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Design for X Project
Task 1

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1. Contents Page

Table of Contents

1. Contents Page	2
2. Introduction	3
3. Background	4
Concept Design Appraisal.....	4
Expected Customer and End-User Needs.....	4
Identification of primary customer segments	4
Importance of visual appeal in market acceptance	5
4. Methodology	6
Design and Development Work Undertaken	6
Quality Function Deployment (QFD) Analysis	6
Design for Assembly (DFA).....	8
5. Analysis.....	10
Optimisation of Design Efficiency and Manufacturability.....	10
Application of SCAMPER as Rationale for specific design changes.....	10
Manufacturing Process Proposal	12
Recommended Manufacturing Processes by Part	12
Assembly Process for Mass Production.....	13
6. Conclusions.....	14
7. References	15

List of Tables

Table 1 - Quality Function Deployment.....	6
Table 2 - Lucas Method: Manual Handling Analysis.....	8
Table 3 - Lucas Method: Manual Fitting Analysis	9

List of Figures

Figure 1 - Gripper End Effector: Complete, Clear View	10
Figure 2 - Gripper End Effector: Mechanism.....	10
Figure 3 - Gripper End Effector: Jaw	11
Figure 4 - Gripper End Effector: Complete, Cover applied	11

2. Introduction

The focus is to redesign a gripper end effector for high-volume manufacturing for use across multiple markets. Using comprehensive design methodologies such as Quality Function Deployment (QFD) and the Lucas DFA (Design for Assembly) method, identifying critical areas for improvement.

Analysis details evaluation of the current design, highlighting key functional and original design intentions for customer use. The QFD process uses these customer requirements to create specific engineering characteristics, with a strong emphasis on manufacturability. The Lucas DFA used in conjunction with SCAMPER (Substitute, Combine, Adapt, Modify, put to another use, Eliminate, Rearrange) method further refines the design inputs by identifying inefficiencies, manufacturing difficulties and outlining simplifications to improve assembly and its processes.

Additional considerations around manufacturing processes to support a production rate of 1,000 units per week, anticipating risks in the current design. Based on these insights, recommendations for material selection, component standardisation, and design modifications to improve manufacturability and overall performance.

3. Background

Concept Design Appraisal

Expected Customer and End-User Needs

The general expectations for customer needs can be inferred from the current design of the robotic end effector. A key functional requirement for the gripper is precision and accuracy (Siva Bathula et al, 2023). This requirement is typical for robotic end effectors, which must precisely grasp and release objects with consistent movement, particularly when handling lighter weight items. The weight of the items can also be inferred from the current design. The design should not be expected to handle material of great weight.

Another expectation of the gripper is versatility. The current design, featuring a two-finger claw, is intended for general purpose use, capable of lifting objects of varying shapes (Samuels et al, 2022). The use of plastic jaws further highlights its general-purpose design, providing the potential to handle fragile objects and different materials.

The gripper's current design requires strength and durability, essential for the possibility of constant usage over extended periods. Its robust construction must ensure long term reliability, while plastic components enhance grip strength and friction. The design intent is to handle a variety of objects and withstand continuous, demanding operations.

Identification of primary customer segments

Automotive Industry:

There is significant usage of grippers in the automotive industry (Sliva et al, 2020), where precision and durability are mandatory (Minsch et al, 2016). The gripper must handle a variety of minor vehicle components with precision to ensure proper assembly. With the volume of automotive manufacturing the end effector must also be extremely durable. It needs to withstand 24/7 operation, maintaining consistent performance over long periods without significant wear or failure.

Electricals Industry:

The electricals industry has an increasing demand for tooling created to handle delicate components and precision for assembling small parts (Goh et al, 2022). Precision is critical in this sector to ensure that components are placed accurately, which is essential for the functionality and reliability of the final products. The gripper must be capable of manipulating small, potentially fragile pieces without causing damage, which requires a fine balance of grip strength and control, some are even in use in clean rooms according to Budde et al (2024).

Consumer Goods:

For the consumer goods sector, versatility, speed, and efficiency are key. The gripper must be able to handle a wide variety of shapes, adapting quickly to different products on the production line. High speed operation is necessary (Shah and Pandey, 2018) to keep up with the demands of mass production. Currently, grippers are in use for slaughterhouse automation (Ross et al, 2022). Efficiency in transitioning between different items improves overall productivity and reduces downtime.

By addressing the specific needs of these primary customer segments, the gripper end effector can provide a solution that enhance performance and reliability in diverse manufacturing applications.

Importance of visual appeal in market acceptance

Designing the gripper end effector involves functional performance and market appeal through professionalism, user confidence, perceived value, brand differentiation and identity. While the current design emphasises general design principles, it lacks elements that demonstrate these attributes. *“We instinctively project similar qualities onto objects based on their form. For example, a sports car may be associated with a sense of power, speed and success.”* (Sunstrum et al, 2024). Similarly, modern appearance gives the impression of high quality and reliability. An aesthetically pleasing design improves the perception of the product and reflects positively on the brand. Customers associate well designed products with better engineering and performance. This increases confidence in the product's performance.

Consistent and appealing design strengthens the brand's image and identity. Cohesive design elements across product lines aligns with branding strategies reinforces brand values. This approach helps establish a recognisable brand, improving customer trust and loyalty over time.

