The Pennsylvania State University

The Graduate School

Department of Industrial and Manufacturing Engineering

ADDITIVE MANUFACTURING PROCESSES FOR FABRICATING A MINI ROBOT - COMPUTATIONAL MODELS AND EXPERIMENTAL RESULTS

A Thesis in

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by

Shushu Wang

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The thesis of Shushu Wang was reviewed and approved* by the following:

Vittaldas Prabhu
Professor
Thesis Co-Advisor

El-Amine Lehtihet
Professor
Thesis Co-Advisor

Janis Terpenny
Professor
Peter and Angela Dal Pezzo Department Head

*Signatures are on file in the Graduate School

Abstract

Manufacturing has evolved from mass production to mass customization. Customers now have a stronger desire to join the design stage of products and create personalized products. 3D printing has become a popular approach of personalization because of rapid development and increased accessibility. To create a 3D printing robot arm based on the open-source MeArm robot, this thesis evaluated and compared the cost, time, dimensional and location accuracy, and mechanical properties of robot arm linkages fabricated via different 3D printing machines and processes. It also compared 3D printing parts with MeArm robot in terms of accuracy and mechanical properties. Results show that Object30 Prime is more advantageous in accuracy and strength compared with the other two printers and the MeArm robot. Fortus 250mc produced parts with better accuracy and yield strength than MeArm parts. MakerBot Replicator was the most cost-effective 3D printer, and it produced parts with similar strength to MeArm parts. Polyjet process was advantageous in building speed over the FDM process, but used more expensive raw material. All of the 3D printed parts are strong enough for the robot arm according to FEA simulation result. Moreover, reducing the interior density of the FDM process results in a slightly decrease in building time and material cost, but it also influenced tensile strength and caused a noticeable drop in yield strength. The conclusions discussed important considerations for choosing a proper 3D printing machine and establishing parameters to create a personalized product.

Keywords: Personalization product, 3D printing machines, 3D printing parameters, accuracy, tensile test

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Chapter 1 Introduction and Overview

Manufacturing industry made a big progress since Industrial revolution, because manufacturers were able to provide products more efficient thanks to mass production. However, in recent decades, companies have tried a new strategy called mass production to provide broad provision of personalized products and services (Davis, 1989), and the strategy is considered as an important competitive advantage (Fiore et al., 2003, Salvador, 2009).

Since the 21st century, the manufacturing industry has evolved significantly again. Due to the development of personal computers and Internet, the emergence of 3D printing technologies, and the growth of customer interaction ways, we are entering a new age of personalization. More and more technology hobbyists or even normal customers eager to take part into the design stage of products. 3D printing technologies and online 3D model design communities are expanding quickly to satisfy the need of personalization.

The objective of this thesis is to evaluate the characteristics of different 3D printing machines and processes to provide information for building personalized products. In this thesis, a personalization case study is conducted based on MeArm, an open-source desktop robot arm. It is an existing product with one size version and several color options. People could 3D print this robot arm by themselves, or modify its design and then 3D print it. The thesis compares the results of fabricating our own robot arm with different 3D printers, 3D printing processes and the original laser cutting acrylic MeArm parts in terms of building time, material cost, dimensional accuracy, assembly accuracy, and tensile tests. Based on Penn State resources, three different 3D printing machines, MakerBot Replicator (5th Generation), Fortus 250mc, and Object30 Prime, are applied to the key parts of the robot arm - linkages.

Chapter 2 introduces the development of manufacturing industry paradigms and emphasizes the trend of personalization. The relationship between 3D printing and personalization is also illustrated, which indicates that 3D printing is an important impetus for personalization development. Besides, 3D printing technologies, fused deformation modeling (FDM) and PolyJet printing, are introduced. Research about different 3D printing machines and processes is presented. Additionally, MeArm robot arm is introduced.

Chapter 3 illustrates the linkage mechanism of the robot arm. This chapter also states specimens to be estimated, 3D printing parameters settings and finite element analysis (FEA) simulation constraints.

Chapter 4 compares the 3D printed parts made by different printers and processes from aspects of material cost, building time, dimensional accuracy, assembly accuracy, and tensile tests. Accuracy and strength of the original MeArm parts are estimated as well.

Chapter 5 draws conclusions and puts forward future research opportunities to extend this thesis.

Chapter 2 Background

2.1 Manufacturing Paradigms

The manufacturing industry has evolved through several paradigms for two centuries (Hu and Ko, 2011), including craft production, mass production, mass customization, and personalization (Figure. 1).

“Craft Production” created the product according to customer requests but at a high cost. And such production was not scalable since products were confined to localize geographical regions (Hu, 2013).

“Mass Production” provided large scale production at lower cost compared with craft production. It was enabled by interchangeability and sequenced assembly lines (Hu, 2013). Henry Ford was the one who achieved true mass production with the Model T assembly line. However, such production can only offer very limited product varieties. The father of mass production, Henry Ford has stated that “Any customer can have a car painted any color that he wants so long as it is black” (Ford, 1926).

“Mass customization” aims to provide customized products or services through flexible processes in high volumes at reasonably low costs (Da Silveira *et al.*, 2001). This concept emerged in 1989 (Davis, 1989), and Pine indicate that “Mass customization” become an emerging paradigm from industry to industry all over the world (Pine and Victor, 1993).

Bardakci and Whitelock (2003), Jiang *et al.* (2006), Kaplan and Haenlein (2006), Salvador (2009), and McIntosh (2010) emphasize that mass customization focuses on customer preferences instead of using specific technologies or product mix. In other words, mass customization is “customer centric”.

Kumar A (2007) pointes out that personalization of products and services has been put forward as a business strategy to expand the market share for the past twenty years. Since late 1990s, companies began to produce personalized products (Piller, 2004). Personalized production is the new paradigm of manufacturing. The main difference between mass customization and personalization is that customers are willing to influent and participate in the design of products (Hu, 2011). Mass customization is consumer-oriented but producer-driven while emerging personalization is mainly consumer-driven (Mowatt, 2005).

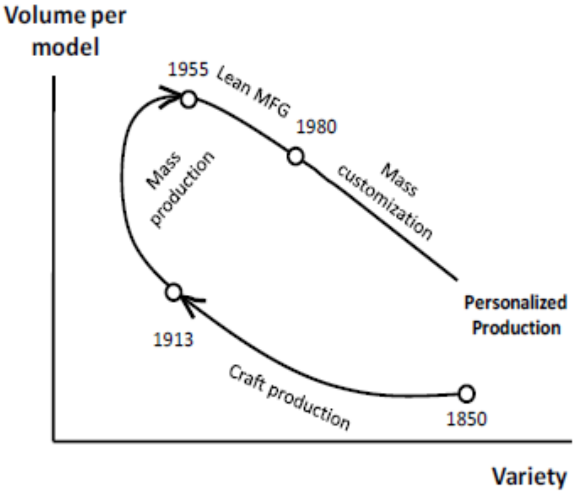


Figure 1. Changes of volume per model of manufacturing paradigms (Hu *et al.*, 2011)

In the mass customization paradigm and the personalization paradigm, the traditional product development processes and supply chain management are changed from mass production to "high-variety-low-volume" production (Tseng, 2014). There are six success factors for the new manufacturing paradigm: customer demand, markets, value chain, technology, customizable offer, and knowledge (Fogliatto *et al.*, 2012). Additive manufacturing has become increasingly significant in recent years because it satisfies the six success factors. Therefore, additive manufacturing enables people to fabricate things as applicable alternatives to purchase mass-produced goods.

2.2 3D Printing and Personalization

3D printers are dropping in price and 3D printing services are becoming easily available, which results in an expanding market. For example, the recent availability of desktop 3D printers is reducing cost barriers (Pettis, 2011). While in 2001 the cheapest 3D printer available in the market cost $45,000, now 3D printers for around $1,000 enable more and more people to take part in customizing products.

3D printing plays a significant role in mass customization and personalization for several reasons:

- Assembly lines and supply chains can be reduced or eliminated. Production and distribution of products could be de-globalized as production is brought closer to customers (Campbell *et al.*, 2011).
- Designs, instead of products, would cross the world as digital files, such as “STL” file, and can be printed anywhere by any 3D printer.
- Products could be manufactured through 3D printing on demand without building up inventories.
- Without tooling cost to amortize into the parts produced, each component can be different, probably allowing true mass-customization of every product (Reeves *et al.*, 2001).

Because of the expansion of online fabrication services, distributed manufacturing networks, local production shops, and personal 3D printers, digital fabrication technology has wider distribution nowadays (Mota, 2011). As a result, hobbyists have more opportunities to produce and distribute goods outside of the centralized manufacturing model. In these “co-creation” platforms, customers are more like “designers” with opportunities to interactively personalize products rather than passive recipients.

The integration of online resources and offline 3D printing fabrication is a significant impetus for personalization development. People can upload their digital design files and get the fabricated object by mail through Shapeways, Ponoko, i.materialize or Sculpteo. Besides, users can reach to local shops and equipment operators through 100kGarages, CloudFab, and MakerFactory. A 3D printer manufacturer, MakerBot, is building up its 3D printers network, and also created Thingiverse, an open-source online database of 3D digital models. Google also established a user-generated sharing website “3D Warehouse”, along with a free 3D modelling program “SketchUp”. And GrabCAD and Turbosquid are similar open-source online design communities. Currently, there are 503,640 3D models on Thingiverse, and 1,230,000 CAD models on GrabCAD. These web-based networks enable designers, or even non-designers without professional CAD background, to fabricate 3D printing products conveniently.

