0.5 mm. Table 1 shows these results.

Table 1: GD&T Evaluation of the Electrical Socket Cover (see Figure 4)

Laser Power = 2		Resolution 0.05 mm		Resolution 0.10 mm	
Callout	Tolerance	Measured	Result	Measured	Result
Flatness 1	0.5	0.172	Passed	0.184	Passed
Flatness 2	0.5	0.202	Passed	0.325	Passed
Flatness 3	0.5	0.261	Passed	0.137	Passed
Flatness 4	0.5	0.168	Passed	0.19	Passed
Flatness 5	0.5	0.702	Failed	0.68	Failed
Flatness 6	0.5	0.439	Passed	0.467	Passed
Cylindricity 7	0.5	0.336	Passed	0.417	Passed
Cylindricity 8	0.5	0.656	Failed	0.615	Failed
Cylindricity 9	0.5	0.466	Passed	0.475	Passed

It could be observed from the results that Callout Cylindricity 8 failed for both scanned CAD models. This callout was associated with one of the counter-sunk holes, and its failure may have resulted from the reconstruction of the triangular mesh in the polygonal model when implementing the “fill holes” tool since approximations were made to complete these awkward regions that had gaps of data. Another geometrical feature noticed to fail from the callouts was Flatness 5, which may have exceeded the set tolerance range due to altercations of the polygonal mesh when relaxing the rough edges of the bordering steep surfaces.

Conclusions

From this study and within the limits of experimental error, it can be concluded that laser power had a significant impact on the quality of the point cloud data captured, as evidenced through several screenshots. This was dependent upon the color and reflective nature of the object being scanned. Excellent capture was obtained for the electrical socket cover with no reflective surfaces at a low laser power.

Also, the amount of surface detail retained from the transition from point cloud model to polygonal model could be controlled by specifying the quantity of the triangular mesh. The higher the triangular mesh, the greater the intricacies were highlighted.

Variation of the scanning resolution greatly influenced the accuracy of the polygonal models in the data editing stage. The lower scanning resolution produced a polygonal model with fewer holes signifies that more information was captured, especially for awkward areas to scan such as the counter-sunk holes.

Inspection through GD&T helped identify which geometrical features of the scanned CAD model were within a specified tolerance when compared to the original CAD model of the object. The effects of variation of laser power and scanning resolution of the six scanning parameters identified on the data editing stage of the design process were investigated. Further research in this area is in progress to incorporate variation of the other scanning parameters and to represent their effects on the data editing stage and the subsequent impact on product manufacturing.

References

[1] Xu, X.W. and L. Song., "Development of an integrated reverse engineering system," *International Journal of Computer Applications in Technology*, Vol. 25, No. 1, 2006, pp 9–14.

[2] Dey, T.K., J. Giesen, and J. Hudson., "Decimating samples for mesh simplification," Proceedings of 13th Canadian Conference on Computational Geometry, Waterloo, Canada, 2001, pp 85–88.

[3] Boissonnat, J.D. and F. Cazals., "Coarse to fine surface simplification with geometric guarantees," *EURO-GRAPHICS '01*, Conference Proceedings, Manchester, UK, 2001, pp 490–499.

[4] Linsen, L., "Point cloud representation," *CS Technical Report 2001–2003*, Germany, 2001.

[5] Pauly, M., M. Gross and L.P. Kobbelt., "Efficient simplification of point sampled surfaces," *Proceedings of 13th IEEE Visualization Conference*, Boston, US, 2002.

[6] Alexa, M., J. Behr, D. Cohen-Or, S. Fleishman, D. Levin, and T. Silva., "Point set surfaces," *Proceedings of 12th IEEE Visualization Conference*, San Diego, 2001, pp 21–28.

[7] Moenning, C. and N.A. Dodgson., "A new point cloud simplification algorithm," *Proceedings of 3rd IASTED International Conference on Visualization, Imaging, and Image Processing*, Spain, September, 2003.

[8] Milroy, M.J., D.J. Weir, C. Bradley, and G.W. Vickers., "Reverse engineering employing a 3D laser scanner: A case study," *International Journal of Advanced Manufacturing Technology*, Vol. 12, 1996, pp 111–121.

[9] Weir, D.J., M.J. Milroy, C. Bradley, and G.W. Vickers., "Reverse engineering physical models employing wrap-around B-spline surfaces and quadrics," *IMechE*, Vol. 210, 1996, pp 147–157.

[10] Hoppe, H., T. DeRose, T. Duchamp, J. McDonald, and W. Stuetzle., "Surface reconstruction from unorganized points," *Computer Graphics*, Vol. 26, No. 2, 1992, pp 71–78.

[11] Curless, B. and M. Levoy., "A volumetric method for building complex models from range images," *Computer Graphics*, 30, Annual Conference Series, 1996, pp 303–312.

[12] Mencl, R. and H. Muller., "Graph-based surface reconstruction using structures in scattered point sets," *Proceedings of the Conference on Computer Graphics International 1998*, (CGI-98), pp 298–311.

[13] Azernikov, S., A. Miropolsky, and A. Fischer., "Surface reconstruction of free-form objects based on multiresolution volumetric method," SM'03, Seattle, Washington, US, June 16–20, 2003.

[14] Bradley, C. and G.W. Vickers., "Automated rapid prototyping utilizing laser scanning and free-form machining," *Annals of the CIRP*, Vol. 14, No. 1, 1992, pp 437–440.
[15] Kaisarlis, G.J., S.C. Diplaris, and M.M. Sfantsikopoulos, "Position tolerancing in reverse engineering: The fixed fastener case," *Pro. IMechE*, Vol. 221, September 2006, pp. 457–465.
[16] ShapeGrabber Incorporated, 2004, *ShapeGrabber® AI310 3D Scanning System Product Guide*, *AI310 User's Manual*, September, 2007.
[17] Geomagic, Inc., *Geomagic® Studio 9 Foundation Training Guide*, Chapel Hill, NC.
[18] Chang, K.H., S. Zahed, E. Mangesh, and C. Zhiqiang., "An integrated testbed for reverse engineering of aging systems and components," *Computer-Aided Design and Applications*, Vol. 3, No.1–4, 2006, pp 21–30.
[19] Geomagic, Inc., *Geomagic ®Qualify 9 Foundation Training Guide*, Chapel Hill, NC.

Acknowledgement

This research was supported in part by the University of the West Indies, St. Augustine Campus, Trinidad, under the Government of Trinidad and Tobago Research Development Fund (26607-447403).

Biography

FAHRAZ ALI is currently a post-graduate student in the Department of Mechanical and Manufacturing Engineering at the University of the West Indies, St. Augustine, Trinidad. He is working on an MPhil project within the areas of product design and development and CAD/CAM.

BOPPANA V. CHOWDARY is a faculty member in the Department of Mechanical and Manufacturing Engineering at the University of the West Indies, St. Augustine, Trinidad. His research interests are in the areas of flexible manufacturing, product design and development, and CAD/CAM.

C.A.C. IMBERT is a Professor of Materials and Manufacturing in the Department of Mechanical and Manufacturing Engineering of the University of the West Indies, St Augustine, Trinidad. He is Chairman of Metal Industries Company Limited, which specializes in tool and die design and manufacture and precision machining.