FINAL DESIGN IMPROVEMENT OF REPLICA TROPHY FROM PROTOTYPE TO MASS PRODUCTION

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July 2022

This dissertation is submitted to

Universiti Sains Malaysia

As partial fulfillment of the requirement to graduate with honors degree in

BACHELOR OF ENGINEERING

(MANUFACTURING ENGINEERING WITH MANAGEMENT)

School of Mechanical Engineering

Engineering Campus

Universiti Sains Malaysia

DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently in candidature for any degree.

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This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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ACKNOWLEDGEMENT

I would like to express my greatest gratitude to the School of Mechanical Engineering, Universiti Sains Malaysia for providing equipment and materials to complete my Final Year Project (FYP). My project would not have completed without the support from different parties. Firstly, I would like to express my deepest gratitude to my FYP supervisor, Assoc. Prof. Dr. Mohd Salman Abu Mansor who had supported me throughout the whole project process. His unconditionally support and providing clear concept had helped me to clear my doubts. His guidance and advises are important in solving problem and accomplish task.

Next, I would like to express my deepest appreciation to the technician of School of Mechanical Engineering who provide suggestions based on their experiences in fabrication and hand-on on the machines. These had helped me in speeding up my progress which allow my progress to be on tracked.

Thirdly, I would like to express appreciation to all my friends who willing to help me to solve my problem. Thanks for their helpful support and motivation throughout the completion of this project.

Lastly, I would like to thank my family members for giving me spirit and moral support to complete my final year project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVATIONS

2D	Two Dimensions
3D	Three Dimensions
ASCII	American Standard Code for Information Interchange
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CMM	Coordinate Measure Machine
CNC	Computer Numerical Control
CATIA	Computer Aided Three-Dimensional Interactive Application
FMEA	Failure Modes and Effects Analysis
NC	Numerical Control
RE	Reverse Engineering
STEP	Standard for the Exchange of Product Data
STL	Stereolithography

ABSTRAK

Trofi berfungsi sebagai pengiktirafan dan peringatan untuk pencapaian tertentu. Kebanyakan replika trofi direka berdasarkan tema acara. Oleh itu, kejuruteraan terbalik adalah cara yang paling sesuai kerana ia mengubah objek sebenar kepada model kejuruteraan dan cara ini digunakan secara meluas dalam industri pembuatan. Dalam kajian ini, ia dikehendaki menambah baik reka bentuk trofi untuk pengeluaran besar-besaran berdasarkan Majlis Sanggar Sanjung USM bagi meraikan kejayaan staf. Objektif projek ini adalah untuk mengenal pasti arah aliran semasa dengan penambahbaikan kefungsian dan penentuan penjimatan kos, penjimatan masa dan peningkatan kualiti bagi menghasilkan reka bentuk akhir trofi replika dalam pengeluaran besar-besaran. Analisis fungsi dan FMEA dijalankan untuk menganalisis kesan mod kegagalan prototaip. Beberapa konsep telah dijana dan dianalisis selanjutnya dalam carta morfologi. Selepas penjanaan konsep, bahan dan proses pembuatan dipilih untuk setiap bahagian. Pengimbas 3D digunakan untuk mengimbas objek (tangan) dan pemerolehan data diperolehi oleh pengimbas. Hasil imbasan dibincangkan untuk mendapatkan output yang lebih baik. Kemasan permukaan struktur tangan bercetak 3D dibincangkan dan diselesaikan dengan proses mengempelas. Laluan alat, kelajuan dan alat yang sesuai dipilih untuk melihat pratonton masa pemesinan dan output bahagian trofi dengan menggunakan simulasi CATIA. Pendekatan ini boleh menyebabkan memakan masa yang singkat kerana ia mengurangkan ralat semasa pemesinan CNC. Kemudian, bahagian yang dipilih masing-masing dihasil oleh mesin CNC dan percetakan 3D. Kos untuk fabrikasi satu trofi dan pengeluaran besar-besaran dibandingkan dan boleh disimpulkan bahawa pengeluaran besar-besaran trofi boleh mengurangkan kos dengan RM93.86 manakala pengeluaran tunggal ialah RM187.54. Akhir sekali Masa yang diambil untuk trofi tunggal ialah 12.20 jam dan 10 trofi ialah 11hari yang disimulasikan oleh perisian Witness Horizon.

ABSTRACT

Trophy serves as a recognition and a reminder for a specific achievement. Most of the replica trophy is designed based on the theme of the event. Therefore, reverse engineering is the most suitable way as it transforms real parts into engineering models and is widely used in manufacturing industry. In this paper, it is required to improve the design of the trophy for mass production based on the event of Hall of Fame Universiti Sains Malaysia (*Sanggar Sanjung*) to celebrate the success of staff. The objectives of this paper are to identify current trend with improvement of functionality and determination of cost saving, time saving and quality improvement in order to produce the final design of replica trophy in mass production. Function analysis and FMEA is conducted to analyze the failure mode effect of the prototype. Few concepts are generated and is further analyzed in the morphology chart. After the concept generation, material and manufacturing process is selected for each part. 3D scanner is used to scan the object (hand) and the data acquisition is obtained by the scanner. The scanned results are discussed to get a better output. The surface finish of 3D printed hand structure is discussed and solved by sanding process. By using the CATIA simulation, suitable toolpath, speed and tool is selected to preview the machining time and output of the part of trophy. This approach can lead to short time consuming as it reduces the error during CNC machining. Then, the selected parts are fabricated by the CNC machine and 3D printing respectively. The cost for fabricating a single trophy and mass production is compared and it can be concluded that mass production of trophy can reduce the costing with RM93.86 whereas single production is RM187.54. Lastly The time taken for single trophy is 12.20 hours and 10 trophies is 11days which is simulated by Witness Horizon software.