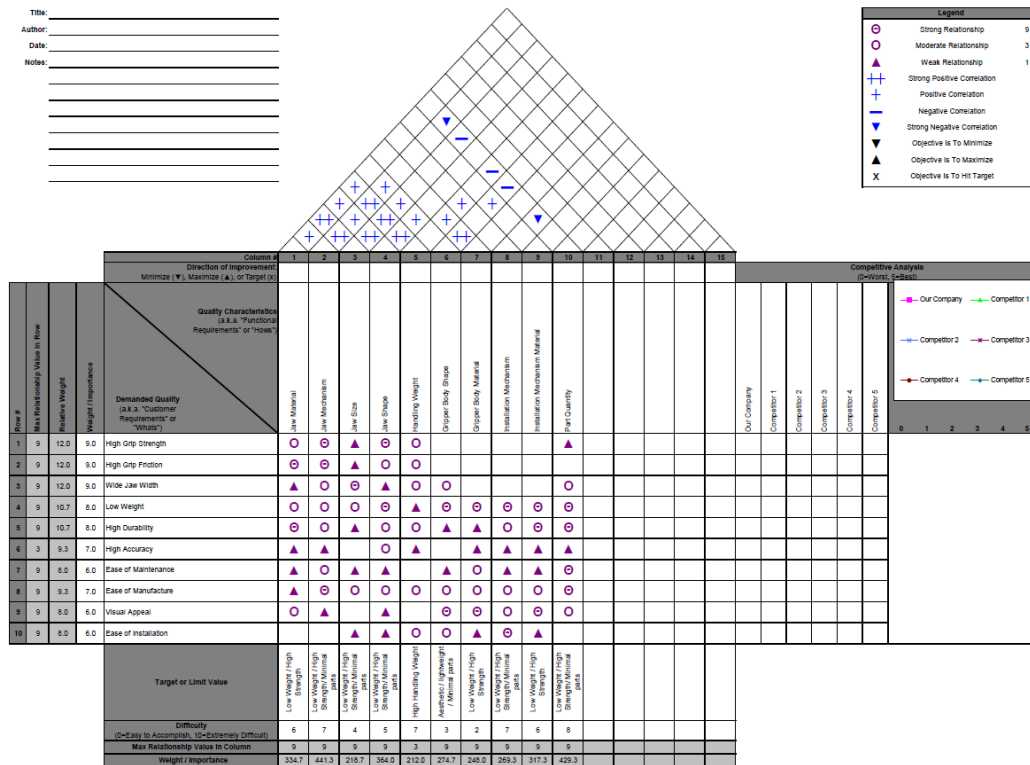
Incorporating these considerations into the gripper's design ensures practical functionality while also enhancing market appeal and overall brand value in the competitive landscape.

4. Methodology

Design and Development Work Undertaken

Quality Function Deployment (QFD) Analysis

Table 1 - Quality Function Deployment



The Quality Function Deployment (QFD) analysis is based on inferred functional and customer needs based on the current design, Used in many industries from construction (Dikmen et al, 2005) to food products (Benner et al, 2003). The aim is to use the customer requirements to define engineering characteristics. This structured approach ensures that customer needs are addressed, improving the product's suitability for larger scale production and more market applications. The QFD analysis differs from the current design by weighting manufacturability higher to target a minimum production volume of 1000 parts per week.

The QFD analysis identifies and scores the importance of critical design characteristics based on customer requirements, determined from the current design. Weightings reflect the priority given to each characteristic. The QFD matrix describes relationships between these characteristics and various design elements. These relationships are critical for informing design improvements. The QFD matrix reveals several insights that will influence the next design:

- In relation to material selection, High strength materials used sparingly to benefit grip strength, durability, and reduce weight.
- The jaw would benefit redesigning for general purpose jaws with an optimised shape and surface. This will be developed to improve grip friction and accuracy while accommodating various object sizes.

- Due to the current mechanism, more robust construction methods will be employed to ensure the end effector can withstand continuous, high-volume operations without significant wear.
- In relation to manufacturing efficiency, the design will incorporate standardised components and simplified assembly processes to facilitate efficient production.
- Additionally, by improving manufacturability the ease of maintenance will be improved, designing components that are easy to assemble and disassemble.
- Modern design elements will be used to improve visual appeal and reinforce the product's perceived value and brand identity.

The insights gained from the QFD analysis will directly influence the next iteration of the gripper end effector design. Focus areas will include:

- Enhancing grip strength and friction through material and jaw design improvements.
- Ensuring durability and reducing weight with robust materials, reducing part quantity and simplifying the jaw mechanism.
- Simplifying manufacturing processes to support large scale production.
- Improving visual appeal to boost perceived value and marketability.
- Designing for easier manufacturing and maintenance to reduce downtime, manufacturing and service costs.

By addressing these areas, the redesigned gripper end effector will be improved for production, meeting the needs of multiple markets. The QFD process ensures that the final product not only satisfies functional requirements but also improves user confidence and perceived value.

Design for Assembly (DFA)

Lucas Method (DFA) Manual Handling Analysis

The Lucas DFA method is a structured approach used to simplify product designs. Stone et al (2004) identifies the methods usefulness in CAD models specifically. Identifying difficulties in handling, highlights improvements for ease of assembly. Specifically, for manual handling analysis, this method evaluates how individual components, and their interactions affect the efficiency and ease of the assembly process. The analysis focuses on minimising handling time, improving ergonomics, and reducing the complexity of assembling parts manually.

Table 2 - Lucas Method: Manual Handling Analysis

Lucas DFA - Manual Handling Analysis					
Part	A	B	C	D	Total
Main Body Lower Plate	1	0	0	0.2	1.2
Main body Upper Plate	1	0	0	0.2	1.2
Jaw A	1	0	0.2	0.3	1.5
Jaw B	1	0	0.2	0.3	1.5
Plastic Jaw A	1	0	0.1	0.2	1.3
Plastic Jaw B	1	0	0.1	0.2	1.3
Bolt A (Front Jaw)	1.5	0.3	0.1	0.2	2.1
Nut A	1.5	0.3	0.1	0.2	2.1
Bolt B (Front Plate)	1.5	0.3	0.1	0.2	2.1
Nut B	1.5	0.3	0.1	0.2	2.1
Servo Motor	1	0	0.1	0.3	1.4
Bolt C (Servo)	1.5	0.3	0.2	0.2	2.2
Nut C	1.5	0.3	0.1	0.2	2.1
Side plate A	1	0	0.2	0.2	1.4
Side plate B	1	0	0.2	0.2	1.4
Back Plate A	1	0.2	0.1	0.1	1.4
Bolt D (Rear plate)	1.5	0.3	0.1	0.2	2.1
Nut D	1.5	0.3	0.1	0.2	2.1
Bolt D (Sheath)	1.5	0.2	0.1	0	1.8
Connecting Arm	1.5	0.2	0.3	0.3	2.3
Bolt E (Mechanism)	1.5	0.3	0.1	0.2	2.1
Bolt E (Sheath)	1.5	0.2	0.1	0	1.8

Using the Lucas DFA method for manual handling analysis on the current gripper design highlights several critical areas. Key problematic elements in the design include the high quantity and variety of bolts used, which complicates assembly despite clear orientations. This is a significant problem, complicating the manual assembly process and increasing the potential for errors and time delays.

