

# ROBOTIC OFF-AXIS FUSED FILAMENT FABRICATION

Gerardo A. Mazzei Capote

A thesis submitted in partial fulfillment of  
the requirements for the degree of

Master of Science  
(Mechanical Engineering)

at the

UNIVERSITY OF WISCONSIN-MADISON

2018

Final Oral Examination: August 11th, 2018



# Approval

The following thesis, **Robotic Off-Axis Fused Filament Fabrication**, developed at the **University of Wisconsin-Madison** has been approved by:

---

*Signature*

**Professor Tim A. Osswald**  
Department of Mechanical Engineering  
College of Engineering  
University of Wisconsin-Madison

---

*Date*



# Abstract

Yada Yada Yada

# Acknowledgments

Thank you Prof. Rudolph and Prof. Osswald for your trust and patience. I couldn't hope for better advisors.

Thank you Tom for your extrusion expertise and your polymer knowledge. The sass that came attached to your friendship was OK too I suppose.

Thank you Luke for building the tools necessary for this whole project to work. That big beard hides a sharp mind -and a lot of patience to answer all my random grammar questions.

Thank you Alec for being an ever-present helping hand, a great classmate, and a good friend. Hope you make ND proud. Keep it up and one day you'll get your *full 15 seconds of screen time* in a Hockey game.

Thank you José for putting up with my constant interruptions *en español* from across the desk, and for sharing lab managing duties with me. Suerte y paciencia para el doctorado.

Thank you to Thibaut, Colby, Johannes, Peilin and Brendan. This thesis would look very empty without your contributions!

Thank you to the entire PEC family for creating a great learning environment. I've grown so much with all of you. I hope that you've learned a thing or two with me as well.

Thank you to Ben, Josh, Diego, Iván, Pfeifer, Ian, Maria, Sianna and Sara for your friendship. Madison was a lot of fun because you were in it.

Gracias a mi familia, a quienes les debo todo. Alejandro, Luana y Gabriel: veo en ustedes inteligencia y carisma que sobrepasan las mías. Úsenlas acompañadas de dedicación y llegarán más lejos que su hermano mayor, que los quiere mucho.

Gracias a Sonya por tu cariño y paciencia. Que este tiempo que pasamos tan lejos nos traiga en creces momentos juntos. Te amo.

# Table of Contents

<b>Front Matter</b>	<b>i</b>
Abstract . . . . .	i
Acknowledgments . . . . .	ii
Nomenclature . . . . .	iv
List of Figures . . . . .	v
List of Tables . . . . .	vi
<b>Introduction</b>	<b>1</b>
<b>1 Background</b>	<b>3</b>
1.1 Additive Manufacturing . . . . .	3
1.1.1 Advantages, Disadvantages and Success Stories . . . . .	4
1.2 Fused Filament Fabrication . . . . .	6
1.2.1 The FFF process . . . . .	7

# Symbols and Acronyms

## **Acronyms**

AM Additive Manufacturing

CAD Computer Aided Design

FDM Fused Deposition Modeling<sup>TM</sup>

FFF Fused Filament Fabrication

RP Rapid Prototyping

SLA Stereolithography

SLS Selective Laser Sintering



# List of Figures

1.1	Process flow of AM . . . . .	3
1.2	Shoes with AM midsoles . . . . .	6
1.3	The basic FFF machine configuration . . . . .	7
1.4	From left to right: stl, toolpath and final part . . . . .	8
1.5	Typical FFF part mesostructure . . . . .	8

# List of Tables

1.1 Advantages and Disadvantages of Additive Manufacturing . . . . .	5
--	---

# Introduction

*Additive Manufacturing* (AM) is an umbrella term that encompasses all fabrication techniques where the final geometry of the part is obtained through superposition of material in a layer-by-layer basis [1]. Developed in the 1980s, this manufacturing technique permits immensely shorter part development cycles, since the transition from a 3D *Computer Aided Design* (CAD) to part fabrication only requires one intermediate step: the use of a slicing engine that converts the geometry of the object into machine instructions [1]. For this reason, AM technologies were initially employed exclusively for prototype development and were referred to as *Rapid Prototyping techniques* (RP). However, recent innovations in the field have caused AM to be perceived as a legitimate manufacturing technology since it is also capable of reproducing complex geometries unattainable through other means [1].

