A SURFACE ROUGHNESS BASED VISUAL AND ANALYSIS SYSTEM FOR SURFACE QUALITY IMPROVEMENT IN FUSED DEPOSITION MODELING RAPID PROTOTYPE MACHINE

By

KHAIRUL FAUZI BIN KARIM
(0430610003)

A thesis submitted
In fulfillment of the requirements for the degree of
Master of Science (Mechatronics Engineering)

School of Mechatronics Engineering
KOLEJ UNIVERSITI KEJURUTERAAN UTARA
MALAYSIA
2006

© This item is protected by original copyright

Table of Contents

List of Figures v

List of Tables ix

Nomenclature xv

Acknowledgements xvii

Abstrak xviii

Abstract xix

Chapter 1: Introduction 1

1.0 Background ………………………………………….………… 1

1.1 Rapid Prototyping (RP) Cycle………………………………….. 2

1.2 Statement of the problem………………………………………. 4

1.3 Research objectives…………………………………………….. 5

1.4 Organization of the thesis………………………………………. 7

Chapter 2: Literature Review 8

2.0 Introduction…………………………………………………….. 8

2.1 Slicing Methods………………………………………………… 9

2.2 Staircase Effect…………………………………………………. 9

2.3 Adaptive Slicing………………………………………………… 11

2.4 Optimum Part Deposition Orientation………………………….. 12

2.5 Surface Roughness…………………………………………….... 14

2.6 Region-based adaptive slicing…………………………………... 21

2.7 Used of Artificial Intelligence in Surface quality improvement.. 21

2.8 Summary……………………………………………………… 23

© This item is protected by original copyright

Chapter 3 Visual Basic, Fuzzy Logic, FDM and Measurement Method 24

3.0 Introduction………………………………………………………… 24

3.1 Visual Basic Programming…………………………………….... 24

3.2 Fuzzy Logic……………………………………………………….. 25

3.2.1 Fuzzy Sets……………………………………………….. 27

3.2.2 Fuzzy Logic Operations………………………………. 28

3.2.3 Fuzzification…………………………………………… 30

3.2.4 Fuzzy Rules…………………………………………….. 30

3.2.5 Fuzzy Inference………………………………………… 30

3.2.6 Defuzzification…………………………………………. 31

3.3 Fused Deposition Modeling 3000 (FDM 3000)…………………… 31

3.3.1 Drive Blocks……………………………………………... 32

3.3.2 The Heating Chamber/Envelope……………………………32

3.3.3 Tips……………………………………………………….35

3.3.4 Measurement Method ………………………………………36

Chapter 4 System Design and Implementation 38

4.0 Introduction……………………………………………………….. 38

4.1 Methodology……………………………………………………… 38

4.2 Surface Roughness Based Visual and Analysis (SRVA) System… 40

4.2.1 Phase 1: Layer development in SRVA……………………. 41

4.2.2 Phase 2: Calculation for the Surface Roughness (Ra)…….. 45

4.2.3 Phase 3: Calculation and Application of Adaptive Slicing.. 50

4.2.4 Phase 4: Adaptive z' level layer thickness and positioning.. 56

4.2.5 Phase 5: Information data to amend CAD drawing………...58

© This item is protected by original copyright

4.3 Region Based Adaptive Slicing Methodology……………………...59

4.4 System Implementation……………………………………………..60

Chapter 5 Results, Discussion and Conclusion. 63

5.0 Introduction……………………………………………………………63

5.1 Proposal 1: Part Orientation In SRVA……………………………...53

5.2 Portion by Portion Measurement Technique in Proposal 1…………77

5.3 Proposal 2: Adaptive Slicing In SRVA……………………………. 79

5.4 Portion by Portion Measurement Technique in Proposal 2…………90

5.5 The Model Dimension Inspection…………………………………..91

5.6 Research contributions and Limitations…………………………….94

5.7 Recommendations for future work…………………………………. 94

5.8 Conclusions…………………………………………………………95

References 96

Appendix A

A1 Inspected Ra data for model on 0^0 part orientation…………………102

A2 Inspected Ra data for model on 45^0 part orientation………………..113

A3 Inspected Ra data for model on 90^0 part orientation………………..124

Appendix B Fuzzy logic parameters 135

Appendix C

C1 The inspected Ra and $Ra_{Average}$ data for the Adaptive Slicing Part…136

C2 The inspected Ra and $Ra_{Average}$ data for the Uniform Slicing Part….139

Appendix D The inspected Ra and $Ra_{Average}$ data for Combined Adaptive Slicing and Uniform Slicing Parts…………………………………..142