The mechanism responsible for opening and closing the gripper jaws is another point of concern. The connection between the servo motor and the right jaw, a tab and bolt, is particularly problematic. This aspect of the design adds unnecessary complexity and a clear failure point, potentially affecting both the ease of assembly and the overall reliability of the gripper.

By addressing these issues, the design can be optimised for better manufacturability and efficiency, reducing assembly time and improving reliability of the gripper in application.

Lucas Method (DFA) Manual Fitting Analysis

Table 3 - Lucas Method: Manual Fitting Analysis

Assembly Step	Lucas DFA - Manual Fitting Analysis						
	A	B	C	D	E	F	Total
Main Body - Servo	2	0	0	0	0.1	0	2.1
Plastic to Jaw A	4.5	1	1	0.5	0.3	0.1	7.4
Bolt A	4.5	0	1	0	0.2	0.4	6.1
Nut A	4.5	0	1	0	0.2	0.4	6.1
Plastic to Jaw B	4.5	1	1	0.5	0.3	0.1	7.4
Bolt A	4.5	0	0.2	0	0.2	0.4	5.3
Nut A	4.5	0	0.2	0	0.2	0.4	5.3
Main Body - Jaw A	4.5	0.1	0.7	0.2	0.5	0.1	6.1
Main Body - Jaw B	4.5	0.1	0.7	0.2	0.7	0.1	6.3
Back Plate	2	0.2	1.2	0.5	0.4	0.2	4.5
Top Plate	6	1	1.2	0	0.6	0.2	9
Bolt B	4.5	0	0.2	0	0.2	0.4	5.3
Nut B	4.5	0	0.2	0	0.2	0.4	5.3
Bolt B	4.5	0	0.2	0	0.2	0.4	5.3
Nut B	4.5	0	0.2	0	0.2	0.4	5.3
Bolt C	4.5	0	0.2	0	0.2	0.4	5.3
Nut C	4.5	0	0.2	0	0.2	0.4	5.3
Bolt D	4.5	0	0.2	0	0.2	0.4	5.3
Nut D	4.5	0	0.2	0	0.2	0.4	5.3
Mechanism Connector	4	1.2	1.2	1	0.7	0.4	8.5
Bolt E	4.5	0	0.2	0.7	0.2	0.4	6
Nut E	4.5	0	0.2	0.7	0.2	0.4	6
Back Side A	0.2	0.2	1.2	0	0.4	0.2	2.2
Back Side B	0.2	0.2	1.2	0.5	0.4	0.2	2.7
Bolt F	4.5	0	0.2	0.7	0.2	0.4	6
Nut F	4.5	0	0.2	0.7	0.2	0.4	6
Bolt F	4.5	0	0.2	0.7	0.2	0.4	6
Nut F	4.5	0	0.2	0.7	0.2	0.4	5.3

The Lucas DFA method for manual fitting analysis evaluates how individual components and their interactions affect the efficiency and ease of the assembly process.

Using the Lucas DFA Method for manual fitting analysis on the current gripper design highlights several critical areas, like those identified in the manual handling analysis. Notably, the complexity of the jaw mechanism is a key area for redesign. The current quantity of parts increases the overall weight, complicates manufacturability, and reduces ease of maintenance. Simplifying this mechanism will directly improve the gripper's performance and reliability.

Additionally, the design of the top plate is highlighted as problematic, primarily due to the servo's assembly position. The current mechanism design, along with the variety of differently sized bolts connecting the top and base plates, significantly complicates the assembly process.

Another concern from a manufacturing perspective is the jaw design. The current design causes difficulties in finding a datum for assembly and alignment, decreasing assembly efficiency. Addressing this issue will increase ease of assembly and improve the alignment accuracy, improving the overall efficiency and reliability of the gripper.

5. Analysis

Optimisation of Design Efficiency and Manufacturability

Application of SCAMPER as Rationale for specific design changes

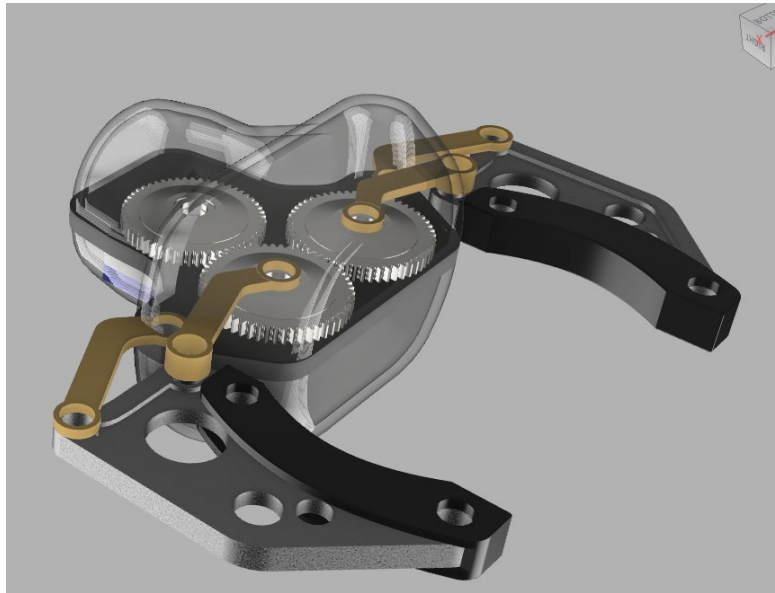


Figure 1 - Gripper End Effector: Complete, Clear View

SCAMPER is a creative thinking technique used to improve or innovate products and processes by exploring seven different approaches: Substitute, Combine, Adapt, Modify, put to another use, Eliminate, and Rearrange. In the redesign of the gripper end effector, SCAMPER was utilised in conjunction with the Lucas DFA and QFD methods to enhance manufacturability, efficiency, and performance.

