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The Effects of Digitising Parameters on Noise in Point Cloud Data: An Investigative Study on a Freeform Model

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Abstract: *In the computer aided design (CAD) industry data acquisition is a rather tedious and time consuming process. It requires a high degree of skill due to adjustments needed to obtain a Non-uniform rational B-spline (NURBS) model from the digitised data. This paper provides a solution for the reduction of noise in point cloud data through the manipulation of digitisation parameters. Experiments were performed using the ShapeGrabber®AI310 laser scanner to evaluate three parameters that contributed to noise generation in the point cloud data. The three selected parameters were environmental light, laser intensity and object reflectivity. Evaluation of the point cloud data was then carried out using 3D and 2D comparisons and Geometric Dimensioning and Tolerance (GD&T) analysis. The study found that laser intensity has the most significant effect in the generation of noise in the point cloud data, whereas environmental light has the least effect of the three parameters examined. The methodology proposed in this research will assist designers and practitioners in improving both the efficiency and effectiveness of design and manufacturing operations.*

Keywords: *Reverse Engineering, Inspection, 3D Digitisation, Freeform Model, Noise, Parameters*

1. Introduction

Today's market is characterised by fast product delivery, and great demands for fresh and distinctive products (Ye et al., 2008). To be competitive, manufacturers need to provide quality products that can be tailored rapidly and inexpensively to suit varying customer expectations (Forrest and Iyer, 2011). Reverse Engineering (RE) principles provide industrial solutions, whereby manufacturers can inspect manufactured products without the need to constantly create prototypes that facilitates a reduction in cost and time and an overall increase in the quality of products. For example, a manufacturing company that creates a product can use RE guidelines to inspect the product to make adjustments in design specifications. In these circumstances, the manufactured product needs to be digitised to obtain a 3D digitised CAD model. The digitised model can then be compared with the original CAD model to determine the extent of variations from the design specifications.

For effective realisation of product concept, in the face of intensive global competition, the upgrade of contemporary design processes is the main focus of modern manufacturing companies (Chowdary et al., 2011; Ali et al., 2013). In addition, different investigations (such as dimensional, stress, thermal and strength analyses) can be carried out on the model, thereby reducing the need to produce physical prototypes of varying designs. This would result in reduced costs and manufacturing time in the design phase of a new product (Forrest and Iyer, 2011).

Product accuracy is critical in the inspection phase of manufacturing. It is the yardstick against which products are judged, and thus determines whether the produced stock is accepted or rejected. Therefore, the 3D digitised model must be designed to closely resemble the physical model. However, the problem of noise persists in 3D digitised data (Gross and Pfiste, 2007). The body of knowledge on RE reveals a gap in the identification of the digitisation parameters which contribute to noise and which subsequently affect the quality of the digitised CAD model (Wang, 2010). Identifying and adjusting such parameters would allow for the generation of an accurate 3D scanned model.

From the literature it is clear that freeform objects would be best suited to investigating the impact of various parameters on the quality of the digitisation process (Campbell and Flynn, 2001. Generally, a freeform object is often assumed to be composed of one or more non-planar and non-quadric surfaces (Campbell and Flynn, 2001). To create a freeform object, an integrated approach to design and development was recently proposed (Ali et. al., 2009; Ali and Chowdary, 2011). This forms the basis for selecting a freeform object to conduct the study.

The paper aims to fill the gap in RE field by providing solutions, through an experimental investigation, which would allow for the variations in a 3D digitised model to be reduced thereby optimising the digitisation process. Subsequently, the question as to how variations due to noise in the point cloud data can be reduced would be answered.

2. Literature Review

The process by which an individual acquires a concept of the design of a product from digitisation of a physical model and generation of the CAD model which can be reused, modified and optimised for downstream operations is generally known as RE (Ismail et al., 2009). Through the use of RE principles reduced inspection time of products would be achieved which results in significant cost reduction that would be passed on to the customer (Geomagic, 2010). This generally involves approval from the customer, who would review the product and manufacturing data to ensure that the product was designed to the customer's expectations and the product that follows will also conform to the stated requirements (Gordon, 2010).

Once there is a need for an object to be inspected, or for a device to be reinvented or evolved, RE tools and techniques can play an important role in enhancing the design and manufacturing operations (Wang, 2010). RE has been globally acknowledged as being a significant step in the product development cycle (Bagci, 2009). Whether it may be used in the design of exterior of automobiles (Aoyama and Suzuki 1999, 375); the design and manufacture of aircraft (Keller et al. 2007, 119); or in the steel milling industry (Pearce 2005, 74), RE provides concepts and tools that are critical to a manufacturing company's operations. Other applications of RE include the recovery of a damaged component, improvement on an existing design, and design of a new part (Yuan et al., 2001).

