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ACMA5002

**Design, Development and
Manufacturing of a 3-Jaw Cobot
End-Effector**

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2008670

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1.0 Introduction

This report will complete a design study on a 3-Jaw End-Effector gripper system utilised for a Collaborative Robot (Cobot).

The report will utilise various design and development methods to optimise a current concept for functionality and manufacturability, enabling the production of 1000-2000 per week.

1.1. Design Brief

The End-Effector will be used within a Printed Circuit Board (PCB) manufacturing industry to pick and place the larger through-hole components accurately whilst preventing damage. It will be utilised within a collaborative environment; therefore, must comply with **ISO/TS 15066:2016** standards. It must be robust and lightweight, whilst being priced competitively.

2.0 Design Appraisal

This section will outline the design expectations and considerations, whilst completing a Quality Function Deployment to aid in the completion of a Design Specification.

2.1. Considerations

The Manufacturing industry is evolving, as is industry 4.0. Therefore, Human-Robot Collaboration (HRC) is receiving a lot of public perception.

Safety considerations adhering to ISO/TS 15066:2016 standards as shown in Appendix One must be made regarding HRC, whilst considering public perception, preventing public anxiety regarding safety, intimidation and job security. Therefore, designing an aesthetically pleasing End-Effector, considering biomimicry to show nature's influence on Engineering, whilst maintaining functionality and safety will increase positive perception (Mohammadi Amin, Rezayati, van de Venn and Karimpour, 2020, pp.1-2).

Misconceptions occur regarding Engineering, such as an Engineer being a person who fixes things such as a mechanic, rather than a person who is an innovative problem solver who designs solutions. Marshall, McClymont and Joyce (2007, pp.12-27) state public perception alters and becomes more positive towards Engineers and Engineering as knowledge increases, particularly within 16-19-year olds.

Thus, considering public perception within the design and manufacturing of the End-Effector will promote Engineers, ensuring their reputation of innovative thinkers, who develop technologies and strategies such as automation, whilst providing safer, more efficient working environments, will alter public perception positively.

2.2. Quality Function Deployment

With the considerations and design brief, one completed a Quality Function Deployment (QFD) as table 1 shows, to further understand the Voice of the Customer (VOC).

Anderson (2014, p.82) states that before product development takes place, products must be defined methodically, setting clear and realistic goals, understanding customer needs and product functionalities whilst developing overlooked requirements.

Table 1 Shows a QFD

			Key:	Relationship scores	Design requirements							
			 Strong positive	 = 9	Decrease Grip Strength	Increase Stroke Size	Increase Jaw Area	Increase Mechanism Backlash Tolerances	Reduce Weight	Increase Hard-Wearing Components		
			 Weak positive	 = 3								
			 Weak negative	 = 3								
			 Strong negative	 = 9								
Customer rating (1 = least, 10 = most important)	6	Pick many different parts & prevent damage										
	3	Lightweight										
	6	High Accuracy										
	9	Function without guarding and comply with ISO standards										
	6	Able to withstand external forces										
	3	Be able to operate after 10,000 cycles										
	3	Low cost										
	Key: x = Company's own product or CP 1 y = Competing product (CP) # SMC 3 Finger Gripper, MHS3-16D z = Competing product (CP) # P-3600			'Z-----Y----- -----Z-----X----- Y'-----X-----Z-----Z-----X----- X'-----Y-----Y-----Y-----Y----- -----X-----Z-----X-----Z-----								
Dimension			gf	mm	mm^2	mm	g	N/A				
Target value			100-600	0-50	30-50	< +0.1	< 300	N/A				
Importance rating			135	81	189	108	63	63				
Relative importance			2	4	1	3	5	5				

The QFD shows customer needs and the design requirements compared to competitors, showing a competitive product, whilst indicating positives regarding relative importance outweigh negatives, thus, all requirements are included in the design specification in section 2.3.

2.3. Design Specification

Table 2 shows a full design specification, developed from the design brief and the QFD.

Table 2 Shows the End-Effector Design Specification

<u>Design Specification: 3-Jaw Cobot End-effector</u>				
Performance				
Grip Force of 100gf to 600gf - Able to withstand 5kgf external load	Stroke – 10mm to 50mm	Time to close/open: 700ms or less	Griper Deviation +/- 0.1mm	Can be utilised with Various Cobot Systems
Size and Weight				
Overall diameter/width – Less than 120mm	Overall Length – Less than 150mm	Less than 1kg in weight		
Power and Supply				
Standard power supply of 230 V Ac and/or Air supply of up to 6-bar (87.0226 PSI)	Accommodation of standard accessories such as pneumatic fittings			
Safety and Environment				
Comply with ISO-15066 Human-Robot-Collaboration (HRC) Standards	Maximum impact and clamping force of 65N	Maximum pressure of 110 N/cm ²		
Maintenance and Life Cycle				
Modular Design for replacement of Actuator or Motor	Able to complete 10,000 open and close cycles			
Budget and Cost				
Entire End-Effector Cost: £200 or less				

3.0 Manufacturing Methods

This section will outline current concept components, highlighting the best manufacturing methods for each component based on their specific function and company requirements, therefore, the Design for Manufacturability will take place in section 4.0.

3.1. Design Components

A Computer-Aided Design (CAD) assembly for the 3-Jaw End-Effector can be seen in figure 1. Some components are transparent for visual purposes. Table 3 shows the various components and their function.

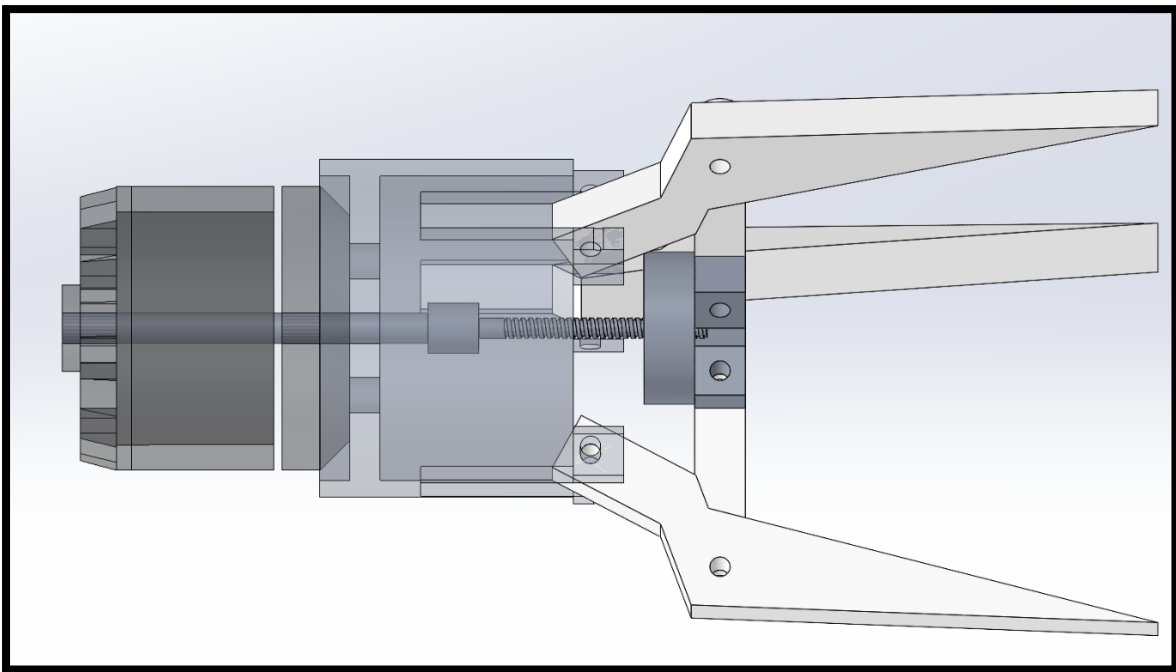
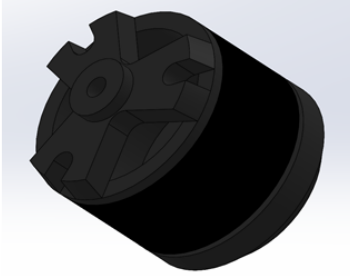
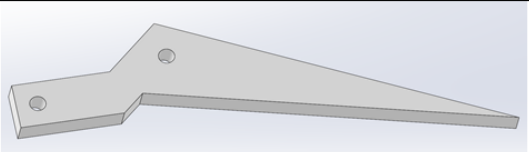
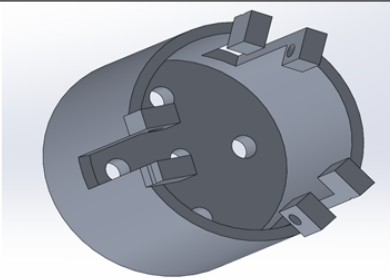
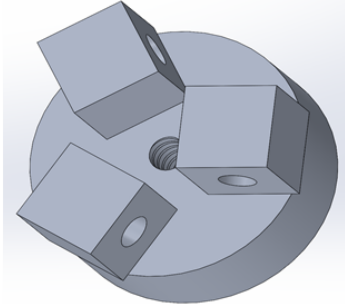
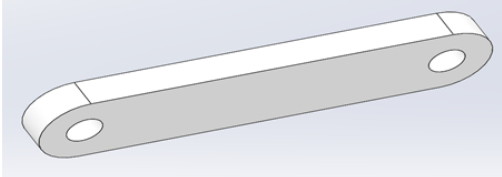
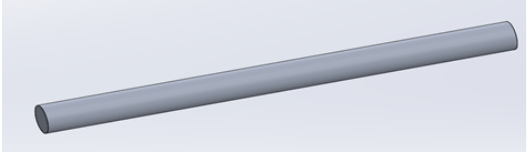
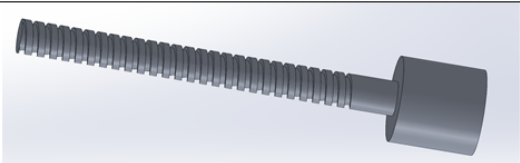


Figure 1 Shows Current CAD Design of the 3-Jaw End Effector

Table 3 Shows the Current 3-Jaw End-Effector Components and their Functions

Component	Function	Current CAD Image
Motor	Turns the shaft and worm	
Jaw	Functions as a gripper tip	
Cylinder	Performs as the end-effector foundation, attaching the motor and joins.	
Drive-plate	Drives the movement of the jaw through joins from the shaft and worm	
Join	Acts as the join for the movement mechanism	
Shaft	Connect the worm to the motor	
Worm	Rotates to move the drive-plate	

3.2. Proposed Manufacturing Methods

This section will outline the best manufacturing method based on each components' functionality, tolerance, output and cost requirements. Section 4.0. will outline the design changes for the Design for Manufacturability (DFM) and other Design for 'X' considerations.

Groover (2010, p.94) states the ability to obtain a tolerance or surface finish is based on the chosen process, stating machining is one of the most accurate, whereas, sand casting for example can be inaccurate.

Specific tolerances are required, therefore, an International Tolerance (IT) Grade Chart can be utilised in table 4, with a more detailed version in Appendix Two. It determines manufacturing precision, with higher precision as the grade number decreases, however, this may also increase the cost. Additionally, Groover (2010, p.597) states additional costs may occur for added processes such as ensuring Geometric Tolerancing, further stating machining can obtain better tolerances, however, longer lead times and higher cost, thus, should be designed out if possible.

To achieve the best Return on Investment (ROI), the highest IT grade which still met the tolerance specification and manufacturing output capabilities was chosen, along with using table 5 of limits and fits with a more detailed version in Appendix Three to understand hole tolerance requirements for functionality.