Mechanism:

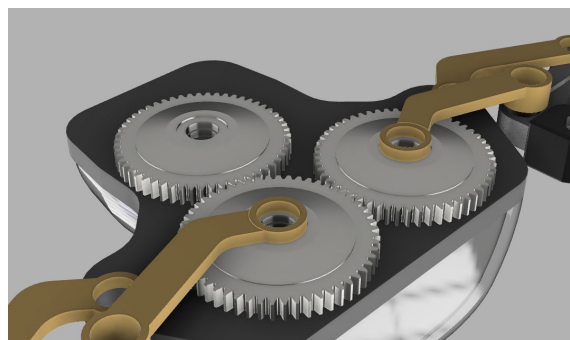


Figure 2 - Gripper End Effector: Mechanism

The mechanism was completely redesigned using standardised components, specifically a 28mm gear, aligning with the SCAMPER principle of substitute. Standardised components were chosen for their availability, cost-effectiveness, and defined stress and strain tolerances, improving reliability, derived from both previous analysis methods. Additionally, the increased number of teeth on the gear enhances grip accuracy and pressure. This

reduced the overall part count and weight, as the original design required parts looping around the main body, demonstrating eliminate. The simplified mechanism also decreased handling weight and increased precision, key functional objectives in the QFD. This elimination of unnecessary parts and the adaptation to a simpler construction make internal components more accessible, benefiting both manufacturing and end user maintenance, critical areas highlighted in the QFD.

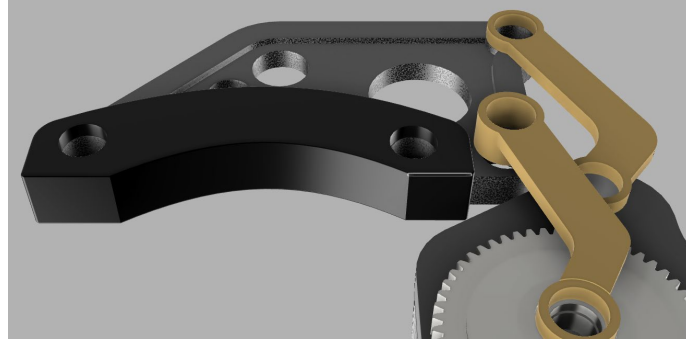


Figure 3 - Gripper End Effector: Jaw

Jaw:

Due to the mechanism change, the jaw connection was redesigned, demonstrating modify. This new double connection, while adding some complexity, remains lightweight and provides a larger working envelope, reducing overall weight and size. The jaw fingers were shortened, illustrating modify, to enhance strength and durability enabled by the mechanism change. The addition of a single direction fitting rubber within the jaw is an adaptation to improve the manufacturing process another critical point from the DFA.

Other Notable Changes:

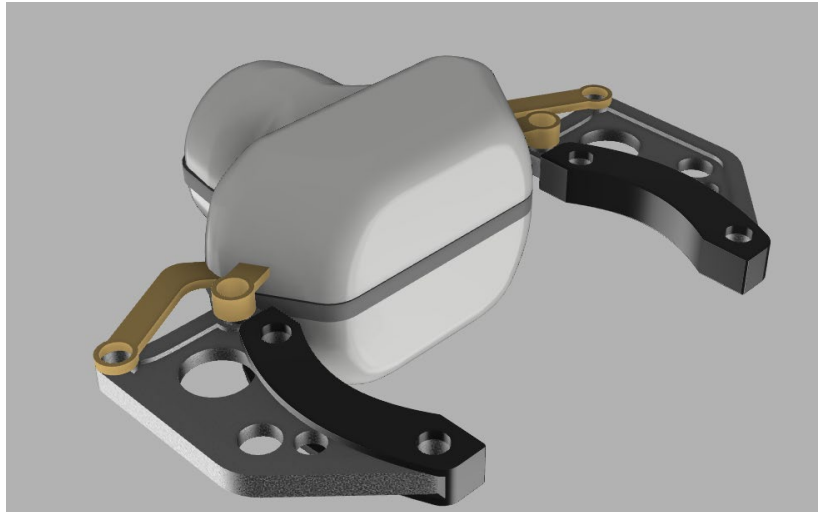


Figure 4 - Gripper End Effector: Complete, Cover applied

The main body was altered by removing the top element, significantly reducing weight, demonstrating eliminate. To protect the mechanism, a moulded plastic cover was added, a substitution that also gave the design a modern, sleek appearance, allowing for branding opportunities to enhance market appeal as mentioned previously.

Relocating the servo motor on the underside and mounting it directly, with the rear gear attached, reduced the overall size and weight of the gripper while maintaining functionality.

Simplifying the rear connection to reduce the number of steel plates, using eliminate, and introducing a simple screw connection facilitated easier mounting to standard robotic systems.

Finally, the number of bolts and screws was significantly reduced, standardising to M6 and decreasing different lengths required, from five to two, which was deemed critical in the DFA, using simplify.

By applying SCAMPER, along with DFA and QFD, the redesign process ensured that the gripper end effector is more efficient, manufacturable, and reliable across diverse applications.

Manufacturing Process Proposal

Recommended Manufacturing Processes by Part

Main Body

Material: Steel

Press Forming: This process involves shaping the steel using a press, which is highly efficient for high-volume production. It's a cost-effective solution due to its speed and ability to handle large batches, making it suitable for mass production. Aligning with economic drivers focused on efficiency and lower per unit costs.

Moulded Plastic Outer Sections

Material: Plastic

Injection Moulding: This process involves injecting molten plastic into a mould to form the outer sections. It is highly efficient and economical for high-volume production and provides consistent quality with minimal material waste.

28mm Gear

Material: Steel

Procurement: Purchasing standardised gears from suppliers is the most cost-effective solution, avoiding the need for specialised manufacturing processes. reducing costs significantly, leveraging supply chain, ensuring consistent quality.

Jaw Connectors

Material: Steel

Press Forming: Like the main body, this method is efficient for producing simple steel parts in high volumes. It is more cost-effective for high-volume production, reducing overall manufacturing costs.

Servo Motor

Material: Electronic/Mechanical Assembly

Procurement: Purchasing ready-made servo motors is the most cost-effective and practical solution. Producing servo motors is costly and complex, making it impractical.

Jaw Fingers

Material: Steel

Press Forming: As mentioned, efficient and cost-effective for high volume production. Additionally, making multiple parts on this process would increase the value of this process in the business.

Rubber Fittings

Material: Rubber

Procurement: Buying pre-made rubber fittings is cost-effective and ensures consistent quality. There is no further need to purchase additional processes to manufacture this part. It adds significant cost initially and ongoing.