3. Research Approach for Analysis of Noise in Point Cloud Data

The proposed methodology consists of 6 phases which support industrial operations through the creation of a digital model that closely resembles the original object. That is, if the digitised part data is not satisfactory, then the problems causing such a result would be corrected and the new data would be validated. The study's research methodology is illustrated in Figure 1. It starts with the design conception of the selected freeform object and continues to analysis phase. The tools used and the expected outcomes of the approach are presented in Table 1.

How each parameter affects the point cloud data can be determined through 3D and 2D comparisons and Geometric Dimensioning and Tolerance (GD&T) analysis. The proposed analysis shows which combination of the selected parameter settings would be beneficial to the industry in the reduction of noise in the point cloud data.

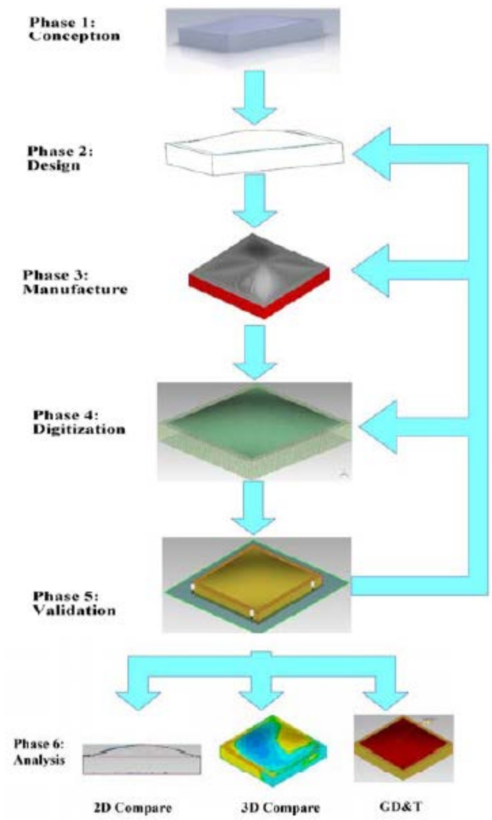

Figure 1. Research Methodology

Table 1. Phases, Tools and Model Outcomes of the Proposed Approach

Phases	Tools	Model Outcomes
1. Conception	• Research • CAD software	Conceptual Free-form Model
2. Design	• CAD software	3D CAD model (IGES format)
3. Manufacture	• CAM software • CNC software • CNC Mill	Freeform object (CLM)
4. 3D-Digitisation	•3D laser scanner • Geomagic Studio®12	Point cloud model (IGES format)
5. Validation	• RE software • Surface profilometer	
6. Analysis	• RE software	

4. Implementation of the Proposed Approach for Analysis of Noise in Point Cloud Data

The six (6) phases of the proposed approach are as follows:

Phase 1 is the conception phase where the purpose and function of the object under consideration are determined. The product conceptualisation tools (such as material research, market research and product research along with analysis through CAD/CAM software) were implemented in this phase. Initially a freeform object that resembles a contact lens was conceptualised to incorporate features in the design to achieve its desired purpose and function. Hereafter, it will be referred to as Contact Lens Model (CLM). CAD/CAM software was then used to render the concept into a solid CAD model. This conceptual model was further developed in the design phase.

Phase 2 is the design phase where the freeform model, conceptualised in Phase 1, is manipulated specifically to create the final model of the selected object. This was performed by examining the scope of the space to create the freeform object using CAD software. Dimensional specifications were then applied to the solid CAD model. After achieving the design specifications, the solid CAD model was converted to the IGES file format to be used in the downstream phases of manufacture, validation and analysis.

Phase 3 is the manufacturing phase. In this phase, the solid CAD model created in the design phase is manufactured to produce the CLM (see Figure 2). To achieve the CLM, the solid CAD model is initially sent to the CAM software in an IGES format. CAM software is then used to simulate the tool path and to generate NC code in order to produce the CLM by using the CNC milling machine. A work piece of 100mm x 100mm x 25mm is then selected to be tooled for simulation. High-density polyethylene (HDPE) plastic is selected as the work piece material. This material was selected since it allowed for the fastest machining of the CLM which was found to be 2 hours. The tool selected was a 4mm bull end mill, as this provided the deepest cut into the work piece: a cut of 9.435mm.