© This item is protected by original copyright

List of Figures

Figure

1.1 The Rapid Prototyping cycle. ……………………………………………….. 3

1.2 Proposed Rapid Prototyping Cycle……………………………………… 6

2.1 Effect of layer thickness on surface finish (P.M. Pandey et al.)…………… 10

2.2 Staircase effect in RP parts (Pandey et al., 2003)…………………………. 15

2.3(a) Typical surface profiles obtained over a 2 mm sample length for 45° build orientations (Pandey et al. 2003)………………….................. 17

2.3(b) Typical surface profiles obtained over a 2 mm sample length for 70° build orientations (Pandey et al. 2003)……………………..……… 18

2.4 Definition of A_i (P.M. Pandey et al., 2003)………………………….……...20

3.1 The process flow in Fuzzy Logic…………………………………………...26

3.2 Descriptions of Fuzzy Sets………………………………………………… 29

3.3 FDM 3000 machine (http://prl.stanford.edu)..33

3.4 The Extrusion Head of FDM. (http:// www.cs.cmu.edu.)............................... 34

4.1 The process flow for the proposed SRVA system………………………… 39

4.2 Development of layer diameter…………………………….…………43

4.3 Development of layer-by-layer…………………………………………….. 44

4.4 Graph representation of calculating Surface Roughness. …………………..46

4.5 Plotting Surface Roughness data in Bar Graph…………………..………49

4.6 Example of Plotting Bar Graph after calculating Ra……………………… 52

4.7 Example of the Ra(x) as a setting level for adaptive slicing………………..53

4.8 Example of Plotting Bar Graph after applying the adaptive Slicing ………………………………………………………………55

© This item is protected by original copyright

4.9 Example of Optimum Ra(x) Graph presented in SRVA……………………61

4.10 The idea of Region Based Methodology……………………………………62

5.1(a) The CAD model of a cylinder with 0^0 part orientation shown in the Insight software………………………………………………..65

5.1(b) The CAD model of a cylinder with 0^0 part orientation shown in the SRVA system (top view) with Ra_{Max}= 42……………………66

5.1(c) The CAD model of a cylinder with 0^0 part orientation shown in the SRVA system (front view) with Ra_{Max}= 42……………….……..67

5.2(a) The CAD model of a cylinder with 45^0 part orientation shown in the Insight software ………………………………………………68

5.2(b) The CAD model of a cylinder with 45^0 of part orientation shown in the SRVA system (top view) with Ra_{Max}= 11……………………69

5.2(c) The CAD model of a cylinder with 45^0 of part orientation shown in the SRVA system (front view) with Ra_{Max}= 11……………….……..70

5.3(a) The CAD model of a cylinder with 90^0 of part orientation shown in the Insight software ………………………………………………71

5.3(b) The CAD model of a cylinder with 90^0 of part orientation shown in the SRVA system (top view) with Ra_{Max}= 1…………………….. 72

5.3(c) The CAD model of a cylinder with 90^0 of part orientation shown in the SRVA system (front view) with Ra_{Max}= 1……………………73

5.4 Surrounding support suggested by the Insight software for 45^0 part orientation………………………………………………………76

5.5 Semi cylinder with uniform slicing in .STL file……………………………80

5.6 Evaluation of Ra value before applying slicing method in the SRVA system, Ra_{Max}= 62 ……………………………………………….…81

© This item is protected by original copyright

5.7 Evaluation of Ra value after applying the adaptive slicing method in the SRVA system with Ra_{Max}= 31 ……………………………… 83

5.8 The SRVA system presents the data information of Ra_{Max}= 31, the Optimum Slice Count before applying adaptive slicing method= 60, and the Optimum Slice Count after applying adaptive slicing method = 56……………………….. 85

