Feature-based Support Generation in Fused Deposition Modeling (FDM) Machine

by

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LIST OF SYMBOLS

L_i	Vector formed by $V_{i-1}V_i$
L_{i+1}	Vector formed by V_iV_{i+1}
$\vec{l}_i$	Unit vector of L_i
$\vec{l}_{i+1}$	Unit vector of L_{i+1}
V_{i-1}	Vertex of V_{i-1}
V_i	Vertex of V_i
V_{i+1}	Vertex of V_{i+1}
V'_i	New position vertex of V_i due to offset by the layer thickness, t
L'_i	Equidistant line of L_i due to offset by the layer thickness, t
L'_{i+1}	Equidistant line of L_{i+1} due to offset by the layer thickness, t
α	Self-Support angle
t	Layer thickness
(x_i, y_i)	Vector formed by coordinate $V_{i-1}V_i$ from the origin
(x_{i+1}, y_{i+1})	Vector formed by coordinate V_iV_{i+1} from the origin
POA_{ex}	Area of POA for exterior contour ring
POA_{in}	Area of POA for internal contour ring
A_{ex}	Area of the external contour ring
N	Total amount of layers for part model
n	Number of internal contour ring
$\bigcap$	Intersection operation
$\bigcup$	Union operation
P	Layer P
Q	Layer Q
P'	Projection of layer P to layer Q in z direction
Q'	Offsetting of Layer Q
$CSRA_k$	Cross-Sectional slice Region Area of lower layer
$CSRA_{k+1}$	Cross-Sectional slice Region Area of upper layer
$CSRA'_k$	Cross-Sectional slice Region Area of offset lower layer
$k+1$	Level of upper layer
k	Level of lower layer

RA	Resultant Area between *CSRA* of upper layer and *CSRA* of lower layer
RA'	Resultant Area of upper and offset lower layers
m	Amount of Base-Support layer
RA_1	Resultant Area at level 1
RA_2	Resultant Area at level 2
V_{pq}	Input for MLP 1 network (total volume)
O_{rq}	Output and input for MLP 1 and MLP 2 networks, respectively
S_{pq}	Input for MLP 2 network (number of support structures)
p	Model used in the optimization
q	Pre-defined part deposition orientation direction
r	Stage of network

LIST OF ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
AI	Artificial Intelligent
AM	Additive Manufacturing
ANN	Artificial Neural Network
BSS	Base-Support Structure
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CNC	Computer Numerical Control
CSRA	Cross-Sectional slice Region Area
ESF	External-Supported Feature
ESS	External-Supported Structure
ESV	External-Supported Volume
FDM	Fused Deposited Modeling
FIL	Feature Interaction Loop
FIS	Feature Interaction Surface
FV	Flat Volume
GA	Genetic Algorithm
GP	Genetic Programming
LM	Layered Manufacturing
MLP	Multilayer Perceptron
NC	Numerical Control
NSR	Non-Supported Features
ODM	Orthogonal Deposition Manufacturing
OPDO	Optimum Part Deposition Orientation
POA	Permitted Overhang Area
RP	Rapid Prototyping
SLA	Stereolithography Apparatus
SSF	Self-Supported Feature
SSV	Self-Supported Volume
STL	Stereolithography
SVR	Support Vector Regression

