Sub-delta volume generation for recognition of freeform cylindrical surface part model

Ahmad Faiz Zubair¹, Mohd Salman Abu Mansor²,*

¹, ² School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia.

Email: ¹afz15_mec008@student.usm.my, ²,*Corresponding author: mesalman@usm.my

Abstract. Material removal volume of lathe machining part model can be calculated and simulated by delta volume generation in recognition of its feature. To minimise production cost, material removal volume has to be optimised. This paper presents a case study of feature recognition for freeform cylindrical surfaces. Once surfaces detected as spline surfaces, duplication and lofting of the surfaces will generate new sub-delta volume (SDV). These SDV’s volumes were then calculated to find the overall delta volume (ODV). Differentiation between ODV in term of ODV error ( ) is then calculated to indicate differences between manual calculated ODV (ODVmanual) and algorithm generated ODV (ODValgorithm). Two freeform part models were verified with the develop algorithm and show very less .

1. Introduction
Volume decomposition method is a feature recognition method which intends to decompose feature shape from its geometric information. By decomposing these features, exact volume for material removal volume of the part model can be expected. Features that been recognised will represent its own geometric shape leading to more understanding and ease of processing of desired output. Besides the application for feature recognition [1]–[6], this method were applied in many applications such as CAD’s simplification [7], [8], recognising uncut region for EDM [9] and many more.

In previous works, sub-delta volumes were classified by machining processes in term of sub-delta volume for finishing (SDVF) and sub-delta volume for roughing (SDVR) [2]. To manage gaps produced because of surface continuity, sub-delta volume for finishing filled region (SDVF-FR) are developed. To generate decompose body of recognised regular surfaces specifically analytic surfaces, the recognised surfaces is duplicate and lofted via a translation in normal vector direction [4]. These approaches however founded to have problems in dealing with cylindrical surfaces due to the absent of parting line. Regular surfaces of symmetrical and non-symmetrical cylindrical part model had been recognised in[2], but, freeform surfaces had not yet been recognised. The major challenge in generating sub-delta volumes for freeform faces is in identifying its physical significance. The complex geometry of spline surfaces need to be extracted and a new body of sub-delta volume generated.
In this study, Overall Delta Volume (ODV) of part models with freeform surfaces is generated. To validate errors produced by the ODV, manual ODV from CAD part model and stock model volume are calculated. To decrease the number of errors generated, gaps and overlapping bodies are managed by generations of SDVF-FR and Boolean operations.

2. Technical definitions
Sub delta volumes are the volume generated by the algorithm to recognized features. Definitions of SDVF, SDVR and SDVF-FR will be explained in the next subsections.

\[
\text{Stock model volume, } V_s = ODV_{\text{manual}} + V_{\text{CAD}}
\]

\[
ODV_{\text{algorithm}} = \sum_{i=0}^{n} \text{SDVF} + \sum_{i=0}^{n} \text{SDVF-FR} + \sum_{i=0}^{n} \text{SDVR}
\]

\[
\Delta ODV = \frac{(ODV_{\text{algorithm}} - ODV_{\text{manual}})}{ODV_{\text{manual}}} \times 100
\]

2.1. Sub Delta Volume for Roughing (SDVR)
Roughing process will be done to remove the largest possible material from stock model. Material to be removed in roughing will be in the range of 2.5mm - 20 mm. Roughing thicknesses will be asked by the algorithm from user. Boolean operations will be implemented to generate SDVR bodies. Body of SDVF and part model body will be subtracted from the stock model to generate exact shape of SDVR. Although in machining roughing will be prior to finishing, the developed algorithm will generate SDVR after stock model and SDVF generation. To minimize errors and for the ease of planning, SDVR bodies will be generated in four sections which are in top, bottom, left and right section.

2.2. Sub Delta Volume for Finishing (SDVF)
Machining of finishing process will be done in range of 0.75mm-2mm after roughing with depth of cut recommended 0.25mm by using High Speed Steel (HSS) cutting tool [10]. Body of SDVF are generated by duplicating recognised faces and new body created by lofting via finishing thickness. Duplicated faces will be offset rather than translated to ensure uniform thickness. Figure 1 shows the concept of SDVF generation. F1 and F2 are the freeform surfaces recognised by the algorithm. Algorithm will generate SDVF bodies (SDVF1 and SDVF2).

![Figure 1. SDVF body generation for freeform faces F1 and F2](image)

![Figure 2. SDVF-FR body in yellow to fill gap of planar and freeform SDVF generation](image)

2.3. Sub-delta volume for finishing filled region (SDVF-FR)
To remove overlapping and gap between SDVF, SDVF will be filled and intersection of the SDVF bodies will be removed by using Boolean operations of subtraction between the bodies. These gaps happens as surface continuity of G0 (single point touching but not tangent) between adjacent surfaces. Surface continuity happens when two or more surfaces touches each other. Figure 2 shows SDVF-FR in yellow colour that generated between planar SDVF and freeform SDVF.
2.4. Freeform surfaces
Spline face with continuity of C1 (tangent continuity) and above along with u and v parameter of G1 and above are considered as freeform surface by the developed algorithm. If faces with C0 and G0 (non-tangent continuity) state algorithm will consider it as two different faces. Representation of common freeform face is by Bezier, B-Spline or NURBS face [11], [12]. This paper will adopt freeform surfaces based on feature global shape (FGS) and semantics parameter [13].

3. Algorithm frameworks
Overall algorithm is developed to cater the overall feature recognition process. Its include four stages that are: 1) part model validations, 2) part model orientations, 3) surfaces recognition, 4) delta volumes generation and 5) ODV compilations. The process stages are shown in Figure 3.
Part model validations include processes of compelling the CAD model to be in .SAT format and in cylindrical shape. Topological structures of part model are also extracted during this stage.