While offering great advantages over traditional part fabrication methods, AM comes with its own set of limitations and disadvantages: First and foremost, the use of a stratified build approach tends to produce extremely anisotropic parts. Secondly, the geometric accuracy of the object produced is highly dependent of process parameters, particularly of the thickness of the layers. Finally, as of the time of this writing, AM lacks the standardization and scrutiny that are associated to most traditional manufacturing techniques [1].

*Fused Filament Fabrication* (FFF), also known under the trademark *Fused Deposition Modeling* (FDM<sup>TM</sup>), represents perhaps the most prevalent AM technique in the market due to the advent of low-cost, desktop 3D printers in the early 2010s [2]. Due to the broad availability of machines and relatively low costs of material, there's a surging interest in optimizing FFF to produce small batches of end-user grade parts. Success stories are varied, but examples include vacuum form molds, fixtures, jigs, and tools used to aid assembly lines in the automotive industry [3, 4, 5]. However, this technology still faces the challenges and limitations that currently affect the field of AM as a whole. Namely, anisotropy introduced through the layer-by-layer build approach makes it difficult to assess the expected mechanical behavior of FFF parts when subjected to important mechanical stresses [2]. For these reasons, multiple attempts have been made to characterize the anisotropy of FFF objects. Recent studies performed by Koch *et al.* [6] and Rankouhi *et al.* [7] show that the ultimate tensile strength of FFF coupons is sensitive to process parameters such as the layer thickness and, in particular, the orientation in which the plastic strands are laid during the build process

-henceforth referred to as the bead orientation. However, literature related to preventing failure through design is scarce, given the difficulty of using commercially available FFF machines to produce test coupons with unconventional bead orientations, as well as the limitations inherent to commonly used failure criteria that make it difficult to develop an accurate failure surface.

This research applies a novel criterion, tailored for anisotropic materials, to develop a failure surface for FFF parts through mechanical testing of coupons under various types of loading conditions. Certain test specimens were produced using a unique, in house developed off-axis 3D printer that allowed production of coupons in unconventional configurations. Such surface can be an invaluable tool in part design, since catastrophic failure can be prevented in the early stages of part development. This could potentially allow a broader embrace of FFF as a legitimate manufacturing technique in highly demanding engineering fields, such as the aerospace or automotive industries -where part failure is to be avoided at all costs.

This work offers a comprehensive overview of AM technologies and FFF in Chapter 1. Chapter 2 details the failure criterion used, as well as outlining its advantages over similar criteria. Chapters 3 through ? detail the experimental setup followed, as well as outlining noteworthy results. Finally, Conclusions and Recommendations are given in Chapter ?? in the hopes of guiding future work on the topic.

# 1 Background

## 1.1 Additive Manufacturing

*Additive Manufacturing* (AM) technologies had their beginnings in the decade of the 1980s. During this time, various independently developed patents were filed across the globe, describing a process that would construct an object by selectively adding layers of material -as opposed to removing excess matter or deforming mass to obtain a desired shape. This represents the core definition of AM: any technology where the final geometry of the manufactured object is obtained through controlled addition of material qualifies as an Additive Manufacturing technique [1].

Advancements in the fields of computing, *Computer Aided Design* (CAD), and controllers, among other technological developments, were necessary to translate the patents into working prototypes, with some eventually becoming the foundations of commercially successful companies -such as 3D Systems in 1986 and Stratasys in 1989 [1, 8, 9]. However, the basic process of AM has remained largely unchanged from its first iteration in the late 80s: First, a computer model of the object is made using CAD software and exported under the *.stl* file format. Afterwards, the part geometry is stratified, or “sliced”, and translated into machine instructions using a specialized software called *slicing engine*. An AM machine then follows said instructions, commonly referred to as the *toolpath*, to build the object in layers. Finally, the part is available to the user. Depending on either the requirements of the part, or the specifics of the AM technique used, some post-processing may be required [1]. A visual representation of the process is shown in Figure 1.1.

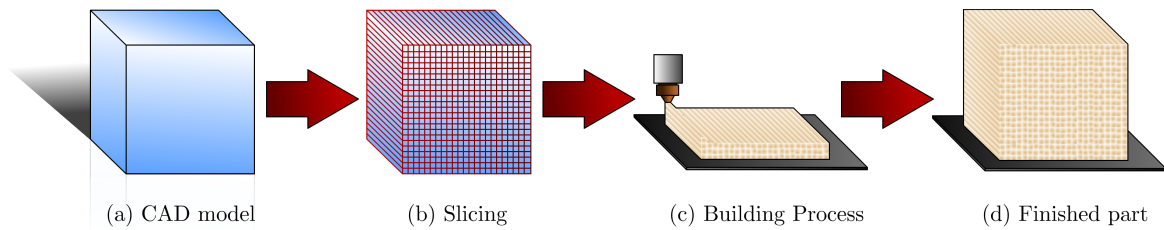


Figure 1.1: Process flow of AM

While all AM technologies operate on the same basic process flow described above, the specifics of each AM technique vary substantially, ranging from processes that use paper and binder, all the way through metal-based, laser tracing technologies. Since this is a rapidly evolving field, no general consensus exists for classifying the multiple AM processes available. However, the classification system proposed under the ASTM/ISO 52900 standard [10], has been somewhat accepted by the field and divides AM technologies as follows:

1. **Binder Jetting:** AM techniques where a binding agent is used to selectively promote cohesion in powder materials -generally gypsum, sand or metallic powders [10, 11].
2. **Directed Energy Deposition:** AM processes where a focused thermal energy source (i.e. laser, electron beam, plasma arc) is used to fuse materials as they are being deposited in the build volume. Materials are almost exclusively metals [10, 11].
3. **Material Extrusion:** In this type of AM technology, material is dispensed through a nozzle or orifice. Fused Filament Fabrication belongs to this classification. Materials are almost exclusively thermoplastics [10, 11].
4. **Material Jetting:** AM techniques where build material is deposited selectively in droplets. Materials are usually wax or thermoplastics, but there are examples of metal-based, material jetting techniques [10, 11].
5. **Powder Bed Fusion:** AM processes where portions of a powder bed are selectively fused through application of thermal energy. *Selective Laser Sintering* (SLS) belongs to this category. Materials are usually thermoplastic polymers or metals [10, 11].
6. **Sheet Lamination:** In this type of AM technology, the final part is formed by bonding sheets of material -usually paper or composites [10, 11].
7. **Vat Photopolymerization:** In this AM process, a liquid photopolymer is selectively cured by a light source. *Stereolithography* (SLA), arguably the first AM technology, belongs to this category. Due to the nature of this technique, the only materials used are photopolymers [10, 11].

### 1.1.1 Advantages, Disadvantages and Success Stories

Since AM processes allow a relatively direct conversion of a CAD model into a constructed object, they were originally exclusively used for prototype development. For this reason, they were initially classified as “*Rapid Prototyping*” (RP) technologies. This terminology is still used today, however, it is being superseded by *Additive Manufacturing* since its potential to become a proper fabrication technique exists [1]. However, while being capable of quickly jumping from part design to manufacturing is a

great advantage, AM has its own set of drawbacks. Table 1.1 summarizes the most noteworthy set of advantages and disadvantages typical of most AM technologies.

Table 1.1: Advantages and Disadvantages of Additive Manufacturing

Advantages	Disadvantages
Faster product development cycles [1]	Part quality highly dependent on process parameters [1]
No additional tools needed for part fabrication[1]	Stratified build generally results in anisotropic parts [1, 2]
Cost effective for small batches of parts [12, 13, 14]	Costly for production of more than hundreds of parts [12, 13, 14]

Out of all the described advantages and disadvantages, the high anisotropy of AM parts is responsible for the slow embrace of AM in highly demanding engineering fields -such as the aerospace and automotive industries. The highly anisotropic mechanical behavior makes it extremely difficult to predict part failure, therefore, it can't be implemented in engineering applications where catastrophic failure is to be avoided at all costs. Even so, success stories of implementation of AM in industrial environments are abundant. Below is a number of relatively recent examples:

- **Volkswagen Autoeuropa:** This automotive assembly plant implemented the use of FFF machines to manufacture tools, jigs and fixtures used in their assembly line. They now produce 93% of the tools that were historically externally sourced, and have reportedly cut their tool development time and costs by 95% and 91% respectively [5].
- **General Electric:** GE is currently producing in Alabama a complex fuel nozzle injector for the LEAP jet engine, using powder based, metal AM. The complex geometry of this component could not be manufactured by any other manufacturing technique. The production plant is expected to have 50 AM machines producing 35,000 fuel nozzle injectors annually by 2020 [15].
- **Adidas and New Balance:** Both shoe companies have developed separate approaches to constructing highly optimized, 3D printed midsoles for high performance running sneakers. New Balance makes use of SLS technology to build the intricate geometry of their “*Zante Generate*” sneaker, using powdered TPU elastomer as the parent material. The designed honeycomb structure of the midsole, combined with the flexible material used, are supposed to improve the comfort and support brought by the shoe [16]. Adidas on the other hand chose to develop the “*AlphaEDGE 4D LTD*” running shoe using the CLIP technology by Carbon3D. While the cell geometry in the midsole is also supposed to bring performance and comfort improvements, the final ambition of Adidas is to perfect the technology to a point where a customer can simply go to a shoe store,

have their feet scanned, and receive a fully customized shoe with a 3D printed midsole that fits their particular needs [17, 18]. In both cases, the geometry of the midsole can only be produced by AM. The intricate structures in the midsoles can be seen in Figure 1.2.



