

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

**Open-Source Conversion of
Stratasys FDM Vantage X
Rapid-Prototyping Machine**

A thesis presented in partial fulfilment of the requirements for the degree of

Master of Engineering

in

Mechatronics

at Massey University, Albany,

New Zealand

George Graham Hare

2014

Abstract

3D Printing or Additive Manufacturing is quickly redefining how companies design and develop products (Maxey, 2014). Increasingly, with advances in technology and materials, end-use parts are now being manufactured.

Wellington Drive Technologies Limited (WDTL), a world leading supplier of energy saving, electronically commutated motors (ECM) are based in Albany, Auckland. They use fused deposition modelling (FDM) to prototype new products and concepts. WDTL suffered a failure of a Stratasys FDM Vantage X machine used to 3D print prototype parts. The cost of rectifying the problem put the machine beyond economic repair. The machine was therefore gifted to Massey University, Albany.

Mechanically the machine was in good working order, it made sense therefore to attempt to resurrect the machine for research purposes. However, due to the cost of OEM repairs, and the associated research limitations, it was decided that where possible, open-source solutions should be sought.

The purpose of this dissertation is to prove the viability of replacing closed-source proprietary hardware and software solutions with open-source. The electronics and firmware were designed around the MakerBot Thing-O-Matic while ReplicatorG was used for the front end, all of which are open-source.

Ironically on the 19th June 2013, almost a year after starting this project, Stratasys bought MakerBot, taking a big stake in the consumer based 3D-Printer market. Subsequent releases of Makerware (MakerBot's successor to ReplicatorG) have been made closed-source.

Acknowledgements

Professor Olaf Diegel and Associate Professor Johan Potgieter of the School of Engineering and Advanced Technology (SEAT), Massey University, Albany Campus without whom this project would never have happened.

Garry Armstrong and Ashley Reid for their support during my studies. Ryan Brookes and Brian Young of the Defence Technology Agency (DTA) for allowing me to dedicate my time and efforts to further my knowledge of additive manufacturing in general for the benefit of the New Zealand Defence Force.

My wife, Alexandra for her constant support and re-assurance and not least, my sons Dominic and Thomas, for their understanding and patience over the past two years.

Also to the too numerous to mention friends and colleagues who have come through my lab over the past two years to see what it is I'm going on about at the lunch table.

Table of Contents

Abstract.....	i
Acknowledgements.....	ii
List of Figures.....	v
List of Tables.....	viii
1 Introduction.....	1
1.1 OEM Machine Limitations.....	2
1.1.1 Materials.....	3
1.1.2 Process Parameter Control.....	4
2 Literature Review.....	6
2.1 Definition.....	6
2.2 Additive Manufacturing Technologies.....	6
2.3 Fused Deposition Modeling (FDM).....	12
2.4 The Open-Source Model.....	13
2.5 Development of Open-Source FDM Machines.....	15
3 Mechanical Design.....	21
3.1 Motors.....	21
3.1.1 Servo Motor Theory.....	21
3.1.2 Stepping Motor Theory.....	24
3.2 Front Panel Controller.....	30
3.3 Extruder Head Solenoid.....	33
3.4 Other Hardware Modifications.....	34
4 Electrical Design.....	35
4.1 Power Supply.....	35
4.2 Extruder Head.....	55
4.3 Motherboard.....	69
5 Firmware Development.....	75
5.1 Extruder Controller.....	76
5.2 Power Supply Controller.....	77
5.2.1 Additional UART.....	77
5.2.2 UPSPacket Class.....	78
5.2.3 Heater Control.....	79
5.2.4 Digital Output Control Functions.....	84

5.2.5	AC and DC PSU Status.....	85
5.2.6	Tool Commands.....	85
5.3	Motherboard.....	86
5.4	Print Reliability.....	90
6	Software Design.....	92
6.1	ReplicatorG 0040.....	92
6.2	ReplicatorG 0037.....	95
7	Calibration.....	100
8	Testing.....	106
8.1	Temperature.....	106
8.2	Flow & Feed Rate.....	109
8.2.1	Manual Base Layer Parameters.....	109
8.2.2	Manual Interface Layer Parameters.....	110
8.2.3	Manual First Layer Parameters.....	110
8.2.4	Manual Remaining Layer Parameters.....	111
8.2.5	Result of Manual Coded Test Box.....	111
8.3	Skeinforge Raft Modifications.....	112
8.3.1	Raft Modification Discussion.....	113
8.4	Automatic gcode Generation.....	113
8.4.1	Results of Automatically Coded Box.....	114
8.5	Chamber Temperature.....	114
9	Conclusion.....	116
	References.....	118