Phase 4 is the digitisation phase and has five (5) steps which are data acquisition, data capture, data editing, data fitting and analysis. In the data acquisition phase the selected object is prepared. For this purpose three parameters, environmental light, laser intensity and object reflectivity, were selected to carry out the experiments. The proposed approach taken to examine how the selected parameters affect the digitisation process, more specifically, the acquisition of point cloud data was done by adjusting each parameter to its discrete limits. In this regard, the environmental light parameter was set as either on or off; the object reflectivity parameter was either shiny (high) or non-shiny (low); and the laser intensity parameter was either strong or soft. This approach would produce conclusive data for investigating the effects of each parameter. In the data capture phase, un-ordered point data were obtained through digitisation. The point data then underwent a process where it was registered and merged to create a point cloud model. Registration is important to complete the digitisation of freeform objects.

Registration of the freeform model at this stage leads to the creation of the point cloud model. The point cloud model is then sent to the data-editing phase. In the data-editing phase, cleaning of the object is performed.

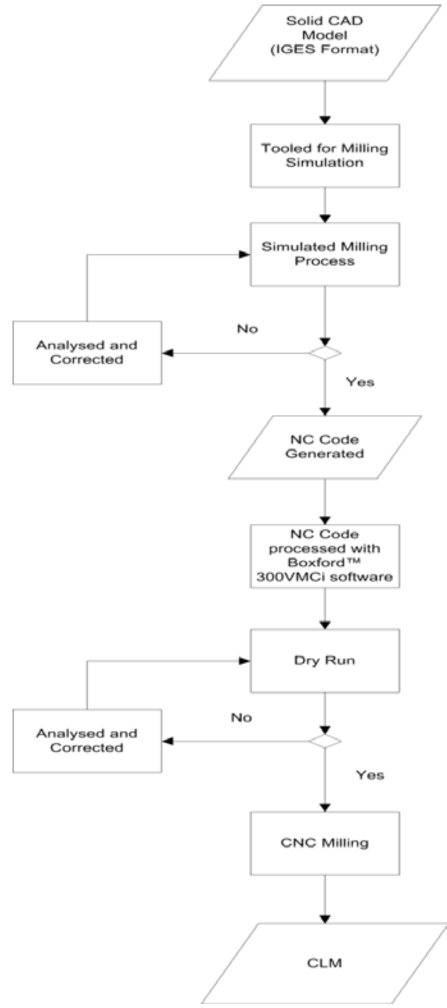

Figure 2. Workflow of Phase 3 Manufacturing

Functions such as repair intersections, fill holes, boundary repair and decimating triangles are applied to clean the model. The result of these functions was eventually a triangulated model.

In the data-fitting phase, functions such as contour detection and extraction, patch constructions, grid construction and surface fitting are applied to the triangulated model to transform it into a CAD model. This phase is especially critical when taking into consideration freeform objects, as it examines the surface, and groups data points into sets subsequently giving a suitable single surface (see Figure 3). With the obtained CAD model, analysis can then be performed.

Phase 5 is the validation phase. In this phase, the results of the test runs are validated before they are analysed. Validation of the results would ensure confidence in the data used. A surface profilometer was employed on the digitised CLM to obtain the dimensional information, with special emphasis placed on the free-form curve. The profilometer software was then applied to extract the data from the surface profilometer.

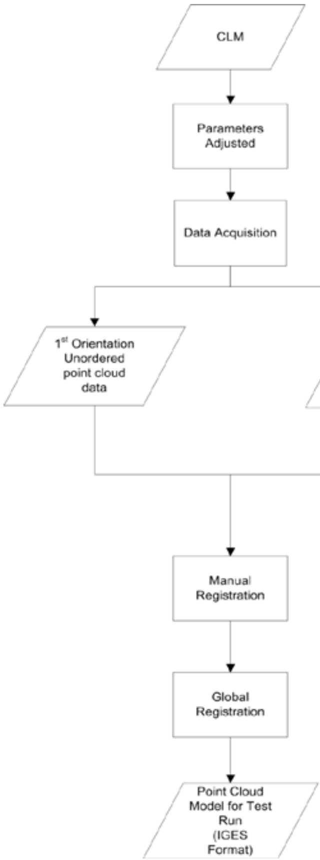

Figure 3. Workflow of Phase 4 Digitising

The dimensions of the digitised CLM were then evaluated using the RE software. Once the information from the two different sources is similar, it can be deemed as validated data which can be used for analysis. Data from the two sources are considered to be similar once the data variations do not exceed 4%. This would result in a 96% confidence in the data being analysed.