Table 4 Shows an International Tolerance (IT) Grade Chart (International Tolerance Grade Chart/Table | IT Grade Number and Applications | CNCLATHING, 2020)

Application, Process	Tolerance (μm)	IT Grade
Slip blocks, reference gages	1-2	1
High quality gages, plus gages	2-3	2
Good quality gages, gap gages	3-5	3
Fits produced by lapping	4-10	4
Ball bearings, Diamond or fine boring, fine grinding	5-12	5
Grinding, fine honing	6-20	6
High quality turning, broaching	12-35	7
Center lathe turning and boring, reaming	14-50	8
Horizontal or vertical boring machine	30-80	9
Milling, slotting, planing, metal rolling or extrusion	50-100	10
Drilling, rough turning and boring, precision tubing	70-140	11
Light press work, tube drawing	120-240	12
Press work, tube rolling	150-500	13
Die casting or molding, rubber moulding	250-1000	14
Stamping	400-1400	15
Sand casting, flame cutting	500-2000	16

Table 5 Shows Limits Fits and Tolerances (Limits Fits and Tolerances: Understanding Definitions & Selection: Practical Use, 2020)

	HOLE BASIS	SHAFT BASIS		
CLEARANCE FITS	H11/c11	C11/h11	LOOSE RUNNING FIT	FOR WIDE COMMERCIAL TOLERANCES OR ALLOWANCES ON EXTERNAL MEMBERS.
	H9/d9	D9/h9	FREE RUNNING FIT	NOT FOR USE WHERE ACCURACY IS ESSENTIAL, BUT GOOD FOR LARGE TEMPERATURE VARIATIONS, HIGH RUNNING SPEEDS, OR HEAVY JOURNAL PRESSURES.
	H8/f7	F8/h7	CLOSE RUNNING FIT	FOR RUNNING ON ACCURATE MACHINES AND FOR ACCURATE LOCATION AT MODERATE SPEEDS AND JOURNAL PRESSURES.
	H7/g6	G7/h6	SLIDING FIT	NOT INTENDED TO RUN FREELY, BUT TO MOVE AND TURN FREELY AND LOCATE ACCURATELY.
	H7/h6	H7/h6	LOCATIONAL CLEARANCE FIT	PROVIDES SNUG FIT FOR LOCATING STATIONARY PARTS; BUT CAN BE FREELY ASSEMBLED AND DISASSEMBLED.
TRANSITION FITS	H7/k6	K7/h6	LOCATIONAL TRANSITION FIT	FOR ACCURATE LOCATION, A COMPROMISE BETWEEN CLEARANCE AND INTERFERENCE.
	H7/n6	N7/h6	LOCATIONAL TRANSITION FIT	FOR MORE ACCURATE LOCATION WHERE GREATER INTERFERENCE IS PERMISSIBLE.
INTERFERENCE FITS	H7/p6*	P7/h6	LOCATIONAL INTERFERENCE FIT	FOR PARTS REQUIRING RIGIDITY AND ALIGNMENT WITH PRIME ACCURACY OF LOCATION BUT WITHOUT SPECIAL BORE PRESSURE REQUIREMENTS.
	H7/s6	S7/h6	MEDIUM DRIVE FIT	FOR ORDINARY STEEL PARTS OR SHRINK FITS ON LIGHT SECTIONS, THE TIGHTEST FIT USABLE WITH CAST IRON.
	H7/u6	U7/h6	FORCE FIT	SUITABLE FOR PARTS WHICH CAN BE HIGHLY STRESSED OR FOR SHRINK FITS WHERE THE HEAVY PRESSING FORCES REQUIRED ARE IMPRACTICAL.

3.2.1. Motor/Power

An off-shelf Drive should be purchased, reducing complex manufacturing and maintenance requirements, thus, reducing costs.

3.2.2. Jaw

The Jaw requires a 3000-6000 manufacturing output per week, whilst possessing high tolerances, strength and a good surface finish. Therefore, **Die Casting** has been chosen due to the cast reusability, thus having the best ROI for **Rapid Manufacturing**. It further provides high strength components with good surface finishes, enabling efficient part-picking functionality.

Die casting can achieve **+0.12mm** tolerances, however, to meet the design specification H7 tolerance holes will be required, thus, a secondary process has been chosen with a **3-axis CNC Milling Machine**, providing **reaming** which allows for **+0.008mm** tolerances as Appendix Two shows (Groover 2010, p.94).

3.2.3. Cylinder

The Cylinder is the foundation as it attaches multiple components. The manufacturing output is 1000-2000 per week. As this is still high, **Die Casting** will also be used. Furthermore, to meet the H7 hole requirements, a secondary **5-axis CNC Milling Machining** will be utilised to achieve IT grade 8 tolerances with **reaming**, thus, achieving low-cost and high-output from die casting whilst limited secondary process machining achieves tolerances to prevent play in the connected components (Groover, 2013, p.206).

3.2.4. Drive-Plate

The Drive-Plate can use an IT grade of 14, therefore, to achieve the output requirements, **Die Casting** will also be utilised, However, Concentricity Geometric Tolerancing is required in the centre, with H7 hole tolerances for the connections, thus, a secondary **5-axis CNC Milling Machining** will take place, thus, including tapping of the centre hole and reaming of the connection holes.

3.2.5. Join

The Join requires 3000-6000 manufactured parts per week. Simple geometry, with high accuracy requirements for mechanism functionality, means **Laser Cutting** is the best option to provide low-cost, rapid manufacturing, limiting waste material. Velling (2020) states the accuracy of $\pm 0.1\text{mm}$ is achievable which satisfies the design specification.

3.2.6. Shaft

The Shaft can be bought from a supplier in standard lengths. An automated **Cutting Machine** can cut the shaft to length accurately, saving time and money. IT Grade 8 is required thus, suppliers must adhere to this with additional concentricity and straightness **Geometric Tolerancing**.

3.2.7. Worm

To prevent loss of rotational function from defects in straightness and concentricity, **Geometric Tolerancing** is required, thus, IT grade 8 is required which can be obtained from a **Lathe**, with a male thread added within the same process.

4.0 Design and Development

This section will develop the design further for functionality, manufacturability and mentioned considerations ensuring it meets the design specification.

4.1. DFMEA

To manage risk a Design for Failure Mode Effect Analysis (DFMEA) has been carried out in table 6.

Table 6 Shows a DFMEA for the 3-Jaw End-Effector

Item Name: 3-Jaw Cobot End-effector		FMEA Team: Joshua Thorngate				Prepared by: Joshua Thorngate								
						FMEA Date (Orig): 08/05/2021				Revision #: 1				
Item Function	Potential Failure Mode	Potential Effect on Customer Because of Defect	S E V	Potential Causes	O C C	Current Process Controls	D E T	R P N	Actions Recommended	Resp.& Target Date	S E V	O C C	D E T	Fut ure RPN
What is the component, function, or feature?	In what ways can the Component, Subsystem or System potentially fail to meet the Design Intent ?	What is the impact on the Key Output Variables (customer requirements) or internal requirements?	How Severe is effect to the customer?	List every conceivable failure and/or failure mechanism for each failure mode	How frequent is cause likely to Occur?	What are the Existing Controls & Procedures (Fail-Safe, Tests, Mathemat.Calcs) that prevent either the cause or the failure mode	How probable is Detection of cause?	Risk Priority # to rank order concerns	What are the actions for reducing the Occurrence of the cause, or improving Detection? Should have actions on high RPN's or EASY FIXES	Who's Responsible for the recommended action? What date?	Future Severity	Future Occurrence	Future Detection	Fut ure RPN
Gripper Tips	Potential snapping of tips	Loss of function	10	External force exceeds 1kg - Material and design not capable of higher loads	5	Stress analysis on component with chosen material	5	250	Alter design for strength and change to a higher yeild strength material	Joshua Thorngate	10	1	5	50
Gripper Tips	Sharp edges causing bodily harm	Harm to operator	10	Gripper tips designed with a sharp edge and does not meet ISO/TS 15066:2016 standards	7	No current control method - calcuation can be used to depermine pressure.	8	560	Redesign to ensure tip is not sharp, calucate new pressure ensuring it meets ISO/TS	Joshua Thorngate	2	7	8	112
Gripping force	Gripper strength too high	Damage to external customer components	8	Jackscrew and motor has no play in the system. Jackscrew is too strong	5	No process to turn down or dectec jackscrew force from the motor.	10	400	Redesign to utilise Pneumatic on a bore, which can be contolled with a pressure regulator with sensors	Joshua Thorngate	8	2	1	16
Gripping force	Gripper strength too high	Harm to operator	10	Jackscrew and motor has no play in the system. Jackscrew is too strong	3	No process to turn down or dectec jackscrew force from the motor.	10	300	Redesign to utilise Pneumatic on a bore, which can be contolled with a pressure regulator with sensors	Joshua Thorngate	10	2	1	20
Connecting rod (Join) - used to connect driving plate to gripper	Interferances when in operation	Reduced function due to interference - eventual damage to gripper	8	Part designed without a clearance	4	No process to stop or detect	10	320	Create clearance and add bushings	Joshua Thorngate	8	2	10	160
Connecting rod (Join) and Drive plate	Rod interference with drive plate (used as mechanical stop)	Damage to gripper componets	5	No set mechanical stop - grippers can open fully and thus the rods stop on the drive plate	8	No process to stop or detect	10	400	Create a mechnaical stop	Joshua Thorngate	2	2	10	40
Cylinder and jaw gripper tips	Interferances when in operation	Reduced funtionality due to motion speed	5	No clearance have been designed into the component	8	No detection other than noticing the reduced speed	8	320	Create clearance and add bushings	Joshua Thorngate	5	2	8	80

4.2. Design for X

Anderson (2014, p.126) states one should **Design for Everything** known as **Design for X**. This involves one designing not just for functionality utilising CAD software, but also making considerations regarding manufacturability, assembly, safety and so on. Therefore, utilising the design specification, considerations and DFMEA, one has made all the relevant changes as shown in figure 2.

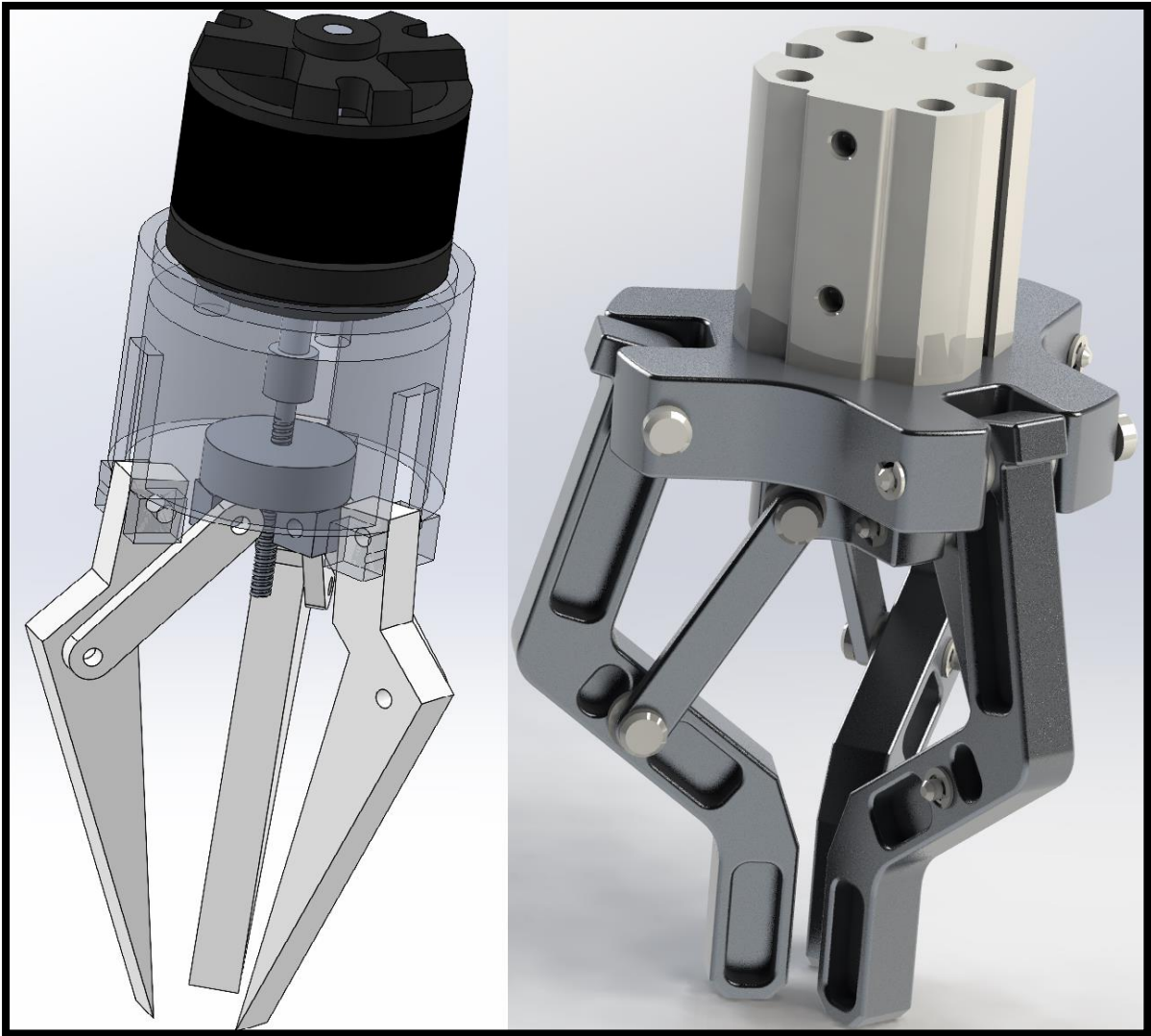


Figure 2 Shows the 3-Jaw End-Effector on the Left with the Redesign on the Right

The first design change was standardising the fastening methods for ease of automation, assembly, and serviceability. M3 British Standards Institution (BSI) screws were used to mount the Actuator to the Cylinder.

2mm h6 pins with clips were used as figure 3 shows, to limit tool requirements, allowing for easy assembly and maintenance. Bushes were utilised as figure 4 shows, with 3mm h6 external and 2mm H7 internal diameters, allowing the pins to create the pivot, whilst preventing wear to the part due to the bushes, increasing accuracy and serviceability.