2.3 3D Printing Technologies

Generally, 3D printing technology creates physical products from a computer generated design file by joining or forming input substrate materials layer by layer. It is also known as additive manufacturing (AM) in order to differentiate it from traditional subtractive manufacturing processes. The key principle behind additive processes is layerization: “slicing” digital 3D models into horizontal layers and building one layer at a time. 3D printing has been used for more than two decades mainly for rapid part prototyping and small run production in various industries (Gibson *et al.*, 2010). The overall market of AM products and services has expand to a

$1.325 billion industry (2010 estimate) and is predicted to be over $5 billion by 2020 (Wohlers, 2011).

There are seven major 3D printing technologies today: photo-polymerization, material extrusion, sheet lamination, binder jetting, material jetting, powder bed fusion, and direct energy deposition (Berman, 2012). Some of these technologies are commercialized while others are still under research. In this work, two 3D printing techniques are used: fused deposition modeling (FDM) and PolyJet 3D printing.

2.3.1 Fused Deposition Modeling (FDM)

Fused deposition modeling (FDM) was developed by S. Scott Crump in the late 1980s and was commercialized in 1990 by Stratasys (Wohlers and Gornet, 2012). The FDM machine extrudes and deposits a semi-molten thermoplastic filament in a crisscross manner layer by layer from the bottom up as illustrated in Figure 2.

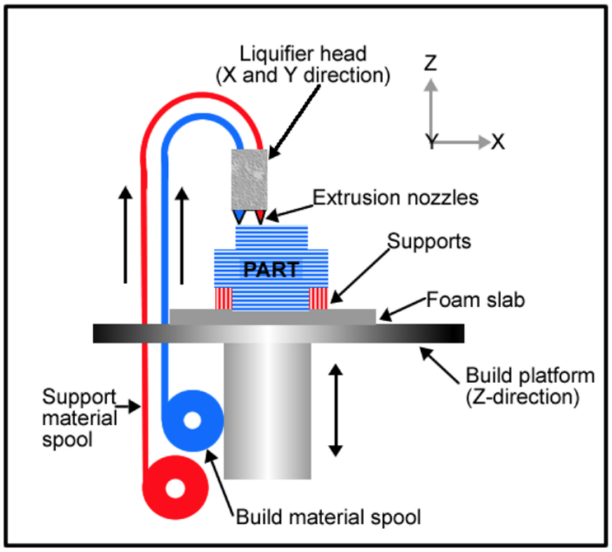


Figure 2. FDM process illustration (Sidambe, 2014)

The market for commercial extrusion-based additive manufacturing systems is now dominated by FDM machines made by Stratasys (Turner *et al.*, 2014). 2011 Wohler's report pointed out that Stratasys' market share of 3D printing machines is 3.5 times that of other manufacturers. The Fortus 250mc machine used in this thesis is one of the FDM machines from Stratasys.

The rapidly expanding personal fabrication market (Lipson and Kurman, 2010) is dominated by FDM. The growth of these systems is due to the expiration of Stratasys' initial patents on FDM (Turner *et al.*, 2014). For personal FDM fabrication systems, the open-source RepRap project is the most popular one. Stratasys is a major competitor in this field with its Mojo and uPrint printers, while MakerBot, Bits-from Bytes, and Up! Machines are other notable competitors for personal desktop 3D printers. Besides, MakerBot was acquired by Stratasys in 2013.

The working process of FDM can be considered as three stages:

1. Pre-processing: Build a 3D model and export the model as an STL file (stereolithography file format). For different printers, specific software is required to transform the STL file to the format that fits the printer. In these software, generally, tool path will be calculated automatically, printing parameters like infill rate and layer thickness can be adjusted, and printing orientation need to be decided. After that, preview of the 3D printing toolpaths and also the estimation of building time and material amount can be generated.

2. Production: The printer head moves along a toolpath in the X-Y plane forming the part, and the platform holds the part and moves vertically in the Z direction. The material is extruded in a semi-molten state and the newly deposited material fuses with adjacent material that has already been deposited (Ahn *et al.*, 2002).

3. Post-processing: The raft and support structure will be removed in this step. However, there are different ways to remove supports depending on the 3D printer type. For example, MakerBot Replicator 5th Generation uses the same material for the raft, the support structure and the model (Figure 3). The raft and the mesh like support material needs to be broke away manually. Removing the raft manually probably results in parts deformation or even parts damage. But for the FDM machine from Stratasys, the support material can be dissolved in detergent and water.

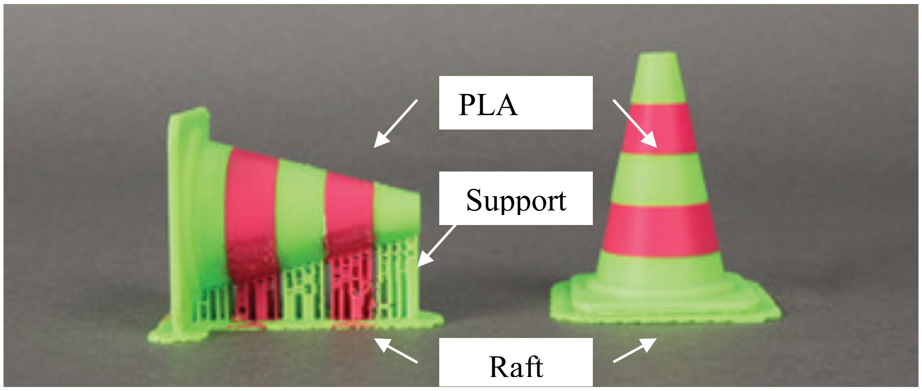


Figure 3. MakerBot 3D printing part with support and raft (Kerry, 2013)

2.3.2 PolyJet 3D Printing

PolyJet 3D printing is a relatively new form of additive manufacturing and was patented in 1994 by Sachs et al. (1994). It is similar to inkjet printing. But instead of jetting ink drops onto paper, PolyJet 3D printers jet UV curable liquid photopolymer onto the building platform (PolyJet Technology, Stratasys). Figure 4 describes the typical working principle of PolyJet printing technology. It can create complex shapes, fine details and smooth surfaces, and it represents one of the fastest rapid prototyping processes (Ainsworth *et al.*, 2000). 3D printing materials often have large tolerance due to high surface roughness, but the PolyJet materials maintain low roughness. Also, PolyJet materials were observed to have higher tensile and flexural properties than other 3D printed materials, but the tested strength is lower than which is reported by the manufacture company (Pilipovic *et al.*, 2009). Additionally, PolyJet is able to make a part with multiple materials.

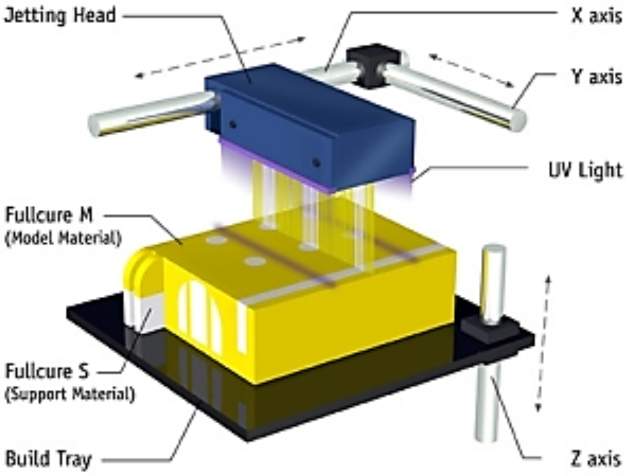


Figure 4. PolyJet process illustration (Stratasys)

The detailed working process of PolyJet:

1. Pre-processing: Just like the FDM process, build a 3D model and export the model as an STL file. After the STL file is imported into the build-preparation software, the placement of photopolymers and support material will be calculated automatically.

2. Production: Tiny droplets of liquid photopolymer are jetted and immediately cured by UV along the building tray.

3. Post-processing: The support material is usually hard plastics-like in 3D printing technologies. But for PolyJet, the support material is different: the gel-like material can be removed by hand or with water easily.

2.3.3 Characteristics of 3D Printing Processes

When fabricating 3D printed customized parts, especially for an assembly with functional requirements, characteristics including mechanical properties and dimensional accuracy are significant. And the manufacturing speed and cost are also crucial factors for 3D machines and process selection. A number of studies on 3D printing process characteristics have been carried out. Generally, benchmark parts are tested in these studies. Mahesh *et al.* (2004) develop specific part design for benchmark tests and evaluat abilities of different processes. Kim and Sung (2006) make several benchmark tests using various additive manufacturing processes for functional prototypes. Kim and Oh (2008) perform quantitative comparisons of mechanical properties, accuracy, roughness, speed, and material cost of several rapid prototyping processes, such as stereo lithography (SL), FDM, PolyJet, and selective laser sintering (SLS). Their test results show that the PolyJet process is advantageous in terms of tensile strength, surface roughness, dimensional accuracy, and building speed compared with FDM, but the FDM process is more cost-effective. Baich and Manogharan (2015) investigate the relationship of infill density with mechanical properties, production cost and time of FDM process. 3D Matter website (2015) posts an article illustrating the influence of infill rate, layer height and infill pattern on mechanical performance for the PLA 3D printing.

2.4 A Desktop Robot Arm-MeArm

MeArm Robotics, a UK company, designs accessible starter kits for coding and robotics. Their open source product, MeArm robot arm, is a good choice for education or STEM subjects (MeArm Robotics). It is a 4-axis pick and place robot arm controlled by Arduino powered with 6V batteries. 4 servos' angles can be controlled by a joystick, and the corresponding angles are shown on a LCD screen. MeArm only provides one size version with several color options in the same material. The robot parts are laser cut from acrylic sheets and assembled with M3 self-tapping screws. Figure 5 shows the latest version of MeArm.