CHAPTER 1
INTRODUCTION

1.1 Project Background

Trophy serves as a recognition and a reminder for a specific achievement. The word trophy is derived from the Greek *tropaion* [1]. Trophy is awarded in many types of competition or event such as sports, professional awards, music and appreciation rewards. The event of Hall of Fame Universiti Sains Malaysia (*Sanggar Sanjung*) is an annual basis of event to celebrate the success and personal satisfaction that honours the creative and innovative spirit as well as rewards hard works and dedication to the staff for their achievement. The event began in 2001 and is award to the contributions of USM staff in research, publication, personality, quality, creativity and teaching categories [2].

Reverse engineering transforms real parts into engineering models and concepts while the conventional engineering transforms engineering model into real part. Reverse engineering is widely used in the manufacturing industry. This is because reverse engineering has a broad range area in manufacturing such as mechanical engineering, software engineering, animation, electronics etc. CAD/CAM system is used in reverse engineering which is a huge advantage in producing existing or redesign product. 3D laser scanner and high-resolution microscopy makes reverse engineering easier. With the recent advancement in reverse engineering has elevated the technology in many industries including aerospace, automotive, medical device, sports equipment and toys [3].

3D printing which is a type of additive manufacturing is a process where uses successive addition of material in creating physical objects from geometrical representation (CAD). In recent years, 3D printing is widely used in mass customization and production of any open-source design. Besides, 3D printing uses high quality material to meet consistent build high quality devices with wide range of material such as metal, ceramic, polymer and combination of hybrid and composites [4].

Computer numerical control (CNC) is the numerical control system in which a dedicated computer is built into the control to perform basic and advanced NC functions. The manufacturing process of CNC machining can be simulated virtually and no need to make a prototype or a model. This saves time and money. These machines can manufacture several components to the required accuracy without any fatigue. CNC was initially applied to metal working machinery and is expanded to robotics, grinder and welding.

Trophy can be produced using different type of materials such as metal, plastic, wood and glass. Trophy is a product that need to produce based on the theme of the event and are required to produce in mass production for multiple rewards in the same event. Therefore, in order to meet the demand, the fastest and most convenient way to manufacture the trophy is the best. Reverse engineering, 3D printing, and CNC machining will be the most suitable method to produce the trophy in term of mass production. With the help of reverse engineering, the process of produce development is fastened by scanning the existing product into CAD and modify the design.

This project is to identify the trend of current trophy which related to the theme and improve the design of the trophy in term of functionality. Propose of the new design for the trophy based on current trend. The new design is improved based on the prototype given. The purpose to redesign the prototype is increase the functionality of the trophy and produce the product in mass production. Cost and time saving method as well as the improvement in quality of the replica trophy need to be considered in the selection of materials and fabrication methods.

1.2 Problem Statement

Final design improvement for replica trophy of the event Sanggar Sanjung USM to produce in mass production. The existing replica trophy in the market can only be used for displayed. Therefore, improvement in the functionality and redesign of the prototype is required to suit with the theme. Application such as reverse engineering, 3D printing and CNC machining can be applied in the design improvement in order to improve the quality of replica trophy and the cost and time saving method.

1.3 Objectives

1. To identify the current trend of replica trophy in order to improve the functionality for mass production.
2. To determine the cost saving, time saving and quality improvement method to produce the trophy for mass production.

3. To produce the final design of replica trophy for mass production.

1.4 Scope of Work

Conduct function analysis and FMEA of the prototype. Few concepts are generated and is further analyzed in the morphology chart. After the concept generation, material and manufacturing process is selected for each part.

CAD drawing in SolidWorks for each part is modelled for 3D printing and other fabrication tool. 3D scanner is used to scan the object (hand) and the data acquisition is obtained by the scanner. The output is then filtered to get a better output. Surface reconstruction is continued with CATIA V5. By using the CATIA simulation, suitable toolpath, speed and tool is selected to preview the machining time and output of the trophy. Then, it is fabricated by the CNC machine and 3D printing.

1.5 Outline of Thesis

Chapter 1

- Describe about project background, definition of research such as design improvement using reverse engineering, 3D printer and CNC machine, problem statement, objectives and scope of project.

Chapter 2

- Includes the review from other literature such as journal, book, and website that related to study project.

Chapter 3

- Describe about the methodology of the project.

Chapter 4

- Final concept description, discuss the scanned and edit the output result fabricate output result and cost estimation.

Chapter 5

- Conclude about the project and future work to further improve the project.

CHAPTER 2
LITERATURE REVIEW

2.1 Overview

This chapter reviews about published journal with different project using the method of reverse engineering such as the reproduction of worn spare parts in the automotive industry. Besides, the review on comparison of the speed in scanning between non-touch sensing, 3D scanner and traditional touch probe sensing, CMM. Moreover, 3D printer parameter, infill pattern and application were reviewed in this chapter for further understanding. The reviews of optimization method to processing the complexed 3D solid surface on CNC machining had done. It is also reviewed about the decision-making tool selection, cutting parameters and tool path on 5-axes milling machine.

2.2 Reverse Engineering

Varady et al. [5] studied the process of reverse engineering of shape by introducing various reconstruct strategies. The procedure of reverse engineering is classified into four steps which are data acquisition, pre-processing, segmentation and surface fitting and CAD model creation. The most crucial part in reverse engineering is data acquisition. The practical problems in data acquisition are calibration, accuracy, accessibility, occlusion, fixturing, multiple views, noise and incomplete data, statistical distributions of parts and surface finish. Edge-based and face-based methods are the approaches for segmentation and surface fitting. The boundaries in the point data representing edges between surfaces is joined for the first method whereas the second method infers connected regions of points with similar properties with the same surface. However, the segmentation for free-form geometry emphasizes on the global approximating surfaces, curve network based surfaces, arbitrary topology surfaces and functionally decomposed surfaces.