Assembly Process for Mass Production

- Assembly Preparation - Processes: Cleaning, deburring, and inspection to ensure parts meet quality standards.
- Servo Motor Installation - Process: Mounting with screws or bolts, connecting power and controls.
- Mounting the 28mm Gears - Process: Alignment tools for accurate positioning.
- Main Body and Jaw Connectors - Process: Fastening using bolts and nuts.
- Rubber Fittings - Process: mechanical fixing into jaw fingers.
- Moulded Plastic Outer Sections - Process: Snap fit to secure plastic covers.
- Final Assembly
- Processes: Testing, calibration, and final inspection for functionality and quality control.

By selecting the most cost-effective and efficient manufacturing processes, the robot end effector can be produced economically while maintaining high quality and reliability for large-scale production.

6. Conclusions

The gripper, end effector, redesign for high volume manufacturing utilised Quality Function Deployment (QFD) and the Lucas DFA (Design for Assembly) method, assisted by SCAMPER. These methodologies identified inefficiencies and critical improvement areas. The QFD analysis prioritised manufacturability to meet a production target of 1,000 units per week, resulting in the targeted use of high strength materials, simplified jaw mechanisms, and standardised components for enhanced durability and reduced complexity.

The Lucas DFA method highlighted manual handling and fitting issues, leading to a streamlined assembly process with fewer parts and improved reliability. SCAMPER was used for significant changes, such as substituting in standardised components, eliminating unnecessary parts, and modifying the mechanism to achieve a more efficient and robust design.

Efficient manufacturing processes, including steel press forming, plastic injection moulding, and procurement of components, were selected to ensure cost-effective, high-quality production. This redesign addresses functional and customer needs while including considerations for market appeal and brand value, positioning the gripper end effector as a versatile and durable solution across diverse manufacturing applications.

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Task 2

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1. Contents Page

Table of Contents

1. Contents Page	2
Table of Contents	2
List of Figures.....	3
2. Introduction	4
3. Background	5
Example Methods of Additive Manufacturing.....	5
3D Printing (Material Extrusion).....	5
Directed Energy Deposition (DED)	5
Powder Bed Fusion (PBF)	5
Tools Used in Additive Manufacturing.....	5
Comparison of Additive Manufacturing Techniques	6
Topology Optimisation:.....	6
Generative Design:	6
Comparison:	6
4. Methodology	7
Design process and rationale	7
Chosen Part: Drone Arm	7
Rationale for Choosing Topology Optimisation.....	7
Use of Topology Optimisation	8
Geometry Attributes.....	8
Applied Forces and Constraints	8
Mesh Geometry	9
Study Finalisation	9
5. Results.....	12
Finite Element Analysis (FEA).....	12
Further Manufacturing Considerations.....	13
6. Conclusions.....	14
7. References	15

List of Figures

Figure 1 - Initial Drone Arm Design (Simplistic).....	7
Figure 2 - Drone arm with applied forces	8
Figure 3 - Initial drone arm mesh	9
Figure 4 - Mesh reduction through scaling.....	9
Figure 5 - Topology Optimisation: Heatmap and Material usage	10
Figure 6 - Topology Optimisation: Generated Mesh	11
Figure 7 - Topology Initial simplification.....	11
Figure 8 - Topology Second Iteration.....	12
Figure 9 – Topology final Iteration Simulation.....	12

2. Introduction

Additive manufacturing (AM) has revolutionised design and production (Suarez et al, 2024), enabling the creation of complex geometries and optimised structures difficult to manufacture with traditional methods. There are various AM methods, including Directed Energy Deposition (Thakkar et al, 2020) and Powder Bed Fusion (El Hassanin et al, 2024) and more commonly, 3D printing. These techniques are advancing in industries such as aerospace, automotive, and healthcare, allowing rapid prototyping with significant material reduction and production speed benefits.

AM is applied to creating and optimising a drone arm. The design process leverages topology optimisation, a computational method that optimises material use within a design area under constraints. Combined with finite element analysis (FEA), this allows for a lightweight yet strong drone arm. Adjusting the design to minimise weight while maintaining structural integrity leads to performance and efficiency improvements. The study discusses practical steps in the drone arm's creation, highlighting challenges like balancing computational demands with design complexity and trade-offs to ensure manufacturability.

3. Background

Additive Manufacturing (AM) includes various technologies that build objects layer by layer from digital models. Beyond basic 3D printing, which is widely known, AM includes advanced methods like Directed Energy Deposition and Powder Bed Fusion. These techniques create intricate geometries, minimise material waste, and more efficient prototyping across industries such as aerospace, automotive, healthcare, and consumer goods.

Example Methods of Additive Manufacturing

3D Printing (Material Extrusion)

This method uses a continuous filament of thermoplastic material, melted and extruded through a nozzle to build objects layer by layer (Jiang and Koike, 2024). It's popular for rapid prototyping, consumer products, and educational models due to affordability and ease of use. Hobbyists, educators, and small businesses commonly use 3D printing.

Directed Energy Deposition (DED)

DED directs a laser, electron beam, or plasma arc to melt materials as they are deposited, ideal for adding material to existing components (Rousseau et al, 2018). This makes it valuable in aerospace and defence for manufacturing high-strength, complex parts with precise material placement. DED can utilise multiple materials simultaneously, modifying specific properties within a single component.

Powder Bed Fusion (PBF)

PBF selectively fuses areas of a powder bed using a heat source like a laser or electron beam. Technologies such as Selective Laser Sintering (SLS) (Zhang et al, 2024) and Electron Beam Melting (EBM) use different materials for different applications. PBF is adept at producing intricate geometries in both metal and polymer parts, utilised predominantly in aerospace, medical, and automotive industries. Its precision enables the production of detailed components such as medical implants (Sarkar and Kapil, 2024) and lightweight structural parts.

Tools Used in Additive Manufacturing

Several different process and tools are utilised within additive manufacturing processes. For example, the use of fundamental manufacturing processes, CAD software, Slicing software and simulation packages:

- 3D Printers: Machines executing AM processes, varying from desktop models to industrial grade equipment.
- CAD Software: Tools like Autodesk Fusion 360, SolidWorks, and Tinkercad, for creating detailed 3D models.
- Slicing Software: Programs such as Ultimaker Cura, PrusaSlicer, and Simplify3D, converting CAD models into instructions for 3D printers.
- Simulation and Analysis Software: Software like ANSYS and Abaqus for simulating and analysing the printing process and structural integrity.

