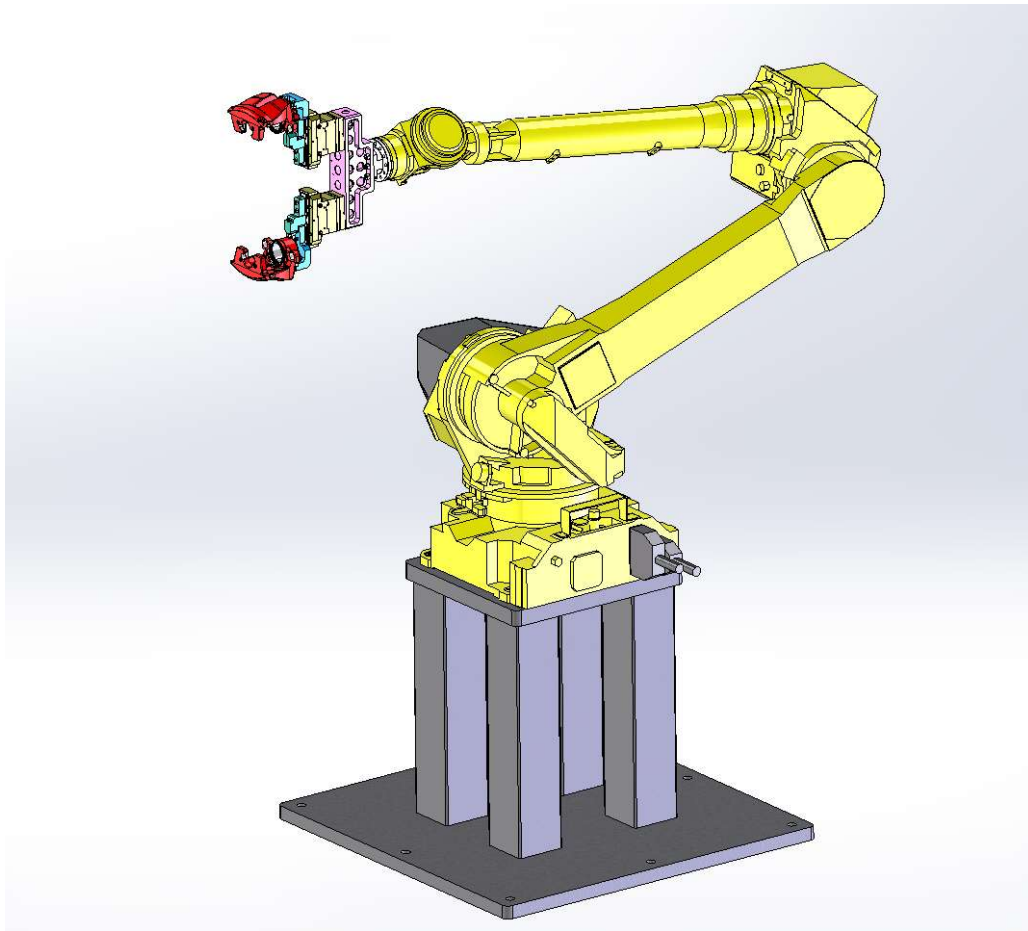




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Major Project

INTEGRATION OF JAGUAR HOUSING PRODUCTION
INTO AN AUTOMATED CELL

Jordan Williams
2115209

Declaration of Authenticity

‘This thesis is the result of the author’s original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.’

Signed: *J. Williams*

Acknowledgement

I am deeply grateful to my dissertation supervisor, Jordan Jenkins, whose guidance, expertise, and support, particularly in Automation, have been instrumental in making this project possible. I would also like to express my gratitude to my employer, Continental, for their continuous guidance and support throughout this dissertation, which has significantly contributed to its success. Finally, I would like to thank my family, whose collective support and encouragement have been indispensable.

Abstract

This project aimed to automate Jaguar housing production by moving the manufacturing process to an existing automated cell within Continental. To successfully automate production, the current manufacturing process was comprehensively analysed and rearranged to accommodate the cell's capabilities; this formed the foundation of the project's success. Following this, new machine tooling and fixtures were designed, a new gripping mechanism was developed for the robot to handle the housings, and a new loading table was designed to feed the cell with material. Additionally, new programs were produced for the CNC machines, and a preliminary robot program was produced. Extensive inventory and compatibility checks leveraged existing resources where feasible to ensure cost-effectiveness.

Finite Element Analysis (FEA) facilitated the analysis of the end-effector's structural integrity and durability under static and fatigue loading conditions. Informed conceptual modifications were made to reinforce targeted areas of the design to enhance durability and reliability. Optimisation of the loading nests played a pivotal role in enhancing overall efficiency. Conceptual modifications, including guides, streamlined the loading process by improving operator ergonomics and mitigating the risk of misaligned components, leveraging the benefits of additive manufacturing allowed for simple and cost-effective solutions.

Following the cell's design, Arena simulation software was utilised to analyse its output and resource utilisation, ensuring its validity and efficiency. This analysis provided a comprehensive understanding of the cell's performance, identifying potential bottlenecks and optimising resource allocation. The validation process confirmed that the cell design met the required operational criteria, demonstrating its effectiveness and readiness for implementation.

In conclusion, automating the production of Jaguar housings represents a significant milestone and technological advancement. Further recommendations have been made to refine and continuously improve the manufacturing process, providing a guideline for future progression.

