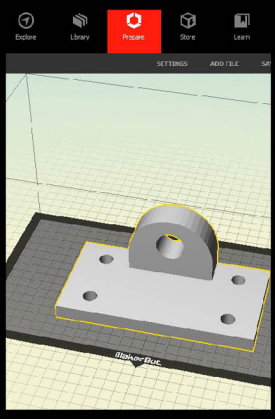

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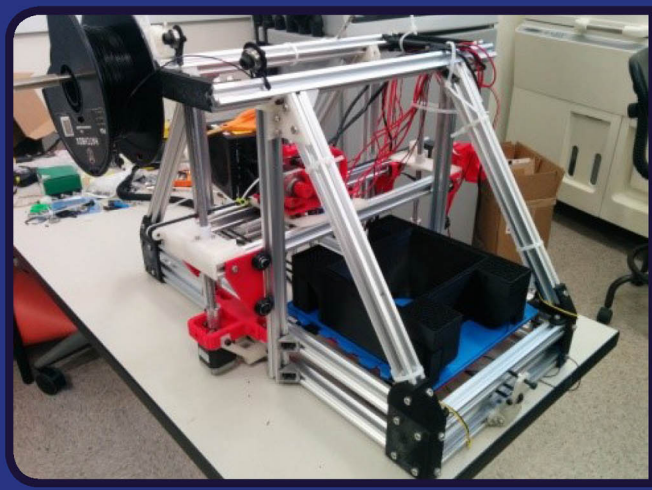

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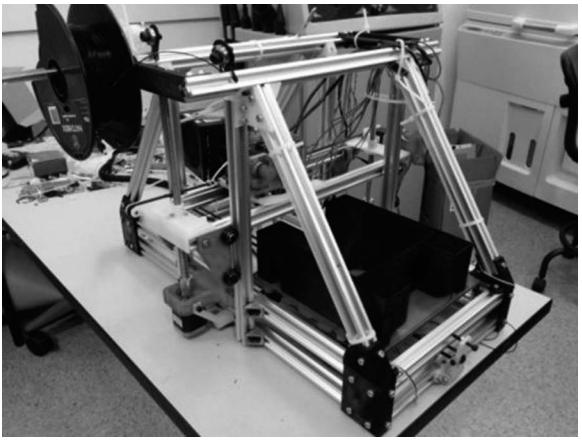

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This book is in memory of my late parents (Osman Ali and Nurunnessa Noorani) and my teachers, who taught me the importance of hard work, honesty and lifelong learning.

The book is dedicated to my family: Zarina (wife), Sabrina (Daughter), Alejandro (son-in-law), and Layla and Elana (my two beautiful grandchildren).

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Contents

Book Organization xv
Preface xvii
Acknowledgments xix
About the Author xxi

1. Introduction 1
1.1 Introduction 1
1.2 The World of 3DP 2
1.2.1 What Is 3DP? 2
1.2.2 What Is RP? 3
1.2.3 The History of 3DP 3
1.2.4 Applications of 3DP 5
1.2.5 The Basic Process of 3DP 5
1.2.6 Industries Using 3DP 6
1.3 Growth of RP and 3DP Systems 7
1.3.1 Growth of RP 7
1.3.2 3DP Sales by Regions 9
1.3.3 Units Sold by U.S. Companies 10
1.3.4 3D Printer Technology Development 10
1.4 Current Popular 3D Printers 11
1.4.1 MakerBot Replicator 2 12
1.4.2 FormLabs 1+ 12
1.4.3 Ultimaker 2 14
1.5 Applications in Education and Industry 15
1.5.1 Choosing the Right 3D Printer for Specific Application 15
1.5.1.1 Preproduction Applications 16
1.5.1.2 Digital Manufacturing 16
1.5.2 Applications of 3DP in Product Development 17
1.5.3 Application in Reverse Engineering 18
1.5.4 Product Development Using a Low-Cost RE Process 18
1.5.4.1 Project Objective 18
1.5.4.2 Procedure 19
1.5.4.3 Results 20
1.5.4.4 Conclusion and Discussion 20
1.5.5 Application in Casting and Pattern Making 21
1.5.6 Application in RT 22
1.5.7 Application in RM 23
1.5.8 Jet Engine Applications 23

1.5.9 On-Demand Parts in Space 25
1.5.10 Medical Applications 26
1.5.10.1 Bioprinting Tissues and Organs 26
1.5.10.2 Implants and Prosthetics 26
1.5.10.3 3D Printed Dosage Forms and Drug Delivery Devices 27
1.6 Summary 28
1.7 Questions 29
References 29