5.9 The Uniform Slicing part model with layer thickness size of 0.3556 mm in the Insight software…………………………………….…86

5.10 The Uniform Slicing part model with z layer thickness of size 0.3556 mm in the SRVA system……………………………………. 87

5.11 The adaptive slicing part model with layer thickness size of 0.1778 mm in the Insight software. ………………………………88

5.12 The Adaptive Slicing part model with z layer thickness size of 0.1778 mm in the SRVA system……………………….............. 89

5.13 The direction measurement for the Model Dimension Inspection (including Proposal 1 and Proposal 2 for 0^0 part Deposition orientation) with control parameters: the Model Temperature of 270 ^{0}C, the Support Temperature of 233 ^{0}C and the Envelope Temperature of 70 ^{0}C……………………………………93

A1.1 Graphical illustration of the portion by portion measurement to inspect the $Ra_{Average}$ value for 0^0 part deposition orientation……………. 103

A2.1 Graphical illustration of the portion by portion measurement to inspect the $Ra_{Average}$ value for 45^0 part deposition orientation……………114

A3.1 Graphical illustration of the portion by portion measurement to inspect the $Ra_{Average}$ value for 90^0 part deposition orientation………………125

© This item is protected by original copyright

C1 Graphical illustration of the portion by portion measurement to inspect the $Ra_{Average}$ value for 0^0 part deposition orientation (the Adaptive Slicing part) ……………………………………………137

C2 Graphical illustration of the portion by portion measurement to inspect the $Ra_{Average}$ value for 0^0 part deposition orientation (the Uniform Slicing Part) ……………………………………………140

© This item is protected by original copyright

List of Tables

Table

3.1 The universe of discourse values for all elements…………………………25

3.2 The control parameters in FDM 3000……………………………………35

3.3 The tips size and layer thickness in the FDM 3000………………………35

4.1 Adaptive Slicing data information………………………………………..58

5.1 The Ra_{Max} for each selected part deposition orientation………………………74

5.2 The comparison data between inspected $Ra_{Avarage}$ and Ra Fuzzy Logic…….78

5.3 Comparison data between inspected $Ra_{Average}$ and Fuzzy logic output……..91

5.4 The comparison data of the fully cylinder dimension in proposal 1 and proposal 2 (part deposition orientation 0^0)………………….92

A1.1 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 265 ^{0}C, the Support Temperature of 210 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C……………………………………………………104

A1.2 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 268 ^{0}C, the Support Temperature of 210 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C……………………………………..…………...105

A1.3 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 270 ^{0}C, the Support Temperature of 210 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C……………………………………………………….106

A1.4 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 265 ^{0}C, the

© This item is protected by original copyright

Support Temperature of 222 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C ……………………………………………………….107

A1.5 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 268 ^{0}C, the Support Temperature of 222 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C……………………………………………………..…108

A1.6 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 270 ^{0}C, the Support Temperature of 222 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C ……………………………………………………..……109

A1.7 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 265 ^{0}C, the Support Temperature of 233 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C………………………………………………………..…110

A1.8 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 268 ^{0}C, the Support Temperature of 233 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C…………………………………………………….…….111

A1.9 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 270 ^{0}C, the Support Temperature of 233 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C…………………………………………..…………112

A2.1 Inspected Ra data for model on 45^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 265 ^{0}C, the Support Temperature of 210 ^{0}C and the Envelope Temperature

© This item is protected by original copyright

of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C……………………………………….…………….115

A2.2 Inspected Ra data for model on 45^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 268 ^{0}C, the Support Temperature of 210 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C…………………………………………………………116

A2.3 Inspected Ra data for model on 45^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 270 ^{0}C, the Support Temperature of 210 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C…………………………………………………….……….117

A2.4 Inspected Ra data for model on 45^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 265 ^{0}C, the Support Temperature of 222 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C……………………………………………………..….118

A2.5 Inspected Ra data for model on 45^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 268 ^{0}C, the Support Temperature of 222 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C…………………………………………..………….119

A2.6 Inspected Ra data for model on 45^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 270 ^{0}C, the Support Temperature of 222 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C…………………………………………….……....120

A2.7 Inspected Ra data for model on 45^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 265 ^{0}C, the Support Temperature of 233 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C…………………………………………….……….121

© This item is protected by original copyright

A2.8 Inspected Ra data for model on 45^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 268 ^{0}C, the Support Temperature of 233 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C……………………………………………………………122