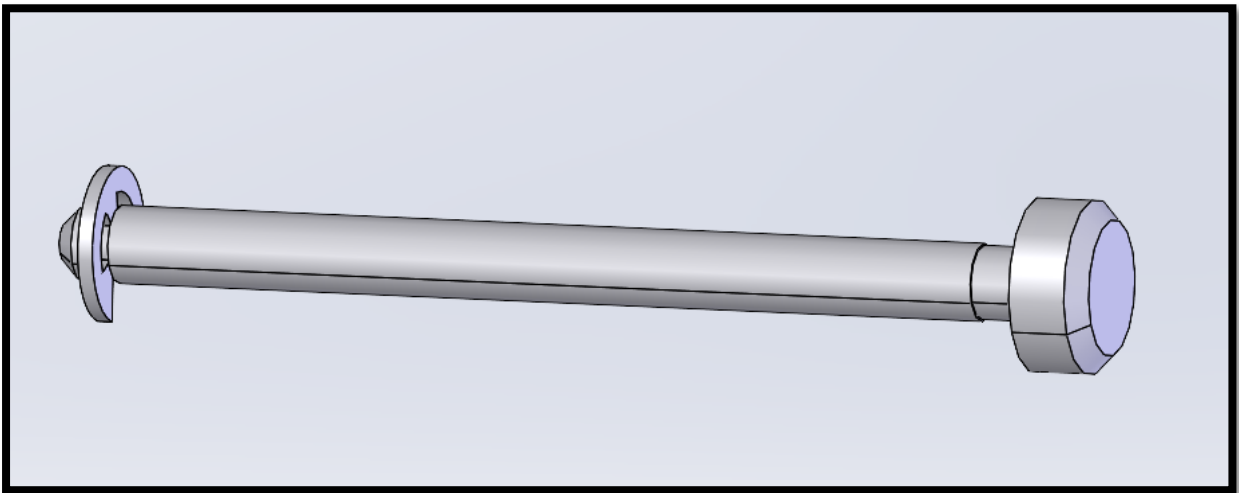


Figure 3 Shows the Standard Pin and Clip

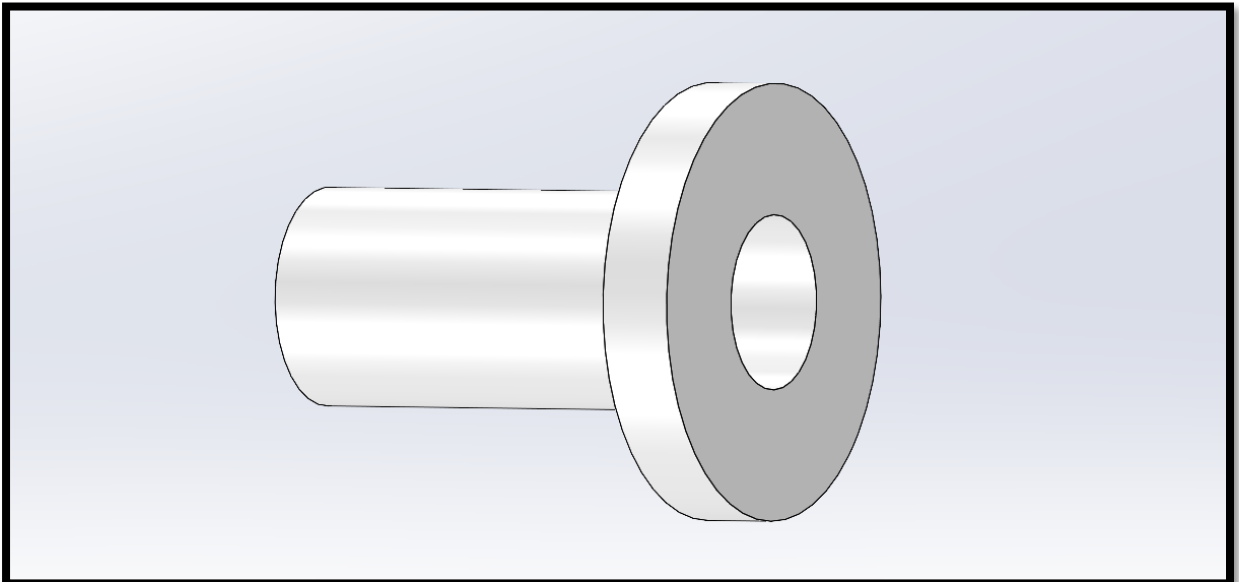


Figure 4 Shows the Standard Bush

4.2.1. Motor/Actuator

The Motor was replaced with a 10mm^2 bore 15mm stroke actuator as figure 5 shows, ensuring a low-cost off-shelf product was utilised of which pressure can be controlled. Although variable stroke options are not available, the reduced pressure allows for the pick of any component as the gripper will stop once the part is fully gripped and aligned. Additionally the secondary function is the internal bore acts as a mechanical stop, adhering to the changes in the DFMEA and preventing damage to the End-Effector components as figure 6 shows. This meets ISO/TS 15066:2016 standards as operating at full 6 bar pressure:

$$F = P \cdot A$$

$$F = 6 \cdot 10$$

$$F = 6N$$

$$F = 612\text{ gf}$$

Whereby:

P=Pressure

F=Force

A=Cross Sectional Area

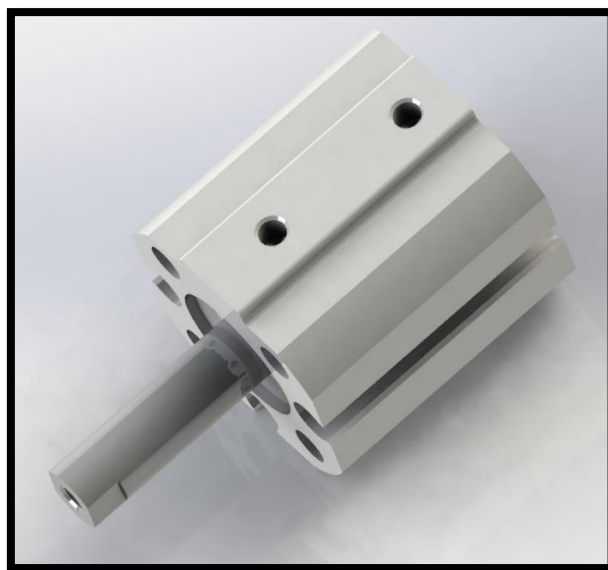


Figure 5 Shows the Pneumatic Actuator

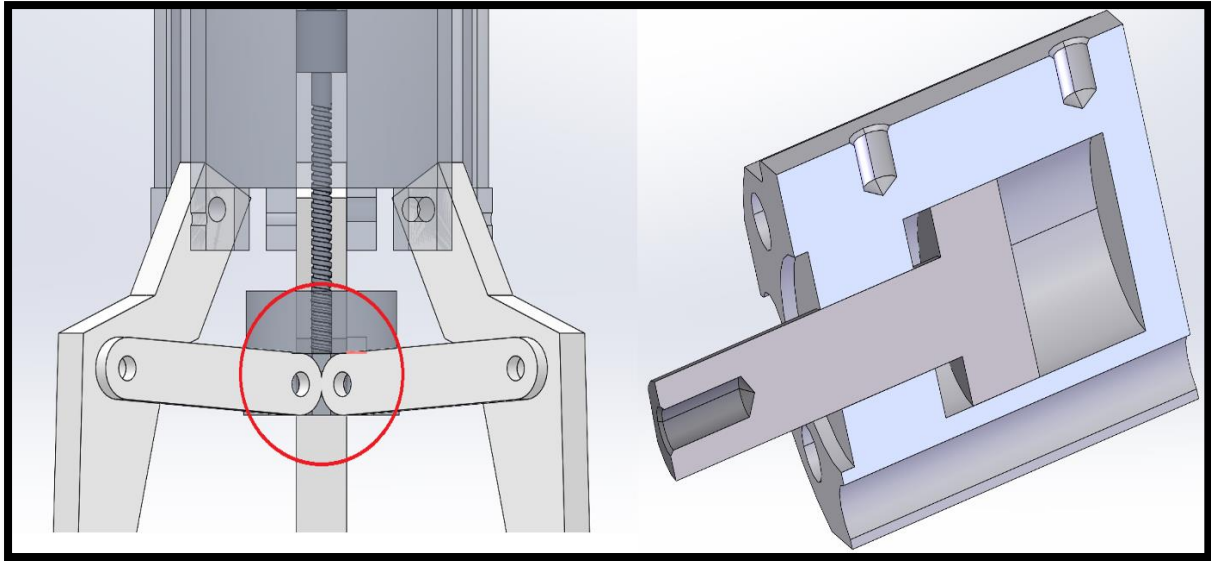


Figure 6 Shows the old Mechanical Stop vs the new Mechanical Stop

4.2.2. Jaw

Figure 7 shows the redesigned Jaw, following the actions from the DFMEA, such as increasing the cross-sectional area, ensuring that if a 5kg load from the force generated from a Cobot such as a Universal Robot 5 was placed on the gripper, then the gripper would no longer break as shown in figure 8. Furthermore, due to the area change from 0.05mm^2 to 48mm^2 , pressure at the tip with a 5kg Cobot payload has decreased as shown with the formula:

$$P = \frac{F}{A}$$

$$\therefore P = \frac{F \cdot g}{A}$$

$$\therefore P = \frac{5 \cdot 9.81}{48}$$

$$P = \frac{49.05}{48}$$

$$P = 1.02 \text{ N/mm}^2$$

$$\therefore P = 102 \text{ N/cm}^2$$

Therefore, the redesign now meets the ISO/TS 15066:2016 standards stated in the design specification whereas the old design had a pressure of **98000N/cm²**.

Furthermore, for functionality, flat edges as figure 7 shows have been placed on the gripping section allowing a more uniform grip, aiding in picking and preventing external part damage. A **Poka-Yoke** section has been added to the top, preventing the part from being assembled in the wrong orientation as the holes will not be able to line up when connecting to the Cylinder.



Figure 7 Shows the Redesigned Jaw

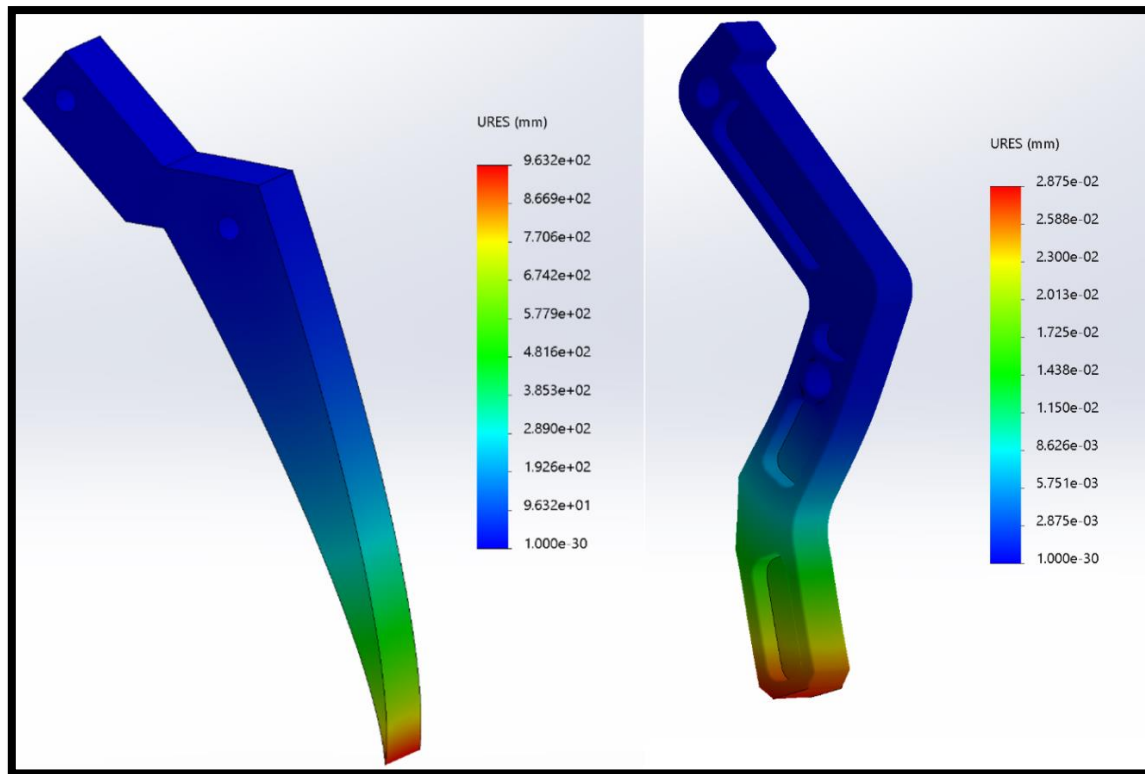


Figure 8 Shows a Stress Analysis Comparison

For this component, **Aluminium 1060** will be the utilised material over the concept PVC 0.007 Plasticized, due to its **Castability** as stated by Groover (2013, p.204), and its environmental benefits, which will be discussed later. Secondly, the material has stronger yield strength compared to its' density as table 7 and 8 show, with figure 9 showing Aluminium's strength to density ratio. This is another reason for the results shown in figure 8. Additionally, Aluminium is soft, thus, preventing possible damage to PCB component during picking.