Second stage caters the orientations of part model. Orientation of part model is important as lathe machining will associate to two axes that are \(x\)-axis and \(z\)-axis. Top and bottom surfaces of part model will be identified and if these surfaces are not in vector direction of \(x\)-axis, part model will be re-oriented. Detail explanations on part model orientations via its cylindrical axis are done in previous work [14].

Next stage will be the surfaces recognition. Although regular or analytical surfaces are essential to be recognised, this paper is focusing on freeform surfaces. Therefore, work on regular faces had been published in previous work [2]. Algorithm is built to recognised spline face by FACE topology \textit{is spline face} API function. Spline surface(s) that been recognised will then executed to generate its SDVF. SDVF is generated by creating additional body that is similar geometrical shape by finishing thickness, \(t\).

Freeform face recognitions and SDVF generation pseudo code:

```plaintext
Define CAD part model data input in .SAT file
Determination of part model volume, \(V_{CAD}\)
Extraction topological structure, surfaces, \(S_i (i = 1, 2, \ldots, n)\), edges, \(E_i (i = 1, 2, \ldots, n)\)

\textbf{for} \(i = 1: S_n\) all \(n\) surfaces
  \begin{itemize}
  \item Evaluation surface type
  \item \textbf{if} \(S_i = \) Spline surface, analytic faces type hold FALSE
  \item Copy surface into \(S_{d1}\) and \(S_{d2}\)
  \item Offset \(S_{d2}\) by \(t\)
  \item Loft \(S_{d1}\) and \(S_{d2}\) into new sub volume \(SDVF_i\)
  \item Save \(SDVF_{(i:n)}\)
  \end{itemize}
\textbf{end if}
\textbf{end for} \(i\)

Next process
```

Moreover, other sub-delta volumes such as SDVR and SDVF-FR will be generated.
The last stage of the developed algorithm is ODV compilations. All sub-delta volumes will be called and calculation of its volume and surface area will take place. Summations of all the volume will be the ODV. Summary of all calculations will be display at the output window.

4. Verifications

Two part models were used to verify the developed algorithm. These part models are an example of turning machining part model with freeform surfaces. The part models are chess queen and chess bishop. Sub-delta volumes are differentiated by colours. SDVF for regular surfaces are presented in green colour, SDVF for freeform surfaces by red, SDVF-FR by yellow, SDVR by blue colour. Moreover, cyan colour represents fillet, sphere and de-feature model and grey colour represents part model’s internal feature.

Chess bishop consist combinations of regular and freeform surfaces and one internal feature. Besides that, this part model also consist fillet and sphere feature. Fig. 3(a) shows the exploded view of all the sub-delta volumes. Balloons indicators of features are matching with Table 1’s column three (no body) for the ease of understanding. Fig. 3(b) shows results displayed by the window console. These results indicate every sub-delta volumes recognised by the algorithm and display volume and surface area of the sub-delta volumes. Summation of all the volume and surface area for all sub-delta volumes will be displayed as well. To measure how long the developed algorithm takes to generate all the sub-delta volume, timing function is applied and time consume to generate the volumes is displayed.

Moreover, another part model is being tested with the algorithm that is chess bishop. It consists of combinations of regular and freeform surfaces, fillet, sphere and SDVF-FR. Fig. 4 shows the exploded view of all the sub-delta volumes and Fig. 5 shows results displayed by the window console. Stock model volume for this part model is 247273 mm$^3$ and $V_{CAD}$ is 50850.9mm$^3$. From Eq. 1 $ODV_{manual} = 196422.1$ mm$^3$. To validate the amount of ODV error produce, Eq. 3 is applied and result shows that it’s producing $\Delta ODV = 0.003\%$.

| Table 1 Volume of sub-delta volumes of Chess Bishop Part model | Table 2 Volume of sub-delta volumes of Chess Queen Part model |
|---------------------------------------------------------------|---------------------------------------------------------------|
| **No.** | **Body** | **No of body** | **Volume (mm$^3$)** | **No.** | **Body** | **No of body** | **Volume (mm$^3$)** |
| 1 | Planar SDVF | 6 | 1162.32 | 1 | Cylindrical SDVF | 2 | 1169.39 |
| 2 | Freeform SDVF | 4 | 6013.2 | 2 | Planar SDVF | 6 | 2916.542 |
| 3 | Fillet SDVF | 8 | 4089.75 | 3 | Freeform SDVF | 4 | 9618.32 |
| 4 | Sphere SDVF | 1 | 210.59 | 4 | Fillet SDVF | 8 | 4435.7 |
| 5 | Pocket | 1 | 1242.5 | 5 | Sphere | 1 | 81.2818 |
| 6 | SDVR | 4 | 184300.44 | 6 | SDVF-FR | 1 | 330.866 |
| 6 | SDVF | 4 | 241777.6 | 7 | SDVR | 4 | 241777.6 |
| **Total** | | | 197018.8 | **Total** | | | 260329.7 |
Figure 4. Result for Bishop Part model. (a) Exploded view (b) Results from console window

Stock model volume for this part model is 363398 mm$^3$ and $V_{CAD}$ is 103728 mm$^3$. From Eq. 1 $ODV_{manual} = 259670$ mm$^3$.

To validate the amount of ODV error produce, Eq. 3 is applied and result shows that it’s producing $\Delta ODV = 0.0025\%$.

Figure 5. Result for Queen Part model. (a) Exploded view (b) Results from console window
5. Conclusion
The developed algorithm is proven to recognised freeform surfaces. Two part models with combinations of regular and freeform surfaces were verified and $\Delta ODV$ show very less amount. This works will be useful in order to plan for machining of the freeform surface that is different with regular surface geometrical properties.

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