A2.9 Inspected Ra data for model on 45^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 270 ^{0}C, the Support Temperature of 233 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C…………………………………………………………...123

A3.1 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 265 ^{0}C, the Support Temperature of 210 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C…………………………………………………………126

A3.2 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 268 ^{0}C, the Support Temperature of 210 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C…………………………………………………………127

A3.3 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 270 ^{0}C, the Support Temperature of 210 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C…………………………………………………………128

A3.4 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 265 ^{0}C, the Support Temperature of 222 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C…………………………………………………………129

A3.5 Inspected Ra data for model on 0^0 part orientation in FDM 3000

© This item is protected by original copyright

with control parameters: The Model Temperature of 268 ^{0}C, the Support Temperature of 222 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C……………………………………………………130

A3.6 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 270 ^{0}C, the Support Temperature of 222 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C……………………………………………………131

A3.7 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 265 ^{0}C, the Support Temperature of 233 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C……………………………………………………..132

A3.8 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 268 ^{0}C, the Support Temperature of 233 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C……………………………………………………133

A3.9 Inspected Ra data for model on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 270 ^{0}C, the Support Temperature of 233 ^{0}C and the Envelope Temperature of 60 ^{0}C, 65 ^{0}C, 70 ^{0}C……………………………………………………134

B1.1 Fuzzy logic input parameters……………………………………………..135

B1.2 Fuzzy logic output parameters…………………………………………….135

C1 Inspected Ra and RaAverage data for the adaptive slicing model using T12 (0.1778 mm) on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 270 ^{0}C, the Support Temperature of 233 ^{0}C and the

© This item is protected by original copyright

Envelope Temperature of 70 ^{0}C……………………………………………..….138

C2 Inspected Ra and RaAverage data for the Uniform Slicing model using T16 (0.3556 mm) on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 270 ^{0}C, the Support Temperature of 233 ^{0}C and the Envelope Temperature of 70 ^{0}C………………………………………………………..….141

D Inspected Ra and Ra$_{\text{Average}}$ data for the Combining part on 0^0 part orientation in FDM 3000 with control parameters: The Model Temperature of 270 ^{0}C, the Support Temperature of 233 ^{0}C and the Envelope Temperature of 70 ^{0}C………………….………142

© This item is protected by original copyright

Nomenclature

t	Slice or layer thickness
θ	Build orientation
$Ra(\mu m)$	Surface roughness (centerline average)
Ra_{70°,Ra_{90°	Surface roughness for 70° and 90° build orientation, respectively
Ra_{av}	Average surface roughness of the part
Ra_i	Surface roughness of i^{th} trapezium an estimation of build time of FDM part (dimensionless)
A_i	Area of i^{th} trapezium
$Ra_{(n)}$	Average value of surface roughness for layer n (dimensionless).
$Ra_{(n)Left}$	Value of surface roughness at the left side of layer n (dimensionless).
$Ra_{(n)Right}$	Value of surface roughness at the right side of layer n (dimensionless).
$Adaptive\ Ra_{(n)Right}$	The average value of surface roughness in the right side of adaptive layer n (dimensionless).
$Ra_{(n)Right}$	Value of surface roughness at the right side of layer n (dimensionless).
$Ra_{(n+1)Right}$	Value of surface roughness at the right side of layer (n+1) (dimensionless).
$Adaptive\ Ra_{(n)Left}$	Average value of surface roughness in the left side of adaptive layer n (dimensionless).

© This item is protected by original copyright

$Ra_{(n)Left}$	Value of surface roughness at the left side of layer n (dimensionless).
$Ra_{(n+1)Left}$	Value of surface roughness at the left side of layer (n+1) (dimensionless).
$z_{(n+1)}$	Height position for $z_{(n+1)}$ level from origin reference.
$z_{(n)}$	Height position for $z_{(n)}$ level from origin reference.
R	Layer thickness ratio
m	Uniform slicing layer thickness
n	New adaptive slicing layer thickness
$Adaptive\ z'_{(n)}$	Position for adaptive layer n.
$z''_{(n+1)}$	Position for $z''_{(n+1)}$ level (data information from .STL file)
$z''_{(n)}$	Position for $z''_{(n)}$ level (data information from .STL file)
Ra	Surface roughness (µm)
Ra_{Max}	Maximum value of surface roughness (dimensionless)
Ra(x)	Allowed maximum limitation value (dimensionless)