Comparison of Additive Manufacturing Techniques

Topology Optimisation:

Topology optimisation is a computational design technique that optimises material layout within a design space, considering loads and constraints to reduce weight or increase stiffness. It is particularly useful in aerospace (Wang et al, 2024) and automotive industries for lightweight yet strong components. This technique also aids in developing medical implants for specific patient needs (Garcia-Avila et al, 2024). By minimising material usage, topology optimisation offers cost savings and environmental benefits, enhancing structural performance by concentrating material at critical points. However, the results can be complex and challenging to manufacture with traditional methods. Additionally, it requires significant computational resources and advanced manufacturing techniques.

Generative Design:

Generative design uses algorithms to explore a wide range of designs based on specified constraints and objectives, such as material usage, strength and weight. Ideal for various industries, this approach enables the creation of unique, optimised designs from furniture and architecture, balancing aesthetics and functionality (Bucher et al, 2023). Creating a multitude of design possibilities, leading to innovative solutions that traditional methods are unlikely to consider. Generative design evaluates numerous designs but can be overwhelming, requiring time investment to select the best option. It demands substantial computational power and time, particularly for complex designs, and may require adjustments for manufacturability.

Comparison:

Both topology optimisation and generative design are valuable in additive manufacturing, each with unique strengths and limitations. Topology optimisation excels in refining existing designs for material efficiency and performance, while generative design has greater capability in considering a wide range of innovative solutions to meet multiple objectives simultaneously.

4. Methodology

Design process and rationale

Chosen Part: Drone Arm

The choice of a drone arm was chosen to demonstrate AM techniques in Fusion 360. This selection benefits the illustration of the AM process and design optimisation methods, particularly topology optimisation.

A drone arm demonstrates additive manufacturing techniques as a critical component in drone design, directly influencing the performance, stability, and payload capacity. The geometric requirements and the need for lightweight, yet robust structures make them ideal for showcasing the capabilities of AM.

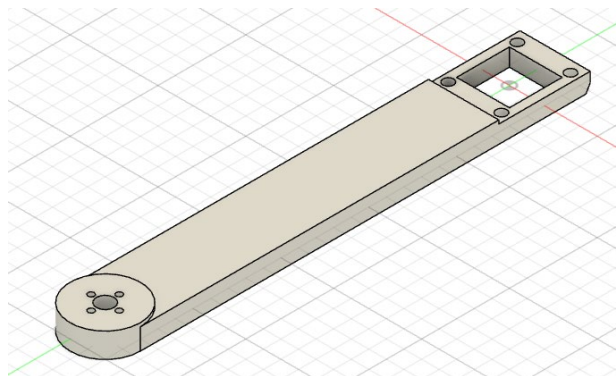


Figure 1 - Initial Drone Arm Design (Simplistic)

Furthermore, the use of a drone arm highlights the practical applications of AM in the aerospace and defence industries, where the demand for lightweight, strong, and efficient components is required. By focusing on a component with real world relevance, the demonstration gains significant practical value, providing insights that are directly applicable to industry challenges.

Rationale for Choosing Topology Optimisation

When improving the design of a drone arm, topology optimisation is a highly effective method. Topology optimisation is the best selection for existing designs to reduce material usage, which is critical for components like drone arm. By removing unnecessary material, this method directly addresses the need for weight reduction in an aerospace type application. Ensuring that the drone arm can withstand stresses while being lightweight, a critical factor in improving flight efficiency and payload capacity.

Generative design can produce highly innovative and complex forms. However, the designs might present significant manufacturing challenges. Topology optimisation, on the other hand, typically produces designs that are more compatible with current AM technologies, ensuring that the optimised drone arm can be feasibly produced.

Topology optimisation was chosen over generative design for its material efficiency, performance enhancement, ease of use, computational efficiency, and better alignment with manufacturing capabilities.

Use of Topology Optimisation

A simplistic design, without an optimised part, was deliberately used to demonstrate the full functionality of topology optimisation.

Geometry Attributes

The first step involves defining the geometry attributes of the drone arm. This includes specifying both preserved and fixed geometry. Defining preserved geometry is critical to ensure that essential features such as screw holes, interfacing parts or other connection points are not altered during the optimisation process.

The preserved geometry in this design includes a 30mm diameter surrounding the motor mounting section. This area is kept intact to prevent any interference with the motor spindle and fixing points, maintaining functionality.

Another preserved area in the design is the mounting plate at the opposite end to the motor mount, ensuring it remains untouched to maintain its attachment to the drone body.

The fixed area defined includes the fixing points to the drone itself, replicating real world conditions to ensure the design's practicality. Providing more information to the simulation model increases effectiveness in real world applications.

Applied Forces and Constraints

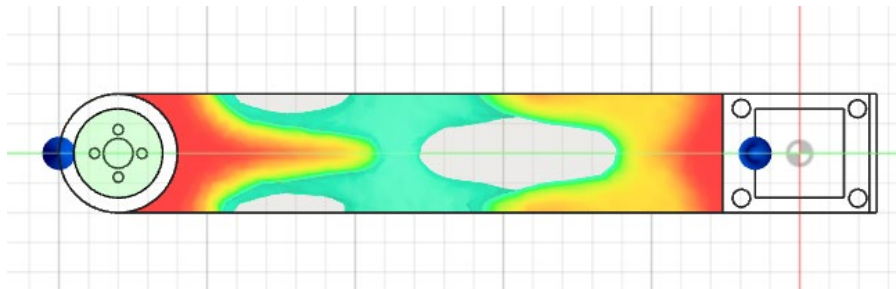


Figure 2 - Drone arm with applied forces

The forces applied were calculated based on the intended use of the drone. It is anticipated that the drone will handle a maximum total load of approximately 2.5kg, a typical figure allowing for the attachment of basic equipment such as a Li-Po (Lithium Polymer) battery, ESC (Electronic Speed Controller), and potentially a small camera. The motors under consideration are standard hobbyist brushless motors, each generating four horsepower and weighing 52g. To convert grams and kilograms into newtons, a conversion factor was applied, assuming Earth's gravity at 9.81m/s^2 . However, the calculation is based on static considerations, not as accurate for application.