Glossary

<u>Term</u>	<u>Description</u>
CNC	Computer Numerical Controlled
AMS	CNC machine manufacturer
STAMMA	CNC machine manufacturer
Bleed Port	Location used to bleed brake fluid
Connect Port	Location where a brake connects to the car
End-Effector	Attached to the end of a robot's arm and facilitates interactions
AI	Artificial Intelligence
ML	Machine Learning
RGB-D Camera	Red, Green, and Blue – Depth Camera
LiDAR	Light Detection and Ranging
AGV	Automated Guided Vehicle
IR	Infrared
FEA	Finite Element Analysis
AM	Additive Manufacturing
DLP	Digital Light Processing
CLIP	Continuous Liquid Interface Production
PLA	Polylactide
ABS	Acrylonitrile Butadiene Styrene
PEEK	Polyether Ether Ketone
CAD	Computer-Aided Desing
CAM	Computer-Aided Manufacturing
SI	International System

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1.3 Justification

The market for Jaguar housings has exhibited a significant surge in demand. Analysis indicates that the escalation in customer demand commenced in early 2023 and is projected to persist at these heightened levels until 2026. Furthermore, it is noteworthy that the order for these housings is set to last until 2032, highlighting the sustained demand for this product in the foreseeable future.

Additionally, customer demand for the product produced in the automated cell has significantly reduced. Production requirements can be easily met on various machines at Continental, meaning the only automated cell and most technologically advanced equipment within the organisation is not being utilised. The rise in demand for Jaguar housings, paired with the underutilised automated cell, presents an opportunity to streamline and optimise production.

1.31 Jaguar D7a Demand & Production Levels

In Figure 2, the weekly demand for the initial ten weeks of 2024 is represented alongside the current backlog from the preceding year. It is visible that for the first ten weeks, a production requirement of 9000 (4500 pairs) is required, including the components in the backlog.

B/Log			Fixed								
			Fist OES								
Product	Plate Type	Plnd	Date Added / checked	+/- 6 WK Req	E/C?	Casting	Total	0120 / WH	1150 / WIP	Launch	Status
11-3601-9035-1-95	Zinc	ongoing	17/10/23	-976	1,833	11-3601-0417-0-00	2809	2603	206	MAX 3 or ST8	Planned on Stama 8
11-3601-9036-1-95	Zinc	ongoing	17/10/23	-951	1,858	11-3601-0417-0-00	2809	2603	206	MAX 3 or ST8	Planned on Stama 8
Backlog	Week 01	Week 02	Week 03	Week 04	Week 05	Week 06	Week 07	Week 08	Week 09	Week 10	TOTAL
976	320	192	222	352	256	352	415	624	365	367	4441
951	360	232	256	330	224	416	376	582	357	361	4445
											8886

Figure 2 - Week Customer Demand

Figure 3 illustrates that production levels during the first week failed to meet the demand. This shortfall is due to an absence of production on Monday, highlighting the delicate balance between production capacity and demand. While a complete week of production is sufficient to produce a surplus of components, it leaves minimal allowance for scheduled maintenance or unanticipated breakdowns.

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Figure 3 - Week One Production

1.32 Underutilised Equipment

The organisation is underutilising valuable equipment, notably in the automated cell's absence of brake calliper production. Initially acquired in 2017 to complete an order of WV brake callipers, the completion of the order leaves the automated cell without work. Consequently, repurposing this cell presents an opportunity to boost production levels, affording the organisation more flexibility in its production of hydraulic brake systems.

1.4 Current Process

Throughout the entire manufacturing process, from receipt of raw materials to shipping the final products to customers, maintaining a focus on safe material handling is essential to uphold quality standards. This emphasis on material handling is due to these painted components; ensuring the paint is not damaged during manufacturing is essential in producing Jaguar brake callipers. The current process uses two operations to machine the housings before they move to the plating plant. The first operation is on a 4-axis, twin-spindle CNC machine, meaning two parts are machined simultaneously. Figure 4 describes this operation, which is the bulk of the machining process and results in a significant cycle time. After the first operation's completion, the housings are transported to a 5-axis, twin-spindle CNC machine that produces four parts per cycle. This operation is used to machine the 'ports', where the brake fluid enters the housing when braking is initiated.

Machined Part Number		Part Description		Casting Number	
11-3601-9035-1-00		Red JLR FN+60 Housings.		11:3601:0417:000	
Machine	Operation	Total Qty	Layer Qty	Signed	Date
Gemini Max 3 / Stama 8.	Mill Recesses, Disc Clearance, Bore Details, Bush Holes.		L1		
			L2		
			L3		
Stama 7.	Bleed & Connect Ports, M6 Fixing Holes.		L1		
			L2		
			L3		
Galv.	Plate Zn8yvs		L1		
			L2		
			L3		
			L1		
			L2		
			L3		
Assembly					
Plating Data	Bin Qty	JIG	LIB No	Code	
	80	58	50	Zinc	
All Parts must be inspected and de-burred before moving to next operation.					

Figure 4 - Jaguar D7a Machining Process

The paint has both an aesthetic and practical role in the function of the brake calliper, ensuring delicate material handling is essential in the manufacturing process. Many precautions are taken throughout the process to ensure the paint does not get damaged; however, due to the nature of material handling, it is common for the paint to get chipped or blemished during manufacturing; these parts are identified and isolated by an operator after assembly. The callipers are then sent through a rework coating process on the paint track.

1.5 Aims

This project aims to integrate the production of Jaguar D7a housings with the existing automated cell, shown in Figure 5. The shift entails multiple challenges, including CNC programming, robot programming, fixture design, and end-effector design, and it promises proportionate rewards in terms of versatility, productivity, and market competitiveness. Integrating a gripping mechanism to handle Jaguar housings will be essential for the effectiveness of the cell. Similarly, designing and implementing a fixture for machining the bleed port on the 3-axis CNC machine is necessary to produce a complete component in the cell. This integration aims to relieve the pressure on the current manufacturing process by increasing the production of Jaguar housings. The increase in production would also mean that additional weekend and night shifts would no longer be necessary to meet customer demands.