© This item is protected by original copyright

Acknowledgements

I would like to express my sincere gratitude to my research supervisor, Dr Muhamad Rizon Muhamad Juhari and Dr Sazali Yaacob of the Department of Mechatronics, Kolej Universiti Kejuruteraan Utara Malaysia and Dr Abdul Halim Zulkifli of the Department of Mechanical Engineering, Mara Technology University for their continuous and invaluable guidance as well as advice throughout the course of accomplishing the research project. The insight and wisdom gained are undoubtedly immense.

Special thanks are due to a number of persons whose names deserve to be mentioned for their assistance – Dr Ishak, Mr Azhar Ahmad and Mr Norijas Abd Aziz of Mechanic laboratory, University Science Malaysia and Mr Hajazi, Electrosoft.co.

On top of that, I would like to give due credits to my dear parents - Hj Karim Salleh and Hajah Ramlah Hamid, my dear parent in-laws – Hj Yacob Warno and Hajah Sugaibah, my affectionate wife – Fatmawati, and my ever cheerful childrens – Nur Hidayah, Nur Syafiqah, Muhammad Nur Mu’izzuddin and Muhammad Nur Naqiuddin, for their constant love and patience.

Last but not the least to everyone who has in one way or another contributed to the success of the research project.

© This item is protected by original copyright

Abstrak

Sistem SRVA yang telah dimajukan telah berjaya memperbaiki permukaan lengkap serta meminimumkan masa pembentukan model prototaip di dalam FDM. Keputusan menunjukkan bahawa peningkatan bahagian orientasi pembentukan lapisan mengurangkan nilai kekasaran permukaan. Bagi orientasi 0^0 dan 90^0 bahagian pembentukan lapisan, nilai kekasaran permukaan adalah menghampiri nilai keluaran daripada “fuzzy logic” di mana perbezaan peratusannya adalah 1.78% dan 1.52%. Maka nilai yang dikira di dalam SRVA sistem boleh diterima pada orientasi ini.Walaupun begitu, bagi orientasi 45^0 bahagian pembentukan lapisan, ia adalah 2.26% lebih tinggi daripada nilai keluaran “fuzzy logic” kerana semasa proses pembentukkan, penyokong model sekeliling memberi kesan kepada permukaan lengkap model prototaip. Bagaimanapun, nilai ini boleh di terima kerana penyokong model sekeliling tidak diberi penekanan di dalam penyelidikkan ini. Keputusan juga menunjukkan bahawa kaedah pemadanan penghirisan memperbaiki kekasaran permukaan model prototaip. Kekasaran permukaan yang telah diukur dengan kaedah ini menunjukkan 1.22% lebih rendah berbanding tanpa kaedah pemadanan penghirisan, tetapi 0.56% lebih tinggi daripada yang diperolehi oleh “fuzzy logic”. Keputusan ini diperolehi tanpa perlu mengulangi pembinaan model atau bahan kerja di dalam FDM untuk penghasilan kualiti kekasaran permukaan yang baik memandangkan kaedah yang dicadangkan di dalam tesis ini berjaya memoptimakan kitaran RP, maka masa pembinaan di dalam RP dapat dikurangkan.

© This item is protected by original copyright

Abstract

In rapid prototyping (RP), part deposition orientation and surface finish are two significant concerns, but they are contradicting with each other. In model building in RP, a concession is commonly made between these two features to get good quality surface roughness at a short build time. A concession among these two contradicting concerns can be achieved via an adaptive slicing method; on the other hand, selection of an appropriate part deposition orientation will further provide an improved solution. In this thesis, an effort towards determining an optimum part deposition orientation and adaptive slicing method for Fused Deposition Modeling (FDM) process for enhancing part surface finish, and hence, reducing build time (repeating process in RP cycle) is proposed. The quality of the surface roughness is determined by using visual and analysis. This Surface Roughness Based Visual and Analysis (SRVA) system is obtained based on the calculation of surface roughness (Ra). In this present work, the Region Based Adaptive Slicing method is applied in building the model in FDM. The proposed methodology allows the RP user to observe and analyze the prototype model before fabricating the prototype model in the FDM. A program based on fuzzy logic is also used to verify the input and output parameters obtained from the proposed method.