2. How Does 3D Printing Work? 31
2.1 Introduction 31
2.2 3D Printing and Conventional Manufacturing 31
2.3 Basics of 3D Printing Process 34
2.3.1 Creation of Solid Model 35
2.3.2 Conversion to STL File 36
2.3.3 Slicing the File 39
2.3.4 Making the Prototype 40
2.3.5 Postprocessing 40
2.4 Problems with the STL File Format 42
2.5 Other Translators 43
2.5.1 Modern File Formats 43
2.5.1.1 VRML File 43
2.5.1.2 AMF File 43
2.5.1.3 3MF File 44
2.5.1.4 OBJ File 44
2.5.2 Older File Formats Still in Use 44
2.5.2.1 3DS 44
2.5.2.2 IGES File 44
2.5.2.3 HPGL File 45
2.5.2.4 CT Data 45
2.6 Future Manufacturing Format Developments 45
2.7 Case Study: Design and Printing of Eye Bracket 46
2.7.1 Introduction 46
2.7.2 Project Procedure 48
2.8 Summary 52
2.9 Questions and Problems 52
References 54

3. Design of a 3D Printer 55
3.1 Introduction 55
3.2 Necessary Parts 56
3.3 Functional Description and Design Analysis 56
3.4 Build Process 60
3.5 Future Improvements 64

3.6 Questions 66
References 67

4. Calibrating the 3D Printer 69
4.1 Introduction 69
4.2 Types of 3D Printing Software 70
4.3 3D Printer Software Configuration Using Marlin 70
4.3.1 Configuring MARLIN 71
4.3.2 Testing the 3D Printer Movement 73
4.4 The First Print 74
4.4.1 Creating or Downloading a Part 74
4.4.2 Configuring the Cura Software 75
4.4.3 Final Print Configuration 76
4.4.4 Accuracy 76
4.4.5 Fill 76
4.4.6 Skirt 77
4.4.7 Speed and Temperature 77
4.4.8 Support Structure 77
4.4.9 Filament 78
4.4.10 Printing 78
4.5 Summary 78
4.6 Questions 78
References 79

5. Materials for 3D Printing 81
5.1 Introduction 81
5.2 Types of Materials 82
5.2.1 Polymers 82
5.2.1.1 Thermoplastic Polymers 82
5.2.1.2 Thermosetting Polymers 83
5.2.1.3 Elastomers 85
5.2.2 Metals 85
5.2.3 Ceramics 86
5.2.4 Composites 87
5.3 Liquid-Based Materials 88
5.3.1 Polymers 88
5.3.2 Metals and Composites 89
5.4 Solid-Based Materials 89
5.4.1 Polymers 89
5.4.2 Metals 90
5.4.3 Composites 91
5.5 Powder-Based Materials 91
5.5.1 Polymers 91
5.5.1.1 Thermoplastics 91
5.5.1.2 Polymer Composites 91

5.5.1.3 Elastomers 92
5.5.1.4 Powders 92
5.5.1.5 Selected Properties 92
5.5.2 Metals 92
5.5.2.1 Selective Laser Sintering 92
5.5.2.2 SLS and Hot-Isostatic Pressing 93
5.5.2.3 Direct Metal Laser Sintering 94
5.5.2.4 Direct Metal Deposition 94
5.5.3 Ceramics 94
5.5.3.1 Aluminum Oxide 94
5.5.3.2 Zirconium Oxide 94
5.6 Common Materials Used in 3D Printers 95
5.6.1 PLA 95
5.6.2 ABS 95
5.6.3 PC 96
5.6.4 Polymides (Nylon) 96
5.7 Materials Selection Considerations 96
5.7.1 Application 96
5.7.2 Function 97
5.7.3 Geometry 97
5.7.4 Postprocessing 97
5.8 Summary 97
5.9 Questions 98
References 98

6. Classifications of Rapid Prototyping and 3D Printing Systems 99
6.1 Introduction 99
6.2 FDM Systems 100
6.2.1 Stratasys RP Machines 100
6.2.2 Principles of FDM 100
6.2.3 The FDM Process 102
6.2.4 Machines 103
6.2.5 Stratasys J-750 103
6.2.6 Stratasys Dimension Elite 104
6.2.7 Stratasys Objet Eden260VS 105
6.2.8 FDM 3D Printing 105
6.2.9 MakerBot Replicator 106
6.3 SLA Systems 106
6.3.1 The Details of SLA Process 107
6.3.2 The SLA Process 107
6.3.3 SLA 3D Printing 108
6.4 SLS Systems 110
6.4.1 SLS Overview 110
6.4.2 3D Systems sPro 60 HD 111

6.4.3 Sinterit Lisa SLS 3D Printer 111
6.5 Thermal Inkjet Printing Systems 112
6.5.1 Stratasys Polyjet Connex3 Inkjet 3D Printer 113
6.6 Comparisons between Printing Processes 114
6.7 Questions 114
References 115