(a) New Balance Zante Generate [16]



(b) Adidas AlphaEdge 4D LTD [18]

Figure 1.2: Shoes with AM midsoles

Note that in the cases presented, the main reason behind the usage of AM was either reduction expenses associated with producing small batches of parts, or the capability of reproducing a unique and complex geometry. This is a trend that is observed in most of the literature describing implementation of AM into industrial scenarios.

While the advantages and disadvantages described here cover the field of AM as a whole, each technique comes with its own set of pros and cons that may make it the preferred method to reproduce a particular product or geometry. This work, however, focuses solely on FFF. The specifics of this process are described in detail in Section 1.2.

## 1.2 Fused Filament Fabrication

*Fused Filament Fabrication* (FFF) is an AM technology where the final geometry of the part is obtained through controlled extrusion of a liquid, self-hardening material - usually a thermoplastic polymer in molten state [1]. Originally developed by Stratasys in the 1980s under the - still trademarked - *Fused Deposition Modeling* (FDM<sup>TM</sup>) moniker, it has recently become one of the most widely used AM techniques due to the advent of low-cost, desktop FFF machines in the early 2010s caused by the expiration of key patents from Stratasys [1, 2].



### 1.2.1 The FFF process

At its core, the typical FFF machine consists of a heated build surface commonly referred to as a *build plate*, a specialized tool known as a *printhead*, and the fabrication material -supplied in the form of spools of thermoplastic polymer filament. The printhead is itself composed of a heating element, a nozzle, and some form of driving mechanism that pushes the filament downward. As the thermoplastic material is moved through the heated chamber, polymer melt is formed and extruded through the opening at the tip of the nozzle, producing a *bead*. The molten polymer can then be deposited upon the build plate, where controlled movements of the printhead and the fabrication surface gradually construct the final geometry of the part in a layer-by-layer build approach [1]. The typical setup of an FFF machine can be seen in Figure 1.3. In this example, the printhead moves in the  $x$ - $y$  plane, while the build plate moves in the  $z$  direction.

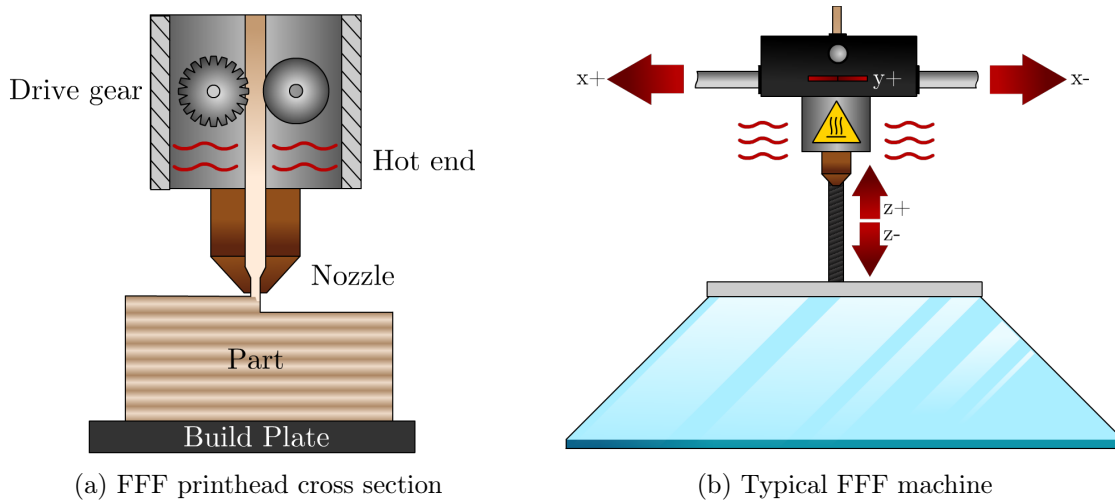


Figure 1.3: The basic FFF machine configuration

Like all AM technologies, the FFF process starts in a computer with a CAD model converted to the *.stl* file format. The geometry is then translated to machine instructions through a *slicing engine*, where the user inputs a plethora of process parameters that include nozzle and build plate temperatures, print speed, layer thickness and build orientation. Finally the *toolpath* is executed by the FFF printer, building the object in a layer-by-layer basis – sometimes referred to as *2.5D* printing [1, 4]. Figure 1.4 shows an abridged version of the process. The  $z$  axis indicates the intended build direction. Note how some of the finer details in the original CAD file are lost in the printed part – due in part to the layer height and build orientation selected.