Werner et al. [6] concentrated the method of reverse engineering for free-form surfaces and discussed on the geometric coordinate measurement of the free-form surfaces. In order for the succession of reverse engineering, techniques such as coordinate measurements, surface approximation, CAD/CAM systems and CNC milling machine are used to solve the problem occurred. By using these techniques, computer and CNC machine are required which results in lesser equipment used significantly cost is reduced. Besides, transfer of data is simplified, and machining error is reduced which makes reverse engineering practical in many applications.

Zhang et al. [7] describes the reverse engineering processes from object digitalization, CAD model to NC machining by taking the core die of the inlet of a diesel as an example. The three main operations of RE are digitalization of the object by acquiring the 3D shape of the product, processing of measured data where data is processed to fulfil the requirements and creation of CAD model to represent the relevant data of the product. After Yu Zhang had fabricated the die using the method suggested. It was showed that RE is an efficient approach that able to reduce the produce development cycle as well as the quality of the design with complex surface.

Louis and Shields [8] discussed the capabilities of Next Engine 3D scanner and analysed on the advantages and limitations of 3D scanner. Next Engine 3D scanner can accurately represent the actual colour and geometry of the object. The scanner had no issues in capturing the general shape and detail geometry of the object. However, the scanner could not scan the object with reflective material due to the nature of laser where the light reflects back to the scanner. Besides, dark colour surface object was unable to scanned by the scanner at all.

Milroy et al. [9] compared the non-contact sensing (3D laser scanner) with traditional touch probe sensing (CMM). Injection moulding die shape is used for the demonstration of the efficiency and viability of 3D laser scanner. As a result, 3D scanner ease and speed up the process in acquiring data, multiple and complex surface patches are able to reconstruct. Moreover, 3D laser scanner is compatible with the latest CAD/CAM software which allow the transfer of part into solid cad model.

Kumar et al. [10] discussed the application of reverse engineering in manufacturing industry such as mechanical, aerospace, software and medical industry. The reproduction of engine spare parts for repair and replacement of worn-out components is one of the applications. Many companies have resorted to digital scanning and reverse engineering to get the accurate geometric data for automobile parts including spoilers, running boards, fenders and wheel covers. Besides automobile, other product development processes such as household and machining tools approach reverse engineering as it allows the generation of surface by 3D scanning techniques.

2.3 3D Printing

Shahrubudin et al. [11] presented the overview of types of technologies, application and material of 3D printing. Seven groups of 3D printing is listed in ASTM Standard including binding jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization which is not limited to prototype only but in the making of real products. Capability to produce parts in wide range of materials such as ceramic, metal and polymers. Aerospace, automotive, food, healthcare and medical, architecture and construction and electronic industry uses 3D printing to produce specific product as it provides benefits.

Ngo et al. [12] studied the limitation and challenges of layer-by-layer appearance. 3D printing provides the freedom and ability to produce complex structures but there are some disadvantages such as high costs, unable to produce large product and mass production, inferior and anisotropic mechanical properties, material limitation and defects. During the layer-by-layer process, void formation between layers increased the porosity which will reduce the mechanical performance due to the weak bonding in between layers. Transferring of CAD model to 3D printing part causes defects especially in curved surface. Lastly, the appearance for 3D printing in buildings, toys and aerospace need to be improved in future technology.

Brett et al. [13] investigated on the complexity, customization and production volume in additive manufacturing (3D printing). From the case study, if the product has higher levels of complexity and customization then 3D printing is the best choice to use. Whereas for product with low volume, low complexity and low customization, 3D printing may be a choice if the cost is low and lead time is reduced. Small custom parts such as Invisalign braces act as an instance by producing in high volumes using additive manufacturing. Brett provided a product map for 3D printing products as a reference system to evaluate the products, sustainability of printing and impact of printing.

Lee et al. [14] reviewed the materials used in 3D printing processes in recent development. The materials are smart materials (shape memory polymers), ceramic (UV curable monomers), electronic (conductive polymers and quantum dot), biomaterials (hydrogels and functional inks) and composites (VeroWhite Plus & Tango Black and Barium titanate). Ceramic material is one of the challenges in 3D printing as it unable to fuse together by applying heat like metals and polymers. However, ceramic parts can be produced with the current technology without any crack and large pores. 3D printing is versatile in the fabrication of electronic components such as capacitors, resistors and inductors and it is widely used in the mass-customized electronics in the industry.

Wu et al. [15] reviewed on the quality issues in 3D printing on past work. The most crucial quality issues are aesthetics (rough surface), conformance to specifications and performance that depends on its purpose. Thus, quality control techniques is needed for 3D printing. First of all, the acquisition step is the important step that affects the quality of the 3D printed object, the resolution must be sufficient high enough to get clear image. Next, the incoming material must be checked properly to make sure it is fit to use as the manufacturing process of 3D printing is created by a single type of material. Moreover, early termination of the 3D printing process is required when the first few layers do not meet satisfaction. Furthermore, issue such as clogging of material on the nozzle is crucial to the quality where thermal management of 3D printing is enhanced to monitor the performance.

Khan et al. [16] investigated on various infill pattern available in 3D printing software by evaluating the mechanical properties of the product. The infill pattern affected the tensile and flexural strength of the 3D printed product. Four infill pattern which were rectilinear, concentric, honeycomb and hilbertcurve were used for the experiment. Firstly, the temperature and movement speed was set as these parameter can affect the printing quality of the specimen. From the study, From the investigation, it was found that rectilinear infill pattern achieved high strength and flexural strength compared to other 3 infill patterns.