WSS	Water Soluble Support
2D	Two Dimensioning
3D	Three Dimensioning

Pembentukan Sokongan Asas Sifat dalam Mesin Pemodelan Pengendapan Melakur

ABSTRAK

Pembentukan Sokongan Asas Sifat merupakan teknik yang dicadangkan di dalam mesin Pemodelan Pengendapan Melakur. Teknik ini mampu memberi maklumat tentang isipadu dan bilangan struktur sokongan di mana ia berkait rapat dengan penghalaan pengendapan model. Terdapat dua jenis asas sokongan dalam pembentukan model produk Pemodelan Pengendapan Melakur, iaitu Asas Sokongan Sendiri dan Asas Sokongan Luaran. Asas Sokongan Sendiri tidak memerlukan bahan sokongan manakala Asas Sokongan Luaran melibatkan penggunaan bahan sokongan tambahan dalam pembentukannya. Pada masa kini, pelbagai teknik telah dicadangkan untuk mengenal pasti sifat adalah terhad kepada proses pembuatan yang spesifik. Daripada aspek yang lain, proses perancangan LM adalah tidak automatic sepenuhnya dan menjuruskan ke arah penurunan kualiti produk dan meningkatkan keupayaan untuk membuat kesilapan. Tambahan pula, banyak kesilapan yang terjadi adalah di sebabkan penglibatan manusia dalam proses yang kritikal ini. Isu lain ialah format fail STL yang digunakan untuk memindahkan data CAD kepada proses perancangan pembuatan berlapis menghasilkan kehilangan maklumat rekabentuk dan fungsi sifat. Penentuan Penghalaan Pengendapan Model yang optimum adalah didapati sukar dan mengambil masa yang panjang untuk dibina yang mana ianya dipengaruhi oleh kelajuan dan pertukaran hujung muncung ketika pemendapan bahan. Objektif utama tugasan ini adalah untuk mengintegrasikan antara Rekabentuk Terbantu Komputer dan Pembuatan Terbantu Komputer dengan menggunakan teknik asas sifat. Ini dapat membantu dalam mengautomasikan perancangan proses Pemodelan Pengendapan Melakur sebelum pembuatan model dengan pengurangan ralat manusia. Dalam tugasan ini, jumlah minimum isipadu dan bilangan struktur sokongan dipilih bagi menentukan penghalaan pengendapan model yang optimum. Tugasan yang dijalankan juga tertumpu kepada penambahbaikan kawasan permukaan tidak bersentuh di antara struktur sokongan dan model.Ketepatan rangkaian ditentukan melalui lima struktur MLP (Struktur 1 hingga 5). Ketepatan untuk semua struktur MLP pada spesifik nod adalah dianalisi. Hasil gabungan struktur MLP 1 dan MLP 2 adalah dengan jumlah isipadu dan bilangan struktur sokongan yang minimum akan dipilih sebagai Penghalaan Pengendapan Model yang optimum. Proses mengoptimumkan parameter ini dilakukan dengan menggunakan rangkaian neural buatan. Proses mengoptimumkan jumlah isipadu dan bilangan struktur sokongan dilakukan dengan menggunakan rangkaian neural buatan. Paramter ini juga perlu dipertimbangkan disebabkan kos fabrikasi dan masa pembinaan. Model yang telah melalui proses penambahbaikan seterusnya dihasilkan dengan menggunakan mesin FDM-3000. Keputusan Penghalaan Pengendapan Model yang optimum dibandingkan dengan model yang telah digunakan di dalam kerja-kerja yang terdahulu. Hasil kajian ini menunjukkan bahawa penghalaan yang sama telah dikenalpasti. Keputusan eksperimen juga menunjukkan bahawa persentuhan antara struktur sokongan dan model telah ditambahbaik sebanyak 38%. Permukaan tidak bersentuh pada kawasan yang tidak diperlukan dari kedudukan yang paling atas hingga kedudukan yang paling bawah oleh struktur sokongan telah dihasilkan. Teknik ini juga boleh digunakan dalam percetakan teknologi 3D terkini.

Feature-based Support Generation in Fused Deposition Modeling Machine (FDM)

ABSTRACT

Feature-based Support Generation is a technique that has been proposed in Fused Deposition Modeling (FDM) machine. This technique can provide information of volume and amount of support structure which are closely related to orientations of part deposition. There are two types of support features in FDM part model development, which are Self-Supported Features (SSF) and External-Supported Features (ESF). The SSF requires no support material while ESF involves the use of additional support material in their fabrication. Currently, various techniques have been suggested to identify features are limited to a specific manufacturing process. In other aspect, the LM process planning is not fully automatic and lead to part quality degradation and increases the possibility of making errors. Furthermore, many errors are occurred due to the involvement of human in this crucial process. Other issue is that the Stereolithography (STL) file format representation is used to transfer the CAD data to the LM process planning resulting to the loss of design and functional feature information. Determining the OPDO was found to be difficult and consumed longer build times that influenced by the speed and the change of nozzle's tip during material deposition. The main objective of this work is to integrate between Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) using a feature-based technique. This will help in automation of FDM process planning prior to the manufacturing of part model with less human error. In this work, the minimum volume and amount of support structure are selected in order to determine the optimum part deposition orientation. This work also focuses on the improvement of the non-contact surface area between the support structure and part model. The accuracy of the network is determined through five MLP structures (Structures 1 to 5). The accuracies for all MLP structures at specific hidden nodes are analysed. The output of combination of MLP 1 and MLP 2 structures with a minimum total volume of support structure and a minimum number of support structure will be chosen as an OPDO. The optimization of total volume of support structure and number of support structure is performed using an Artificial Neural Network (ANN). These parameters are also to be considered due to their fabrication cost and build time. The improved part model is then manufactured by using a FDM-3000 machine. The results of OPDO are compared with the models that have been used in previous works. The findings show that the same orientation is identified. The experimental results also show that the contact between the support structure and part model is improved by 38%. The non-contact surface at unnecessary area from the top to the bottom of developed support structure was produced. This similar technique can also be used to produce the part using a current technology of 3D printing.