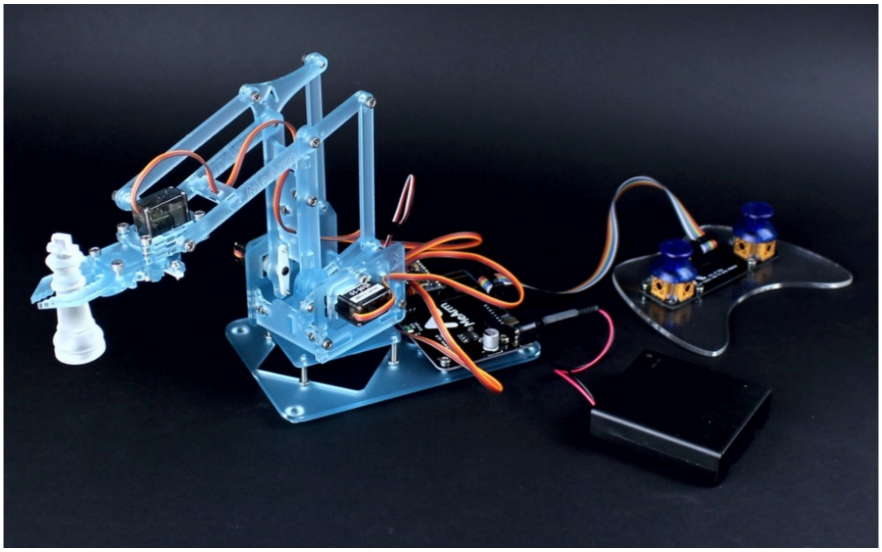


Figure 5. MeArm v1.0 with control board and joystick

The gripper is driven by a pair of planar linkage mechanisms with revolute joints: one side is a 4-bar linkage and another side is a 7-bar linkage as shown in Figure 5. Each mechanism is driven by a servo. Besides, two mechanisms are connected with two bars, which enables each servo to control the whole linkage mechanism.

It is an open-source product. The 2D drawing is shared on their website. Some hobbyists posted their 3D printing design based on an older version of this product in Thingiverse (URL: http://www.thingiverse.com/search/page:1?q=mearm&sa=), which is a good example of using 3D printing technologies for personalization. These hobbyists, however, focused only on the fabrication without the evaluation of 3D printing results such as dimension accuracy, tensile strength, and comparison with the original product.

Chapter 3 Case Study-3D Printing of A Desktop Robot Arm

This 3D printing work focuses on the linkage of MeArm. The robot arm contains 8 different linkage parts between the gripper and the base. These parts have been 3D printed with three different printers. To evaluate the quality of personalization parts - 3D printed parts, dimensions are measured, assembly tolerance is calculated, and tensile tests are conducted. The evaluation results are also compared with the original parts shipped from MeArm Robotics.

3.1 Personalization Preparation

MeArm Robotics shares the 2D drawing of the parts in nominal dimensions online. As the first step of personalization, a 3D SolidWorks model of MeArm was built based on the 2D drawing. Figure 6 shows the 3D model with linkages in yellow color.

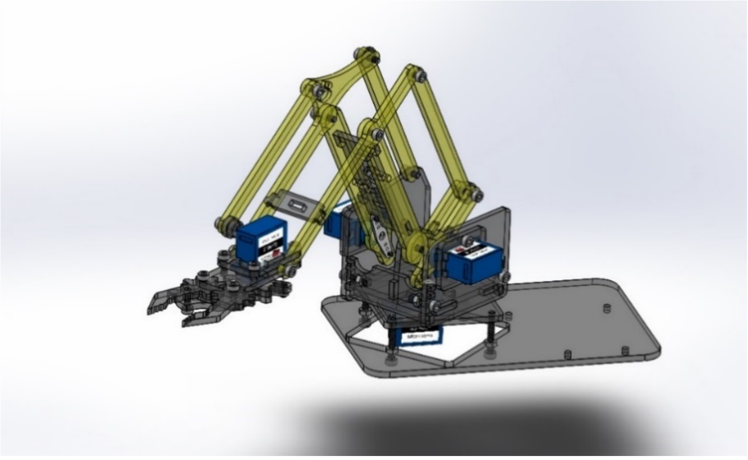


Figure 6. 3D model of MeArm

3.2 Test Procedures

In this work, three different 3D printing machines are applied: Makerbot Replicator (5th Generation), Fortus 250mc, and Object30 Prime. The Makerbot Replicator (5th Generation) is available in Penn State Maker Commons, while the Fortus 250mc and Object30 Prime are available in the Additive Manufacturing and Reverse Engineering Lab in the Department of Industrial and Manufacturing Engineering. Table 1 shows the official published specification of these three machines from their website. Note that MakerBot only provide the precision of moving head positioning, but no accuracy of building parts.

Table 1. 3D printing apparatus specification

Apparatus Model	Process	Material	Accuracy (mm)	Layer Thickness (mm)
MakerBot Replicator (5th Generation)	Fused deformation modeling (FDM)	Polylactic acid (PLA)	-	0.100~0.400
Fortus 250mc	Fused deformation modeling (FDM)	Acrylonitrile butadiene styrene (ABS)	±0.241	0.178 0.254 0.330
Object30 Prime	PolyJet	Rigid Opaque photopolymers	±0.100	0.016 0.028 0.036

3.2.1 Specimens Fabrication and Dimension Measurement

Figure 7 shows the parts to be 3D printed. In order to evaluate the quality of assembly with M3 self-tapping screws and investigate the accuracy of gripper location, several dimensions are measured: circular hole diameter, distance between holes, and part thickness. The nominal dimension in Figure 7 (a) is from the 2D drawing shared on MeArm website, and the nominal thickness is 3mm. At the meantime, Figure 7 (b) illustrates the 3D printing orientation.

To inspect dimensional accuracy of one set of specimens, the diameter of 16 circular holes and 10 values of distance between holes are measured; the average value of part thickness at 3 different points of each part is considered as the thickness of that part. The circular holes are for assembly with screws to form revolute joints. M3 screws need to self-tap into holes with 2.65mm diameter, and 3mm holes are able to rotate easily around the screws.

The holes and locations are measured using SmartScope Flare from Optical Gaging Products, and parts thickness is measured with digital caliper. The dimensions of parts from MeArm Robotics are also measured for comparison.

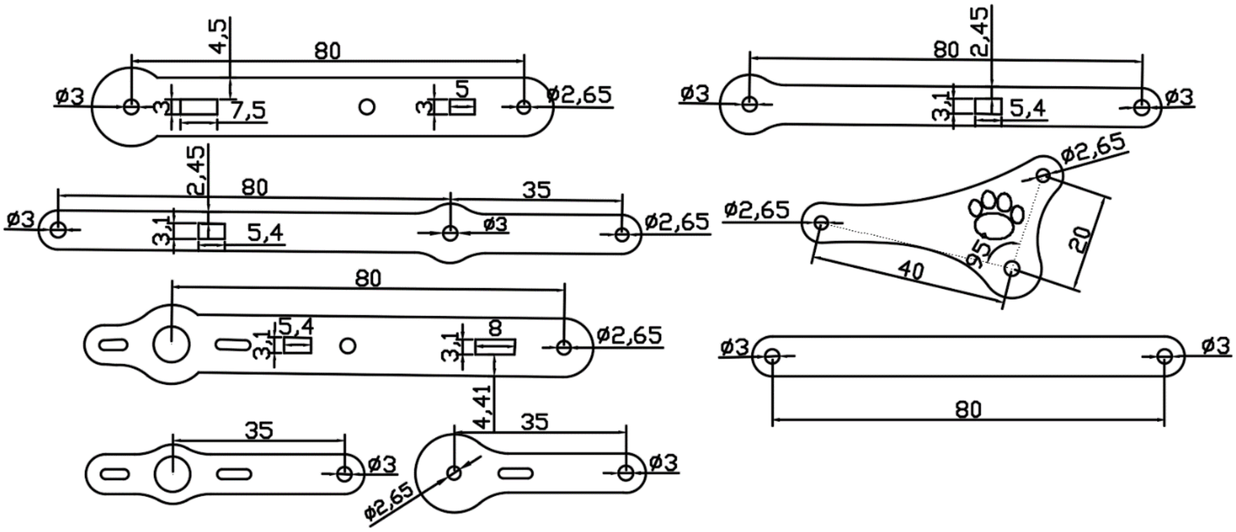


Figure 7. (a) nominal dimension for measurement

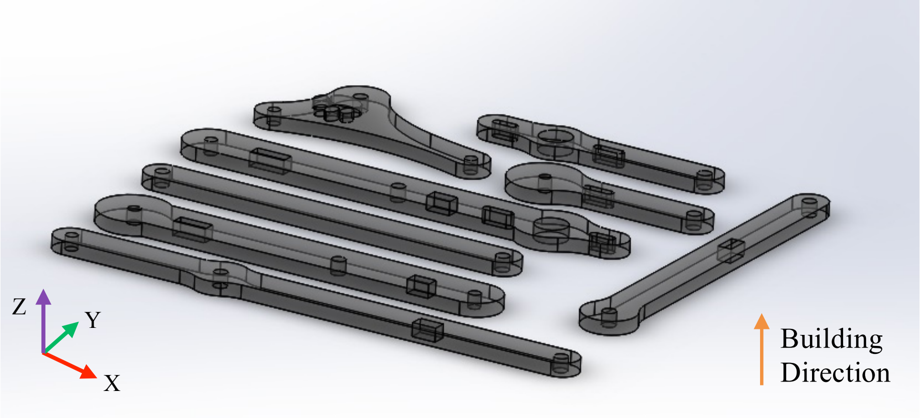


Figure 7. (b) 3D printing orientation

Figure 8 shows the linkage mechanism, and the red color parts are the driving links.