Pereira et al. [17] reviewed the object orientation for 3D printing. 3D objects were printed by adding material layer by layer. The best object orientation results in lower printing time and lower creation of supports. The printing time was affected by the orientation because the number of slices is based on the object orientation. Object orientation had high impact on the printing time, accuracy of the printed object and costing.

Some requirements were stated in the study for best object orientation which were maximization of the number of perpendicular surfaces, up facing horizontal surfaces, holes with their axes in the slicing direction, base surface and the minimization of the number of slope surfaces, the total area of overhang surfaces, the total number of slices, the height of required support structures

2.4 CNC Machining

Rozmarina et al. [18] presented the methodology in implementing CATIA V5 in simulation of CNC machining process. Selection of appropriate shape and semi-finished parts as well as the suitable material of parts is the first step for the simulation of CNC machining using CATIA. Suitable material cutting tools and cutting conditions for machining is selected based on the catalogue or findings. The following step is the determination of manufacturing processes which are designed to model assembly in CATIA. CAM system is used to simulate the manufacturing processes. Implementation of the software provides advantages in the machining process such as high accuracy, determination of machining time which contributed to the costing.

Liu et al. [19] studied on the method for the estimation of CNC machining time. Estimation of machining time is crucial in the planning and scheduling of manufacturing process, the estimation is based on the material removal rates, NC programs and machine characteristics. Methods of the estimation of machining time: Proposed NC machining time estimation framework, Feature-based rapid NC programming, Geometry process information, NC program, Machine characteristics, Cutting conditions and feed rate. Liu compared the feature-based NC program with NC program and machine characteristics. From the study, the proposed method is much more accurate than NC program and machine characteristics approach as the geometry-process information, cutting speed, NC program and machine tool information is considered in the proposed method. As the cutting speed is estimated thus it results in more accurate of time estimation.

Li et al. [20] proposed an approach in process planning and cutting parameter optimization in order to minimize energy consumption. Less energy consumption is achieved by maximizing the feed rate and cutting depth. Cutting parameter is dependent on the process planning with machining operation, machine and cutting tool. Impacts are shown on the time efficiency, machine workload and cost with the combination of process planning and cutting parameter.

Kandarp et al. [21] focused on the optimal tool selection for mass production. There are a few steps in tool shape selection, first the material removal is calculated followed by the estimation of scallop height then selection of process parameters. Kandarp compared the radiused and ball nose end mill tool in this paper. As results, a single tool is never optimal for the entire sculptured surface, tool that able to remove the majority of the surface can be used first then the second tool is used to clean up the rest. Radiused end mill shows a better result in flat surfaces from the experimental however, ball nose end mill is commonly used for complex surface.

Song et al. [22] focused on the optimal tool path strategy during CNC machining for better machinability performance. Three tool path strategies are discussed in this journal which are inward helical, outward helical and back and forth whereas the cutting parameters were remain constant. Actual and simulation of machining time for different tool path are compared which results in a little variation between the actual and simulated machining time. However, the result showed that the tool wear for inward and outward helical were high compared to back and forth. The overall tool wear occurred rapidly when machining high hardness brittle material.

Osman et al. [23] presented the optimal roughing operation in CNC machining. In the study, Machining orientations for roughing operations are developed to accommodate the orientations proposed by the visibility programme. The first approach proposes additional orientations for the roughing operation and the second approach is based on extracting and splitting the roughing operations. Machining simulation has been conducted to evaluate the practicality of both approaches and to discover the optimum roughing orientation angles. Cutting parameters are determined based on the work-piece, materials and cutting tool sizes. Roughing processes can be improved using the optimum cutting orientations proposed significantly minimizing the fabrication and thus increase the production rate.

Kariuki et al. [24] focused on the generation and optimization of pocket milling tool path of CNC machining. Pocket milling is a process where material is removed inside a closed boundary by using CAM. The tool path for generating pocket was influenced by the machining time, cutting forces, chatter vibrations, length of cutter path and energy consumption. The optimal parameter for higher efficiency can be integrated by CAM software.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Overview

This chapter explain the method use to complete the research. This includes to identify the existing type of product use to scan, concept generation then continue with scanning process using Laser 3D scanner Next Engine. After obtained the scan output of the product, further edit process using CATIA V5 and SolidWorks software. The material selection and manufacturing process selection are considered. Steps to fabricate and assembly the product had also included in this chapter. The overall process flow of the research is shown in Figure 3.1.