CHAPTER 1

INTRODUCTION

1.1 Overview

Traditionally, design and manufacturing activities in industry are performed at separate sections. The design engineer designs the part prior to the development of operation sequences by manufacturing engineer. However in some cases, the modification of design must be made by manufacturing engineer for some reasons such as manufacturability and cost of the product. The modified design will affect the original functions of the product. The changes in design delay the marketing, hence, reduce its market competitiveness. In conventional manufacturing, the integration of design and manufacturing of a product is therefore needed in order to reduce the design lead time (McMahon *et al.*, 1993; Zulkifli, 1999).

The scenario of prototype development in industry has changed. The development requires to introduce the product faster to the market at lower cost with less design modification. This requirement demands on how to shorten the product design time, the development cycle and reduce development cost. The product must also be able to form with any geometric complexity in various applications in order to increase the competitiveness (Daniel *et al.*, 2014; Shuaib *et al.*, 2015; Xueling *et al.*, 2012; Zhenwen *et al.*, 2015).

Layered Manufacturing (LM) is found to have new possibilities to fulfil the changes in this scenario (Dai *et al.*, 2014; Daniel *et al.*, 2014; Ivanova *et al.*, 2013;

Novakova-Marcincinova *et al.*, 2012; Yang *et al.*, 2014). The first LM process was developed by Charles Hull in 1986. The LM is a volume additive manufacturing process in which 2D layer-by-layer deposition of material is stacked gradually from lower to upper to develop 3D physical model directly from Computer Aided Design (CAD). This technology is able to build any complex shapes which are nearly impossible to carry out by using conventional machines. In LM, most of CAD data are converted into Stereolithography (STL) file format before transferring them to the machine. A major advantage of this technology is that the designer has the ability to actually print out any ideas and creativities without limit.

The steps involve in LM start with the development of CAD model. Current activities in LM require human involvement in order to integrate between CAD and CAM systems especially to determine the orientation of part deposition in process planning. The errors and the repeating LM cycles due to human involvement lead to the development of automatic system for all steps in process planning.

In this research, the feature is introduced in order to automate the selection of orientation of part deposition in Fused Deposition Modeling (FDM) machine. The FDM is an extrusion-based LM process which requires support generation to prop up hollow geometrics and overhanging features of a part during manufacturing process. The features that have been identified in FDM process planning is as the key elements in the integration of orientation of part deposition and support generation (Kulkarni *et al.*, 2000).

This work will focus on manufacturing feature in FDM. The feature is considered to represent the way how to manufacture it. It can be extracted by decomposing the successor layer into volumetric units belong to non-support or support feature (overhanging area). The non-support feature is defined as successor layer areas or volumes which have full support from the immediate previous stacked layers, while the support feature is known as successor layer areas or volumes covered partially or may not be covered at all by the immediate previous stacked layers. The External-Support Structures (ESSs) are employed to improve the manufacturability of layers which do not have a layer adjacency or with only partial adjacency in the build direction (Yang *et al.*, 2003).

In FDM, the support features contain Self-Supported Feature (SSF) and External-Supported Feature (ESF). This work focuses on extracting ESF which is able to determine the volume and number of ESS. These features will be studied in details for the optimization of part deposit orientation in FDM.