Phase 6 is the analysis phase. In this phase RE software is used to analyse the data to compare the solid CAD model and the point cloud model. The two models would first have to be aligned before the analyses can be performed using 3D Compare and 2D Compare. Figure 4 shows the workflow of Phase 6 analysis.

For the analysis purpose, the solid CAD model was set as the reference object whereas the obtained point cloud model was set as the test object for that specific test run. 3D Compare produces a 3D colour-coded mapping of the differences between the 2 models. It shows areas of deviation between the two models and produces the standard deviation of data from one source with another. Meanwhile, 2D compare generates cross-sections and illustrates the deviations between the test and reference models. Similar to 3D Compare a standard deviation was also obtained. From the analysis the average deviational error between the two models was recorded.

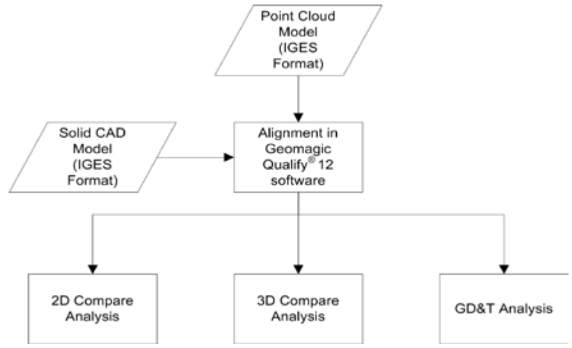

Figure 4. Workflow of Phase 6 analysis

5. Testing

Testing determines the effects of the three different parameters on the generation of noise in the point cloud data. This is done by changing the parameters during digitisation at their discrete limits, since it is often difficult to determine in advance which parameters will be poorly determined (Stolovitzky et al., 2007).

The light parameter was examined by turning the light on or off during the digitisation process. This is done by shining the suitable light source in the area where the physical model is being digitised. In this instance the light source on the object would be considered as “on” for the parameter. Next, the area being scanned was covered and all the light sources in the laboratory turned “off”. This would ensure that light is not present in the environment when digitising, and thus the parameter would be considered “off”.

The reflectivity parameter was examined by the physical freeform object being either in the high or low state. The material of the physical model is high-density polyethylene, which is dull in colour. This dullness was deemed sufficient enough to be the “low” case for the reflectivity parameter. For the “high” reflectivity case of the parameter, the physical model was sprayed thoroughly with a bright chrome coating. The coating gave a very shiny physical model. The model was deemed as shiny if a light source is shone on the object and light is reflected. The conditions were satisfied for the object to be classified as shiny and for that parameter to be labelled as “high” in this instance. The intensity of the laser parameter was examined by adjusting the scanner laser intensity as either strong or soft.

Different combinations of these parameters can be attained during scanning, and thus a methodology was formulated to examine each one individually. Combinations were used to calculate how many test runs needed to be performed. This was done as the order of arrangement of the parameters in the group does not necessarily need to be taken into account. For estimation of the number of combinations, the following equation (Billinton and Allan, 1992) was used:

$$C_r^n = \frac{n!}{r!\,(n-r)!}$$

Where 'n' is the total number of combinations and r is the number of selections.

Thus, given that the number of combinations of parameters is 3 and 1 parameter would be evaluated in each case the combination would be C_1^3. There are two extreme cases for each parameter to be evaluated. Thus, the total amount of experiments required is $C_1^3 + C_1^2 = 8$. A summary of the analysis can be seen in Table 2.

Table 2. A Summary of Analytical Results from Validated Data

Test Run	Point Cloud Data (points)	3D Compare Standard Deviation /mm	2D Compare Standard Deviation /mm	GD&T Analysis	Average Error /mm $x10^{-1}$
1	18,692,296	1.852	1.354	N/A	8.461
2	18,229,916	2.221	0.328	N/A	3.150
3	11,726,541	0.882	0.706	N/A	7.611
4	7,092,321	1.524	2.817	•Surface Profile = 4.425 • Flatness = 8.963	6.655
5	7,363,409	0.357	0.295	•Surface Profile =1.985 • Flatness = 0.487	3.155
6	4,201,667	0.303	0.353	•Surface Profile =1.855 • Flatness = 0.459	2.050
7	5,354,592	0.327	0.249	•Surface Profile =1.809 • Flatness = 0.483	2.420
8	16,436,977	1.887	0.518	N/A	5.567

6. Discussion

The analysis of all the test runs confirmed empirically that the parameters selected for the research had an overall, individual effect in the generation of noise in the point cloud data. Inferences were drawn from the results of the 3D and 2D compare and average error variation between the two. The parameter of environmental light generates noise in the point cloud data significantly for a highly reflective object. Test run 4 supports this where the environmental light was on and the object reflectivity was high. This combination of light and reflectivity showed quantitatively that noise would be introduced significantly in the point cloud data. Test run 7 on the other hand showed that when reflectivity is low, environmental light does not have a significant effect on the object, though it should be noted it can introduce noise as shown from test run 6. However, out of the three parameters, reflectivity introduces the least amount of noise in the point cloud data.