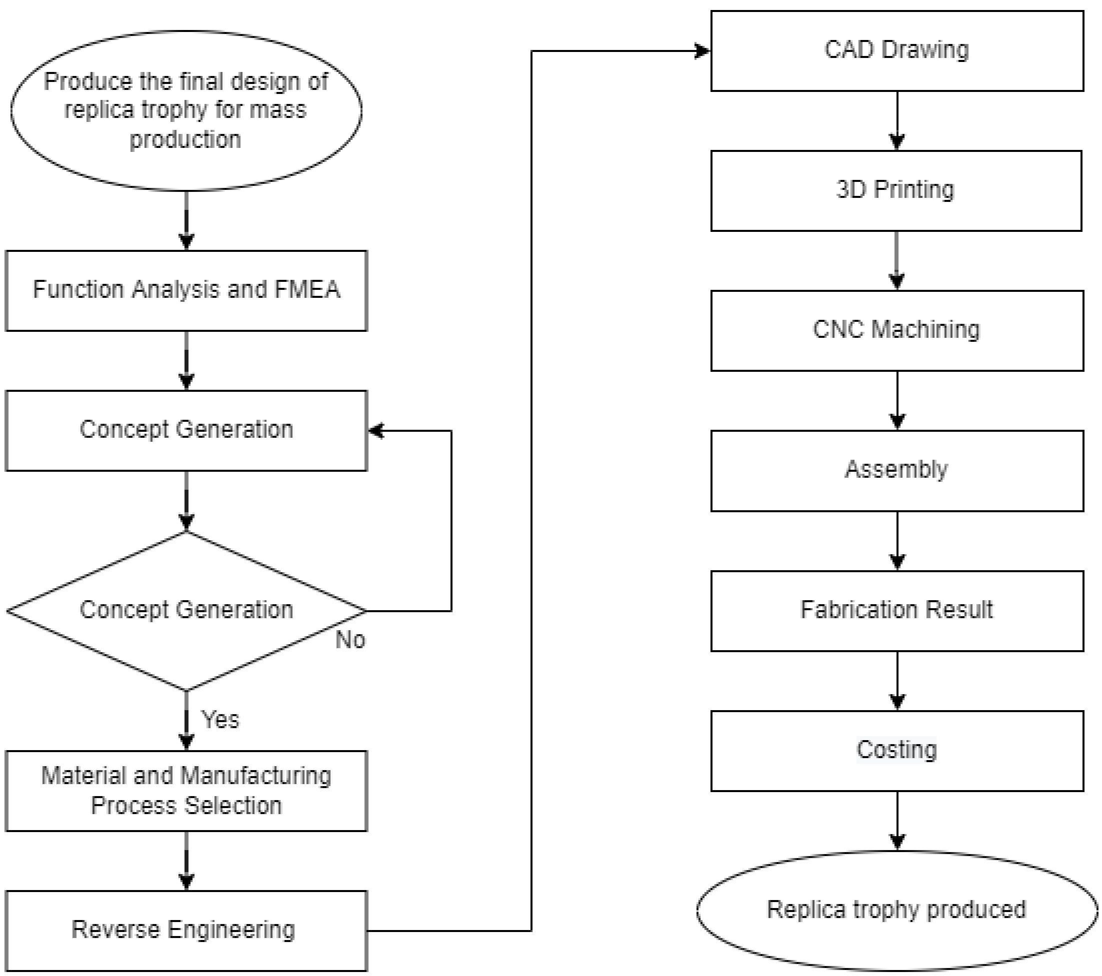


Figure 3.1: Overall process flow chart

3.2 Identifying existing trophy

The essential step for design improvement of trophy is to identify the existing trend of trophy in current market. Thus, benchmarking had been done to study the existing trend of trophy as shown in Table 3.1.

Table 3.1: Existing trend of trophy in current market

Trophy	**Description**
F1 Trophy 	Date of manufacture: 2014 Weight (kg) : 5 Height (mm) : 580 Diameter (mm) : 185 (Widest point) Material: 24K gold-plated trophy, milled from solid aircraft-grade aluminium blocks, is then lovingly hand-polished. Design: • Three gold stripes on each wing represent power, direction and speed • Base references tyres of both the Singapore Airlines' planes and F1 cars. [25]
Randstad Award 	Date of manufacture: 2013 Material: Gold Design: • Huge magnetic ball in the middle. • Gold little puppet/men stick on due to the magnetic attraction. [26]

3.2.1 Function Analysis

Next, function analysis is conducted to identify and analyse the basic function and secondary function in term of the product's material and shape of every component in the prototype. The prototype contains of 8 functional parts which are trophy shield, stand, clock, petal paper clip, left/right hand, screw hook, corner bracket and hinge. These functional parts will be focused on the function analysis. The general function, primary and secondary function in term of material and shape were identified as shown in Table 3.2.

Table 3.2: Function analysis of each part

Parts	General Function	Function Analysis	
		Material	Shape
Frame	• Support the trophy. • Support other parts of trophy.	Wood Primary • Reduce weight Secondary • Improve appearance	Primary • Distribute stress Secondary • Improve appearance
Stand	• Place trophy on table.	Wood Primary • Reduce weight	Primary • Distribute stress
Clock	• Indicate time • Measure time	Plastic Primary • Reduce weight	Primary • Fit with trophy
Petal Paper Clip	• Hold sheet of papers	Aluminium Primary • Provide strength to hold object	Primary • Fit with trophy
Left/Right Hand	• Improve appearance	Aluminium Primary • Improve appearance	

Screw hook	• Hold clock • Hold keychain	Steel Primary • Provide strength to hold object	Primary • Fit clock
Corner bracket	• Hold left/right hand	Steel Primary • Provide strength to hold object	Primary • Fit left/right hand
Hinge	• Hang object	Steel Primary • Provide strength to hold object	

3.3 Failure Mode and Effect Analysis (FMEA)

After the function analysis, FMEA is conducted to identify the potential failure modes, factors and effects of failure, evaluate the severity, occurrence and detection to obtain risk priority number and suggest corrective action. FMEA evaluation table is used as shown in Table 3.3.

Table 3.3: FMEA evaluation table

Parts	Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Severity (S)	Potential Cause(s) of Failure	Occurrence (O)	Current Design Control	Detection (D)	Risk Priority Number (RPN)	Recommended Action(s)
Frame	Support trophy and	Unstable frame	Unable to hold other parts	9	Poor design during designing process,	5	Material selection	5	225	Use suitable measurement and apply material

	other parts of trophy				excessive force or sudden impact					that can withstand pressure
Stand	Place trophy on table	Trophy unable to stand on table	Unable to use and display	6	Material used is not suitable and sudden force is applied	5	Professional engineering drawing	3	90	Apply material that can withstand pressure
Clock	Indicate time	Not working	Defect product	5	Poor design and wrong material used	3	Quality control	2	30	Designed and manufactured from same background
Left/Right Hand	Improve appearance	Increase weight of trophy	Unstable trophy	7	Material used is not suitable	6	Material and process selection	4	168	Designed and apply suitable material
Petal Paper Clip	Hold sheet of paper	Breakage due to overstress	Unable to hold paper	5	Poor tolerance and dimensioning	2	Professional engineering drawing	1	10	Designed and manufactured from same background
Screw hook	Hold clock and act as key holder	Breakage due to overstress	Unable to hold other parts	2	Poor tolerance and dimensioning	1	Tensile test	1	2	Designed and manufactured from same background
Corner bracket				2		1		1	2	
Hinge				2		1		1	2	

3.3.1 Highest Risk Priority Number (RPN)

RPN is calculated by multiplying the severity, occurrence, and detection ratings from the FMEA table. The higher the RPN, the more focus is needed to the part. As for the prototype, it is known that the part with higher RPN will be focus for design improvement. Table 3.4 shows that frame, left/right hand and stand will be focused on the design improvement.