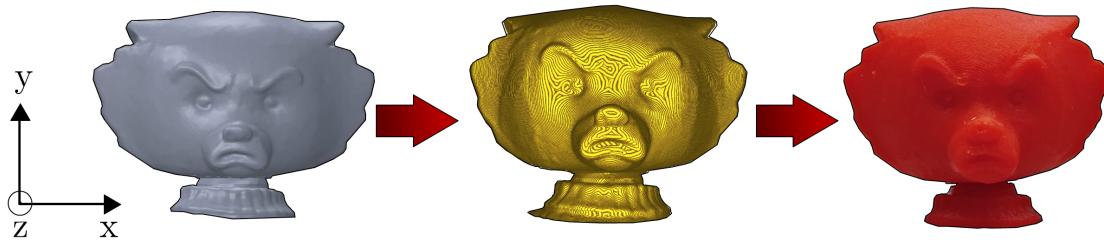
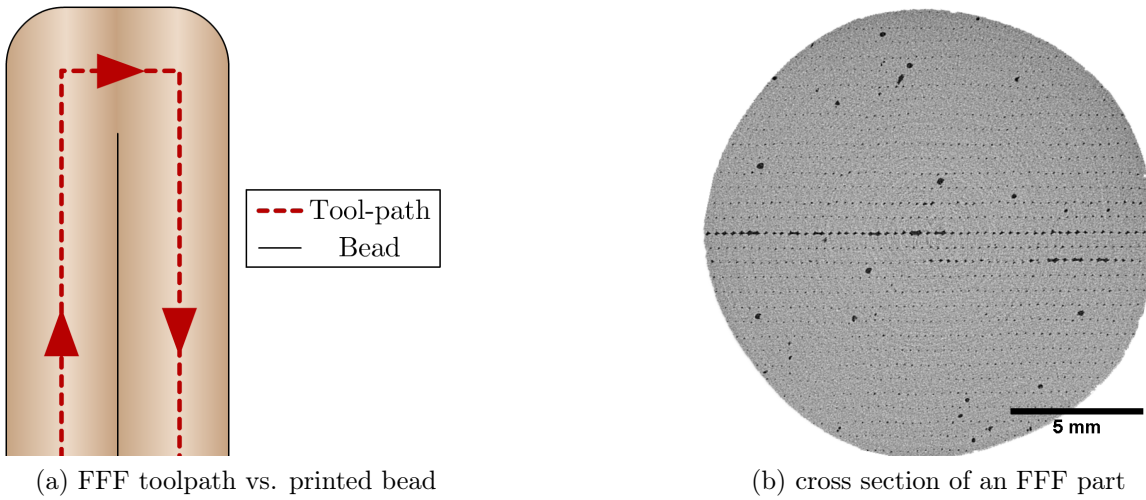


Figure 1.4: From left to right: stl, toolpath and final part

The process is capable of producing complex geometries that would be otherwise hard to reproduce through other polymer processing techniques, such as injection molding. It is however bound by the disadvantages described in [1.1.1](#)