List of Figures

Figure 1: FDM Machine General Design (Crump, 1992).....	12
Figure 2: RepRap Darwin (http://en.wikipedia.org/wiki/File:Reprap_Darwin.jpg)	15
Figure 3: RepRap Mendel (http://www.cnccookbook.com/img/OthersProjects/3DPrinting/reprap.jpg).....	16
Figure 4: MakerBot Replicator (http://www.zahncenternyc.com/wp-content/uploads/2014/08/MakerBot-Replicator.jpg).....	17
Figure 5: Simplified AC Motor Control.....	22
Figure 6: Quadrature Incremental Encoder Output Waveform (http://sine.ni.com)	24
Figure 7: Cross-section through Single-Stack VR Stepping Motor.....	25
Figure 8: Cross-section of three-stack variable reluctance stepper motor (http://www.industrial-electronics.com).....	26
Figure 9: 2-Phase Hybrid Stepper Motor (http://www.engineersgarage.com)...	27
Figure 10: Stratasys FDM Vantage X Front Panel Controller.....	30
Figure 11: Message Snooping using Dick Smith Electronic RS-232 to USB Adapters.....	31
Figure 12: Replacement FPC.....	33
Figure 13: OEM Power Supply PCB.....	36
Figure 14: Incoming Supply Distribution.....	39
Figure 15: Heater Control.....	39
Figure 16: High Voltage DC Rectifier.....	40
Figure 17: Auxilliary Power Control.....	41
Figure 18: Power Supply Board - Top Copper.....	41
Figure 19: Power Supply Board - Bottom Copper.....	42
Figure 20: Low-Side Switching Modification.....	42
Figure 21: Arduino Mega Redundant Power Supply.....	43
Figure 22: Serial Interface Board in UPS.....	44
Figure 23: Serial Communications.....	45
Figure 24: RS-485 Serial Interface.....	46
Figure 25: RS-485 Interface PCB.....	47
Figure 26: MAX31855 Thermocouple Interface.....	48

Figure 27: E-Stop Protected Contactor Control.....	49
Figure 28: DC Power Rail Monitoring.....	50
Figure 29: Arduino Mega 2560 Power Supply Controller.....	50
Figure 30: Power Control PCB - Top Copper.....	52
Figure 31: Power Control PCB - Bottom Copper.....	53
Figure 32: Power Supply & Power Control PCB's Fitted.....	54
Figure 33: MakerBot Extruder Controller v3.6 (thing:4969).....	56
Figure 34: ATmega328P Micro-controller.....	56
Figure 35: USB Interface to ATmega328P Micro-controller.....	57
Figure 36: MAX31855 Thermocouple Interface.....	58
Figure 37: RS-485 Serial Interface.....	59
Figure 38: A3950 Full-Bridge DC Motor Control.....	60
Figure 39: Extruder Power Supply.....	61
Figure 40: Extruder Controller Top Copper.....	62
Figure 41: Extruder Controller Gnd Plane.....	62
Figure 42: Extruder Controller Vcc +5v Plane.....	62
Figure 43: Extruder Controller Bottom Copper.....	62
Figure 44: HVDC Switching on Backplane.....	64
Figure 45: HVDC Backplane PCB Layout.....	65
Figure 46: MotherBoard with Extruder Daughter Boards Fitted.....	66
Figure 47: Opto-Isolator / Solenoid Voltage Switching Circuit.....	67
Figure 48: Opto-Isolator / Solenoid Voltage Switching Board.....	68
Figure 49: Extruder Motherboard with modified Opto-Isolators and Solenoid Switching.....	68
Figure 50: Motherboard Schematic Design.....	70
Figure 51: Motherboard - Top Copper.....	71
Figure 52: Motherboard - Bottom Copper.....	71
Figure 53: FPC Keypad Interface.....	72
Figure 54: FPC Keypad PCB.....	72
Figure 55: SD Card Interface.....	73
Figure 56: SD Card PCB.....	73
Figure 57: Motherboard fitted to back of FCP.....	74
Figure 58: Oven Temperature Control Log, Default Parameters.....	82
Figure 59: Oven Temperature Control, Update Interval 5s – 60 Degrees C.....	83

Figure 60: Oven Temperature Control, Update Interval 5s – 80 Degrees C.....	83
Figure 61: Oven Temperature Control, Update Interval 5s - 100 Degrees C.....	84
Figure 62: Original 0040 Control Panel.....	93
Figure 63: Modified 0037 Control Panel Layout.....	97
Figure 64: Machine Options - Chamber Tab Added.....	98
Figure 65: Chamber PID Parameter Entry Tab.....	99
Figure 66: Extruder Temperature Error Measurement.....	103
Figure 67: Extruder Heater Rise-Time.....	105
Figure 68: Extruder Heater Stability.....	105
Figure 69: Microscopic image of Manually Coded Test Box.....	111
Figure 70: Cut-away of Test Print, Showing Hexagonal Fill Pattern.....	114

List of Tables

Table 1: Stratasys FDM Vantage X Specifications (Stratasys, 2006).....	2
Table 2: ASTM Additive Manufacturing Technology Catagories.....	11
Table 3: Gray Code vs Binary Coded Decimal.....	23
Table 4: Magnetic Field Direction in a 2-Pole Hybrid Stepper Motor.....	27
Table 5: XBR-2910 Specifications	28
Table 6: Longs 34HS1456 Stepping Motor Specifications.....	29
Table 7: Serial Output Data from FPC.....	32
Table 8: 3-Phase Power Supply Loading.....	40
Table 9: Extruder Head Pin-Out.....	63
Table 10: PID Paramenter Settings.....	104
Table 11: Extrusion Temperature for Stratasys PC-ABS Filament.....	108