Table 7 Shows PVC 0.007 Plasticized Material Properties

Property	Value	Units
Elastic Modulus	69000	N/mm ²
Poisson's Ratio	0.33	N/A
Shear Modulus	27000	N/mm ²
Mass Density	2700	kg/m ³
Tensile Strength	68.9356	N/mm ²
Compressive Strength		N/mm ²
Yield Strength	27.5742	N/mm ²
Thermal Expansion Coefficient	2.4e-05	/K
Thermal Conductivity	200	W/(m·K)
Specific Heat	900	J/(kg·K)
Material Damping Ratio		N/A

Table 8 Shows Aluminium 1060 Material Properties

Property	Value	Units
Elastic Modulus	6	N/mm ²
Poisson's Ratio	0.47	N/A
Shear Modulus	2	N/mm ²
Mass Density	1290	kg/m ³
Tensile Strength	13	N/mm ²
Compressive Strength		N/mm ²
Yield Strength		N/mm ²
Thermal Expansion Coefficient		/K
Thermal Conductivity	0.16	W/(m·K)
Specific Heat	1600	J/(kg·K)
Material Damping Ratio		N/A

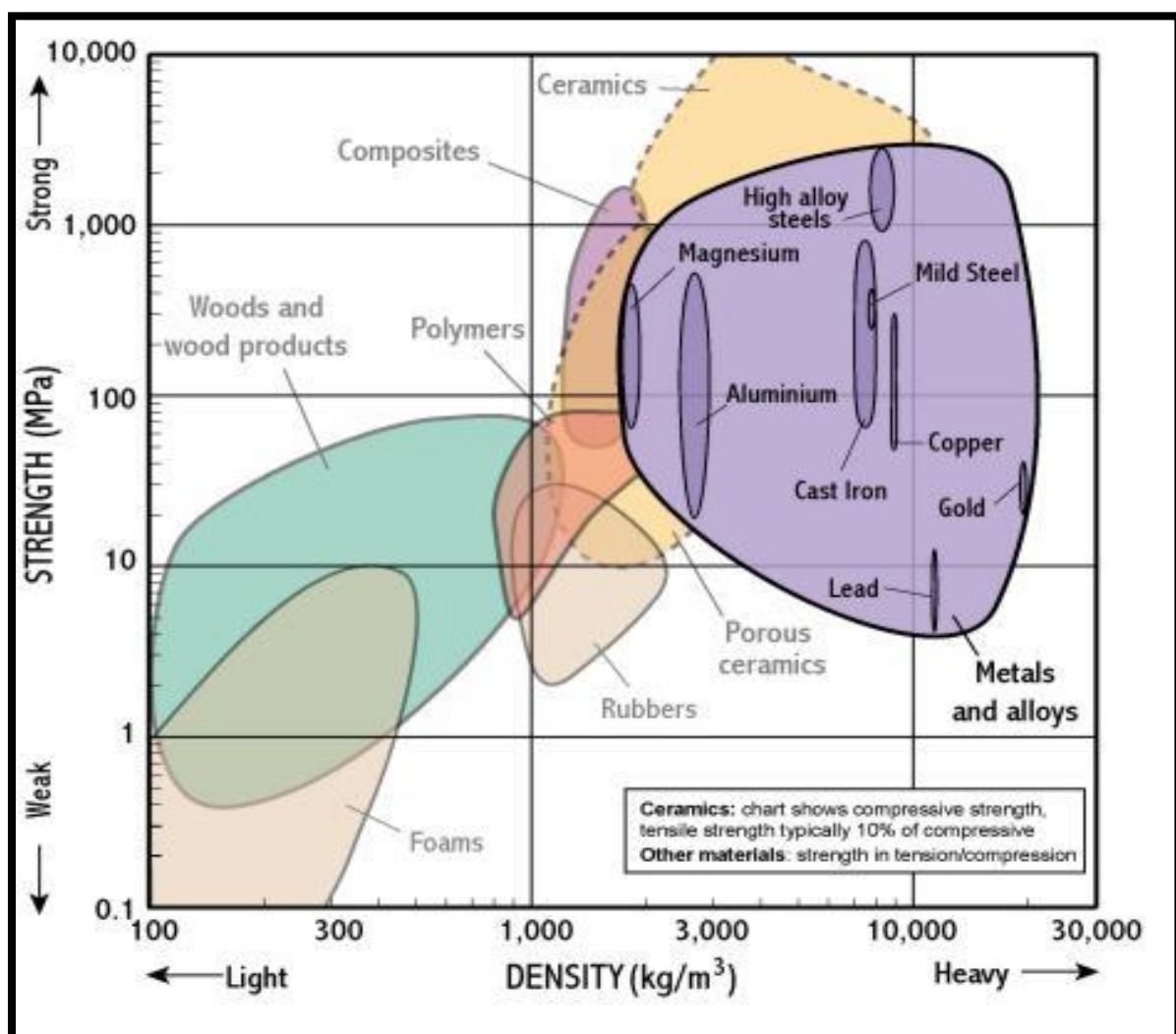


Figure 9 Shows Material Strength to Density Merit Function (Strength - Density, 2021)

DFM was considered, as Groover (2013, p.200) and Groover (2010, p.253) state considerations are required to ensure defects do not occur.

Sharp Corners have been eliminated with a **minimum** of **1.5mm radius fillets** added to corners and **0.5mm radius** added to edges, to prevent **Hot Tearing** and **Cracks** from stress concentration.

Section Thickness has been redesigned to be uniform throughout, as figure 10 shows. This prevents **Hot Spots** causing **Shrinkage Cavities** due to time differences with solidification and cooling. **Lightening holes** have been added to reduce weight and material, however, to prevent the hot spots, **Ribs** have been added which further adds strength.

Drafts have been added with a **2-degree angle** from a centre plane to allow for easy removal of the mould from either side of the part. 2-degree drafts have also been added into the lightening holes to allow for that section of the mould to be removed easily.

Holes have been modified to **3mm diameter H7** clearance holes which allow for the h6 bush to be pushed into at assembly. An Engineering drawing in figure 10 shows some of the redesigned features for reference to how these would be added to this part and other parts mentioned later on.

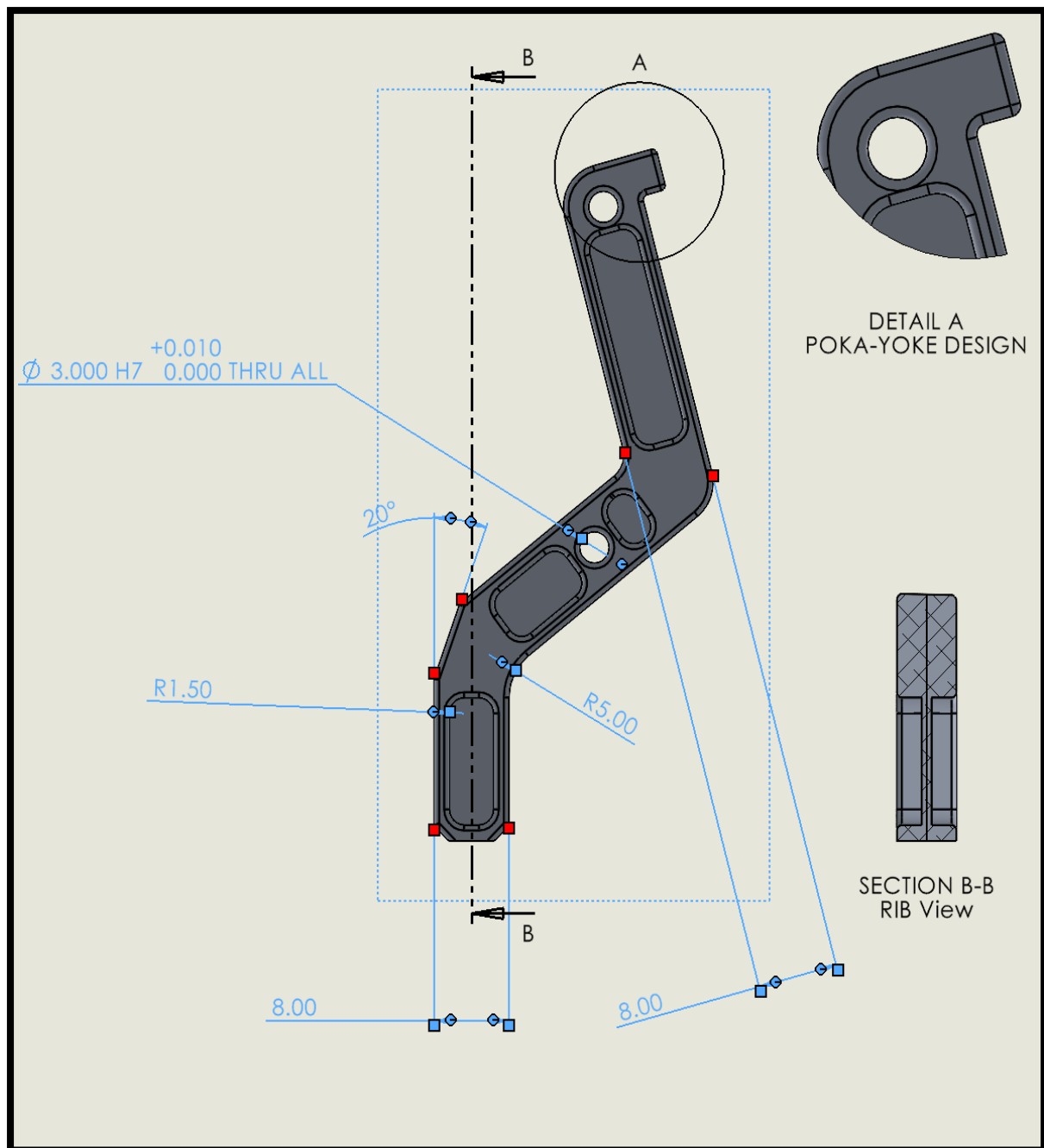


Figure 10 Shows an Engineering Drawing of the Jaw

4.2.3. Cylinder

The Cylinder was redesigned significantly for manufacturability as figure 11 shows. The **Geometric Complexity** has been reduced significantly allowing for a less complicated mould design which would save time and money, whilst reducing manufacturing defect risks. **Undercuts** and **Recesses** have been removed thus, removing the requirements for **Cores**. The part has been designed with an even **Section Thickness**, hence the shape, to prevent **Hot Spots**.

To eliminate **Hot Tearing** and **Cracks**, a **minimum of 1.5mm radius fillets** have been added to the corners and **0.5mm radius fillets** added to the edges.

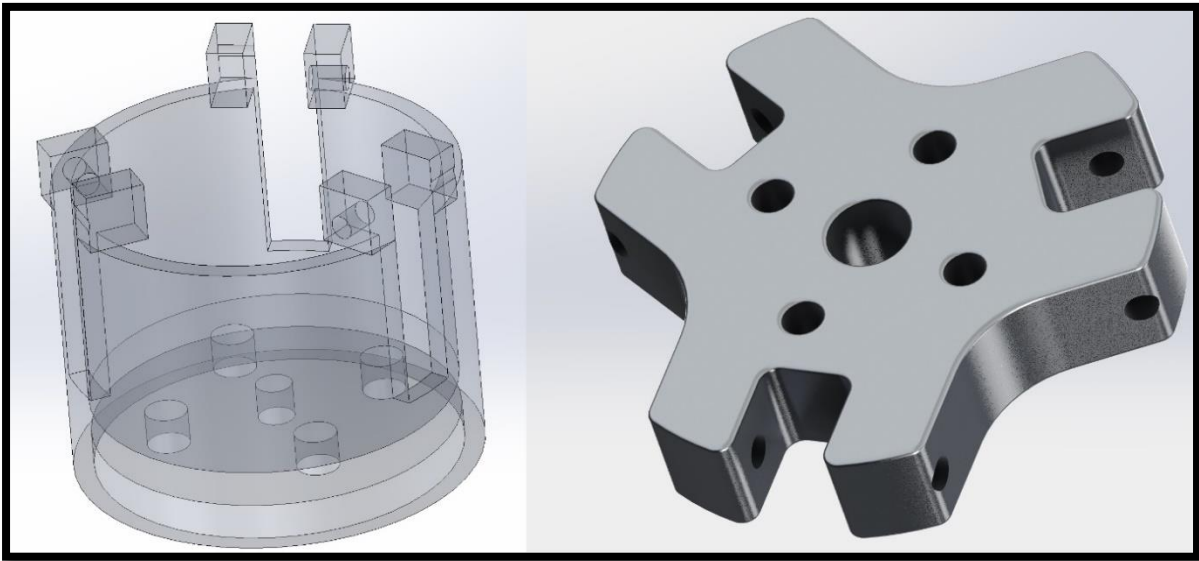


Figure 11 Shows design changes to the Cylinder

To increase design efficiency for automation, complete symmetry has been achieved in all planes, including rotational symmetry. Face symmetry was achieved by ensuring the centre hole for the Actuator rod to be moved through and the surrounding Actuator to Cylinder mounting holes were all through holes.