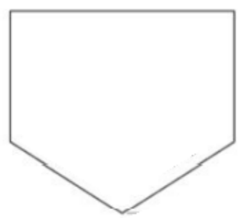
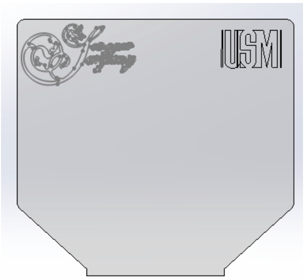
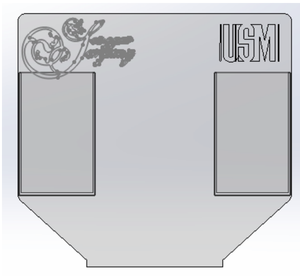
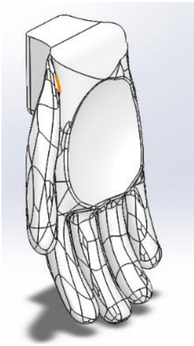
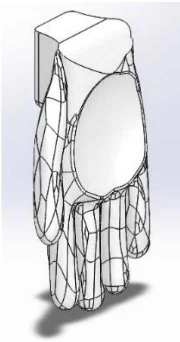
Table 3.4: Highest risk priority number

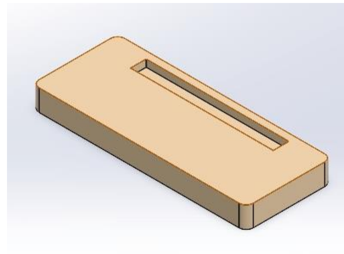
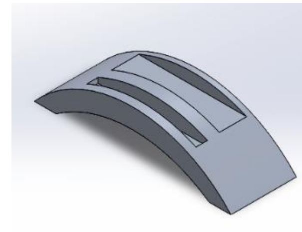
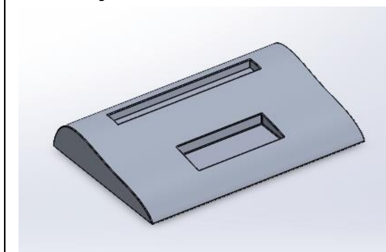
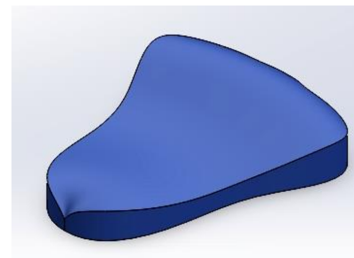
No.	Parts	Risk Priority Number (RPN)
1	Frame	225
2	Left/Right Hand	168
3	Stand	90

3.4 Concept Generation

After the FMEA process, redesign concept generation is the following step by creating new concepts for the trophy. Our main goal of concept generation is to increase the functionality of the replica trophy. Morphological is prepared to compare the most suitable design with different alternatives and current prototype design. The current design of prototype is cited from F. Mun Yee, 2019.

Table 3.5: Morphology chart of each part

	Current [27]	Alternatives		
Frame		Sharp base frame 	Frame without slot 	Frame with slot 
Left/Right Hand		Flex fingers 	Straight fingers 	

Base		Flat base 	Curve base 	Aerodynamic base 
Petal		Free form surface 		

3.5 Concept Selection

Concept selection is done to narrow down the alternatives to the best design. The selection is based on the concept screening and concept scoring.

3.5.1 Concept Screening

Concept screening is conducted to consider the rating of concept with the selection criteria of the trophy based on the morphology chart. The selection criteria of the concept screening are the stability, attractive design, ergonomic, convenient to use and the ease of manufacturing. Each of the advantage of the concept will represented by "+" while in disadvantage state will show in "-" and so on "0" for no differences. The net score is sum up as follow:

$$Net\ score = (Sum\ of\ +) - (Sum\ of\ -)$$

Flex fingers has the higher score which it will be the final decision for the parts where concept scoring is not needed. The frame with photo slot has the highest score followed by frame without photo slot while sharp base frame will not continue to the next section of concept scoring. Same goes to the base, aerodynamic base and curve base are continued to the section, concept scoring (Appendix A).

3.5.2 Concept Scoring

To further investigate the rating of each concept, concept scoring can help to determine the weight of each of the selection criteria that will contribute to the selection of concept. Each criterion is weighted with different score during concept scoring. The sum of score is calculated by multiplying the rating of each concept with the weight of the criteria. The result analysis is shown in Appendix B. The final selection of frame and base are frame with photo slot and aerodynamic base as they had the highest score.

$$Total\ Score = (Weight\ of\ Criteria\ 1 \times Rating\ of\ Criteria\ 1 + \cdots + (Weight\ of\ Criteria\ N \times Rating\ of\ Criteria\ N)$$

3.6 Material and Manufacturing Process Selection

The material selected to fabricate the base and petal of the trophy is Aluminium 6061 which is light in weight and suitable to apply in 5 axis CNC machining. Aluminium 6061 is a heat treatable alloy which has an excellent corrosion resistance that able to maintain the appearance of the trophy. Moreover, aluminium is the most suitable material to use in the production of base and petal of trophy because other materials such as wood and plastic are unable to fabricate using 5 axis CNC machine. CNC machining is selected to fabricate petal and base due to its low machining time and good surface finishing.