The inference that can be made from the laser intensity parameter is that of the three parameters examined, this parameter introduces the most noise at its maximum discrete mode. This can be seen in test run 8 where the other two parameters were at their discrete modes, compared to test run 7 where the environmental light parameter was at its maximum discrete mode and the other two parameters were at their minimum discrete mode. This can also be seen in test run 5 where the parameter object reflectivity was at its maximum discrete and the other two parameters were at the minimum discrete mode. In summary, the results indicate that laser intensity has a significant effect on noise in the point cloud data when compared to the other parameters.

With respect to noise generation, the object reflectivity parameter has a significant effect especially when any sort of light is present. This is evident from test run 1 which had a larger point cloud data compared to test run 3 where it was lower when the same consistent conditions were applied to the other two parameters. This can also be seen in test runs 2, 8, 4 and 7. This was also consistent with respect to the average error for the comparison of test runs all except for test run 2 and test run 8. The object reflectivity in test run 8 was relatively low, however the point cloud generated had a significant amount of noise which can be seen visually.

In this case, the scattered light on the surface of the object due to the strong laser intensity caused a huge amount of noise to be generated in such a way that the point cloud model became distorted. This showed that the addition of noise in the point cloud model is a factor to be examined, since noise in the point cloud data in the form of reflected light can be isolated visually and cleaned whereas the noise generated due to scattered light would require a more complex process of elimination. This phenomenon can be seen in Figure 5.

7. Conclusion

From the preceding analysis, the following conclusions can be drawn.

1) Of the three parameters examined in the generation of noise in the point cloud data, the laser intensity parameter has the most significant effect on the test

object.

2) The environmental light parameter has the least effect in the generation of noise in the point cloud data.

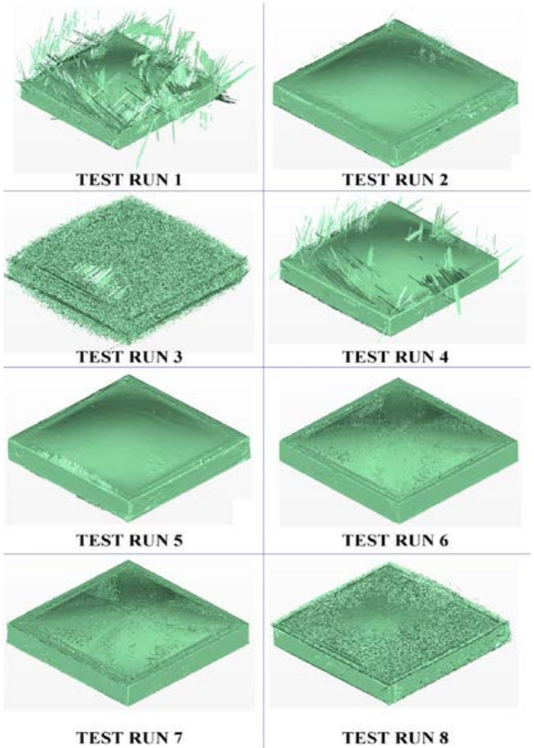

Figure 5. A phenomenon of the test runs

3) The recommended optimum settings for digitising a reflective object are low laser intensity and complete elimination of environmental light.
4) The optimum settings for digitising a non-reflective object are the total elimination of environmental light and setting the laser intensity at medium level.

The results provide a foundation for expanding the body of knowledge in RE. It should be noted that though the focus is RE, the methodologies used in this study can be translated into other areas in the scientific field. Lessons can be learnt from this research and applied to various areas such as medical, filming, and manufacturing industries.

The research can be expanded by examining more parameters that can affect the point cloud. Three parameters worth investigating in the future are air quality, colour of the material and temperature of the environment (Andrews and Phillips, 2005). Additional research can include the use of the methodology, presented here, with contact digitisers such as the coordinate measuring machine (CMM).

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