The ESS traditionally has contact with the part model that tend to degrade the quality of surface finish (Ahn *et al.*, 2005, 2007; Alexander *et al.*, 1998; Majhi *et al.*, 1999; Pandey, 2003). This problem can be resolved by implementing the concept of features during fabricating the support structure.

1.2 Definition of Feature

In manufacturing process, features are used to integrate between CAD and CAM systems. In general, feature can be divided into three categories and they are: 1) Functional feature, which is related to their function, design and performance; 2) Design feature, which is expressed in geometric terms, primitive design functions (such as block, cylinder and slot) and their combination and 3) Manufacturing feature, is that the volumetric unit to be removed or added in conventional machining and LM, respectively, during manufacturing processes (Salomons *et al.*, 1993). Through features, the integration between CAD and Computer Aided Manufacturing (CAM) systems can be used to resolve this problem.

The Artificial Neural Network (ANN) is used to optimize the orientation of part deposition based on the total volume and number of support structure as a main input parameters.

1.3 Statement of the Problems

The issues related to this work are identified and stated in this section.

i. Feature-based technique is highly significant for integrating CAD and CAM systems. Various techniques have been suggested in this system to identify features but they are limited to specific manufacturing process (e.g. volume removal for Computer Numerical Control (CNC) machining. (Kerbrat *et al.*, 2010).

ii. In manufacturing process, the LM process planning is not fully automatic and lead to part quality degradation (e.g. dimensional accuracy and surface finish) (Pandey *et al.*, 2007) and increases the possibility of making errors. In this process planning, most of the steps such as creation of geometric model using a solid modeler, determination of suitable deposition orientation, slicing, generation of material deposition paths, part deposition and then post processing operations are done automatically except the orientation of part deposition. The specific manufacturing standard makes feature-based techniques difficult for the manufacturing system to adopt an existing feature extraction system.

iii. There is no generic interface to accommodate the use of features in the LM process. Furthermore, the Stereolithography (STL) file format (as a de facto standard) representation is used to transfer the CAD data to the LM process planning resulting to the loss of design and functional feature information.

iv. In feature extraction, it is difficult to reconstruct geometric and manufacturing features from a volume enclosed by spatial triangles without any topological relationship (Yang *et al.*, 2003).

v. Other issue is also related to the process planning in selecting the Optimum Part Deposition Orientation (OPDO). Furthermore, many errors are occurred due to the involvement of human in this crucial process. Determining the OPDO was found to be difficult and consumed longer build times that influenced by the speed and the change of nozzle's tip during material deposition for both part model and support (Thrimurthulu *et al.*, 2004).

In FDM, there is only one build direction (vertical direction). Hence, the adjacency is considered in a single building direction. This study is work on the system that can extract the features with respect to the FDM. The ANN is proposed in this system in order to automate the process planning for selecting the OPDO.

1.4 Research Objectives

The objectives of the research are listed below.

i. To employ a Feature-based Support Generation data extraction technique to automate the process planning in FDM.

ii. To select the OPDO through features in which the information of support structure can be determined. The automation of this work can be achieved by the integration between CAD and CAM.

iii. To improve the contact areas between part model and support structures using extracted features. The reduction of unnecessary support volume assures to enhance the surface quality of final part model by reducing unnecessary support volume.

1.5 Scope of Research Work

The scope of this work involve the use of Artificial Intelligence (AI) to determine the optimum part deposition orientation. Six pre-defined orientations of the part are identified. Two main parameters, the total volume of support structure and the number of support structure which have a significant effect on final product are chosen. The optimization approach using ANN is used for this purpose. The work is also looking at the improvement of the parts' surface using feature-based technique. Overall, the activities in process planning of FDM machine will be automated.

1.6 Organization of the Thesis

The thesis is presented in six chapters as follows:

Chapter 1 introduces the background of Layered Manufacturing (LM) technology. The problem statement and objectives of the research are stated. It also gives the overviews of the topics to be included in the thesis.

Chapter 2 reviews the work in the field of feature-based method and process planning in LM. The emphasis on the systems that utilize the Artificial Intelligent (AI) approach for selecting the OPDO are presented.

Chapter 3 describes the methodology and system organization of the Feature-based Support Generation system developed in this work. This methodology is applied when dealing with the support features for generating the support structure.