3mm diameter H7 Jaw attachment holes have been designed, and the section whereby the Jaw fits into as shown in figure 12 has been designed with a **clearance** which the original concept as figure 13 shows did not have. It further allows for hard-wearing bushes to be inserted.

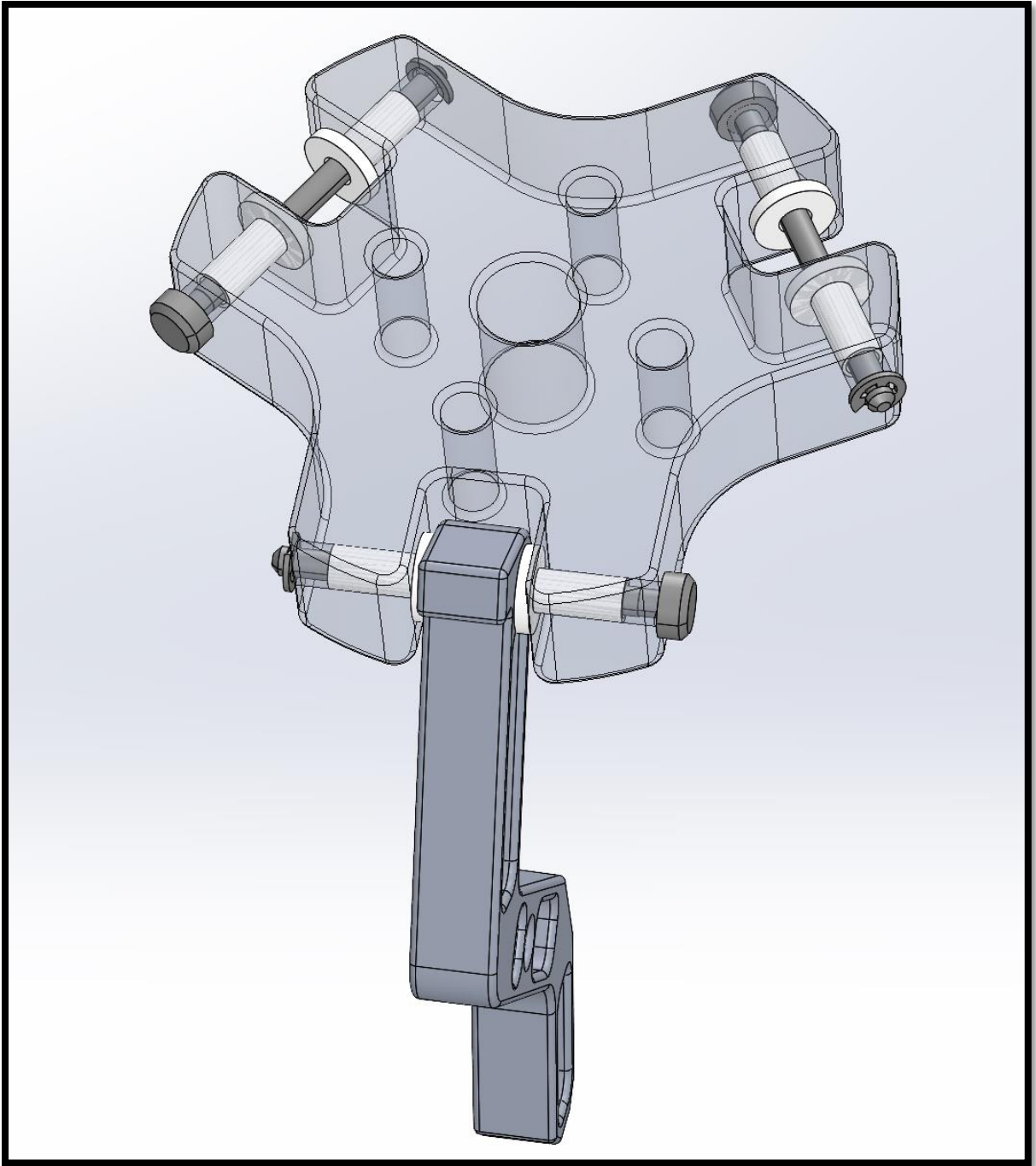


Figure 12 Shows the Redesigned Cylinder with the Jaw Sub-Assembly

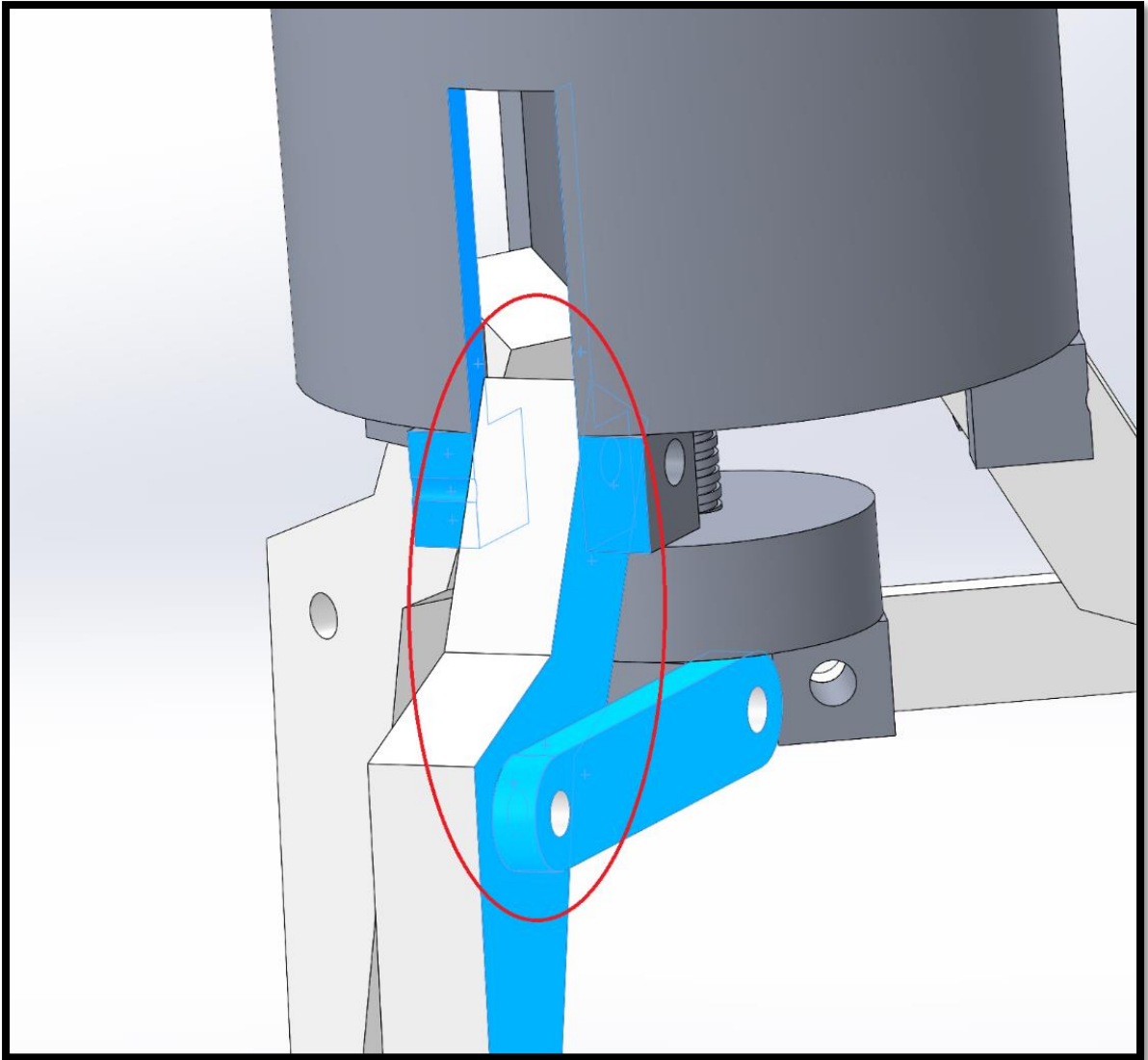


Figure 13 Shows no Clearance between Moving Components on the Original Design

Drafts were also designed into the part having a **2-degree angle** on either side of the through a mid-plane split line, to allow for easy extraction of the part.

Aluminium 1060 will also be utilised for the Cylinder. Furthermore, Groover (2013, p.204) states it's easily machinable therefore, secondary processes for the adding and **Reaming** of **3mm H7** Jaw location holes are easily achieved.

4.2.4. Drive-Plate

The Drive-Plate was redesigned, combining it with the worm and shaft as figure 14 shows.



Figure 14 Shows the Redesigned and Combined Drive-Plate

Combining the three components in the design allows for a reduction in manufacturing process methods, therefore, saving time and money. Secondly, it allows for **Poka-Yoke** as the Drive-Plate can now only be mounted in one direction and that's with its' added M5 male threaded shaft to the M5 female thread at the end of the Actuator rod. It allows for increased design efficiency and ensures no backlash occurs with the components.

Geometric Simplicity has been added, removing the Drive-Plate **Undercuts** preventing the need for **Cores** and reducing defect risks. Additionally, rotational symmetry has been added for assembly efficiency, ease of automation and machining.

2-degree Draft angles have been added to the shaft with other drafts added in the opposite direction to the three spokes. Furthermore, it can be seen that the part has been designed with an even **Section Thickness**, preventing **Hot Spots**, therefore, **Shrinkage Cavities**.

3mm H7 holes have been added to allow for the bushes to be pushed into the part, which again will be completed with machining, along with the shaft having concentricity and straightness tolerances.

0.5mm radius fillets have been added to edges with a **minimum** of **1.5mm** in corners to prevent casting failures from stress raisers creating **Hot Tearing** and **Cracks**.

Additionally, the location holes were adapted for clearances of the join, due to interference on the original concept as figure 15 shows.

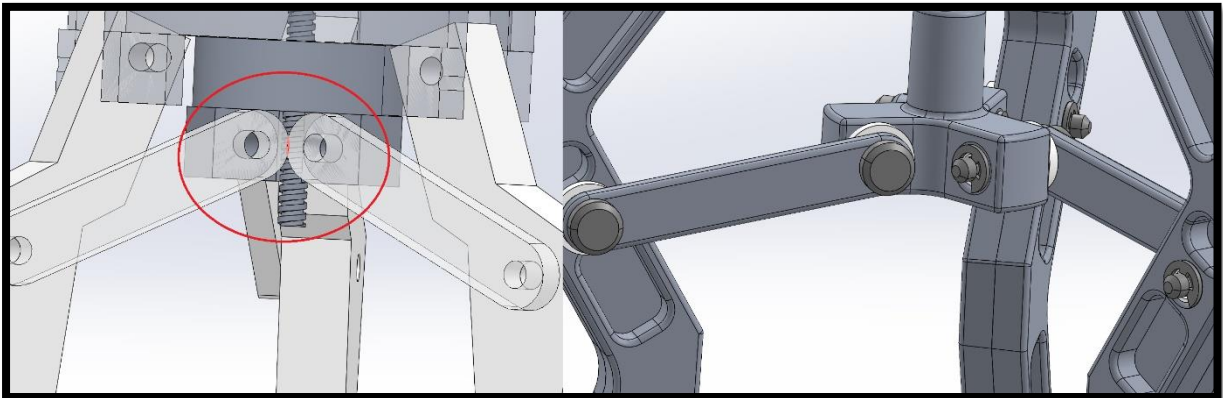


Figure 15 Shows how Redesigning the Hole Location has Prevented Part Interference

4.2.5. Join

To increase **Design Efficiency** the Join was going to be redesigned with the pins intertwined into the design of it as figure 16 shows.