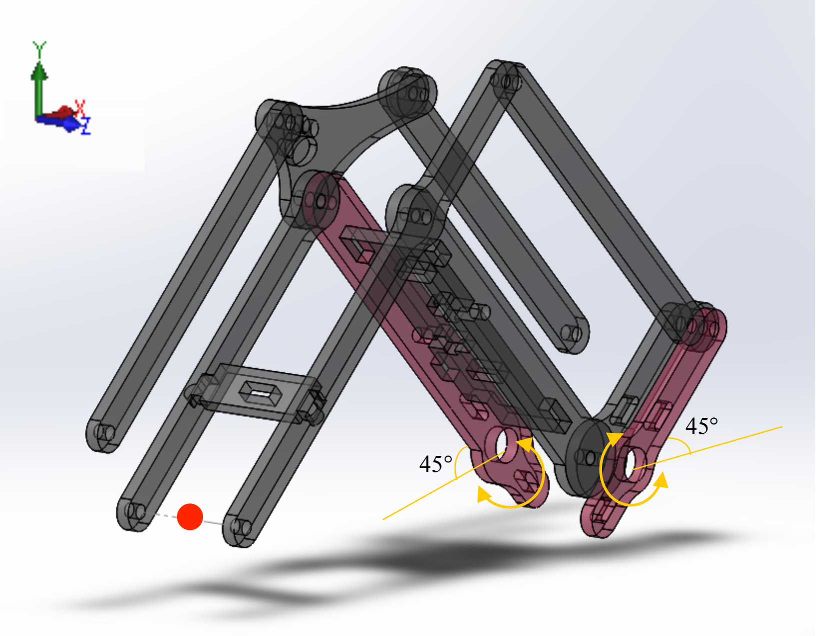


Figure 8. Linkage mechanism

With the measurement results of key dimensions, assembly simulation can be conducted in SolidWorks to check the accuracy of gripper location. In the static FEA simulation, the servo angles are set to 45° to the xz plane as shown in Figure 8. In other words, the angles of driving links are fixed. The red dot is the midpoint of two holes that connect the gripper, and the location of the red dot is considered as the gripper location in this mechanism. It is assumed that only the linkages have dimensional errors. The errors of all the other parts and assembly of screws, and the tolerance of servo angles are not considered. The assembly with parts in the nominal dimension will decide the nominal gripper location.

Various manufacturing parameters can be adjusted in build-preparation software, such as layer thickness, interior density, internal structure style, etc. For the FDM process, 2 different interior densities are applied for each machine in this thesis: 100% and 50% infill rate with layer thickness 0.150mm for MakerBot Replicator, and Solid and Sparse-low density with 0.178mm layer thickness for Fortus 250mc. The Object30 Prime offers a 0.016mm layer thickness with glossy surface. One set of linkage specimens are printed under each setting option listed in Table 2, while other parameters just following the machine default setting. Therefore, 5 sets of linkage specimens are printed.

Table 2. Manufacturing parameters

Specimen	Apparatus Model	Material	Layer Thickness (mm)	Interior Density	Internal Structure
1	**MakerBot Replicator (5th Generation)**	MakerBot PLA Filament	0.150	100%	Rarse
2				50%	
3	**Fortus 250mc**	ABSplus-P430	0.178	Solid	Linear
4				Sparse-low density	
5	**Object30 Prime**	Rigid opaque material (VeroBlue RGD840)	0.016	-	-

In order to have a more comprehensive comparison of the accuracy of gripper location of the three 3D printers, a simulation is carried out to get more data for gripper location. First, the deviations of distance between holes are assumed to follow normal distributions, and the quality requirement of 3D printing parts is supposed to be ±2σ based on the manufacturer's official dimensional tolerance. Second, for each machine type, 50 deviations are sampled from the normal distribution for every distance value. And the sampled deviations are added to the distance for every linkage. Third, linkages with modified distance between holes are assembled in SolidWorks. For each machine type, 50 assemblies are achieved and the corresponding gripper location is recorded.

Since MakerBot company does not provide estimating dimensional accuracy, this thesis takes ±0.500mm as the dimensional accuracy based on the work of Melenka *et al. (2015)*, and the official dimensional accuracy of Fortus and Object is ±0.241mm and ±0.100mm as stated in Table 1.

3.2.2 Mechanical Properties

To have a preliminary evaluation of stress and strain on the parts when the robot arm is working, a finite element analysis (FEA) simulation is performed on the linkage mechanism in SolidWorks, and simulation constraints are illustrated in Figure 9. The simulation is to evaluate the stress and strain of each link when robot arm is picking up an 1N object (including gripper weight) with each servo produces a torque of 0.17N.m according to the micro servo specification (GOTECK GS-9018 Specification). "Fixed Hinge" is applied to the revolute joints of the robot arm.

To evaluate if the materials are able to stand the force, and also to compare their mechanical performance, tensile tests are done on 3D printing specimens. For each set of specimens, the blue color part in Figure 9 was taken for tensile test because there is no other hole between two assembly holes, and it was loaded until the breaking point. Additionally, tensile test results are compared between specimens from 3D printing and MeArm parts.

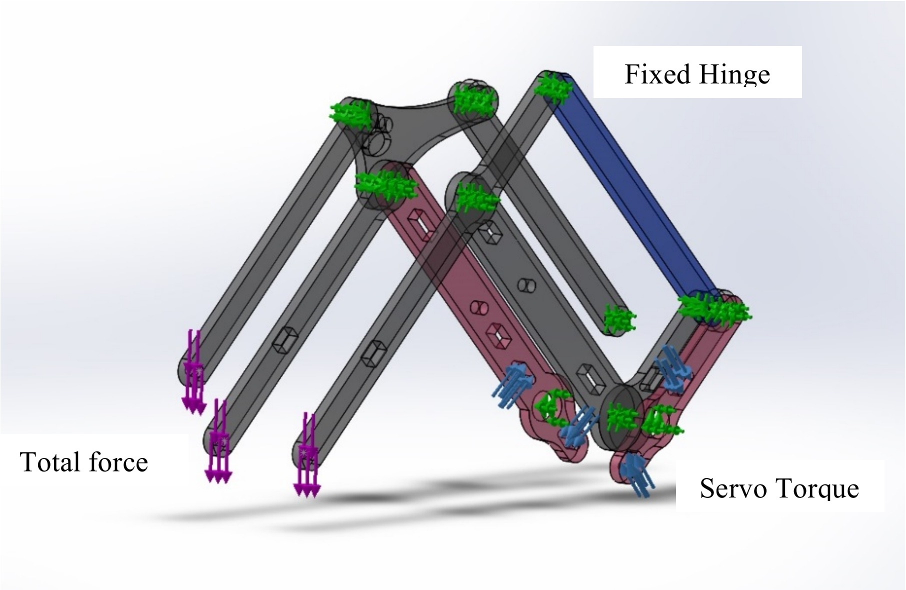
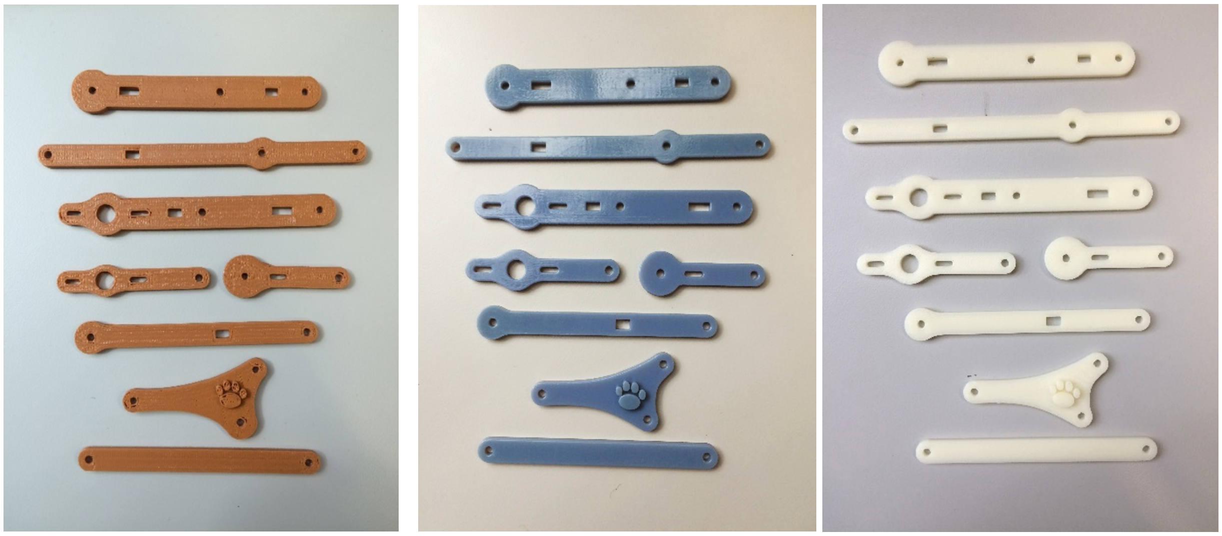


Figure 9. FEA simulation constraints

Chapter 4 Results and Discussions

4.1 Specimens Fabrication Result

Based on the manufacturing parameters setting of 3D printers in Chapter 3, 5 sets of specimens are fabricated and shown in Figure 10.



(a) (b) (c)

Figure 10. Specimens fabricated by 3D printers: (a) MakerBot Replicator; (b) Fortus 250mc; (c) Object30 Prime

Due to the process characteristics of filament deposition, the FDM process may result in small gaps between the filaments. The parts printed by MakerBot Replicator have larger gaps than those of the Fortus 250mc. The PolyJet process produces parts with smoother surfaces and realistic plastic appearance.