1.6 Automated Cell Setup

The current automated cell setup is tailored for machining brake callipers. It comprises two 5-axis AMS Gemini MAX CNC milling machines and one 3-axis STAMMA 530 CNC milling machine, the primary machining tools within the automated cell. These machines have cutting-edge technology to perform precise and complex machining operations. The M-710iC/50, /70 standard model Fanuc robot serves as the automated material handling system within the cell. It is programmed to load raw materials onto the CNC machines, retrieve finished parts, and transfer them to the unloading conveyor, where the operator will retrieve them for inspection. The loading table is where the operator places the raw material for the robot to retrieve. It consists of twelve individual loading nests with proximity sensors so the robot can determine if material is present. A light barrier prevents the robot from entering the loading area when the operator places raw material on the table.

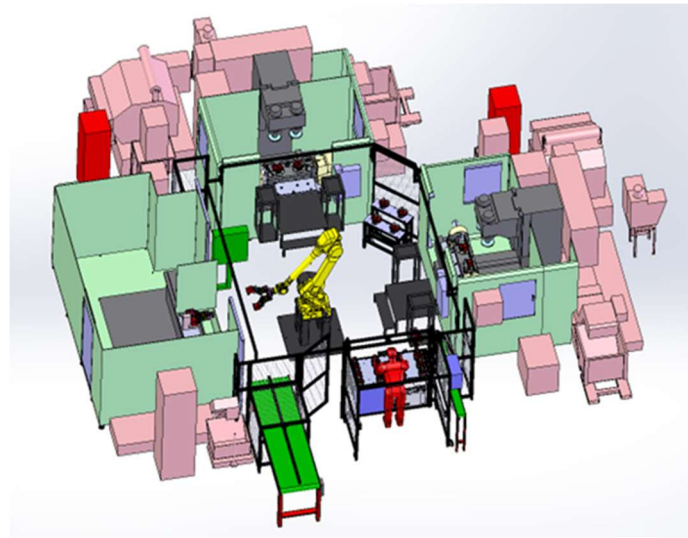


Figure 5 - CAD Model of Automated Cell

1.7 Objectives

The primary goal is to improve manufacturing efficiency and product quality; integrating Jaguar housing production into the automated cell also aims to enhance operator safety and well-being. The project aims to minimise the risk of ergonomic-related strains among operators by reducing the need to manually handle parts, particularly delicate and heavy components like Jaguar housings. With the automated cell handling material tasks, the operator can focus on overseeing the process, performing quality checks, and addressing unforeseen issues. This integration improves workplace safety and overall productivity, as operators can perform tasks comfortably without the physical strain of manual handling. Ultimately, prioritising operator well-being aligns with the broader objectives of increasing calliper production; this project will be successful if the following four main goals are achieved.

1.71 Objective 1

Conduct a comprehensive and informed research and literature survey relevant to the project's scope. This includes identifying and analysing existing literature, academic papers, industry reports, and relevant data sources. The aim is to establish a strong understanding of gaps in current knowledge and explore the latest relevant trends and developments in automation to integrate the findings into the project.

1.72 Objective 2

Developing an end-effector that can effectively handle the Jaguar housings within the existing automated cell setup, as well as compatibility with the CNC milling machines, loading table, and Fanuc robot, is essential. Optimising grip strength and stability whilst achieving fixture clearance will ensure seamless integration in the manufacturing process.

1.73 Objective 3

Producing a fully machined component offers a unique challenge due to the specific angle of the bleed port. The bleed port currently demands a 5-axis CNC machine, but to produce a finalised part, it must be machined using a 3-axis CNC machine.

1.74 Objective 4

Develop nests for the operator to place parts. The nests must be ergonomic to optimise workflow and enhance productivity. Additionally, these nests are engineered to securely hold the housing in a fixed position, ensuring consistent alignment for the robot to handle the housings accurately.

1.75 Objective 5

Producing optimal programs for the CNC machines and Fanuc robot. Advanced programming techniques will reduce cycle times and ensure seamless machine and robot coordination to achieve peak performance and productivity.

1.8 Timing Plan

A Gantt chart was produced to give the project a visual roadmap, outlining the sequential progression of key milestones. Each milestone represents a critical stage in the project's lifecycle and is split into five categories: Concept Development and Planning, Design and Development, Manufacturing and Fabrication, Integration and Testing, and Final Testing. This chart facilitates effective planning, resource allocation, and progress tracking by providing a structured overview of tasks. (Meardon, 2022), offering insights into the project's timeline.