7. Scanning and Reverse Engineering 117
7.1 Introduction 117
7.2 Measuring Devices 118
7.2.1 Overview 118
7.2.2 Contact-Type Measuring Devices 120
7.2.3 Noncontact-Type Measuring Devices 121
7.2.3.1 Laser Scanning Systems 121
7.2.3.2 CT Scanning Systems 125
7.3 CAD Model Construction from Point Clouds 127
7.3.1 Preprocessing 128
7.3.2 Point Clouds to Surface Model Creation 128
7.3.3 Medical Data Processing 132
7.4 Data Handling and Reduction Methods 132
7.4.1 3D Grid Methods 133
7.4.1.1 Extraction of Points 134
7.4.1.2 Analysis 135
7.5 Applications of RE 136
7.5.1 Applications 136
7.5.2 Product Development and Manufacturing 136
7.5.3 Entertainment 138
7.5.4 Biomedical Engineering 138
7.5.5 Other Applications 138
7.6 Case Studies 139
7.6.1 Case 1: Recreation of Mechanical Parts 139
7.6.1.1 Introduction 139
7.6.1.2 Methodology 139
7.6.1.3 Prototype of Mechanical Part 141
7.6.2 Case 2: RE Prosthetics 141
7.6.2.1 Introduction 141
7.6.2.2 Methodology 142
7.6.2.3 Mold of Human Fingers 142
7.6.2.4 Computer Model of Human Fingers 142
7.7 Summary 144
7.8 Problems 144
References 145

8. Common Applications of 3D Printers 147
8.1 Introduction 147

8.2 3D Modeling Software 148
8.3 Design and 3D Printing of an Everyday Bottle Opener 150
8.3.1 Introduction 150
8.3.2 Detailed Design 151
8.3.3 Results and Conclusions 154
8.4 Design and 3D Printing of a Flower Vase 154
8.4.1 Introduction 154
8.4.2 Detailed Design 154
8.4.3 Results and Conclusions 156
8.5 Recreation of Human Face Using Reverse Engineering 156
8.5.1 Introduction 156
8.5.2 Detailed Design 157
8.5.3 Results and Discussion 159
8.5.4 Conclusion 163
8.6 Recreation of Human Fingers for Accident Victims 164
8.6.1 Introduction 164
8.6.2 Detailed Design 165
8.6.3 Results and Discussion 167
8.6.4 Conclusion 173
8.7 Summary 173
8.8 Questions 174
References 174

9. 3D Printing in Medicine 177
9.1 Introduction 177
9.2 Medical Applications of 3DP 178
9.2.1 Teaching Aids and Simulators 178
9.2.2 Presurgical Planning Models 178
9.2.3 Customized Surgical Implants 179
9.2.4 Mechanical Bone Replicas 179
9.2.5 Prosthetics and Orthotics 179
9.2.6 Bioprinting 180
9.3 Types of Medical Imaging 180
9.3.1 X-Ray Technology 181
9.3.2 Nature of X-Rays 182
9.3.3 Applications of X-Rays 182
9.3.4 Magnetic Resonance Imagery 183
9.3.5 How MRI Works 184
9.3.6 CT 184
9.4 Software for Making Medical Models 186
9.4.1 Materialise's Interactive Medical Image Control System and the CT Modeler System 186
9.4.2 Visualization Tools 186
9.4.3 Visualization and Measurements Tools 187

9.5 Materials for Medical Applications 188
9.6 Methodology for Printing Medical Models 189
9.7 Benefits of 3DP in Medicine 190
9.8 3D Printing of a C1 Vertebrate from CT Scan Data 191
9.8.1 Objectives and Benefits 191
9.8.2 General Project Process and Software 191
9.8.3 Detailed Process 192
9.8.4 3D Printing the Part 192
9.9 Summary 195
9.10 Questions 195
References 196

10. How to Select Rapid Prototyping and 3D Printer 197
10.1 Introduction 197
10.2 Choosing 3D Printer 198
10.2.1 Safety and Environment 198
10.2.2 Process and Material 198
10.2.3 Quality of Printer 199
10.2.4 Price 199
10.3 Operating Issues 200
10.3.1 Learn to Use It 200
10.3.2 Learn to Maintain It 200
10.4 Accessing 3DP and RP Systems 201
10.4.1 Service Bureau 201
10.4.2 Popular Service Providers 202
10.4.3 Consortia 202
10.4.4 Build Your Own 202
10.5 Development of an Expert System 203
10.5.1 Introduction 203
10.5.2 The Need for RP 203
10.5.3 Need for an Expert System 205
10.5.4 Literature Review 205
10.5.5 Creating the System 207
10.5.6 Selection of Factors 207
10.5.7 Prioritization and Selection 209
10.5.8 Development of MATLAB Program 209
10.5.9 Running the Program 212
10.5.10 Limitations and Future Improvements of the Program 214
10.5.11 Conclusion 215
10.6 Present and Future Trends 215
10.7 Summary 216
10.8 Questions 216
References 217

Appendix A: Glossary of Terms 219
Appendix B: List of Abbreviations 223
Appendix C: MATLAB Program for Expert System 225
Index 263