The developed SRVA system has successfully improved the surface finish and minimized the build time in fabricating the prototype model in FDM. The result showed that increasing part deposition orientation would decrease the Ra value of the model. For 0^0 and 90^0 part deposition orientation, the Ra from measurement are closed to the Ra output from fuzzy logic with percentage differences 1.78% and 1.52% respectively. Therefore, the Ra values calculated from the SRVA system are acceptable for these orientations. However, for 45^0 part deposition orientation, it is 2.26% higher than the Ra output from fuzzy logic because during fabrication process, the surrounding support model affects the surface finish of the prototype model. However, this value is also acceptable because the effect of surrounding support model to the surface finish has not been the focus of the present work. The result also shows that the adaptive slicing method has improved the surface roughness of the prototype model. The inspected Ra obtained by this method is 1.22% lower than that obtained without adaptive slicing method, but 0.56% higher than that obtained by fuzzy logic. This result is obtained without the necessity to repeatedly fabricate the model or piecework in FDM for good quality surface roughness as the proposed method in this thesis successfully managed to optimize RP cycle; hence the build time in RP is reduced.

© This item is protected by original copyright

Chapter 1

Introduction

© This item is protected by original copyright

1.0 Background

Rapid prototyping (RP) is an itinerary of action in which a part is manufactured using layer-by-layer deposition of material. It is an imperative technology as it has prospective to lessen up 30% to 50% of the manufacturing lead-time of the product even the relative part complexity is very high [1,2].

RP is the most common name given to a host of related technologies that are used to construct physical objects directly from CAD data sources. Based on the principle of layer manufacturing, the RP technique begins with the intersection of the 3D model from CAD (typically an .STL file) with layers of 2D horizontal planes. As a result, a stack of 2D geometry contours is attained, each signifying a cross-section of the 3D model.

Next, the raw material is placed on the bench. The computer takes the bottom slice of the 3D model and transmits different levels of energy to the raw material to the location as designated by the geometric contour. The raw material is filled in one slice after another from the bottom-up, and the process is repeated until a complete 3D part is produced.

Nowadays additive technologies in RP process offer advantages in many applications compared to classical subtractive fabrication methods such as milling or turning. However, Fused Deposition Modeling (FDM) is one of commonly used RP processes.

FDM is an extrusion-based RP process, although it works on the same layer-by-layer principle as other RP systems. FDM is capable of using multiple build materials in a build/support relationship and it was developed by Stratasys, Inc. of Eden Prairie, MN, USA in the early 1990s as a concept modeling device that is now used more for creating masters and direct-use prototyping.

1.1 Rapid Prototyping (RP) Cycle

The RP cycle begins with the CAD design, and may be repeated inexpensively several times until a model of the desired characteristics is produced as shown in Figure 1.1. The final file or files must be in solid model format to allow for a successful prototype build. From the CAD file, an export format called the .STL file must be created.

The .STL file, so named by 3D Systems for **ST**ereo**L**ithography, is currently the standard file format for all U.S. RP systems. STL files are triangulated representations of solid models. The individual triangles are represented by simple coordinates in a text file format. STL files are usually stored in binary format to conserve disk space.

After the .STL file is created, it must be prepared differently for various types of RP systems. Some systems can accept the .STL file directly, whereas others require preprocessing. Preprocesses include verifying the .STL file, slicing, and setting up parameters for machines control. Preprocessing is usually done at a computer separate from the RP system to save time and to avoid tying up valuable machine time.