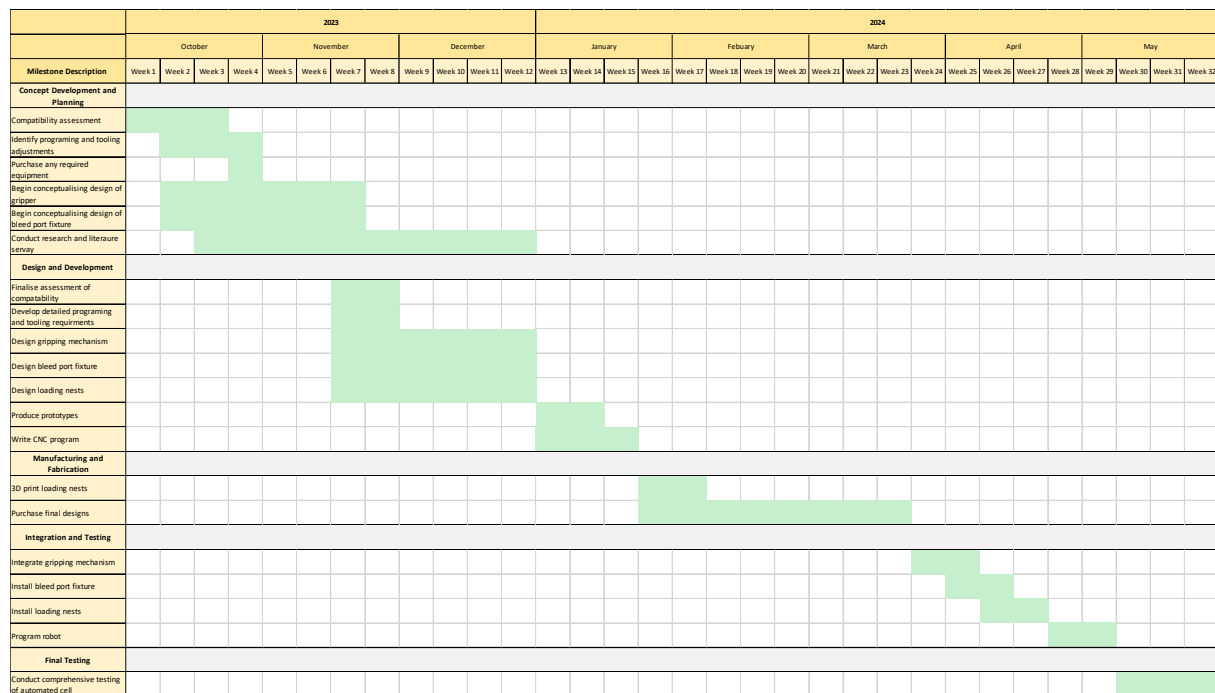


Figure 6 - Initial Gantt Chart

2. Research & Literature Survey

This section aims to conduct a thorough literature survey relevant to the project. Automation and robotics have revolutionised various industries and processes; this literature survey aims to explore and analyse existing research and technologies pertinent to this project's scope to gain insights and identify best practices. This comprehensive review will identify the latest trends and developments in automation and will serve as the foundation for the project by providing valuable context and guidance.

This literature survey aims to address the following key objectives:

- Identify relevant research papers, articles, and publications on automation, robotics, control systems, and related fields.
- Analyse the methodologies, technologies, and approaches used in automation projects.
- Use the findings from the literature to advise the design and implementation of the automation project.
- Identify gaps, challenges, and opportunities for further research.

Addressing these objectives will ensure that the latest research informs the project and practises, maximising its effectiveness, efficiency, and impact.

2.1 Purpose and Benefits of Automation in Manufacturing

Automation is a strategic way of streamlining operations, optimising resource utilisation, and driving continuous improvement. This is achieved by improving several factors, such as lowering operation costs and increasing worker satisfaction and productivity (Impact, 2023). Specifically, automation has profoundly impacted the automotive industry by streamlining assembly lines and minimising errors (Gorlach & Wessel, 2008). It also encourages innovation by allowing manufacturers to produce intricacies which may not be achieved through manual operations (Ina, 2024). Overall, automation can increase production levels through improved manufacturing efficiency by performing faster and more accurate tasks; consistent quality is maintained, reducing defects. Automated machines can run continuously, eliminating downtime associated with human limitations, such as the need for shift changes or breaks. Modern systems are typically designed to be modular and flexible; these systems can also adapt quickly to changing production demands, enhancing flexibility and responsiveness (Javaid, 2022), whilst maintaining high-quality standards.

2.11 Employee Productivity

When harnessed correctly, automation can significantly enhance employee productivity across various industries. Automating mundane or repetitive tasks can allow human workers to focus on more satisfactory activities, benefiting both employer and employee. This increases efficiency and minimises errors, as machines can perform tasks with constant precision. Removing mundane or repetitive tasks can boost employee job satisfaction, leading to a more engaged and motivated workforce (Barytska, 2022). Additionally, automation can positively impact worker well-being; removing physically demanding duties will reduce the risk of strains and injuries, promoting a safer working environment. Removing monotonous tasks can also reduce stress and fatigue among employees (Nazareno & Schiff, 2021), promoting a positive work-life balance. Overall, automation offers vast benefits to both employers and their workforce. It can revolutionise productivity and maximise worker's skills and creativity while allowing machines to handle routine tasks.

2.12 Improved Quality Control

In manufacturing, automation plays a pivotal role in product quality and consistency. Automated inspection systems, such as real-time monitoring technologies and adaptive control algorithms, allow manufacturers to detect defects and deviations early (Szymanski, 2023). This proactive approach to quality minimises defects and enhances customer satisfaction. Expanding on section [2.11], automated systems using robotics can ensure consistent quality by performing tasks considered to be mundane.

These tasks can lead to poor engagement when performed by a human worker, leading to lapses in concentration, which may result in mistakes. Automating these tasks will be beneficial in maintaining high-quality standards (Whitehouse, 2024). Regarding material handling, carefully programmed algorithms can produce exceptional repeatability that surpasses human capabilities. Advanced sensors and vision systems can identify inconsistencies or foreign objects in material, ensuring that a defective part is not transferred further down the production line. Robotic arms precisely handle material with minimal risk of damage, unlike human error or fatigue, and can execute movements with unparalleled repeatability, ensuring material is continuously placed with high precision. (Bara, 2020).

2.13 Cost Optimisation

Upfront costs associated with automating a process, such as purchasing equipment or integration, can be high; however, replacing the need for manual labour can offer quick payback and result in significant long-term savings (Garvey, 2020). Improvements to quality control discussed in section [2.12] will lead to a reduction in waste; automated systems are less prone to errors resulting in defective components (Weever, 2023). Optimising resource utilisation can also reduce waste, and automation allows for the more efficient use of resources such as raw materials, energy, and space. The reduction in waste may also align with an organisation's environmental sustainability goals, further enhancing the benefit of automation.

Additional sources read: (Rüßmann, et al., 2015), (Badkar, 2023), (Kanade, 2024), (Groover, 2024).

2.2 Latest Trends in Robotics and Automation

Researching and analysing the latest trends in robotics and automation will be essential in keeping the project appropriately informed. Advancements in the field, such as robotic arms, AI and machine learning, advanced vision systems, and simulation software, will be reviewed and applied to the project to ensure the cell is fully optimised.