Book Organization

The book is organized into 10 chapters. The objectives of each chapter are described below:

- *Chapter 1: Introduction:* This chapter introduces the readers to the world of rapid prototyping and 3D printing (3DP). Definition, historical development, important developments, and applications are described.
- *Chapter 2: How Does 3D Printing Work?* This chapter provides an introduction to 3DP and rapid prototyping (RP) as part of additive manufacturing. It provides a difference between conventional manufacturing and 3DP. It also describes the basic steps in making prototypes-solid model, data conversion, building the part, software limitations, and a detailed case study.
- *Chapter 3: Design of a 3D Printer:* This chapter provides the details of the construction of a 3D printer. The goal of this chapter is to use available kit components to make an inexpensive 3D printer in-house that can be as fast as the commercial fused deposition modeling printer.
- *Chapter 4: Calibrating the 3D Printer:* This chapter describes the calibration of the printer that is vital for fast, easy, and quality prints. It is the mind of the printer that controls the printer. An open-source software, called *Marlin*, has been used to control all aspects of the printer.
- *Chapter 5: Materials for 3D Printing:* RP materials play a key role in the quality, strength, and accuracy of prototypes. This chapter reviews 3DP materials (polymers, metals, ceramics, and composites) from the fundamental approach by reviewing chemical bonding. It discusses the current 3DP materials and processes and gives advantages and disadvantages of each material.
- *Chapter 6: Classifications of RP and 3DP Systems:* Most printers fall into the categories of liquid-, solid-, and powder-based printers. This chapters describes some of the most common but successful 3D printers on the market today.
- *Chapter 7: Scanning and Reverse Engineering:* In this chapter, the principles and applications of scanners and reverse engineering (RE) are introduced and discussed. RE plays an important role in shortening product lead time. This chapter discusses the background, scanning techniques, data conversion systems, and future trends in RE.

- *Chapter 8: Common Applications of 3D Printers:* The applications of 3DP are mind-boggling. This chapter introduces readers to the common household can opener to designing and printing a flower vase, recreating human face, and medical applications in making human fingers.
- *Chapter 9: 3D Printing in Medicine:* This chapter describes medical imaging and specific applications aspects of 3DP, and also presents 3D printing of a C1 Vertebrate from CT scan data.
- *Chapter 10: How to Select RP and 3DP?* This chapter describes the guidelines for implementing 3DP and RP in the workplace, operations and management issues, and service bureaus. It describes the development of an expert system that can be used to select a particular type of 3DP and RP that suites the needs of the user.

There is enough material in this book to cover a single-semester course. Each instructor can select those portions of the book that cover the topics he or she wants to cover in a particular course. Students can also use the book as reference for other topics that are not covered during the course.

Preface

3D printing (3DP), also known as additive manufacturing (AM) and rapid prototyping (RP), is a technology that takes information from a computer-aided design and "prints" it on a 3D printer, which creates a solid object by building up successive layers of material. The technology was developed in 1989 and, since then, has been expanding exponentially. Figure 1 shows the explosive growth of 3D printers in recent years. 3D printers are similar in many ways to RP machines except that they are cheaper (less than $5000.00), smaller, and sometimes, less accurate in terms of strength and surface finish. Commercial systems, such as stereolithography and fused deposition modeling, have passed into public domain. These are the big companies who have been making big and expensive RP machines for a long time. However, inventors and entrepreneurs around the world are using commercially available kit components to build 3D printers whose prices have fallen from $100,000 to over $500. The author of this book and two of his students have recently designed and built a 3D printer at Loyola Marymount University. The cover page shows the completed printer. The 3DP essentially consists of a frame, extruder, electronics, materials, and software. This project has been a great experience for the author and the students. Now that the printer has been built, the next challenge is the continuous improvement of the printer for its precise control.

The advantage of the digital design is that it can be tweaked easily with a few mouse clicks. The 3D printer can run unattended and make many things, which are too complex for a traditional manufacturing process. In time, these amazing machines may be able to make almost anything, anywhere, anytime. The applications of 3D printer are especially amazing. From 3D printed organs and prosthetics to tools that have been printed in

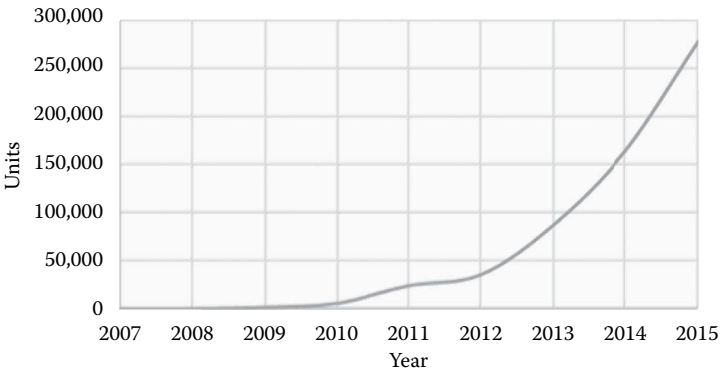

FIGURE 1
Growth of 3D printers.

zero gravity on the International Space Station, not to mention some of the incredible sculptures that redefine what is possible to achieve in a physical medium, 3D printers are being used almost in every industry to transform the way we do things and lead us into a bold new future. 3D printer was even touted by President Obama as having potential to "revolutionize the way we make almost everything" during his 2013 State of the Union address.