(a) FFF toolpath vs. printed bead

(b) cross section of an FFF part

Figure 1.5: Typical FFF part mesostructure

# Bibliography

- [1] Ian Gibson, David Rosen, and Brent Stucker. *Additive Manufacturing Technologies*. 2nd Ed. Springer, 2015. ISBN: 978-1-4939-2112-6. DOI: [10.1007/978-1-4939-2113-3](https://doi.org/10.1007/978-1-4939-2113-3). URL: <http://link.springer.com/10.1007/978-1-4939-2113-3>.
- [2] G A Mazzei Capote et al. “Towards a Robust Production of FFF End-User Parts with Improved Tensile Properties”. In: *Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium*. Austin, TX, 2017, pp. 507–518. URL: <http://sffsymposium.engr.utexas.edu/sites/default/files/2017/Manuscripts/TowardsaRobustProductionofFFFEndUserParts.pdf>.
- [3] Cole Hartman and Veronica de la Rosa. *Benefits of 3D Printing Vacuum Form Molds*. 2014. URL: <http://studiofathom.com/wp-content/uploads/Vacuum-Forming-White-Paper-F001-5-1-2014.pdf> (visited on 02/06/2018).
- [4] Luke Van Hulle. “Robotic Off-Axis Fused Filament Fabrication”. Master Thesis. University of Wisconsin-Madison, 2017.
- [5] Caspar de Vries. *Volkswagen Autoeuropa: Maximizing production efficiency with 3D printed tools, jigs, and fixtures*. 2017. URL: <https://ultimaker.com/en/stories/43969-volkswagen-autoeuropa-maximizing-production-efficiency-with-3d-printed-tools-jigs-and-fixtures> (visited on 02/02/2018).
- [6] Carsten Koch, Luke Van Hulle, and Natalie Rudolph. “Investigation of mechanical anisotropy of the fused filament fabrication process via customized tool path generation”. In: *Additive Manufacturing* 16 (2017), pp. 138–145. ISSN: 22148604. DOI: [10.1016/j.addma.2017.06.003](https://doi.org/10.1016/j.addma.2017.06.003). URL: <http://dx.doi.org/10.1016/j.addma.2017.06.003>.
- [7] Behzad Rankouhi et al. “Failure Analysis and Mechanical Characterization of 3D Printed ABS With Respect to Layer Thickness and Orientation”. In: *Journal of Failure Analysis and Prevention* 16.3 (2016), pp. 467–481. ISSN: 15477029. DOI: [10.1007/s11668-016-0113-2](https://doi.org/10.1007/s11668-016-0113-2).
- [8] 3D Systems. *Our Story*. 2017. URL: <https://www.3dsystems.com/our-story> (visited on 02/15/2018).

- [9] Stratasys. *About us*. 2017. URL: <http://www.stratasys.com/corporate/about-us> (visited on 02/15/2018).
- [10] ASTM International and International Organization for Standardization. *ISO/ASTM 52900:2015-Standard Terminology for Additive Manufacturing- General Principles-Terminology*. West Conshohocken, 2015. URL: <https://www.astm.org/Standards/ISOASTM52900.htm>.
- [11] 3D Hubs. *What is 3D Printing?- The definitive guide to additive manufacturing*. 2018. URL: <https://www.3dhubs.com/what-is-3d-printing{\#}technologies> (visited on 02/26/2018).
- [12] Martin Baumer et al. “The cost of additive manufacturing: Machine productivity, economies of scale and technology-push”. In: *Technological Forecasting and Social Change* 102 (2016), pp. 193–201. ISSN: 00401625. DOI: [10.1016/j.techfore.2015.02.015](https://doi.org/10.1016/j.techfore.2015.02.015). URL: <http://dx.doi.org/10.1016/j.techfore.2015.02.015>.
- [13] Brett P. Conner et al. “Making sense of 3-D printing: Creating a map of additive manufacturing products and services”. In: *Additive Manufacturing* 1 (2014), pp. 64–76. ISSN: 22148604. DOI: [10.1016/j.addma.2014.08.005](https://doi.org/10.1016/j.addma.2014.08.005). URL: <http://dx.doi.org/10.1016/j.addma.2014.08.005>.
- [14] Barry Berman. “3-D printing: The new industrial revolution”. In: *Business Horizons* 55.2 (2012), pp. 155–162. ISSN: 00076813. DOI: [10.1016/j.bushor.2011.11.003](https://doi.org/10.1016/j.bushor.2011.11.003). URL: <http://dx.doi.org/10.1016/j.bushor.2011.11.003>.
- [15] GE Additive. *GE Additive Manufacturing in Alabama: The Future Is Now*. 2016. URL: <https://www.ge.com/additive/press-releases/ge-additive-manufacturing-alabama-future-now> (visited on 03/01/2018).
- [16] New Balance. *The Future of Running is Here*. 2016. URL: <https://www.newbalance.com/article?id=4041> (visited on 03/07/2018).
- [17] Michelle Matisons. *Futurecraft 3D: Adidas Says It Will Turn to 3D Printed Shoes in Near Future*. 2015. URL: <https://3dprint.com/99620/futurecraft-3d-adidas-shoes/> (visited on 03/07/2018).
- [18] Sarah Saunders. *adidas and Carbon Announce Partially 3D Printed AlphaEDGE 4D LTD Shoe*. 2018. URL: <https://www.3dprint.com/203543/adidas-carbon-alphaedge-4d-ltd/> (visited on 03/07/2018).