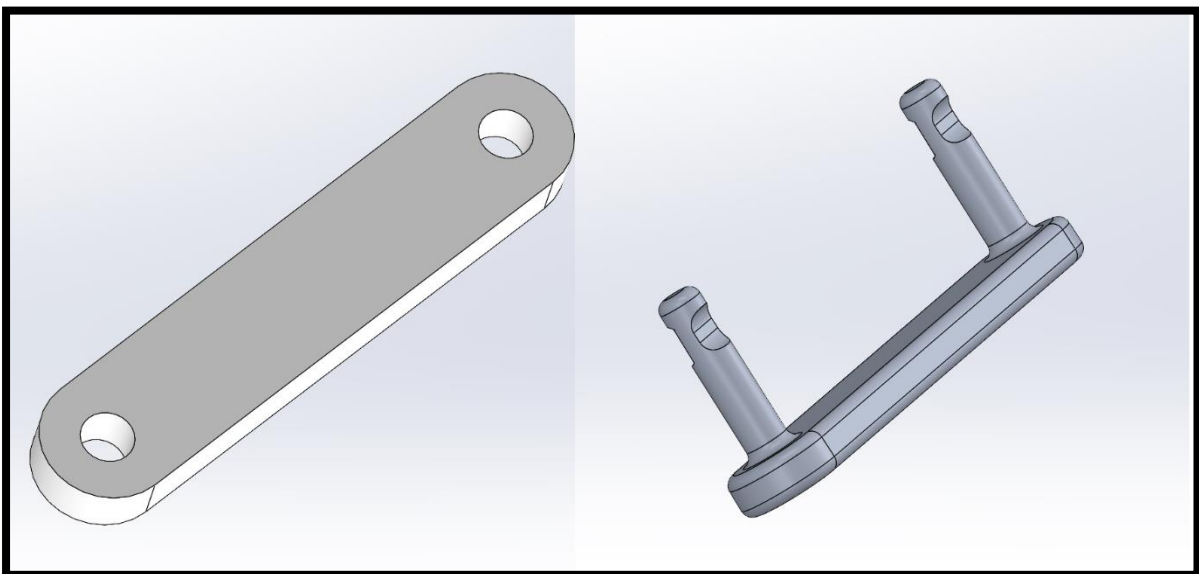


Figure 16 Shows the Concept Design for Intertwined Pins with the Join

Although this would increase design efficiency, it would cause many manufacturing **Risks**. **High tolerance h6 shafts** would increase costs with a secondary process, along with the likely defect rate these small pins would cause. Furthermore, **Aluminium** was chosen for this part due to its strength to density ratio, however, thin pins would break easily as Aluminium has poor fatigue strength (Fatigue of aluminium – aluminium-guide.com, 2021).

Furthermore, utilising pins like the other connection points would allow for standardisation and ease of maintenance.

Therefore, the **original design** has been kept, although the part was made to be **2mm thick** for laser cutting and **25mm** in length for increased operational gripper stroke. This further allows for symmetry in all planes, thus, reducing assembly risks and allowing for automation. Furthermore, laser cutting allows for a faster higher tolerance production.

4.3. Design Considerations and Efficiency

One of the considerations for Design for 'X' was Design for Assembly (DFA), which design efficiency can be determined, utilising "Boothroyd Dewhurst System" and "Lucas DFA Methodology" of which a flow chart to determine component importance can be seen in figure 17 (Cabello Ulloa et al, 2018, p.216). Table 9 shows the design efficiency before and after the changes.

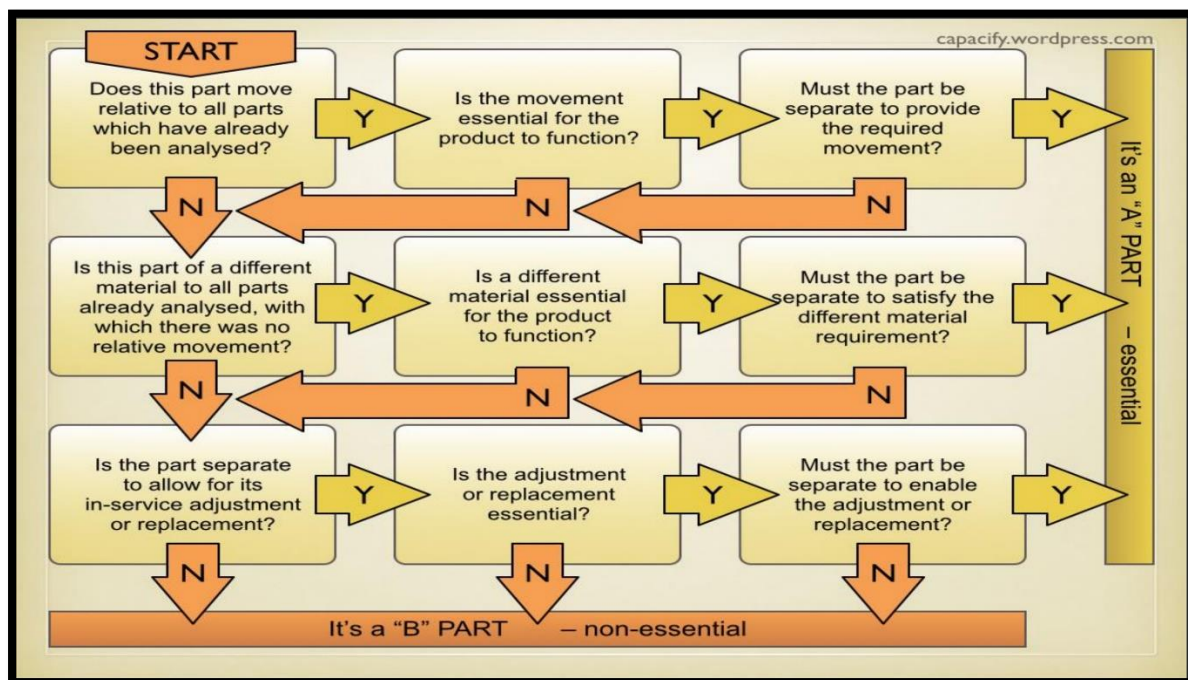


Figure 17 Shows a Flow Chart to Determine Essential and Non-Essential Parts

Table 9 Shows the Design Efficiency Before (Left) and After (Right) Redesign

DFA -Design Efficiency			DFA -Design Efficiency		
Component	Essential	Non-Essential	Component	Essential	Non-Essential
Jaw (Gripper Tip) x 3	3		Jaw (Gripper Tip) x 3	3	
Join x 3	3		Join x 3	3	
Jaw to Join Shoulder Bolt x 3		3	Jaw to Join pin x 3		3
Jaw to Join Nut x 3		3	Jaw to Join Bush x 3	3	
Jaw to Join Ball Bearing x 3		3	Jaw to Join clip x 3		3
Cylinder	1		Cylinder	1	
Cylinder to Join - Shoulder Bolt x 3		3	Cylinder to Join - pin x 3		3
Cylinder to Join - Nut x 3		3	Cylinder to Join - clip x 3		3
Cylinder to Join - Bearing x 3		3	Cylinder to Join - bushing x 3	3	
Drive Plate		1	Drive Plate		1
Drive Plate to Join Shoulder Bolt x 3		3	Drive Plate to Join - pin x 3		3
Drive Plate to Join Nut x 3		3	Drive Plate to Join - clip x 3		3
Drive Plate to Join Bearing x 3		3	Drive Plate to Join - bush x 3	3	
Motor	1		Actuator	1	
Motor to Cylinder Screws x 3		3	Actuator to Cylinder Screws x 4		4
Shaft		1			
Worm		1			
Total	8	33	Total	17	23
Design Efficiency	19.5122		Design Efficiency	42.5	

The redesign increased efficiency to 42.5%, firstly by combining components into single parts. Industry-standard fastening methods such as bearings were assumed for the original concept as none were given. However, bushes are used to replace bearings to prevent part wear and increase accuracy, thus, are now considered essential.

A manual handling and manual fitting analysis were not carried out due to utilising automation. Orientational considerations have been made for automation. Pugh (1990, p.137) states one can utilise DFA for automation hence the standardisation of all BSI screws and standardisation of pins and clips. The End-Effector is assembled from underneath in a logical order and forms

rotational symmetry, as figure 18 shows. This allows for Cobots to easily assembly the End-Effector within jigs (Anandan, 2015).

Furthermore, stroke length, End-Effector dimensions and mass requirements have been achieved as figure 18 and 19 show.

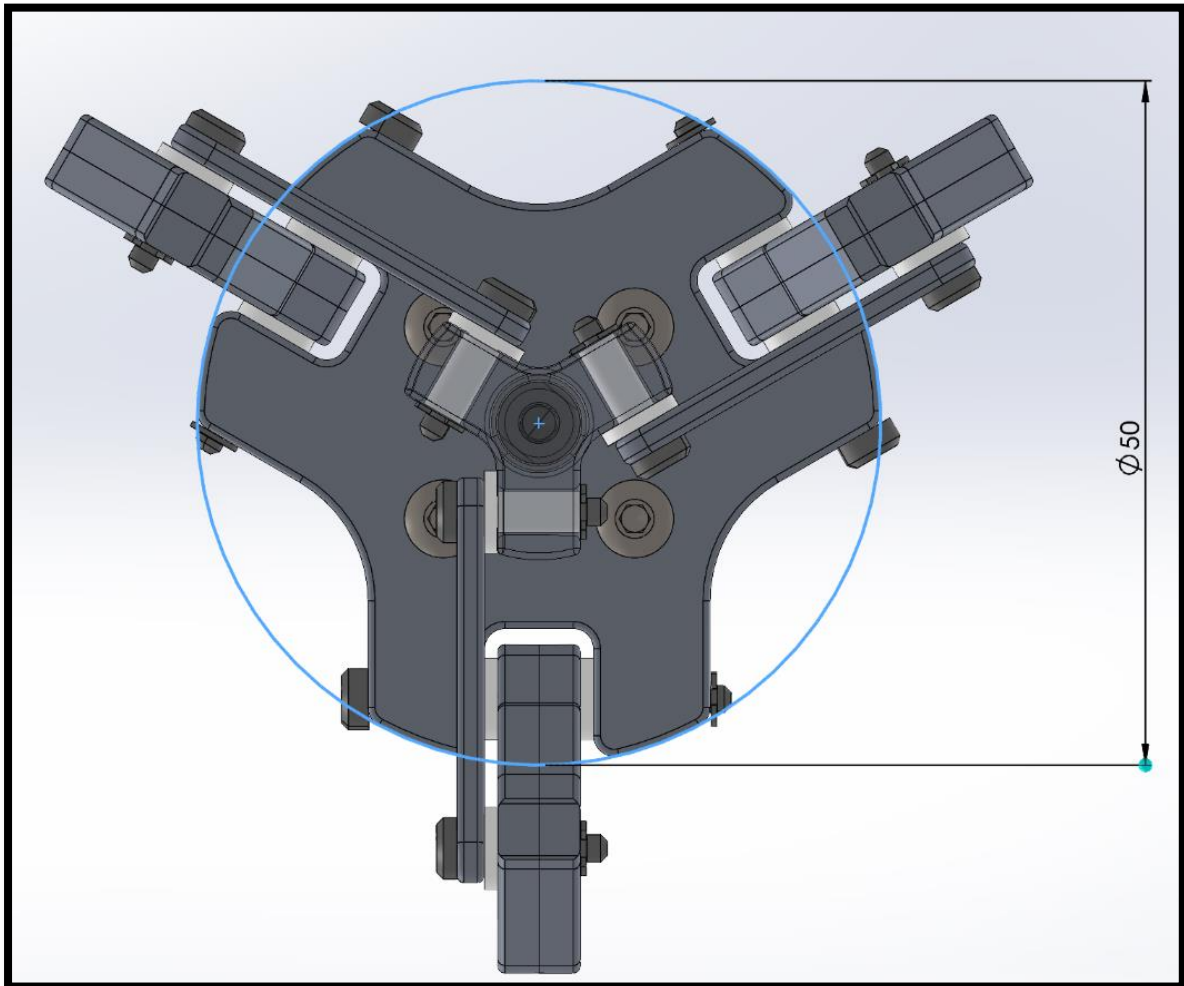


Figure 18 Shows the Assembly Points and Stroke Length for the End-Effector Gripper