Those of us who are engaged in design have been using RP since its inception in 1989. It is a powerful tool that has many advantages. Some of the benefits attributed to RP and 3DP are (1) reduced lead-time to produce prototypes, (2) improved ability to visualize the part due to its physical existence, (3) early detection and correction of design errors, and (4) increased capability to compute mass properties of components and assemblies.

An impressive number of individuals, educational institutions, manufacturing organizations, and industries have discovered RP, 3DP, and their potential benefits. Many high schools, colleges, and universities have purchased and implemented RP machines and 3D printers into their curricula. Students are routinely taught the principles and applications of 3DP. Students use 3DP tools in their laboratory and design/capstone projects. Automobile manufacturers and suppliers are using both 3DP and 3DP to prototype various mechanical components. Aerospace companies mostly use RP machines to produce parts and assemblies for both commercial and military aircraft, as well as in the product development cycle. Manufacturers of business machines use RP and 3DP to prototype computer parts, copier, telephone, and fax machine parts.

The primary purpose of this book is to present the technology, applications, and selection of 3D printer as it relates to the world of concept development, design, and manufacturing. The book is designed for hobbyists, entrepreneurs, high school students, and college/university students for an entry-level course on 3DP in design and manufacturing automation. The book can also be used as a supplement to computer graphics text and manufacturing texts that are currently being used. The book is also intended to serve as a reference for industrial and academic practitioners interested in competitive product design and manufacturing.

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Support from the National Science Foundation has been invaluable in developing the CAD/CAM laboratory and Rapid Prototyping laboratory at LMU. It is the second NSF grant that I received in 1995 that helped me buy the first rapid prototyping (RP) machine and start my work on RP. I am grateful to Parsons Foundation who gave me a grant of $150K in 1997 to purchase my second RP machine and a coordinate measurement machine.

As an international professor, I have worked very closely with Dr. Toshihiro Ioi of Chiba Institute of Technology and Dr. Hideyuki Kanematsu of National Institute of Technology, Suzuka College in Japan, and Dr. Kwang-Sun Kim of Korea University of Technology and Education (KoreaTech) in Cheonan. These professors have invited me to give lectures on RP and 3D printing for their classes, and industries. I am very grateful to these professors for their continued support and encouragement.

I am very grateful to my first reviewers who made corrections and improvements to the chapter contents. I am thankful to my students, Michael Lynch, Patrick Hodgkiss, Cassandra Jacobsen, Cole Merritt, Chris Mitts, Matt Fumo, Max Yarema, Andrew Dominguez, Alex Hendricks, Abdullah Alrashdan, Faisal Aldhabib, Kelly Tivoli, and others who worked with me very closely to develop the chapters of this book. I must acknowledge the encouragement I have received from my wife, Zarina Noorani, to complete the book.

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About the Author

Rafiq Noorani received his BSc degree in mechanical engineering from Bangladesh University of Engineering and Technology (BUET), a master of engineering degree in nuclear engineering, and a PhD in mechanical engineering from Texas A&M University.

He is currently a tenured professor and graduate program director of mechanical engineering at Loyola Marymount University in Los Angeles, California. He previously taught engineering at Texas A&M University, the University of Louisiana at Lafayette, and Gonzaga University in Spokane, Washington before joining Loyola Marymount University in 1989. His teaching interests include CAD/CAM, rapid prototyping, 3D printing, and robotics. He has received over 35 external grants totaling over $2 million including six grants from National Science Foundation (NSF). He has published 12 journal papers and 80 conference papers in national and international journals and conferences. With the help of a recent NSF grant, he has worked with his colleagues to develop an undergraduate program in nanotechnology at LMU.

Dr. Noorani published the first textbook on rapid prototyping in North America in 2006 titled: *Rapid Prototyping—Principles and Applications*. The book was published by John Wiley & Sons. He also became a *Fellow* of American Society of Mechanical Engineers (ASME). According to ASME guidelines, the fellow grade of membership recognizes exceptional engineering achievements and contributions to the engineering profession.

As an international professor, he teaches and lectures on CAD/CAM, 3D printing, and robotics in many countries including Japan, South Korea, and Bangladesh. Dr. Noorani is a professional member of American Society of Mechanical Engineers (ASME), Society of Manufacturing Engineers (SME), and American Society for Engineering Education (ASEE).