Besides, the material used for fabrication of hand structure is Polylactic acid (PLA) which suitable for the 3D printer model in the laboratory. 3D printing is selected to fabricate the hand structure due to light weight to reduce the overall weight of the trophy.

The material for the frame is acrylic as this is the latest trend and material used in trophy in current market. Besides, acrylic is transparent which increases the appearance and uniqueness of the trophy. The shape of the frame is cut using laser cutting by vendor and it's same goes to the engraving of logo on the frame.

3.7 Reverse Engineering Procedure

Reverse engineering contains of two process which are the scanning process and editing process.

3.7.1 Scanning Process

Next Engine 3D scanner is chosen to scan the hand structure. In order to use the scanner, the 3D laser scanner is connected to gripper and a desktop with Next Engine 3D scanner software (Figure 3.2). The object is fix on the gripper to make sure the object is in stable form. The parameter of the object is set in neutral with extended range. The parameter of the range is needed to set the distance between the scanner and the object. For extended range setting, the ideal distances between the scanner and object are 17 inches. The divisions are set at 12 with position 360° to allow the gripper to rotate in according to number of divisions that set in the scanning process. The higher number of divisions, the more accurate the data. However, 12 divisions are used in the scanning due to the consideration of scanning period. The time required to complete the scanning of hand structure is approximately 40 minutes as shown in Figure 3.2.

Figure 3.2: Set up of hand structure for scanning process

After completing the scanning process, the unwanted data such as the gripper is trimmed out from the output on Next Engine 3D scan software. All the output of the scanning is shown in Chapter 4. The file is then saved in STL file format for editing process in CATIA V5 and SolidWorks.

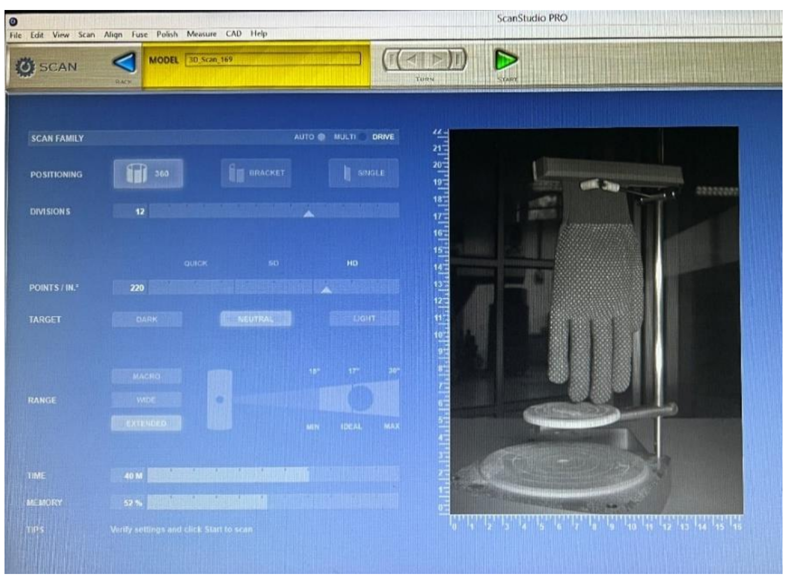


Figure 3.3: Parameter of hand structure in Next Engine 3D scan software

3.7.2 Editing Process

CATIA V5 is a CAD software used as editing tool to recover the surface of the scanned result. The editing process include process of digitized data (point cloud), mesh creation to create mesh from point cloud, mesh smoothing, surface reconstruction to generate surface from mesh output and generation of solid model. SolidWorks is another CAD software used for editing process such as reducing and enlarging the scale and modifying scanned output. The list of icon used in CATIA V5 and SolidWorks for editing process is shown in Appendix C.

Hand Structure

The first step of editing process of hand structure is to open the Digitized Shape Editor workbench from Shape at the Start Toolbar. Then the STL file of scanned output is Import into CATIA with 100% sampling factor. Export icon is clicked to export the file in ASCII format to get the point cloud then click the Import icon again to import the ASCII format file.

After importing the file, the point cloud is filtered to 2mm to reduce the complexity using the Filter function. The Remove icon is used to eliminate all the undesirable points of cloud. Meshing process is continued by Mesh Creation and so on with Mesh Smoothing to smooth the surface of mesh. Then it is followed by filling the holes on the surface of the mesh.

Mesh Cleaner is used to analyse the duplicate triangle of the mesh. The non-manifold edges and non-manifold vertices are removed to clean the mesh. The meshing is done when all the non-manifold edges and non-manifold vertices are completely removed. The hand structure is then continued in Quick Surface Reconstruction workbench to apply the Automatic Surface for the creation of surface on the mesh. The complete structure is saved in STEP file format for further design improvement using SolidWorks.

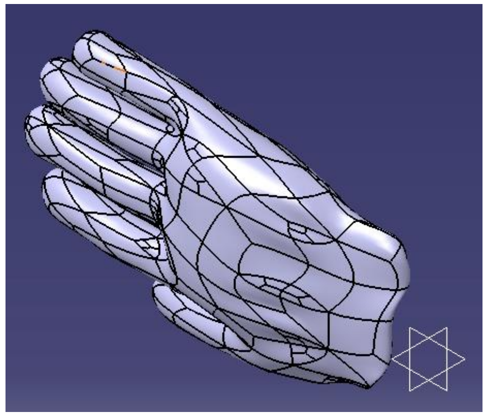


Figure 3.4: Complete hand structure in CATIA V5

Scale Factor

The size of the hand structure is reduced using the scaling function in SolidWorks. The STEP file saved in CATIA V5 is imported into SolidWorks by setting the file type to step. Format in the option button as shown in Figure 3.5.