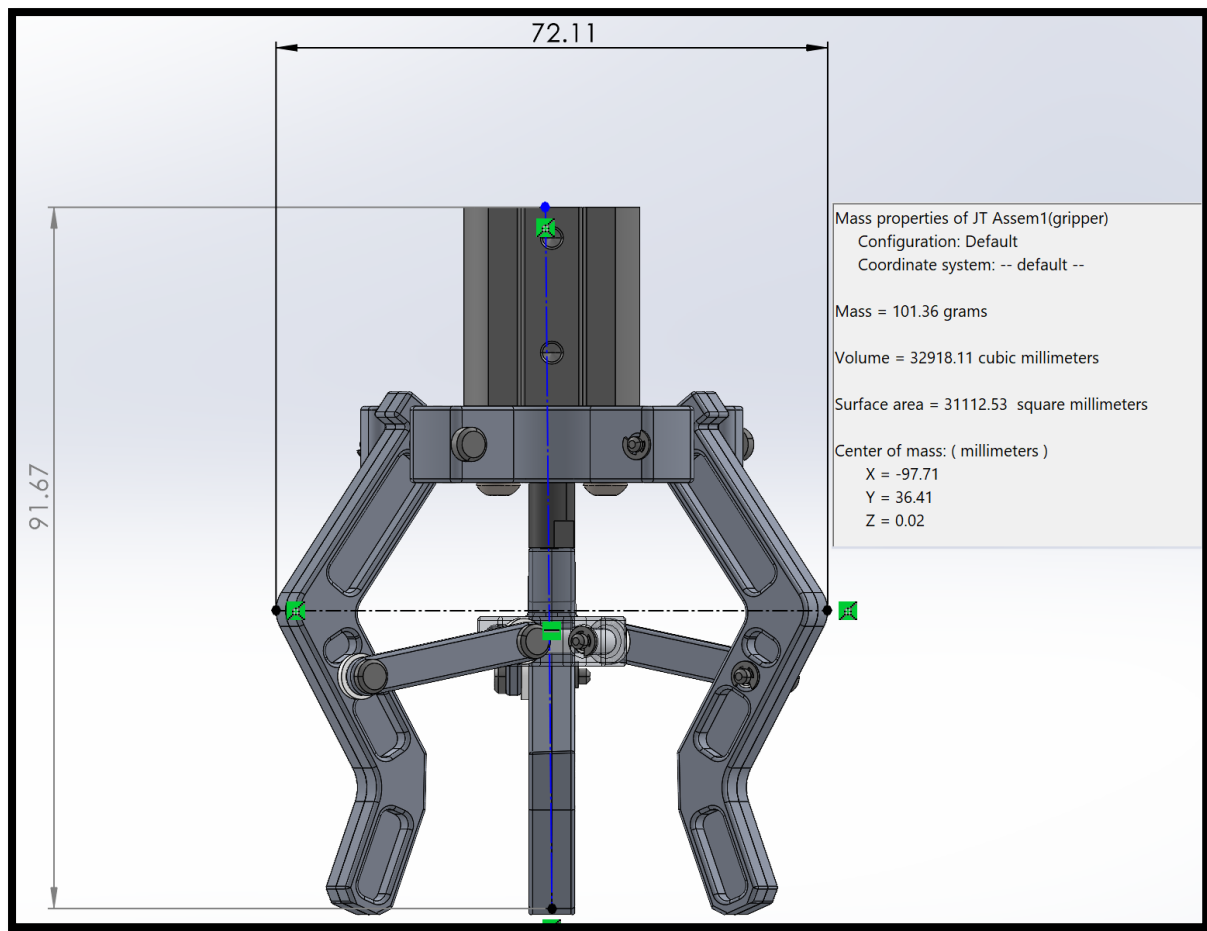


Figure 19 Shows the End-Effector Dimensions and Mass

5.0 Manufacturing Processes

This section will outline the manufacturing sequence and layout.

5.1. Manufacturing Systems

According to Caulfield (2018, p.5), 60% of total product cost occurs from manufacturing, therefore, saving time and money is achieved through easily efficient product design and efficient production design. Manufacturing processes can consist of Cellular, Assembly Line, Lean and Just-in-Time manufacturing.

5.2. Manufacturing Process Type

Discrete Manufacturing will be utilised for this product due to the End-Effector being a **Batch-Model**. It must be noted that the End-Effector does not have a component that allows for connection directly to a Cobot. These are bespoke and can be designed and manufactured as one-off products.

To meet product demand, 2000 per week End-Effectors will be estimated therefore a **Made-to-Order** system will be utilised making just enough to limit stock, whereby a **Just-in-Time** process will also be utilised with an **Assembly Line Manufacturing**.

Manufacturing machines can utilise uploaded files for ease of manufacturing setups such as using Computer-Aided Manufacturing (CAM) files for machining and cast making, with a Drawing Interchange Format (DXF) file for laser cutting. Any waste material can be recycled for the casting process, for environmental and efficiency purposes.

5.3. Manufacturing Process Layout

This section will outline the Manufacturing Process Layout, understanding the reasons and benefits for it.

5.3.1. Logistical Flow

An entire manufacturing process consists of more than just the actual manufacturing, it also contains logistics. Figure 20 shows the entire manufacturing process from supplier to shipping.

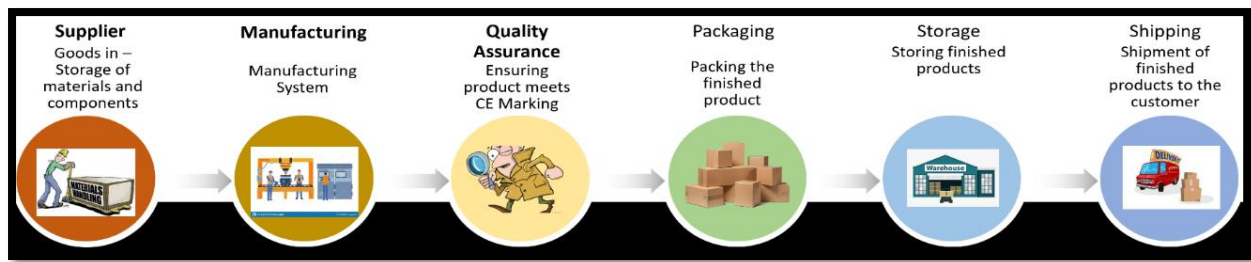


Figure 20 Shows the Manufacturing Logistical Flow

This process flow allows one to understand the best methods for manufacturing efficiency, thus, eliminating waste.

5.3.2. Manufacturing layout

Figure 21 shows the manufacturing layout and sequence utilising a range of techniques to create an efficient manufacturing system.

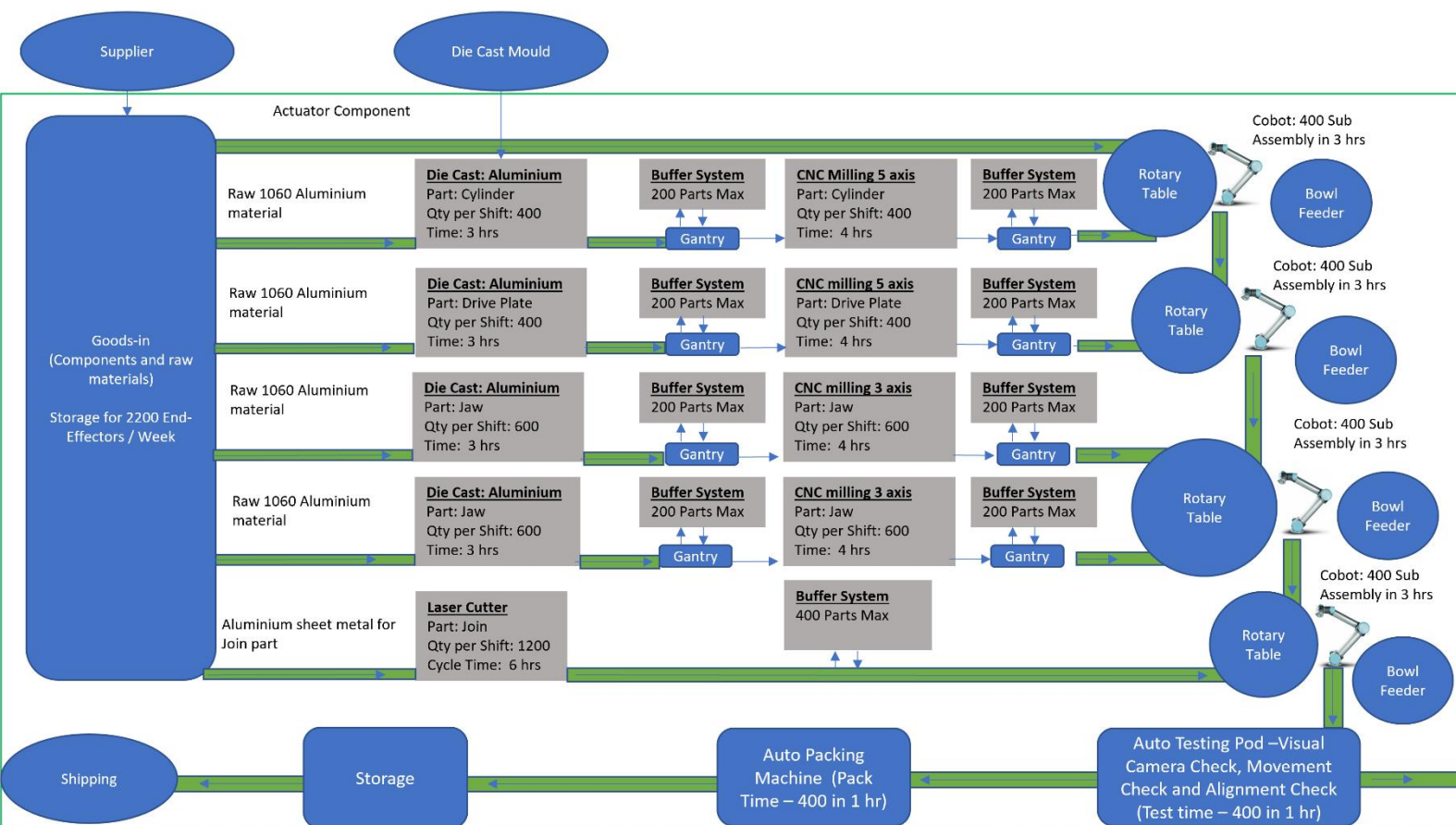


Figure 21 Shows the Manufacturing Process Flow

For environmental purposes, rail transport will be used to deliver stock from the supplier to goods-in, enough to produce 2000 **Made-to-Order** End-Effectors per week, with an additional 200 for contingencies. **Just-in-Time** manufacturing will be utilised, limiting goods-in and finished product stock, thus, reducing **waste**.

A parallel assembly line is utilised for line balancing. For example, an off-shelf Actuator is sent down a transport system when required (Sensor detection), to a Cobot for sub-assembly build on a rotary index table, suggested by Groover (2008, p. 502) which is used for automated part assembly.

Raw Aluminium is sent down its' own parallel transport system into manufacturing machines. For example, the Cylinder will have 1 part manufactured every 27-seconds within die casting, 36-seconds for additional machining (Milling and reaming), 27-seconds for sub-assembly build (Actuator and Cylinder) whereby fasteners fed from bowl feeders are used, then an additional 27-seconds for each Cobot sub-assembly, thus, 171-seconds before a 9-second automated test, if failed, rework occurs by an operator, if passed, it's transported to a 9-second packing machine, thus, one fully processed End-Effector will take 189-seconds. 2000 per week, thus, 400 per day over 5 days would mean a 3, 7-hour shift operation is required.

Initial start-up delay of 27-seconds occurs due to the first sub-assembly build waiting. However, the process is very lean, due to line balancing and parallel assembly. Furthermore, **Gantry Systems** have been utilised to eliminate non-value-added tasks from secondary processes, and **Buffer Systems** have been added to prevent **bottlenecks**, reducing downtime. This further allows for maintenance to be carried out whilst having parts in the buffer to continue the process. Industrial Internet of Things (IIoT) will also be utilised to obtain machine data, to not only optimise the process in terms of line balancing and for predictive maintenance to limit downtime, but also be utilised for optimising energy output, for environmental purposes, thus, increasing positive public perception (Boyes, Hallaq, Cunningham and Watson, 2018, pp.2-3).

The Cobots in the process will utilise the End-Effector to build the other End-Effectors.

"Building the Machine that Builds the Machine" - Elon Musk

This allows one to save on investment, utilising one's own End-Effector. Furthermore, due to the **Product Life Cycle**, the product is in its' infancy, thus, the initial investment is higher with lower sales, thus, to capitalise on the End-Effector, not only will it be used inhouse, but it can

be used to **market** its' capabilities, whilst also allowing the public to perceive Engineering positively, allowing them to understand that Engineers are problem solvers and innovative thinkers.

Additionally, one of the other reasons for utilising Aluminium is that according to How are cans recycled? | Recycle Now (2021) Aluminium is a very easy material to recycle, which utilises a **Circular Economy** concept and further creates a positive public perception of Engineers and their benefit on society.

6.0 Conclusion

The design and development of a 3-Jaw End-Effector was carried out on an initial concept. There were many considerations undertaken regarding functionality, manufacturability as well as public perception.

Many techniques and strategies were utilised to obtain a design specification and limit risks, whilst ensuring optimisation and manufacturability were considered and implemented when designing for 'X'. Public perception and legal responsibilities were also considered within the product and manufacturing process design.

The manufacturing process was chosen based on functionality requirements regarding tolerances as well as manufacturing output requirements. Therefore, the End-Effector was redesigned to meet the design specification obtained through a QFD, whilst allowing for optimisation for manufacturability such as creating symmetrical and Poka-Yoke components and combining components' functionality, thus, increase design efficiency.

A lean process flow was developed to prevent non-value-added work, incorporating manufacturing techniques and innovative technologies, ensuring quality and output was achieved.

Public perception was considered, meeting legal and ethical consideration, such as using recycled Aluminium and using the End-Effector to build other End-Effectors. This allows for sustainability within a Circular Economy process, which increases positive public perception through ethical behaviour as well as marketing the End-Effector in the early Life Cycle stages to potential customers and showing the public Engineering innovations.

References

Aluminium-guide.com. 2021. *Fatigue of aluminum – aluminium-guide.com*. [online] Available at: <<https://aluminium-guide.com/en/mexanicheskie-svoystva-alyuminievyyx-splavov-chast-7-ustalostnye-xarakteristiki/>> [Accessed 7 June 2021].

