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FEA MODELS AND EXPERMENTAL RESULTS OF 3D PRINTING PROCESS FOR FABRICATING A MINI ROBOT

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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 research 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 costeffective 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

I. Introduction

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 research is to evaluate the characteristics of different 3D printing machines and processes to provide information for building personalized products. In this research, 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 research 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.

II. 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.

A. 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 1 shows the 3D model with linkages in yellow color.

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Fig 1.3D model of MeArm

B. 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

C. Specimens Fabrication and Dimension Measurement

Figure 2 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 2 (a) is from the 2D drawing shared on MeArm website, and the nominal thickness is 3mm. At the meantime, Figure 2 (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.

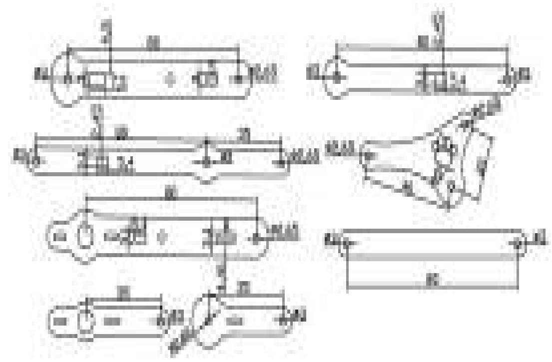


Fig 2(a) nominal dimension for measurement

Fig 2(b) 3D printing orientation

Figure 3 shows the linkage mechanism, and the red color parts are the driving links.

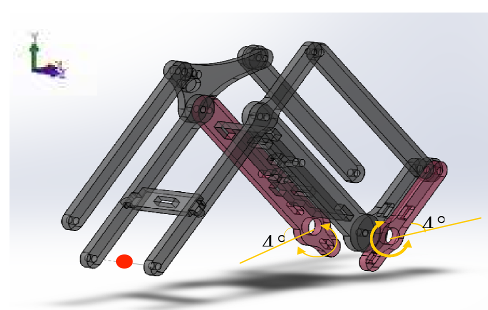


Fig 3. Linkage mechanism

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 research: 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.

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.

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	-	-

Since MakerBot company does not provide estimating dimensional accuracy, this research 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.

III. 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 4. 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.

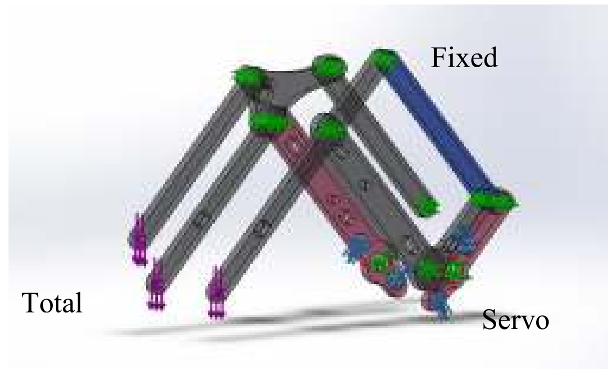
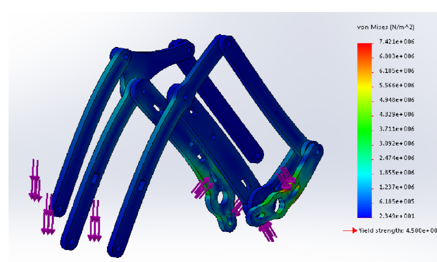


Fig 4. FEA simulation constraints

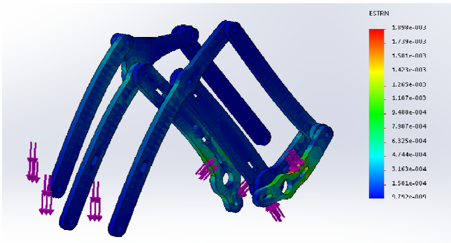
To evaluate if the materials are able to stand the force, and also to compare their mechanical performance, tensile tests are done on 3D printing specimens. For each set of specimens, the blue color part in Figure 4 was taken for tensile test because there is no other hole between two assembly holes, and it was loaded until the breaking point. Additionally, tensile test results are compared between specimens from 3D printing and MeArm parts.

IV. FEA Simulation and Tensile Tests

Based on the 3D SolidWorks model and the FEA constraints, 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 5, the maximum stress and the maximum strain occur at the driving links due to servo torque.



(a)



(b)

Fig 5. 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 research are plastics, the simulation results are similar as shown in Table 3.

Table 3. 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 4 shows the tensile test results of the same part fabricated from different processes, and Figure 6 is a comparison of stress-strain curves.

Table 4. 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

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 research is different from Stratasys' testing specimens

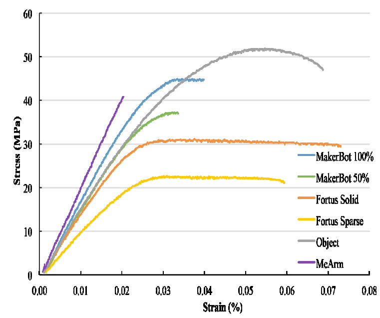


Figure 6. Stress-strain curve comparison

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.

V. Conclusions and Future Work

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 research, 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 research: 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 research, 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.

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.

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