2.21 AI and Machine Learning Integration

AI has made substantial progress in recent years and is revolutionising various industries; while AI in robotics is not yet widespread, it is rapidly gaining momentum (Tyson & Zysman, 2022). AI and machine learning allow robots to learn from data and adapt to changing environments by making informed decisions. In manufacturing, these AI-driven robotics can optimise material handling and improve quality control by continuously analysing real-time data; it would be typical for AI robots to rely on sensors and cameras to obtain this data (Emergent, 2024). To elevate this project, AI and machine learning can recognise patterns in the production cycle, predict outcomes before failures occur, and optimise movements to enhance productivity and cost-effectiveness. As research and development continue in these technologies, AI and machine learning integration with robotics promises to revolutionise manufacturing.

2.22 Advanced Vision Systems

Vision systems play a crucial role in robotics; they serve as a system's eyes, allowing it to perceive its environment and identify objects. The core of this technology is the ability to capture, process and interpret visual data, enabling robots to make informed decisions based on their environment (Sultana, Alam, Su'ud, Mustapha, & Prasad, 2024). RGB-D cameras combine traditional RGB (red, green, blue) imaging with depth capabilities to output real-time data for a robot system. The depth information is retrieved through a depth map created by a 3D time of flight sensor (Kumar, 2023), RGBD vision systems can merge the RGB data and depth data to deliver information in a single frame. This is particularly useful in applications that require the identification of an object as well as measuring the depth, such as a pick-and-place robot. An alternative approach to how a system may receive visual data would be to use LiDAR (Light Detection and Ranging), a method used for distance measurement. The LiDAR device consistently emits a pulse of light; it is reflected to the device after it hits a target. It determines the distance by measuring the time the light takes to meet the target and return (Szczepaniak,

2023). The measurement instruments can be placed on a rotating platform, which enables the device to take points within 360 degrees; the next step is to gather this information and create a 2D or 3D map. These systems are standard in automated warehouse logistics or AGVs (Automated Guided Vehicles); irregular surfaces can limit the technology or when another object obstructs an object. Building on section [2.21], advanced vision systems can perfectly complement AI algorithms by providing crucial real-time data feedback. These systems can accurately identify and locate objects in complex environments by making informed decisions. In contrast, a traditional system may need numerous reference images to identify an object or defect (Alvi, 2023), meaning AI systems would vastly outperform conventional methods. Advanced vision systems can also be utilised to conduct quality inspections; firstly, defects can be detected, such as scratches or misalignments, with high accuracy (AEM, 2022). Additionally, the system can detect and discard foreign objects and anomalies in raw material before it raises a quality concern, ultimately preventing defective parts from being produced. The benefits of integrating AI with an advanced vision system will come at the expense of computational power; vast offline servers will be required to run the AI software (Sharma, 2021), which can significantly increase costs. The implementation of advanced vision systems at Continental can enhance the cell's quality control by preventing misalignments in the CNC machines, which will cause defective parts to be produced; if the misalignment is severe or the wrong component is loaded, costly damage to the machine and the tooling is inevitable.

2.23 Reconfigurability

Flexibility and reconfigurability are essential in manufacturing. Modular robotic systems, comprising interchangeable components, allow easy and fast reconfiguration to adapt systems to production requirements (Spacey, 2023). These may be improvements to the current system or accommodations for the cell to run various product types. When the order for the Jaguar brake systems is complete, the cell can be utilised to produce a new component, making the cell's reconfigurability essential.

2.24 Simulation Software

Advanced simulation software in robotics presents numerous benefits that can significantly enhance the project's success. Simulation software creates a virtual environment in which to design, model, and analyse a process, offering invaluable insights into proof of concept and optimisation before physical implementation (Genesis Systems, 2017). Creating virtual models of a manufacturing setup allows the user to visualise and test different configurations to optimise workflow (Whatley & Peng, 2022). Utilising simulation software for this project would allow for specific tailored solutions to potential issues and can help optimise the cell layout to maximise productivity. Moreover, simulation software enables the user to thoroughly analyse a robotic system's performance. Kinematic and dynamic behaviours can be simulated to assess trajectory and cycle times with high precision (Alvarado, 2021), allowing for fine-tuning of system parameters. Some software incorporating advanced physical engines can simulate interactions such as collision detection, friction, and inertia, allowing the user to predict and prevent inefficient material handling. Furthermore, simulation software can improve communication among stakeholders. Visualising a concept and simulated results can easily be presented to team members, management, or stakeholders, providing confidence and reassurance in the project.

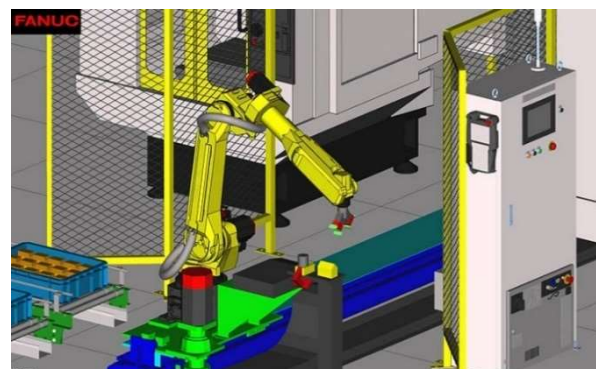


Figure 7 - Fanuc Simulation Software

Additional sources read: (Nozari, Ghahremani-Nahr, & Szmelter-Jarosz, 2024), (blueprism, 2023), (Wilson, 2024), (Visual Components, 2021).

2.3 Contribution of the End-Effector to Automating the Manufacturing Process

The end-effector is a critical component of a robotic system. This component would typically be fastened to the end of the robot's arm and facilitates handling, manipulating or sensing objects; these devices are the primary means by which a robot interacts with a physical environment (Worth, 2023). End-effectors can be customised to perform various tasks, most commonly gripping, welding, cutting, or painting (Bernier, 2021). This project will delve specifically into the development and optimisation of gripping end-effectors; the function of these end-effectors is to pick and place objects with a high degree of delicacy whilst maintaining appropriate grip strength and control.