The building preparation software of 3D printers provides estimated building time and material amount. Table 3 provides the 3D printing material unit cost information of the Penn State Maker Commons and Department of Industrial and Manufacturing Engineering. The unit price of PLA is much cheaper than ABS and the rigid opaque material. Table 4 provides a comparison of building time, material amount and material cost of 5 sets of specimens. Figure 11 is a comparison of 5 sets of specimens in terms of building time and material cost.

Table 3. Material unit cost

Apparatus Model	Material	Material Density (g/cm^3)	Material Unit Cost ($/g)	
MakerBot Replicator (5th Generation)	MakerBot PLA Filament	1.24	0.053	
Fortus 250mc	ABSplus-P430	1.04	Model	0.27
			Support	0.26
Object30 Prime	Rigid opaque material (VeroBlue RGD840)	1.18	Model	0.25
			Support	0.13

Table 4. Building time and material cost comparison

Specimen	Apparatus Model	Interior Density	Building Time (hr)	Material Amount (g)		Material Cost ($)
1	**MakerBot Replicator (5th Generation)**	100%	3.60	37.49		2.0
2		50%	3.42	33.82		1.80
3	**Fortus 250mc**	Solid	3.25	Model	20.74	7.68
				Support	8.78	
4		Sparse -low density	3.00	Model	15.56	6.34
				Support	8.73	
5	**Object30 Prime**	-	1.83	Model	32.00	9.43
				Support	11.00	

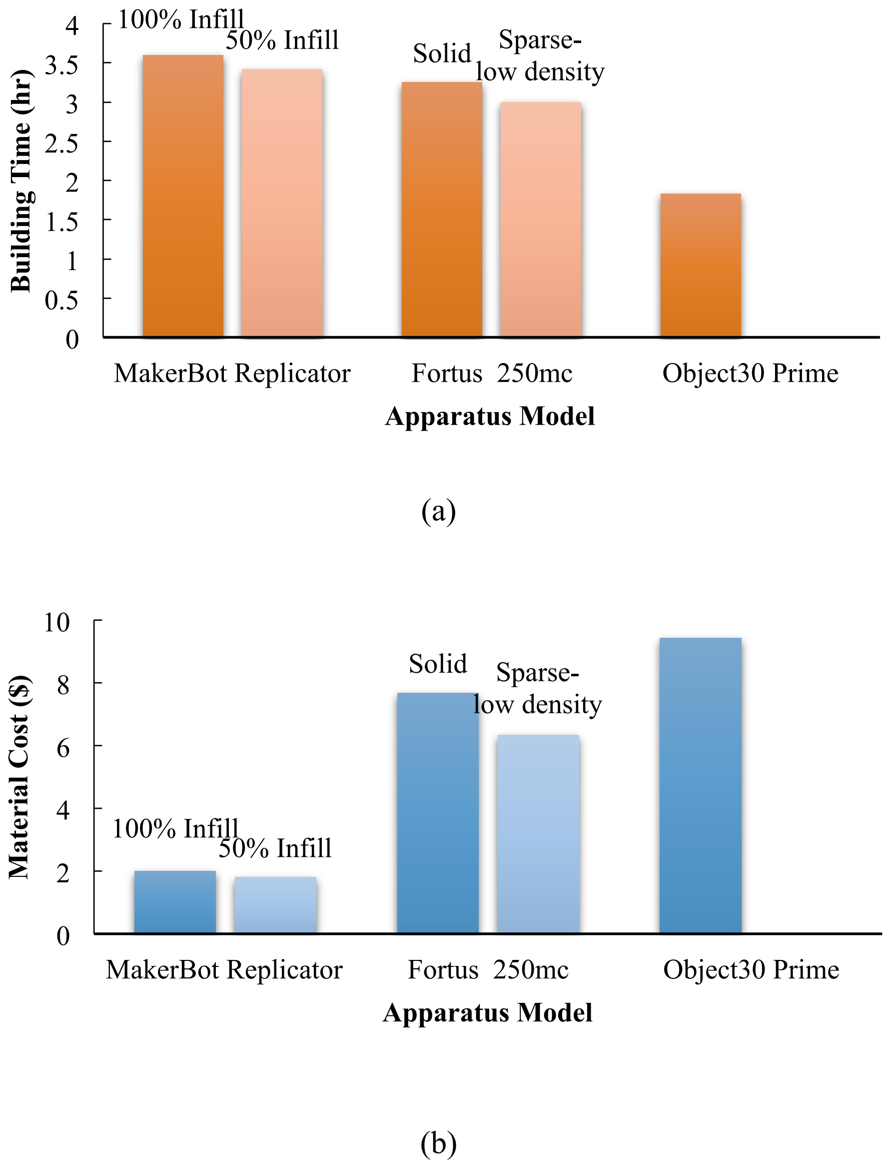


Figure 11. Comparison of apparatus models and processes: (a) building time; (b) material cost

Obviously, the FDM process needs a longer building time than the PolyJet process. To build solid parts, MakerBot Replicator requires a building time about 2 times longer than Object30 Prime. But the building time of MakerBot Replicator is about 15% longer that of Fortus 250mc, which is not a significant difference. Moreover, the reduction of interior density only results in a slight decrease of building time for both MakerBot Replicator and Fortus 250mc.

The PolyJet process has a higher material cost than the FDM process. For solid parts, the Object30 Prime cost around 6 times more than the MakerBot Replicator, and 20% more than the Fortus 250mc. Actually, ABS has a higher unit price ($/g) than Object's material. However, Object still cost more for the same parts due to its higher density. In terms of material cost, not like building time, the reduction of interior density results in an apparent decrease of 16% for MakerBot Replicator and 21% for Fortus 250mc.

4.2 Dimensional Accuracy and Assembly Accuracy

4.2.1 Dimensional Accuracy

To investigate dimensional accuracy, as mentioned in Chapter 3, several dimensions should be measured, including the diameter of circular holes for screws, the relative location of these holes, and the thickness of parts. Figure 12 describes deviations of 5 sets of specimens and MeArm pats regarding circular holes' diameter, relative locations, and thickness.