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1

Introduction

1.1 Introduction

Mastering the art of 3D printed components, sub-assemblies, and products is vital for any product development process. Over the last few years, new and exciting technologies have emerged that are changing the ways that products have been launched. 3D printing (3DP) is an example of such technology, which is revolutionizing the design and manufacturing of new products. This technology is being used to fabricate physical solid models for early verification of concepts, e.g., form, fit, and function as well as reducing lead-times for product development [1].

Not long ago, 3DP was only associated with prototyping. Nowadays, 3DP technology has come a long way from basic rapid prototyping (RP) machines of the 1980s, and 3DP is more than just prototyping with today's materials and technology. 3DP process offers transformative advantages at every part of the manufacturing process from initial concept design to production of final products to be marketed, and all the steps in between. There is extremely large variety of 3D printers and technologies available these days; therefore, it is important to be thoroughly informed in order to choose the right 3D printer for specific applications.

First, 3DP technology as we know it today emerged in 1980s, and a thought of having a personal mini 3DP workstation was a dream. Even just a few years ago, in-house 3DP technology was enjoyed only by a very few professional design engineers, and the applications were very limited to creation

of concept models and simple prototypes. Once considered a luxury, 3DP has proven to yield long-term strategic value by enhancing design-to-manufacturing capabilities and reducing the time to market final products. 3DP technologies have allowed an ever-growing number of creators, designers, engineers, physicians, researchers, academics, and manufacturers to unleash all the benefits of RP/3DP in-house across the entire design process.

Leading manufacturing companies harvested the full power that 3DP technology has to offer and are now using 3DP to evaluate more concepts in short time to improve the decision-making and design process early in product development. As the design process moves forward, technical decisions are iteratively tested at every step to guide decisions, to achieve maximum performance, minimize manufacturing costs, and deliver the highest quality. In the preproduction phase of manufacturing process, 3DP allows accelerated first concept product development and assists with troubleshooting of any problems that may arise. In the final production stage of manufacturing process, 3DP allows for higher productivity, increased flexibility, reduced logistics costs, economical optimization, improved product quality, reduced product weight, less overall parts in the assembly, and greater efficiency in a growing number of industries [2].

In this opening chapter, 3DP will be defined. In addition, study of 3DP history and the importance of this technology for product development will be covered as well. Applications of this technology through a case study and future trends will also be discussed.

1.2 The World of 3DP

The field of 3DP encompasses a wide variety of new methods, technologies, and applications that have already stimulated some fascinating research. Many companies have found exciting new ways to improve product development processes and enhance profitability. The prospect of being a part of this new technology with its promise of radical improvement in the way business is done should be as highly motivating to the reader, as it is to the author. In this section, some definitions and applications of 3DP will be discussed, and examples of some companies that are using 3DP will be given.

1.2.1 What Is 3DP?

3DP, as described in this text, refers to the fabrication of a physical, 3D part of arbitrary shape directly from a numerical description (typically a CAD model) by a quick, totally automated, and highly flexible process without any tooling. According to Wohler's Report 2014, 3DP is defined (as also defined by ASTM International Committee F42) as "fabrication of objects

through the deposition of a material using a print head, nozzle, or other printer technology." However, the term is often used synonymously with *additive manufacturing (AM).* AM is a broader term that encompasses building 3D physical models. Prototypes, patterns, and tooling components using various materials such as plastics, ceramics, metals, etc. [3].

1.2.2 What Is RP?

RP is a technology that also refers to the fabrication of 3D part of an arbitrary shape directly from a numerical description by a quick, totally automated, and flexible process. RP is the term that has been used since 1989 when the RP process was invented. From 1989 to 2005, the additive technology was known as RP. After nearly two decades of the use of RP, the personal 3DP revolution started with an open-source project known as RepRap. Since then, the growth of 3DP has been phenomenal, exceeding over 72,000 units sale in 2013. The difference between RP and 3DP is minimal and the two terms can be used interchangeably. In particular, 3DP is associated with machines that are lower in relative price (<$5000) and overall functional capability. Both RP and 3DP are part of AM.

As it was mentioned before, 3DP is a relatively new technology that creates profound effect on the product development process of design and manufacturing industries worldwide. 3DP technology can prototype parts very rapidly in most cases, i.e., in hours rather than in days or weeks. This technology is quickly expanding to include rapid tooling (RT) and rapid manufacturing (RM). RP, tooling, and manufacturing are technologies that are also widely used these days. 3DP can be sometimes referred to as *desktop manufacturing*, *direct CAD manufacturing*, and *instant manufacturing*.

The unique characteristic of 3DP manufacturing process is that it makes physical prototypes one layer at a time. Therefore, following terms that emphasize this layer-by-layer manufacturing characteristic are sometimes used as well: *layered manufacturing*, *material deposit manufacturing*, and *material addition manufacturing*.