There are several key considerations when designing a gripping mechanism to ensure optimal performance with the intended applications. These considerations include functionality, adaptability, reliability, and efficiency (RG-Group, 2019). Firstly, the application's specific requirements must be identified; the type of objects to be handled, their geometry, weight, and surface characteristics all play a crucial role in determining a gripper design. Another important consideration is the gripping mechanism. Mechanical, magnet, vacuum and adhesive grippers offer unique advantages and limitations; selecting the most suitable mechanism will involve evaluating compatibility with the objects to be handled (Aukes, Heyneman, Duchaine, & Cutkosky, 2011). Additionally, adaptability is critical when the gripping mechanism needs to accommodate a variety of objects or perform different tasks with the same application. Ensuring reliability is essential for an end-effector to maximise production efficiency. The Gripping mechanism must withstand the demands of the intended environment, including factors such as temperature, moisture, dust, and vibration. A robust design and appropriate material selection will improve the gripper's reliability by preventing fatigue failure.

2.3.1 End-Effector Gripping Mechanisms

Mechanical gripping mechanisms are a common and reliable way a robotic system can manipulate an object. This well-established technology usually consists of jaws or fingers to securely grasp an object, ensuring efficient gripping of various shapes and sizes (HVR MAG, 2023). However, mechanical grippers have some limitations regarding irregularly shaped or delicate objects. While adjustment can be implemented to accommodate irregularly shaped objects, the overall adaptability of mechanical gripping mechanisms is often limited. The significant gripping force produced by these mechanisms makes them suitable for many industrial applications (Control Engineering, 2018).

Alternatively, vacuum grippers offer unique benefits when handling objects. These end-effectors rely on suction generated by a vacuum or pump to hold objects with a smooth, non-porous surface. Vacuum grippers are highly effective when handling materials like glass, ceramics, and sheet metal due to their non-contact grip, which reduces the risk of damage to delicate surfaces (Granta, 2023). They also have quick attach and release capabilities, making them ideal for rapid pick-and-place operations. However, their effectiveness diminishes on porous or irregular surfaces due to the risk of the vacuum being lost if the surfaces are not entirely sealed (Zoytek, 2024).

Magnetic grippers utilise magnetic fields to hold ferromagnetic materials securely. These end-effectors offer a reliable grip on objects with a flat or curved ferromagnetic surface and require little maintenance or adjustment (Universal Robots, 2021). The application of this technology is best suited for environments where cleanliness is critical, as they do not leave a residue. However, magnetic grippers are limited to objects with ferromagnetic properties, and magnetism diminishes over time (Miner, 2022). This gripping mechanism can offer unique benefits to this project; however, in a machining environment, the magnet will attract metal filings, which may negatively impact the effectiveness of the gripper.

Finally, adhesive materials can temporarily attach the robot to an object, creating a secure grip when transporting. Adhesive grippers offer versatility when handling irregular objects as they can conform to the contours of the item. The non-contact gripping also reduces the risk of damage to delicate materials.

However, the effectiveness of the adhesive may diminish over time or with repetitive use. These grippers are also limited to surfaces suitable for an adhesive.

2.32 Limitations in Current Gripper Designs

While grippers have evolved significantly over the years, there are still several limitations in current designs that engineers continue to address and improve upon. Many grippers suffer from poor adaptability; they are usually designed for a specific object or application, which can limit their versatility. Grippers optimised for handling one type of object will likely struggle with different shapes, sizes, surface textures or weights. Additionally, grippers can be limited when handling fragile items; if the mechanism is not specifically tailored for a delicate object, excessive force may be exerted, leading to damage or deformation. Achieving the delicate balance between a secure grip and avoiding damage can be challenging. Some pick-and-place systems will rely on precise positioning of the object to be handled successfully. Poorly positioned or randomly oriented objects may be challenging for a system, leading to longer cycle times or possible failure. A gripping mechanism may also struggle when facilitating the movement of a soft or deformable material, such as fabrics or food items. Ensuring a reliable grip without causing damage or deformation remains a significant challenge. Addressing these limitations by carefully evaluating the applications and requirements of the automated system under scrutiny will ensure a reliable and robust design.

Additional sources read: (Tai, El-Sayed, & Shahriari, 2016), (Dorna Robotics, 2023), (EVS, 2023), (Aljarboua, 2019), (Rao, 2024).

2.4 FEA Optimisation Techniques

Finite Element Analysis (FEA) plays a crucial role in modern engineering. This tool is used to simulate and analyse the behaviour of structures under various preset conditions (SimScale, 2018). The application of this tool can significantly enhance the design process. Simulating forces, pressures, and stresses will allow engineers to anticipate how a design will function. Then, necessary adjustments to the design can then be made before manufacturing.

FEA can be utilised to optimise an end-effector design by analysing multiple design iterations; engineers can identify areas for improvement and make modifications to optimise factors such as strength, weight, and cost (Suchdeo, 2024). Additionally, FEA allows the user to assess the durability of a design by simulating fatigue stress. Simulating cyclic loading can highlight potential areas for fatigue failure, prompting design modifications to enhance durability (Laird & Kolb, 2019). Material selection can also benefit from FEA. Running simulations with varying material properties will allow designers to determine the most suitable material for a design (Sindinger, Marschalla, Kralovec, & Schagerl, 2021). Furthermore, FEA can reduce the need for physical prototyping by replacing physical testing with virtual simulation.