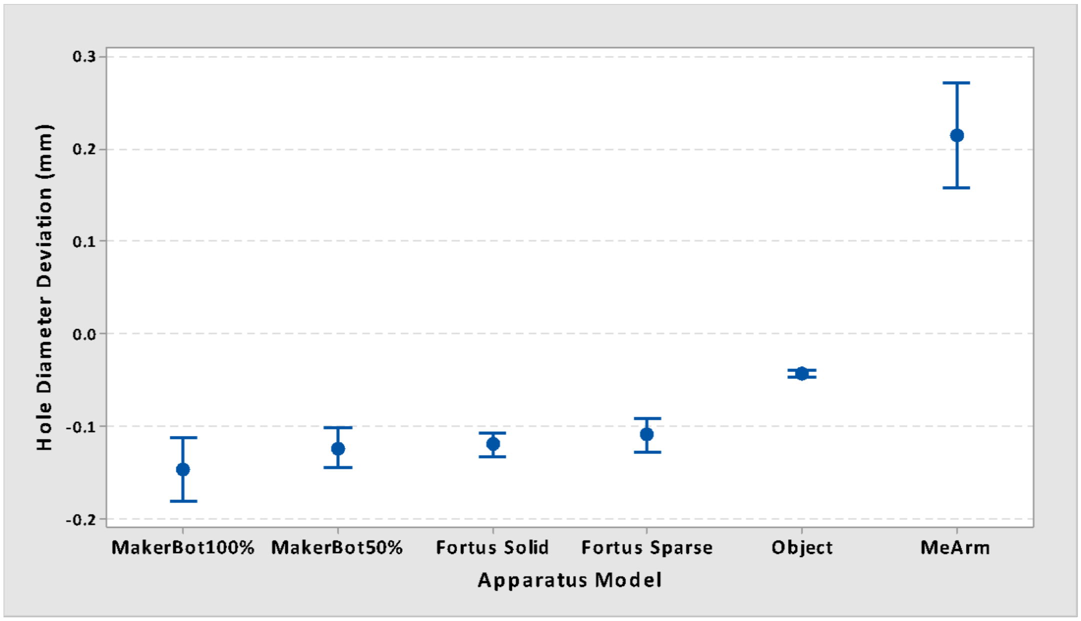


Figure 12. (a) Hole diameter deviation

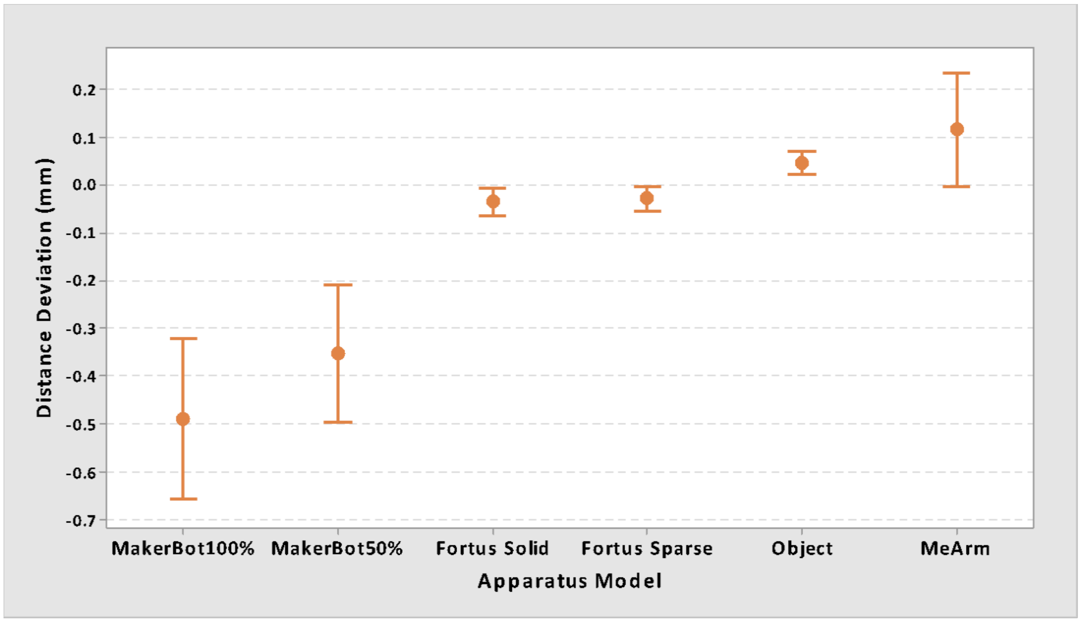


Figure 12. (b) Distance deviation

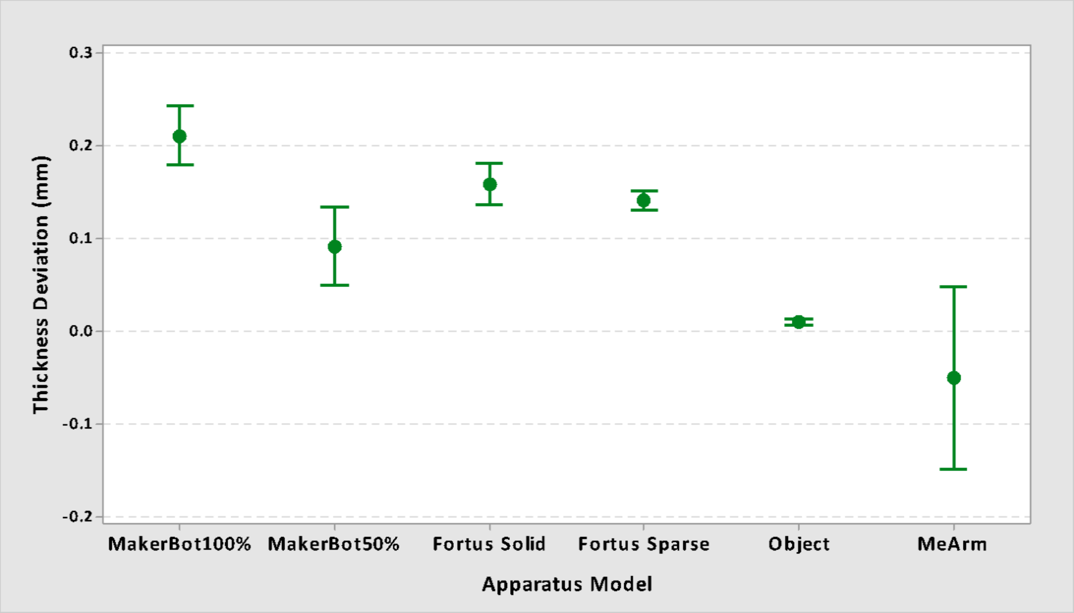


Figure 12. (c)Thickness deviation

Figure 12(a) indicates that Object 30 Prime has the best performance in hole size with the smallest deviation and variance, and MeArm parts are the worst. The original MeArm parts are laser cut from acrylic sheets and the holes have positive deviations compared with the nominal size. In contrast, 3D printing process produces negative deviations, which is a general characteristic of 3D printing because of material shrinkage after cooling. Besides, interior density difference does not have an obvious influence on dimensional accuracy. MeArm parts have large deviations for holes may be the result of design considerations. Probably, design engineers set a large positive tolerance for the holes to make a clearance fitting with screws and enable joints to rotate smoothly.

In Figure 12(b), MakerBot Replicator makes the largest deviation and variance in distance, which means this machine has the worst location precision compare with others. Fortus 250mc and Object30 Prime have smaller deviations. Due to the material shrinkage in 3D printing, MakerBot Replicator and Fortus 250mc have negative deviations. Nevertheless, the deviations of Object30 Prime are positive. The performance of MeArm parts is between MakerBot and other two 3D printers.

Figure 12(c) shows that the Object30 Prime and MeArm have the best performance in thickness, while MakerBot Replicator is the worst. The Object30 Prime has better precision control in the z direction than the other two printers. The nominal thickness is 3mm, and the layer number cannot be an integer with 0.178mm layer thickness for Fortus 250mc.

According to Figure 12, Fortus 250mc and Object30 Prime are more stable in deviations than other processes. For distance between holes, Fortus 250mc has similar performance to Object30 Prime, but Object30 Prime is better in diameter. Kim and Oh (2008) pointed out that the droplet-based nature of PolyJet process may enable it to recreate positive circular features more effectively.

4.2.2 Assembly Accuracy

Based on the measurement of relative location of screw holes and parts thickness, linkages are assembled in SolidWorks. The angles of driving links are fixed as shown in Figure 8. Table 5 lists the deviation of gripper location of 3D printing specimens and the original MeArm parts.

Table 5. Gripper location deviation

Apparatus Model	Interior Density	Deviation (XYZ)
MakerBot Replicator (5th Generation)	100%	(0.81, 0.16, -0.87)
	50%	(0.57, 0.07, -0.42)
Fortus 250mc	Solid	(-0.10, 0.03, -0.61)
	Sparse-low density	(-0.04, 0.02, -0.58)
Object30 Prime	-	(0.10, 0.01, -0.03)
MeArm Parts	-	(-0.22, 0.32, 0.03)

Assembly of MeArm parts has more accurate gripper location than MakerBot parts assembly, but is worse than Fortus and Object. The assembly of Fortus parts has similar accuracy in XY plane with Object, but Object has much better Z axis accuracy. The reason is that Object parts has similar distance accuracy to Fortus parts but have more accurate thickness. The MakerBot Replicator produced the largest deviation for gripper location.

As mentioned in Chapter 3, deviations sampled from normal distributions based on official tolerances and added to the distances of holes. Linkages with modified distances between holes are assembled in SolidWorks. Figure 13 is the plot of XYZ deviations of gripper location of the simulated assemblies. MakerBot Replicator has the largest dimensional accuracy within the three 3D printers, so it has the most dispersive deviations for gripper location, and follows by Fortus 250mc, while Object30 Prime has the smallest deviations.

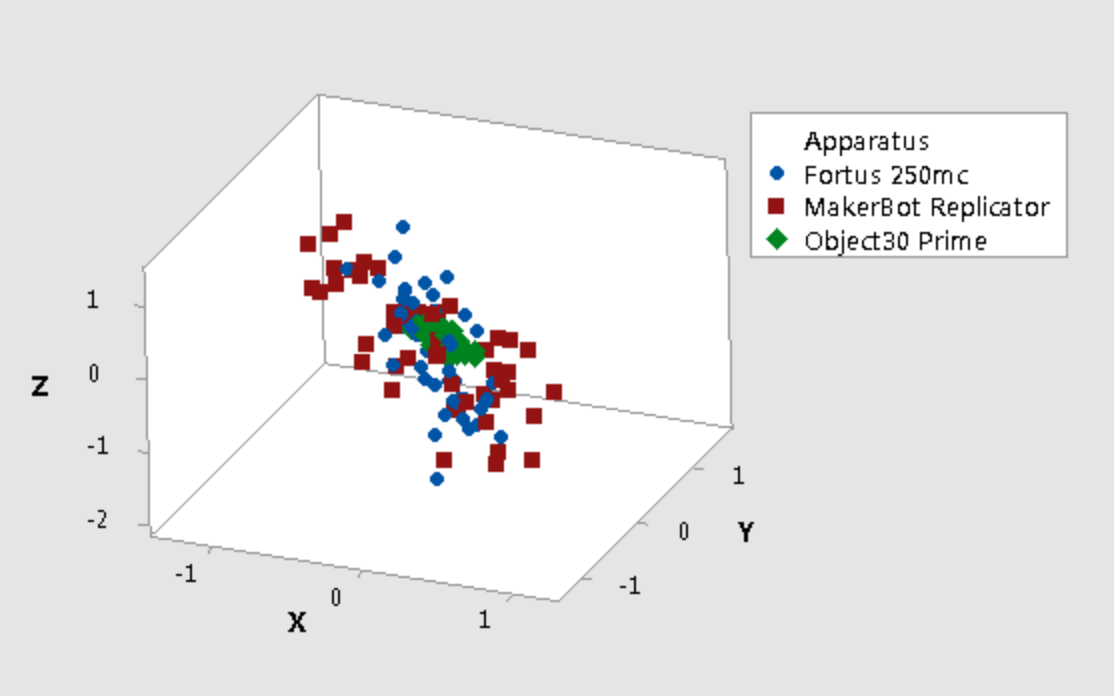


Figure 13. Simulated XYZ deviations of gripper location

4.3 FEA Simulation and Tensile Tests

Based on the 3D SolidWorks model and the FEA constraints mentioned in Chapter 3, static FEA simulation was conducted on the working robot arm linkage mechanism. In the simulation results of acrylic material, the material of MeArm parts, shown in Figure 14, the maximum stress and the maximum strain occur at the driving links due to servo torque.