The force applied to the arm mounting plate was measured at 8 newtons, exceeding the calculated 24.5 newtons distributed across the mounting plates for a drone with four arms. This margin serves as a safety factor against additional forces like wind or drag encountered during flight.

Two additional forces were applied to the motor mount: the downward force exerted by the motor, equivalent to 0.51 newtons (52g converted), and an upward thrust force of 12 newtons necessary to lift and propel the drone, this was calculated from 4 horsepower motors. This figure includes an additional 2 newtons as a contingency in case of incorrect manoeuvring leading to potential drone drop.

Minimal constraints were required, only the key fixing points of the drone arm that are expected in operation. A symmetry plane was added to the model to reduce computational power. For some drone designs with specific directional components, like racing drones, this would hinder the process. They require withstanding substantial forces in specific directions. For general application multiple symmetry points would benefit the construction with relation to maximum forces applied in each direction.

Mesh Geometry

Mesh geometry is a key process used in topology optimisation and FEA as it converts the 3D model into discrete elements this allows for both the optimisation and accurate simulation. Proper mesh generation and adjustment ensure the balance between computational efficiency and result precision, directly impacting the reliability of the analysis.

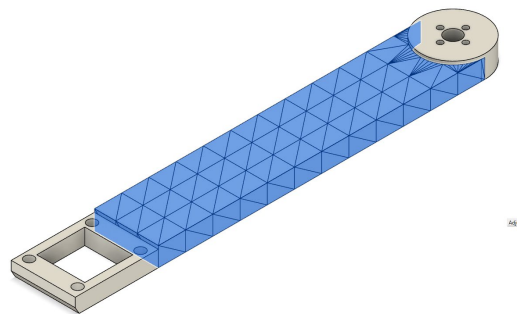


Figure 3 - Initial drone arm mesh

The primary sections of the drone arm originally featured a uniform mesh geometry. However, minor adjustments were necessary to preserve the geometry of the faces containing the fixing points. During the simulation phase for generating the new topology, the mesh size was reduced by scaling. Although this increased the computational power required, it resulted in more precise outcomes.

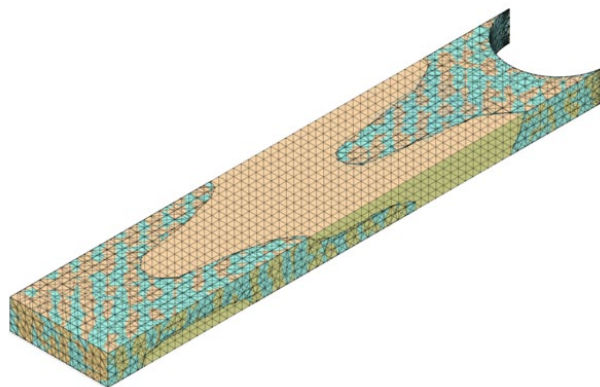


Figure 4 - Mesh reduction through scaling

Study Finalisation

A critical consideration is the selection of materials as the material influences the considered physical properties to the study. In this case, ABS plastic was chosen, a common material for drones.

ABS has a balance of strength, flexibility, and cost effectiveness. However, its thermal properties and susceptibility to degradation over time due to UV exposure must be considered, especially for outdoor applications.

Due to the selection of ABS, the most available and applicable AM method is 3D printing. Anisotropy is a key consideration in this process. When printed layer by layer, ABS can vary directional mechanical properties depending on the orientation. This anisotropic behaviour means that the strength and stiffness of the drone arm may differ along different axis, impacting its performance under different loading conditions.

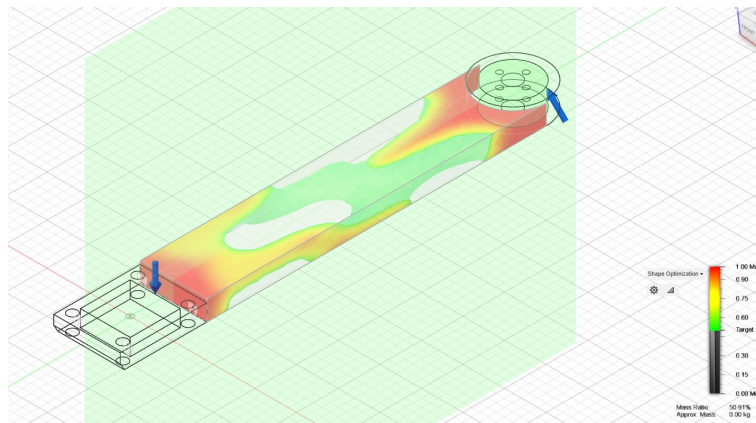


Figure 5 - Topology Optimisation: Heatmap and Material usage

The efficiency of the study design in practical application relies heavily on the quality of information inputted into the analysis. The study demonstrated an approximate 50% reduction in weight. The heatmap indicated areas of stress within the design due to the applied forces, and the topology itself became more intricate to achieve this weight reduction. The precision of material distribution could have been enhanced by further reducing the mesh size and optimising the mesh, though this would require greater computational power.

A significant challenge lies in simplifying the complex mesh model into a manufacturable design. This step requires redesigning the part to closely emulate the optimised mesh model. The success of this process largely depends on the individual's proficiency with the design software. Although the redesigned part lacked some of the finesse of the optimised mesh, it still achieved an approximate 40% weight reduction, which is substantial for drone operation.