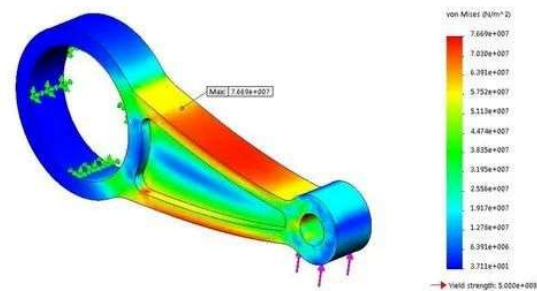


Figure 8 - FEA (Finite Element Analysis)

Different design configurations can be simulated faster and at a lower cost than producing physical prototypes. In the context of end-effector design, FEA can begin with creating a 3D model using CAD software, ensuring an accurate representation of the end-effector geometry. A finite element mesh can then be generated to approximate the geometry into small individual elements for numerical analysis. Loading and boundary conditions, such as applied forces and pressures, are then defined, representing how the end-effector will interact with its environment in its intended use. The simulation can then be run to give insights into how the design and material selection will affect the performance of the end-effector; the data is displayed on the model using a colour chart (Figure 8), and modifications can then be made iteratively until satisfactory results are achieved.

4.41 Topology Optimisation

Topology optimisation is a computational design method used to optimise material layout. It involves iteratively removing unnecessary material from a model whilst insulating structural integrity and performance requirements (Hnin, 2023). By simulating various conditions and constraints, topology optimisation algorithms can generate optimal material distribution to maximise various factors, such as strength-to-weight efficiency or shape optimisation tailored to the designer's specifications (Mozumder, 2010); this process often results in complex, highly efficient structures (Figure 9). Weight reduction is significant in the functionality of an end-effector; lighter components can improve the overall efficiency of robotic systems by reducing inertia, energy consumption, and wear on mechanical components (Bélanger-Barrette, 2014). Additionally, lighter end-effectors can increase the payload capacity of the robot, enabling the handling of heavier components or handling more components at a time. Therefore, topology optimisation can be a valuable tool when designing a component with its strength-to-weight ratio as a high priority.

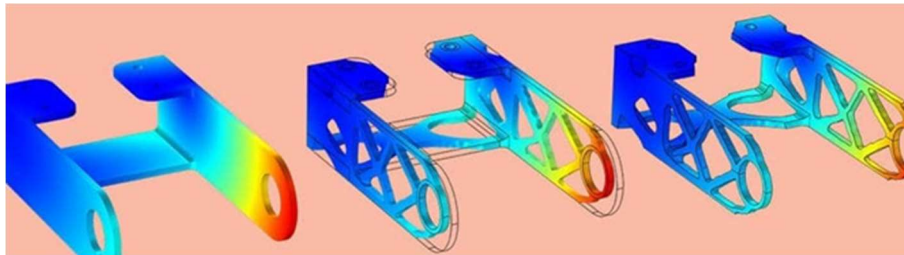


Figure 9 - Topology Optimisation

In conclusion, FEA optimisation techniques will be essential when designing an end-effector. The benefits include performance prediction, optimisation, durability assessment, material selection, and prototype reduction. Leveraging FEA to develop and optimise a design will ensure that performance requirements are met or exceeded.

Additional sources read: (Broekaart, 2015), (Costen, 2019), (Ferris, 2020), (Tipton, 2017).

2.5 Latest Trends in Additive Manufacturing (3D Printing)

Additive Manufacturing (AM), commonly called 3D printing, has revolutionised manufacturing. AM is creating an object one layer at a time; it is the opposite of subtracting manufacturing, which entails removing material until the object has the desired geometry (May, 2022). This layer-by-layer approach to manufacturing enables the creation of complex geometries with high precision, and it has numerous advantages when prototyping (Figure 10), which can significantly influence the design process (Campbell, Bourell, & Gibson, 2012). Print time and quality are two critical factors in the development of additive manufacturing technology. Advancements in hardware, such as higher resolution nozzles,

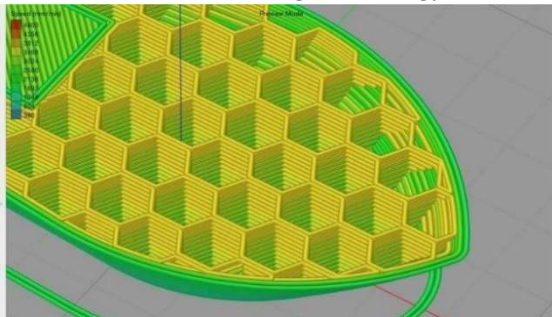


Figure 10 - Slicing Software

precise motion systems, bed levelling mechanisms, and materials improvements, have enhanced additive manufacturing quality. Furthermore, advancements in slicing software have helped to improve print paths and minimise overhangs; this reduces abnormalities in the object, resulting in higher-quality prints with excellent dimensional accuracy and surface finish (Pérez, Carou, Rubio, & Teti, 2020). On the other hand, print time, a limitation of additive manufacturing, has been reduced through

various innovations. Improved extrusion systems allow for faster material deposition (Altıparmak, Yardley, Shi, & Lin, 2022), and the improved slicer software can find the optimal print path, significantly decreasing the time taken to produce complex geometries. Additionally, advancements in

resin-based printing technologies like DLP and CLIP have enabled faster curing times, drastically reducing overall print times for resin-based systems.

2.51 Prototyping

Prototyping plays a crucial role in the design process; utilising AM allows engineers to rapidly produce physical prototypes directly from CAD models, allowing for quick validation of design concepts. This rapid prototyping accelerates the design iteration process, enabling the efficient exploration of multiple design capabilities. Moreover, AM enables the production of accurate and functional prototypes that closely resemble the final product, facilitating more accurate testing. In addition to design validation, AM prototyping can reduce costs associated with traditional prototyping methods by eliminating the need for costly tooling and setup times. The ability to make quick design modifications and produce a prototype also offers significant cost reductions. In summary, incorporating AM into the prototyping phase will ensure an accelerated and improved design process, which is also cost-effective, ultimately delivering a better-quality product.