The last group of terms for 3DP emphasizes the words "solid," "freeform," and "fabrication." This group of terms includes *solid freeform fabrication* and *solid freeform manufacturing*. The word "solid" refers to the final solid state of the material, although the initial state may be solid, liquid, or powder. The word "freeform" stresses the fact that 3DP can prototype complex shapes with little or no constraint on shape form. 3DP is also related to "automated fabrication," which describes new technologies for generating 3D objects from computer files in a completely automated process.

1.2.3 The History of 3DP

Charles Hull, the founder of 3D Systems, is consider as the founder of 3DP. He obtained his first patent for 3DP in 1984 for his stereolithography apparatus

(SLA), which uses UV light to cure photopolymer resin in a vat to make prototypes. The principle of 3DP is that a software can slice a 3D object into layers of particular thickness and a machine can stack them together one above the other, forming the 3D part. In the early 1980s, the computer-aided design (CAD) was still in its infancy, and Mr. Hull had a challenge of how to translate the CAD file in a file format that the 3D printer can interpret and print. Again, with the help of a consulting firm (Albert Consulting Group), he developed the stereolithography (STL) file format that could be used by any 3DP machine. Although people talk about some limitations of the STL file, today, it is still the *de facto* standard for 3DP process. We shall talk more about this STL file in the next chapter [4].

Scott Crump, the founder of fused deposition modeling (FDM) printing process, developed the FDM technology in 1989 and founded the Stratasys company. Crump also developed acrylonitrile butadiene styrene (ABS) materials for the FDM machine that is widely used by a vast majority of 3D printers today. 3D Systems and Stratasys are the two biggest 3DP companies in the world. Over the years, these two companies have acquired other companies with different technologies and have truly become the best and biggest 3DP companies in the world.

Dr. Carl Deckard and Dr. Joe Beaman developed selected laser sintering (SLS) process at the University of Texas in the mid-1980s independently of the SLA and FDM processes. While SLS and FDM were successful in making plastic and nylon parts, none of the technology could make prototypes in metals. SLS was the only technology at that time to make prototyping parts in metals. The technology was originally sold by DTM Corporation, which was later purchased by 3D Systems.

In the early 1990s, the Massachusetts Institute of Technology (MIT) invented inkjet 3D printing, known as 3DP. The license for 3DP was given to Z Corp. In the early 2012, 3D Systems bought the company to acquire all the associated patents and licenses.

Many of the industrial patents of 3D Systems and Stratasys expired a few years ago. Especially, the expiration of FDM technology started the consumer 3DP technology, as we know it today. The 3DP revolution was started in 2005 with the open-source project called RepRap. The purpose of the RepRap project is to make a machine that can replicate itself. With the participation of entrepreneurs and hobbyists, the 3DP revolution is going on in full swing. These 3D printers are very inexpensive (<$5000) but very robust in most cases. Most 3D printers use FDM and stereolithography technology. They use open-source hardware and software to operate. With the advancement of computer technology and electronics and software, these 3D printers are the future. The historical growth of 3D printers since 2005 bears testimony to this effect. Some of the most popular consumer 3D printers of the market are MakerBot Replicator and FormLabs 1+. We shall describe some of the most popular 3D printers in the next few sections of this chapter.

1.2.4 Applications of 3DP

There are many types and classes of physical prototypes, but their main purpose is to minimize risk during the product development process. Some of the specific applications of 3DP technology are mentioned below:

- Communication of product characteristics
- Engineering concept definition
- Form, fit, and function testing
- Engineering change clarification
- Client presentations and consumer evaluations
- Bid proposals and regulation certification
- Styling, ergonomic studies
- Facilitate meeting schedule and making milestones
- Masters for silicone rubber tooling
- Masters for spray metal tooling (all processes)
- Masters for epoxy tooling to be used for injection molding
- Master/Pattern for investment casting
- Tooling for injection molding

1.2.5 The Basic Process of 3DP

There are many different 3DP processes available today that use a variety of materials, such as wax, plastics, metals, and many more. The most widely used and popular 3DP processes are SLA, selective laser sintering (SLS), and FDM. Although there are many different 3DP processes, almost all of the processes operate by forming solid objects, using either liquid, powder-based, or solid materials. This means that all these 3DP techniques follow the same basic process for part creation. This basic 3DP process consists of the following steps [5]:

1. Create a CAD model of the design.
2. Convert the CAD model to STL file format.
3. Slice the STL file into 2D cross-sectional layers.
4. Grow the prototype.
5. Clean and finish the model.

The first step in the process is to create the CAD solid model using CAD software packages, such as AutoCAD, Pro/Engineer, or Solid Works.

In the second step, CAD file of the part to be manufactured is converted into STL file format. Because various CAD software packages use different

algorithms to represent solid objects, STL file format has been selected as the de facto standard in the RP industry. The STL file represents a 3D surface of an object as planar triangles. The file contains the coordinates of the vertices and the direction of the outward normal of each triangle. The STL file format is the best file format to represent all surfaces, in preparation for the "slicing" algorithms. More about the STL file format will be discussed in Chapter 2.