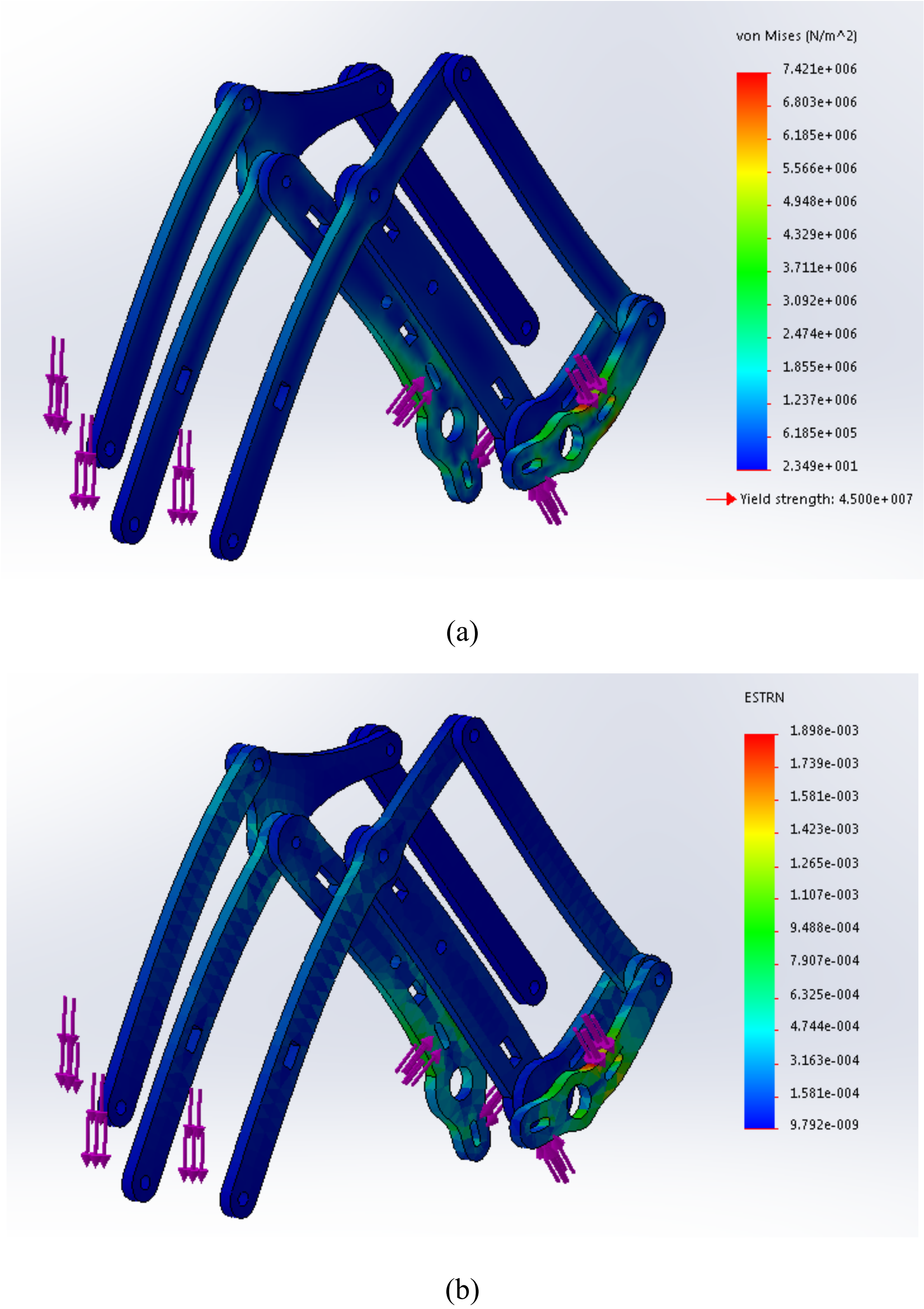


Figure 14. FEA simulation of linkage mechanism (acrylic): (a) result of stress; (b) result of strain

FEA simulation of 3D printing materials are also run in the mechanism. Since all the materials in this thesis are plastics, the simulation results are similar as shown in Table 6.

Table 6. FEA simulation result

Material	Maximum Stress (MPa)	Maximum Strain (%)
MakerBot PLA Filament	7.42	0.19
ABSplus-P430	7.41	0.27
Rigid opaque material (VeroBlue RGD840)	7.42	0.29
Acrylic	7.42	0.19

Table 7 shows the tensile test results of the same part fabricated from different processes, and Figure 15 is a comparison of stress-strain curves.

Table 7. Tensile test results comparison

Process	Material	Density	Yield Strength(MPa)	Tensile Strength (MPa)	Break Elongation (%)
MakerBot Replicator	MakerBot PLA Filament	100%	22.55	45.31	4.0
		50%	1.65	39.14	3.4
Fortus 250mc	ABSplus-P430	Solid	32.13	32.66	7.5
		Sparse-low density	1.22	23.79	6.0
Object30 Prime	Rigid opaque material (VeroBlue RGD840)	-	52.66	54.52	6.9
MeArm Part	Acrylic	-	1.37	42.87	2.0

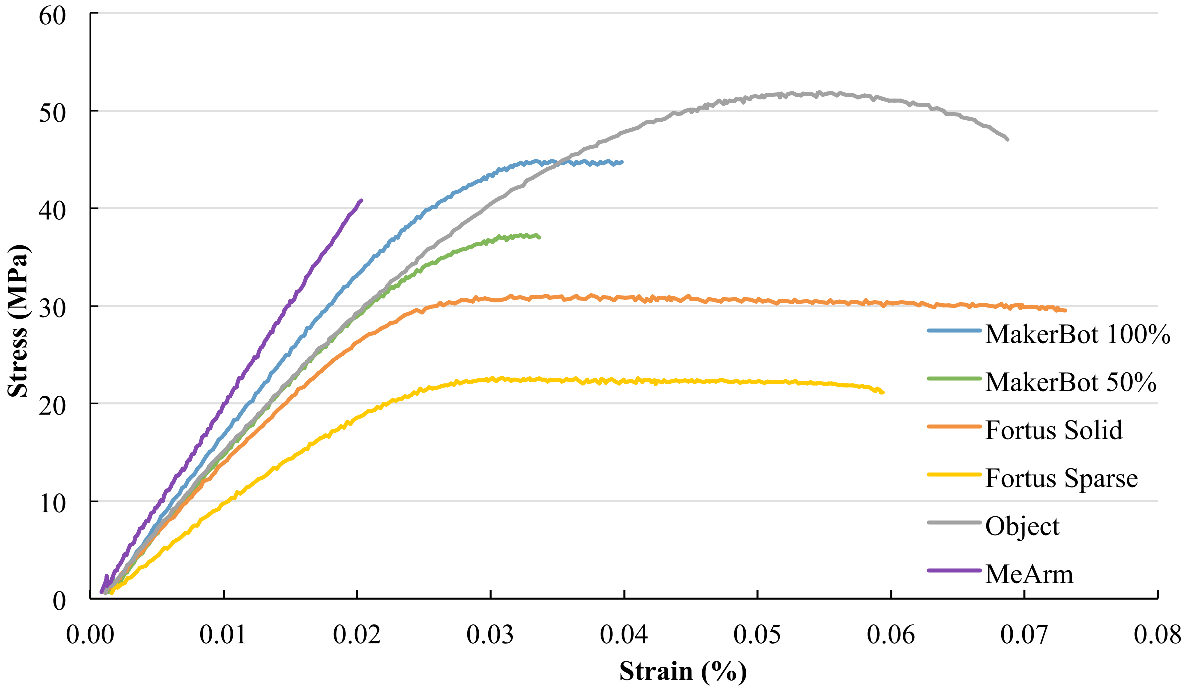


Figure 15. Stress-strain curve comparison

As stated in datasheet from MakerBot, average tensile strength of PLA is 48MPa. And 3D Matter website concluded from several experiments that elongation at break of PLA in 3D printing is 4%-6%. According to the datasheet by Stratasys, for ABSplus-P430, the yield strength is 31MPa, the tensile strength is 33MPa, and elongation at break is 6%; while for VeroBlue RGD840, the tensile strength is 50-60MPa and elongation at break is 6%.

The tensile test results of 100% infill rate PLA, solid ABS, and VeroBlue RGD840 are similar to the official mechanical properties generally. But the elongation at break of VeroBlue is only half of official data, the possible reason might be various, because the specimen geometry and tensile test machine in this thesis is different from Stratasys' testing specimens.

VeroBlue material is the best in terms of both yield strength and tensile strength in this test. And PLA has larger tensile strength than ABS, but yield strength of PLA is not as good as ABS. Besides, 3D printing materials are more ductile than the MeArm acrylic material. When the interior density of PLA and ABS is reduced, the tensile strength is reduced less than 30%. However, the yield strength drops intensely. Therefore, interior density has a large influence on yield strength.

According to the tensile test results and FEA simulation results, 3D printing parts are strong enough for the robot arm. But parts with lower infill rate need to be evaluated carefully for robot arm assembly.

Chapter 5 Conclusions and Future Work

5.1 Conclusions

Nowadays, customers have increasing requirements for customized products. As a result, the desire to take part in the design stage of products has become stronger. 3D printing has become a competitive and popular way for customers to create personalized products. In recent decades, the emergence of lower price 3D printers, online free 3D modeling software, a growing number of online 3D model sharing communities, and easily available 3D printing centers, enable more and more technology hobbyists and even normal customers to create their own personalized products.

To create personalized products through 3D printing, several factors need to be evaluated to ensure efficiency and satisfy functional requirements. In this thesis, a case study focused on the linkage mechanism of a desktop robot arm was carried out. The design was based on an existing open-source product: MeArm Robot.

There are various 3D printing machines in the market now. Three 3D printers were used in this thesis: MakerBot Replicator (5th Generation), Fortus 250mc, and Object30 Prime. Correspondingly, the materials for these three machines were MakerBot PLA filament, ABSplus-P430, and Rigid Opaque Material (VeroBlue RGD840). For the two FDM machines, MakerBot and Fortus, two different interior density settings were applied. Material cost and building time were evaluated and compared for five sets of 3D printing specimens. For all the 3D printing specimens and MeArm parts, following tests were carried out: (1) dimensional and location accuracy of holes were measured; (2) gripper location accuracy was calculated; (3) FEA simulation is performed; (4) tensile tests are done.