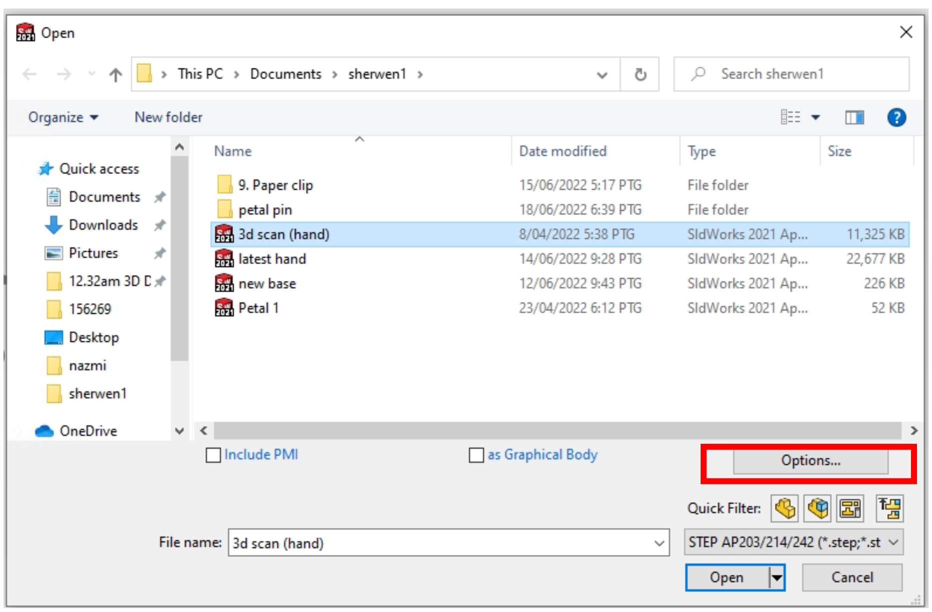


Figure 3.5: Importing of STEP file into SolidWorks by clicking Options button

After importing the step file, Scale feature is selected from the Insert then Feature tab. The size of the hand structure is reduced to 0.55 about the centroid of the hand structure. The drawing of part is drawn in SolidWorks (Appendix D). The hand structure is then mirrored in SolidWorks.

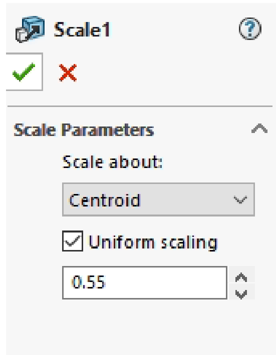


Figure 3.6: Scale feature in SolidWorks

3.8 3D Printing Procedure

Ultimaker Cura software is used for the setting of 3D printing parameters. The final design of hand structure is saved in STL file format for 3D printing process. Both left- and right-hand structure STL file are imported into the software as shown in Figure 3.7. The quality of the printing is set at standard quality with 50% infill to reduce the printing time and material used. Support is generated for the printing, and it can be removed easily after the fabrication (Figure 3.8). The printing time for one hand structure is 3 hours and 44 minutes which consumed of 38g of PLA material.

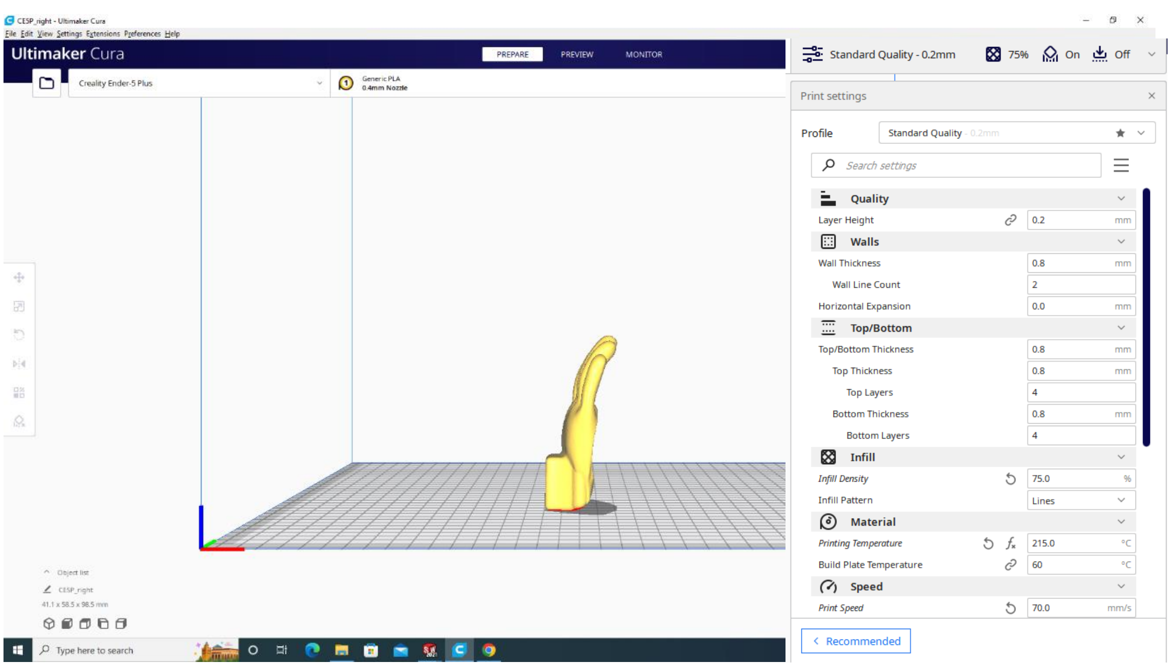


Figure 3.7: Setting of parameters for 3D printing