The third step involves "slicing" of the STL file using a proprietary software program, provided by the manufacturer of the 3DP machine in which the model is to be produced. The preprocessing software imports the STL file, and lets the user orient the part, and adjust the size and slice thickness of the model. The layer thickness may vary from 0.01 to 0.7 mm depending on the capabilities of the machine. Lower slice thickness increases the accuracy of the prototype but also increases the time to build it. The preprocessing software may also generate a structure to support portions of the model during its buildup. Supports are necessary for creating features such as overhangs, internal cavities, and thin-walled sections. 3DP processing software also provides information about how much time and material will be required to make the prototype.

The fourth step involves the actual making of the prototype. Once the STL file is processed and saved, it is sent to the 3DP machine. During this part of 3DP process, the machine essentially acts as a printer by building the prototype one layer at a time. Most modern 3DP machines can operate unattended once the initial setup is completed, and the printing operation is initiated.

The final step is removing the part from the machine and cleaning it before use. This step is also known as postprocessing. It also involves postcuring of photosensitive materials, sintering powder materials, and removing of the support materials. Some prototypes are also subjected to surface treatment, such as sanding, sealing, or painting to improve their surface finish, appearance, and durability.

1.2.6 Industries Using 3DP

Design and manufacturing industries use 3DP technology to reduce the manufacturing time and for marketing their products, and more importantly to cut manufacturing costs. The early uses of prototypes were mainly for visualization to check form, fit, function, and the early verification of design error. 3D prototypes are now used for many other purposes. Functional models and fit/assembly together represent approximately 48.5% of all 3D models used. About 20.4% of 3D printed models are used for patterns for prototype tooling and metal casting. This area of application is expected to increase dramatically in the near future. Figure 1.1 shows how companies are using 3D printed models. Figure 1.2 shows the same data as Figure 1.1 but in terms of the number of units produced for each application of 3D printed models [3].

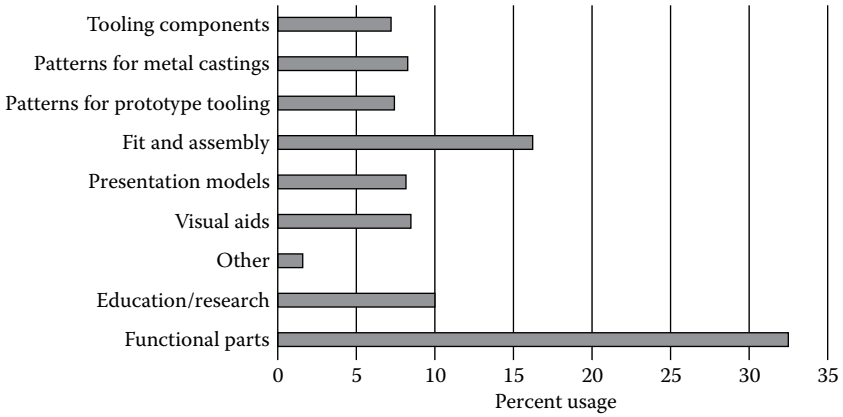

FIGURE 1.1
Purposes of 3D printed models.

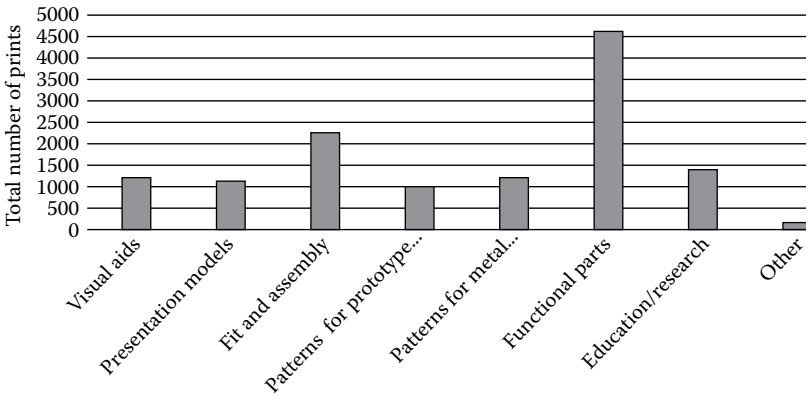

FIGURE 1.2
Number of 3D printed models used per specific application area.

1.3 Growth of RP and 3DP Systems

1.3.1 Growth of RP

While the RP industry continues to grow, the rate of growth has been very flat for the years 1997–2002 due to the lethargy in the overall economy. In spite of this, during 2000–2001, established commercial 3D printer manufacturing companies released new technologies, new materials, and new applications for 3DP machines. Overall, the electronic component and costs have decreased, while computing power increased. This made sales of commercial