Among the three 3D printers applied in this thesis, Object30 Prime had the best performance in building time, dimensional accuracy, and assembly accuracy. The PolyJet process was about 40% faster in building speed than the FDM process. MakerBot Replicator was the most cost effective machine, as its material cost was lower than the other two printers. For the FDM process, reducing interior density resulted in a slightly decrease in building time and material cost. Specimens of both Fortus and Object printers were better in dimensional accuracy and assembly accuracy than the original MeArm robot arm. All the hole diameters of 3D printing parts were smaller than the nominal size because of material shrinkage, which may result in problems of assembly with screws. Moreover, 3D printing parts were thicker than the nominal size in the z direction, which may affect the assembly between linkages and the base of the robot arm.

The tensile test showed that VeroBlue had the largest yield strength and tensile strength. PLA part had larger tensile strength than ABS part and acrylic part, but it was not as ductile as ABS part. Acrylic part was the most brittle of the specimens. According to FEA simulation results, 3D printing specimens were able to meet the mechanical property requirements. Results of tensile test also indicated that interior density reduction may cause a significant decrease in yield strength.

To conclude, 3D printing is cost and time efficiently to make a personalized functional product. Proper 3D printers should be chosen depending on specific requirements. Object30 Prime is suitable for products with strict quality requirements for its superior performance in dimensional accuracy and location accuracy. Object30 Prime is also a good choice for products with high standards for building time or mechanical properties. MakerBot Replicator is the proper machine when cost is the most important concern. Compared with MakerBot, Fortus 250mc is better in terms of accuracy and yield strength.

5.2 Future Work

The accuracy capability of each printer may vary depending on part geometry, dimension, and process. Further research could make more adjustments of interior density for FDM process and consider the building orientation of 3D printing as a factor of experiments to compare the results of building time, accuracy, and tensile tests. To build a functional assembly with 3D printing parts, dimensional compensation needs to be considered due to process properties. Creating more versions of size based on MeArm robot arm with 3D printing and investigating the functional accuracy and supply chain problems might be an interesting and valuable topic in the future.

References

[1] Ahn, S. H., Montero, M., Odell, D., Roundy, S., & Wright, P. K. (2002). Anisotropic material properties of fused deposition modeling ABS. *Rapid Prototyping Journal*, 8(4), 248-257.

[2] Ainsworth, I., Ristic, M., & Brujic, D. (2000). CAD-based measurement path planning for free-form shapes using contact probes. *The International Journal of Advanced Manufacturing Technology*, *16*(1), 23-31.

[3] Baich, L., Manogharan, G., & Marie, H. (2015). Study of infill print design on production cost-time of 3D printed ABS parts. *International Journal of Rapid Manufacturing*, 5(3-4), 308-319.

[4] Bardakci, A., & Whitelock, J. (2003). Mass-customisation in marketing: the consumer perspective. *Journal of consumer marketing*, 20(5), 463-479.

[5] Berman, B. (2012). 3-D printing: The new industrial revolution. *Business horizons*, 55(2), 155-162.

[6] Campbell, T., Williams, C., Ivanova, O., & Garrett, B. (2011). Could 3D printing change the world. *Technologies, Potential, and Implications of Additive Manufacturing, Atlantic Council, Washington, DC*.

[7] Da Silveira, G. (2001). Innovation diffusion: research agenda for developing economies. *Technovation*, 21(12), 767-773.

[8] Davis, S. M. (1989). From "future perfect": Mass customizing. *Planning review*, *17*(2), 16-21.

[9] Eli Whitney Museum and Workshop, Retrieved from http://www.eliwhitney.org

[10] Fiore, A. M., Seung-Eun, L., & Kunz, G. (2003). Psychographic variables affecting willingness to use body-scanning. *Journal of Business and Management*, *9*(3), 271.

[11] Fogliatto, F. S., da Silveira, G. J., & Borenstein, D. (2012). The mass customization decade: An updated review of the literature. *International Journal of Production Economics*, 138(1), 14-25.

[12] Ford, H. (1926). Mass production. *Encyclopaedia Britannica*, 13, 821-823.

[13] Gibson, I., Rosen, D. W., & Stucker, B. (2010). *Additive manufacturing technologies* (pp. 1-3). New York: Springer.

[14] *GOTECK GS-9018 Specification*,
Retrieved from http://www.goteckrc.com/ProductShow.asp?ID=10

[15] Hu, S. J., Ko, J., Weyand, L., ElMaraghy, H. A., Lien, T. K., Koren, Y., ... & Shpitalni, M. (2011). Assembly system design and operations for product variety. *CIRP Annals-Manufacturing Technology*, 60(2), 715-733.

[16] Hu, S. J. (2013). Evolving paradigms of manufacturing: From mass production to mass customization and personalization. *Procedia CIRP*, 7, 3-8.

[17] Ibrahim, M., & Hafsa, M. N. (2014). Dimensional accuracy of additive manufacturing model with different internal structure for investment casting implementation.

[18] Jiang, K., Lee, H. L., & Seifert, R. W. (2006). Satisfying customer preferences via mass customization and mass production. *IIE Transactions*,*38*(1), 25-38.

[19] Kaplan, A. M., & Haenlein, M. (2006). Toward a parsimonious definition of traditional and electronic mass customization. *Journal of product innovation management*, 23(2), 168-182.

[20] Kerry Stevenson. (2013). MakerBot releases three things. Retrieved from http://www.fabbaloo.com/blog/2013/10/3/makerbot-releases-three-things.html

[21] Kim, G. D., & Oh, Y. T. (2008). A benchmark study on rapid prototyping processes and machines: quantitative comparisons of mechanical properties, accuracy, roughness, speed, and material cost. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *222*(2), 201-215.

[22] Kim, G. D., & Sung, J. H. (2006). Bench mark test on rapid prototyping processes and machines for functional prototypes. *Journal of the Korean Society for Precision Engineering*, *23*(6), 187-195.

[23] Kumar, A. (2007). Mass customization: manufacturing issues and taxonomic analyses. *International Journal of Flexible Manufacturing Systems*, *19*(4), 625-629.

[24] Lipson, H., & Kurman, M. (2010). Factory@ home: The emerging economy of personal fabrication. *A report commissioned by the US Office of Science and Technology Policy*.

[25] Mahesh, M., Wong, Y. S., Fuh, J. Y. H., & Loh, H. T. (2004). Benchmarking for comparative evaluation of RP systems and processes. *Rapid Prototyping Journal*, *10*(2), 123-135.

[26] McIntosh, P. (2010). White privilege and male privilege. *The Teacher in American Society: A Critical Anthology*, 121.

[27] MeArm Robotics, Retrieved from https://www.mearm.com/

[28] Melenka, G. W., Schofield, J. S., Dawson, M. R., & Carey, J. P. (2015). Evaluation of dimensional accuracy and material properties of the MakerBot 3D desktop printer. *Rapid Prototyping Journal*, *21*(5), 618-627.

[29] Mota, C. (2011, November). The rise of personal fabrication. In *Proceedings of the 8th ACM conference on Creativity and cognition* (pp. 279-288). ACM.

[30] Mowatt, S. (2005). Impacts of the digital economy: The shift to consumer–driven competition and life–span products. *Digital economy: Impacts, influences and challenges. Hershey, Pa.: Idea Group*, 136-153.

[31] N. Turner, B., Strong, R., & A. Gold, S. (2014). A review of melt extrusion additive manufacturing processes: I. Process design and modeling. *Rapid Prototyping Journal*, 20(3), 192-204.

[32] Pettis, B. (2011). All-Star Line up invests in MakerBot. *MakerBot Blog*.

[33] Pilipović, A., Raos, P., & Šercer, M. (2009). Experimental analysis of properties of materials for rapid prototyping. *The International Journal of Advanced Manufacturing Technology*, *40*(1-2), 105-115.

[34] Piller, F. T. (2004). Mass customization: reflections on the state of the concept. *International journal of flexible manufacturing systems*, 16(4), 313-334.

[35] Pine II, B. J., & Victor, B. (1993). Making mass customization work. *Harvard business review*, *71*(5), 108-117.

[36] *PolyJet Technology*, Stratasys, Retrieved from http://www.stratasys.com/3d-printers/technologies/polyjet-technology

[37] Reeves, P., Tuck, C., & Hague, R. (2011). Additive manufacturing for mass customization. In *Mass Customization* (pp. 275-289). Springer London.

[38] Sachs, E. M., Haggerty, J. S., Cima, M. J., & Williams, P. A. (1994). *U.S. Patent No. 5,340,656*. Washington, DC: U.S. Patent and Trademark Office.

[39] Salvador, F., De Holan, P. M., & Piller, F. T. (2009). Cracking the code of mass customization. *MIT Sloan management review*, *50*(3), 71.

[40] Sidambe, A. T. (2014). Biocompatibility of advanced manufactured titanium implants—A review. *Materials*, *7*(12), 8168-8188.

[41] Sung-Hoon Ahn Michael Montero Dan Odell Shad Roundy Paul K. Wright, (2002),"Anisotropic material properties of fused deposition modeling ABS", Rapid Prototyping Journal, Vol. 8 Iss 4 jpp. 248 – 257

[42] Tseng, M. M., & Hu, S. J. (2014). Mass customization. In *Cirp Encyclopedia of Production Engineering* (pp. 836-843). Springer Berlin Heidelberg.

[43] What is the influence of infill %, layer height and infill pattern on my 3D prints? (2015). Retrieved from http://my3dmatter.com/influence-infill-layer-height-pattern/

[44] Wohlers, T. (2011). Wohlers report 2011: additive manufacturing and 3D printing. *State of the Industry, Wohlers Associates*.

[45] Wohlers, T., & Gornet, T. (2012). History of additive manufacturing. *Wohler Associates, Inc., Fort Collins, Colorado.*