© This item is protected by original copyright

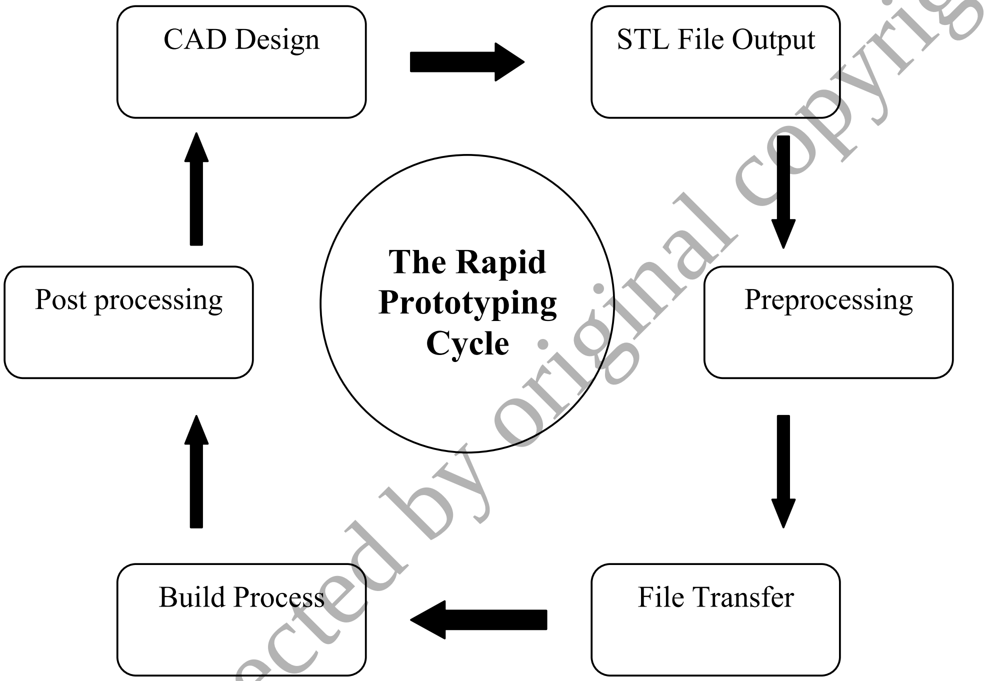

Figure 1.1 *The Rapid Prototyping cycle*

© This item is protected by original copyright

After the .STL has been preprocessed and saved into a new slice format, the new file can then be transferred to the RP system. File transfer can be done several ways, from manually transferring by disk or tape to network transfer. Since more complicated files are usually very large, a local area network or Internet connection is now almost essential for easy file transfer. Once the final file formats are transferred to the RP device, the build process occurs. Most RP machines build parts within a few hours, but can run unattended for several days for large parts.

Upon completion of the build process, post processing of the part must occur. This includes removal of the part from the machine, as well as any necessary support removal and sanding or finishing. If the finished part meets the necessary requirements, the cycle is complete. Otherwise, iterations can be implemented in the CAD file and the cycle is repeated.

1.2 Statement of the problem

In general, all RP technologies use layer-by-layer slicing method and stack one slice after another from the bottom-up to fabricate the model. Basically, there are two important issues here. Firstly, what is the thickness of the layer?, and secondly, how to reduce the gaps between layers which contribute to the staircase effect, and hence, the surface roughness of the prototype model.

The first issue deals with the slicing method of the model. The layer thickness is proportional with surface roughness. If the layer thickness is increased, the staircase effect is increased, and hence, the surface roughness is also increased.

The second issue deals with part deposition orientation. As mentioned earlier, the raw material is filled in one slice after another from the bottom up. If the layers

© This item is protected by original copyright

during the fabrication processes are stacked in different orientation, then there would have some gaps between these layers. In theory, the increment of part orientation would reduce the gap, and hence, improved the surface roughness.

Consequently, to conclude the above statements, it becomes:

$$\frac{LayerThickness}{Part\ Orientation} \propto Surface\ Roughness\ (Ra)$$

Earlier researchers [3,4] have studied this relationships, however, in this present work, the relationship is used to visualize and analyze the surface roughness and then proposed new implementation of RP cycle in FDM.

1.3 Research objectives

The primary objective of the research is to develop a Surface Roughness Based Visual and Analysis (SRVA) system for rapid prototyping (RP) in FDM (as shown in Figure 1.2) to improve surface finish and minimize the build time in RP process. The SRVA system would analyse the .STL file data before transferring it to the FDM machine. Using the SRVA, the RP user can directly attain the optimum part deposition orientation for fabrication of prototyping model in the FDM. The RP user can also analyze the portion which would give high effect of surface roughness and then apply the adaptive slicing method to improve further the surface finish of the model. Therefore, repeating RP cycle which was mentioned earlier in Figure 1.1 would be minimized.

© This item is protected by original copyright