Anandan, T., 2015. *Design Your Product for Producability, Design for Automation*. [online] Automate. Available at: <<https://www.automate.org/industry-insights/design-your-product-for-producability-design-for-automation>> [Accessed 5 June 2021].

Anderson, D., 2014. *Design for Manufacturability*. 1st ed. Boca Raton: CRC Press, pp.82-133.

Boyes, H., Hallaq, B., Cunningham, J. and Watson, T., 2018. The industrial internet of things (IIoT): An analysis framework. *Computers in Industry*, [online] 101, pp.1-12. Available at: <<https://www.sciencedirect.com.ezproxy.uwtsd.ac.uk/science/article/pii/S0166361517307285>> [Accessed 5 June 2021].

Caulfield, J., 2018. *Production Engineering for Manufacture: Production Systems Within a Manufacturing Plant*. 1st ed. UniCourse Ltd, pp.5-8.

Groover, M., 2008. *Automation, production systems, and computer-integrated manufacturing*. 3rd ed. Upper Saddle River, N.J.: Prentice Hall, pp.502-503.

Groover, M., 2010. *Fundamentals of modern manufacturing*. 4th ed. Hoboken, NJ: J. Wiley & Sons, pp.10-971.

Groover, M., 2013. *Principles of modern manufacturing*. 5th ed. [S. l.]: Wiley, pp.200-206.

Marshall, H., McClymont, L. and Joyce, L., 2007. *Public Attitudes to and Perceptions of Engineering and Engineers 2007*. 1st ed. The Royal Academy of Engineering & The Engineering and Technology Board, pp.12-29.

Mohammadi Amin, F., Rezayati, M., van de Venn, H. and Karimpour, H., 2020. A Mixed-Perception Approach for Safe Human-Robot Collaboration in Industrial Automation. *Sensors*, 20(21), pp.1-20.

Pugh, S., 1990. *Total design*. 1st ed. Essex: Addison-Wesley, pp.136-141.

Recyclenow.com. 2021. *How are cans recycled? | Recycle Now*. [online] Available at: <<https://www.recyclenow.com/recycling-knowledge/how-is-it-recycled/cans#:~:text=Aluminium,->

Aluminium%20is%20a&text=Aluminium%20is%20the%20most%20cost,and%20used%20a gain%20and%20again.> [Accessed 31 May 2021].

Velling, A., 2020. *What Are the Advantages & Disadvantages of Laser Cutting?*. [online] Fractory. Available at: <<https://fractory.com/laser-cutting-advantages-disadvantages/>> [Accessed 7 June 2021].

Figure References

Figure 9 - Wwww-materials.eng.cam.ac.uk. 2021. *Strength - Density*. [online] Available at: <http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/strength-density/basic.html> [Accessed 7 June 2021].

Table References

Table 4 - Cnclathing.com. 2020. *International Tolerance Grade Chart/Table | IT Grade Number and Applications* | CNCLATHING. [online] Available at: <<https://www.cnclathing.com/guide/international-tolerance-grade-chart-table-it-grade-number-and-applications-cnclathing>> [Accessed 6 June 2021].

Table 5 - advice-manufacturing.com. 2020. *Limits Fits and Tolerances: Understanding Definitions & Selection: Practical Use*. [online] Available at: <<http://www.advice-manufacturing.com/Limits-Fits-and-Tolerances.html>> [Accessed 6 June 2021].

Appendix One – ISO/TS 15066

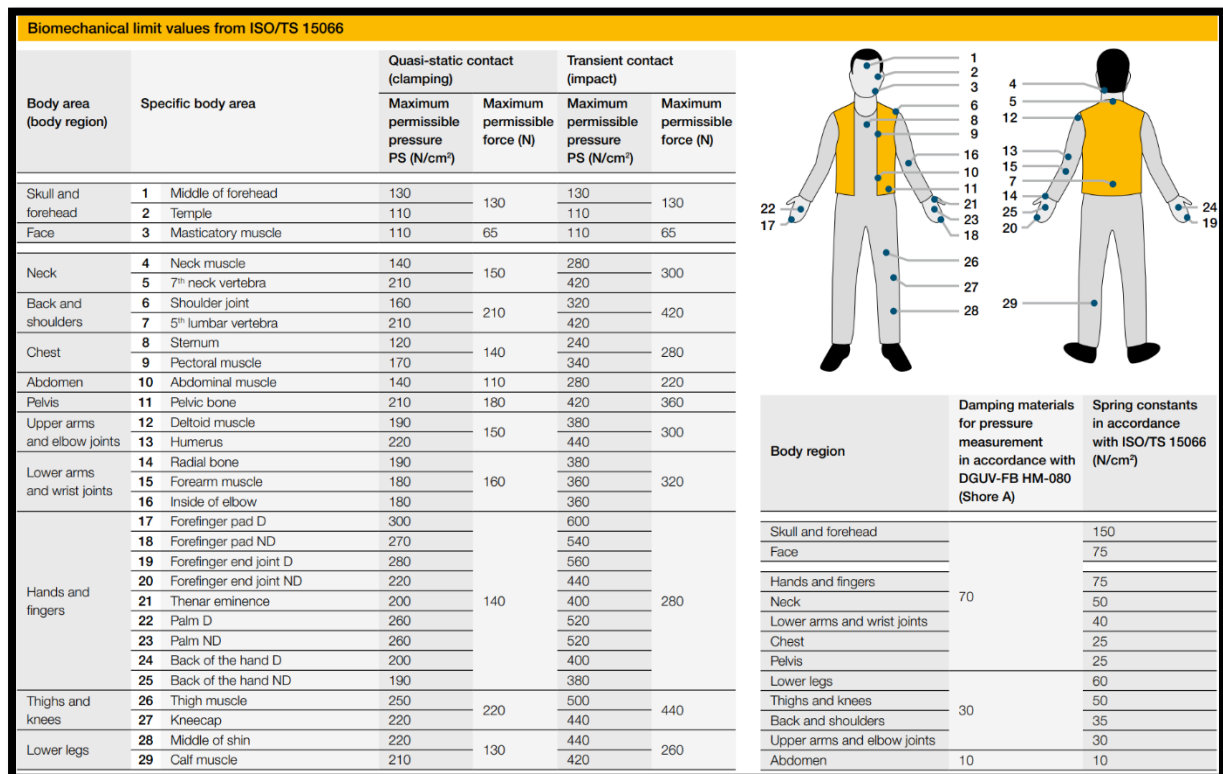


Figure Shows ISO/TS 15066 (All HRC guidance and standards at a glance - Pilz INT, 2018)

Pilz.com. 2018. *All HRC guidance and standards at a glance - Pilz INT*. [online] Available at: <<https://www.pilz.com/en-INT/company/news/articles/196287>> [Accessed 19 June 2021].

Appendix Two – International Tolerance Grade Chart

Table Shows a Detailed International Tolerance Grade Chart (International Tolerance Grade Chart/Table | IT Grade Number and Applications | CNCLATHING, 2020)

Basic Size (mm)		International Tolerance Grade Chart															
IT1	IT2	IT3	IT4	IT5	IT6	IT7	IT8	IT9	IT10	IT11	IT12	IT13	IT14	IT15	IT16	IT17	IT18
above	Up to (include)	TOLERANCE															
		micrometer										milimeter					
-	3	0.8	1.2	2	3	4	6	10	14	25	40	60	0.1	0.14	0.25	0.4	0.6
3	6	1	1.5	2.5	4	5	8	12	18	30	48	75	0.12	0.18	0.3	0.48	0.75
6	10	1	1.5	2.5	4	6	9	15	22	36	58	90	0.15	0.22	0.36	0.58	0.9
10	18	1.2	2	3	5	8	11	18	27	43	70	110	0.18	0.27	0.43	0.7	1.1
18	30	1.5	2.5	4	6	9	13	21	33	52	84	130	0.21	0.33	0.52	0.84	1.3
30	50	1.5	2.5	4	7	11	15	25	39	62	100	160	0.25	0.39	0.62	1	1.6
50	80	2	3	5	8	13	18	30	46	74	120	190	0.3	0.46	0.74	1.2	1.9
80	120	2.5	4	6	10	15	20	35	54	87	140	220	0.35	0.54	0.87	1.4	2.2
120	180	3.5	5	8	12	18	23	40	63	100	160	250	0.4	0.63	1	1.6	2.5
180	250	4.5	7	10	14	20	25	46	72	115	185	290	0.46	0.72	1.15	1.85	2.9
250	315	6	8	12	16	23	27	52	81	130	210	320	0.52	0.81	1.3	2.1	3.2
315	400	7	9	13	18	25	32	57	89	140	230	360	0.57	0.89	1.4	2.3	3.6
400	500	8	10	15	20	27	36	63	97	155	250	400	0.63	0.97	1.55	2.5	4
500	630	9	11	16	22	32	40	70	110	175	280	440	0.7	1.1	1.75	2.8	4.4
630	800	10	13	18	25	36	44	80	125	200	320	500	0.8	1.25	2	3.2	5
800	1000	11	15	21	28	40	50	90	140	230	360	560	0.9	1.4	2.3	3.6	5.6
1000	1250	13	18	24	33	47	56	105	165	260	420	660	1.05	1.65	2.6	4.2	6.6
1250	1600	15	21	29	39	55	78	125	195	310	500	780	1.25	1.95	3.1	5	7.8
1600	2000	18	25	35	46	65	92	150	230	370	600	920	1.5	2.3	3.7	6	9.2
2000	2500	22	30	41	55	78	110	175	280	440	700	1100	1.75	2.8	4.4	7	11
2500	3150	26	36	50	68	96	135	210	330	540	860	1350	2.1	3.3	5.4	8.6	13.5

Cnclathing.com. 2020. *International Tolerance Grade Chart/Table | IT Grade Number and Applications* | CNCLATHING. [online] Available at: <https://www.cnclathing.com/guide/international-tolerance-grade-chart-table-it-grade-number-and-applications-cnclathing> [Accessed 6 June 2021].

Appendix Three – Limits and Fits

Normal sizes Over mm	Up to mm	Loose clearance		Average clearance		Close clearance		Precision clearance		Transition		Interference		Type of fit required
		H9	e9	H8	f7	H7	g6	H7	h6	H7	k6	H7	p6	
—	3	+25 +0	-14 -39	+14 +0	-6 -16	+10 +0	-2 -8	+10 +0	-0 -6	+10 +0	+6 0	+10 +0	+12 +6	Types of shaft (lower case)
3	6	+30 +0	-20 -50	+18 +0	-10 -22	+12 +0	-4 -12	+12 +0	-0 -8	+12 +0	+9 +1	+12 +0	+20 +12	
6	10	+36 +0	-25 -61	+22 +0	-13 -28	+15 +0	-5 -14	+15 +0	-0 -9	+15 +0	+10 +1	+15 +0	+24 +15	
10	18	+43 +0	-32 -75	+27 +0	-16 -34	+18 +0	-6 -17	+18 +0	-0 -11	+18 +0	+12 +1	+18 +0	+28 +18	
18	30	+52 +0	-40 -92	+33 +0	-20 -41	+21 +0	-7 -20	+21 +0	-0 -13	+21 +0	+15 +2	+21 +0	+35 +22	
30	50	+62 +0	-50 -112	+39 +0	-25 -50	+25 +0	-9 -25	+25 +0	-0 -16	+25 +0	+18 +2	+25 +0	+42 +26	
50	80	+74 +0	-60 -134	+46 +0	-30 -60	+30 +0	-10 -29	+30 +0	-0 -19	+30 +0	+21 +2	+30 +0	+51 +32	
80	120	+87 +0	-72 -159	+54 +0	-36 -71	+35 +0	-12 -34	+35 +0	-0 -22	+35 +0	+25 +3	+35 +0	+59 +37	
120	180	+100 +0	-85 -185	+63 +0	-43 -83	+40 +0	-14 -39	+40 +0	-0 -25	+40 +0	+28 +3	+40 +0	+68 +43	
180	250	+115 +0	-100 -215	+72 +0	-50 -96	+46 +0	-15 -44	+46 +0	-0 -29	+46 +0	+33 +4	+46 +0	+79 +50	
250	315	+130 +0	-110 -240	+81 +0	-56 -108	+52 +0	-17 -49	+52 +0	-0 -32	+52 +0	+36 +4	+52 +0	+88 +56	
315	400	+140 +0	-125 -265	+89 +0	-62 -119	+57 +0	-18 -54	+57 +0	-0 -36	+57 +0	+40 +4	+57 +0	+98 +62	
400	500	+155 +0	-135 -290	+97 +0	-68 -131	+63 +0	-20 -60	+63 +0	-0 -40	+63 +0	+45 +5	+63 +0	+108 +68	

Hole size (nominal)

Types of hole (upper case)

Richard Morgan School of Logistics & Manufacturing Engineering

Figure Shows Limits and Fits Tolerance Table with an Explanation (Morgan, 2013)

Morgan, R., 2013. 'Engineering/Technical Drawing' Lecture Notes, University of Wales Trinity Saint David, Unpublished internal company document.