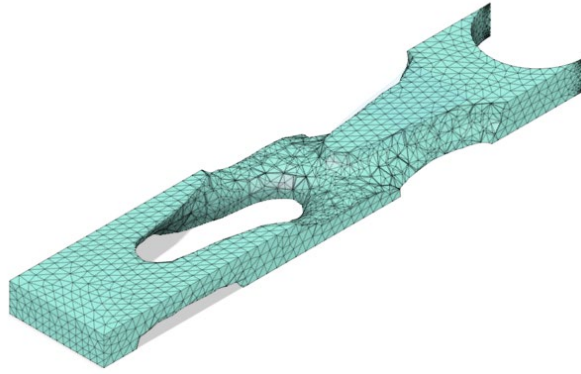


Figure 6 - Topology Optimisation: Generated Mesh

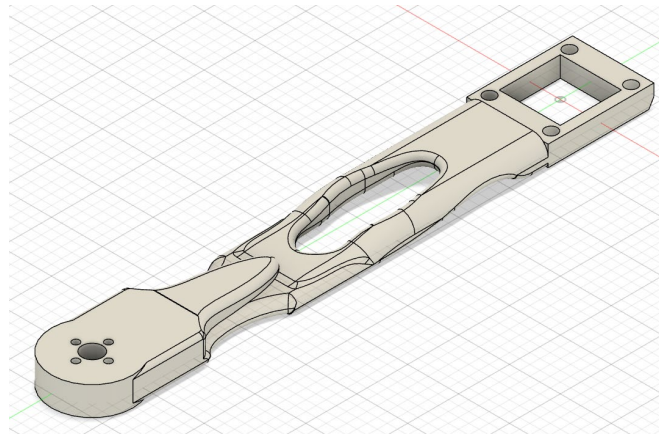


Figure 7 - Topology Initial simplification

Balancing computational demands with practical design remains a key aspect of the process. The initial model's material layout, optimised, demonstrates the potential for significant improvements in efficiency and performance. However, simplifying this intricate model into an effective design highlights the importance of skill in software use and the requirement of iterative development. The redesigned drone arm, despite its less intricate geometry, maintains a considerable weight reduction enhancing the drone's overall strength to weight ratio.

5. Results

Finite Element Analysis (FEA)

The initial study provided an unacceptable displacement, with the part unable to withstand applied forces, showing a displacement of 2mm under the maximum Newton forces.

Proficiency with design software significantly influences the optimisation process. Three iterations were produced further addressing identified weaknesses.

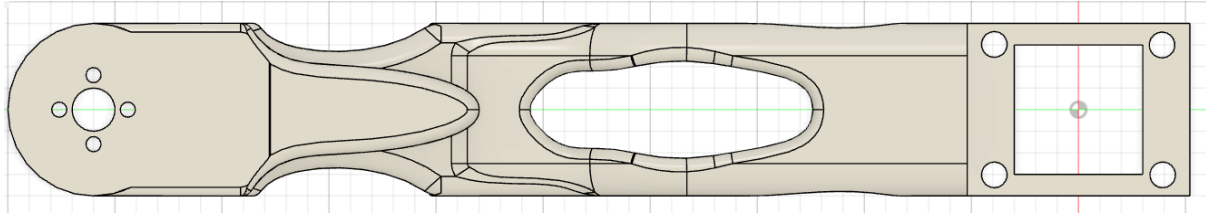


Figure 8 - Topology Second Iteration

The final iteration achieved a reduced displacement of just 0.023mm under maximum Newton forces. Note, the diagram exaggerates displacement to emphasise stress and displacement points.

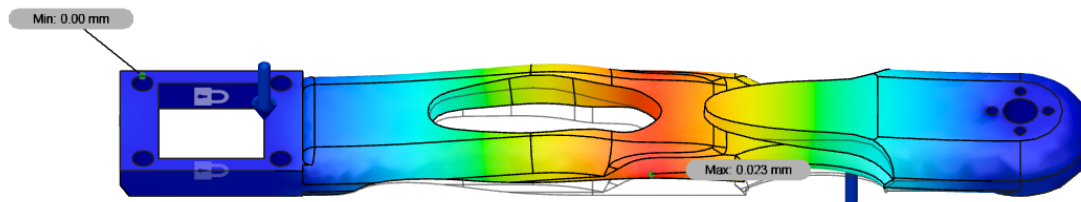


Figure 9 – Topology final Iteration Simulation

The improved design increased material usage by approximately 10% compared to initial topology analysis, due to challenges in accurately replicating the intended mesh structure. Design experience is critical for identifying failure points, design flaws, and weak areas, particularly at certain edges.

Design experience would allow for manufacturing considerations such as shrinkage, porosity, and distortion. As the design should consider uneven cooling during printing. This causes internal stresses that lead to warping or distortion. This is especially problematic for drone arms, where dimensional accuracy and stability are critical. Post processing techniques such as heat treatment or annealing may be required, adding to the overall production time and cost.

The final study, the third iteration, demonstrated substantial improvements. Displacement was primarily due to forces affecting distances between the motor and fixing end, initially overlooked during topology optimisation. Accurate simulation input data is critical for precise outcomes. Inaccurate or simplified inputs lead to underperforming parts, causing further time investment in iterative redesign.

Based on the third iterative redesign, there must also be a consideration for the stress region clearly identified in the FEA. Residual stresses, particularly in this area can affect the mechanical properties. Potentially, reducing its fatigue resistance or causing failure under

load. The design changes account for stress concentrations and ensure that critical areas of the drone arm are adequately supported or reinforced, hence the material increase.

Further Manufacturing Considerations

One of the primary constraints of additive manufacturing, especially in the context of the drone arm design, is the complexity of the shape. In this case, without lattices, the design is more easily manufacturable.

Post processing can involve the removal of support structures used to print overhanging features or complex geometries. These supports add to material usage and production time, impacting overall cost effectiveness. The disposal of unused materials and chemical residues from post processing can have environmental implications, requiring proper handling and recycling practices.

From a cost perspective, while additive manufacturing offers advantages in complex geometry production, the cost per unit volume of material and the energy consumption during printing can be higher compared to traditional methods. However, the ability to combine multiple components into a single printed part can offset some of these costs, particularly in designs like the drone arm where integration and weight reduction are critical.

6. Conclusions

The study demonstrated the effectiveness of Additive Manufacturing (AM) in optimising a drone arm design using topology optimisation and finite element analysis (FEA). By leveraging these techniques, the drone arm achieved significant weight reduction while maintaining structural integrity, critical for enhancing performance and efficiency. The iterative design process highlighted the importance of accurate simulation inputs and proficient use of design software with consideration of challenges such as anisotropic behaviour, shrinkage, and manufacturability.

The final iteration showed a substantial improvement, reducing displacement under maximum forces to 0.023mm. The study highlighted the importance of balancing computational demands with practical design considerations and discusses post processing techniques to ensure dimensional accuracy and stability. Although AM can cause higher material and energy costs, the ability to produce lightweight, integrated components with precise material placement proves its value in high performance applications.

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