2.52 Limitations of 3D Printing

Despite the many benefits of 3D printing with polymers, several limitations exist. Delamination, where layers of the printed object separate, will negatively impact the geometry and structural integrity. The layer-by-layer approach often results in long print times, especially with volumes; the limited build area impedes the ability to produce large volumes, a major setback to AM. Additionally, to construct a new component layer, the process requires an existing layer to build upon. Bridging (creating horizontal spans without support) can limit the manufacturing process; this often leads to sagging in the printed object (Holweg, 2015). Advancements are being made in these areas, but they remain significant considerations when utilising this technology.

The available materials have historically limited additive manufacturing. However, material science advancements have significantly expanded the applications and capabilities of printed components. Printable materials used in additive manufacturing are advancing rapidly; traditional thermoplastics like ABS and PLA are still popular choices. However, advancements in polymers with desired characteristics, such as exceptional strength, heat resistance, and chemical stability, are emerging, such as PEEK. Composite filaments incorporating materials such as carbon fibre or fibreglass also offer improved mechanical properties, facilitating the production of lightweight yet robust components (Amirahmadi, et al., 2024).

Additional sources read: (Iftekar, Aabid, Amir, & Baig, 2023), (Samuel, 2023), (Sacco, 2024), (Chapman, 2022).

2.6 Optimal Programming

Programming is critical in modern manufacturing; it enables the automation and control of machinery and robotic systems. A system or machine is only as effective as its programming. For a manufacturing process to be efficient, careful planning, attention to detail, and following best practices will need to be adhered to ensure optimal performance and accuracy.

2.61 CNC Programming

CNC programming involves creating instructions to control the movement of a machine, typically in the form of G-code. Mills, lathes, and routers commonly use this method to guide cutting tools along a predefined path (Ye, 2023). To achieve optimal results, a CNC programmer must understand the capabilities of a CNC machine, select appropriate cutting parameters, and plan effective tool paths; these factors will minimise cycle times and maximise productivity. One key aspect of

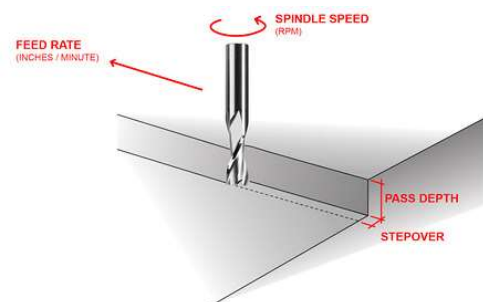


Figure 11 - Speed and Feed Rates

CNC programming is selecting optimal feeds and speeds (Figure 11), considering the material, tool geometry, removal, and desired surface finish (Saunders, 2017). By selecting appropriate cutting parameters, programmers can achieve efficient material removal whilst maintaining tool life. Additionally, a programmer must consider manoeuvring around work-holding devices and fixtures when planning tool paths to prevent collisions.

Compared to CNC programming, CAM software can simplify programming by providing a visual interface to create and edit tool paths, define machining operations, and specify cutting parameters. With CAM software, the user can easily generate complex and precise tool paths, reducing the time and effort required to program machines long-hand (Velling, 2021). Furthermore, CAM software typically offers advanced features such as simulation and tool verification (Figure 12), which allow programmers to visualise and validate tool paths before physically machining material, minimising the risk of collisions and errors.

One key advantage of CAM software is the ability to optimise tool paths efficiently. CAM algorithms analyse a model's geometry, material properties and machining constraints to generate optimal

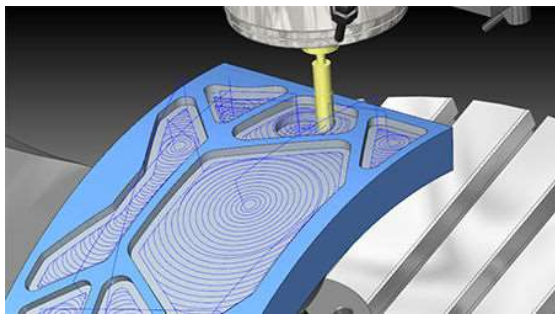


Figure 12 - CAM Tool path Simulation

toolpaths. Using CAM maximises productivity and machining throughput while maintaining high-quality standards; manually programming these changes would be extremely time-consuming and tedious (Geddes, 2019). Furthermore, CAM software also seamlessly integrates with CAD, enabling direct imports of 3D models for programming. This integration streamlines the design-to-manufacturing process, allowing programmers to minimise errors or discrepancies between design and manufacturing and making it an indispensable tool in CNC programming.

2.62 Robot Programming

To control the motion of industrial robots, you must program a sequence of instructions. Robot programming automates tasks such as assembly, welding, material handling and inspection. There are multiple programming languages and methods that can be used to control the motion of a robot effectively, such as teaching pendant programming or offline programming, which can be used to control the motion of a robot and specify sequences. Understanding the kinetic ability of the robot, including the range of motion, payload, and speed limitations, is essential when programming effectively. Additionally, safety considerations are essential in robot programming, and safety features such as interlocks, collision detection features, and emergency stop procedures must be implemented to protect operators and equipment.

Simulation software can significantly impact robot programming by providing the user with a virtual environment for validating and optimising a program before deployment in real-world manufacturing (Figure 13). By using virtual prototyping programs, the user can debug programs without causing disruptions to production, minimising downtime and the associated costs. Simulating programs also offer collision detection opportunities, ensuring equipment integrity and operator safety. This software also allows for reachability analysis and optimal robot trajectories, improving cycle times and enhancing throughput and efficiency.



Figure 13 - Robot Simulation Software

Additional sources read: (Meyer, 2022), (McCrea, 2018)

3. Work Carried Out

This section outlines the work to automate the production process of Jaguar housings, informed by the literature survey. The work undertaken included meticulously reviewing machining operations and identifying new tooling requirements to accommodate these modifications, which required the creation of new CNC programs. The housing geometry was also reviewed to identify a suitable gripping location. Subsequently, an end-effector was conceptualised, accompanied by a fixture design aimed at machining the 'bleed port' and loading nests. With the cell conceptualised, a preliminary robot program was developed.

3.1 Machining Operations

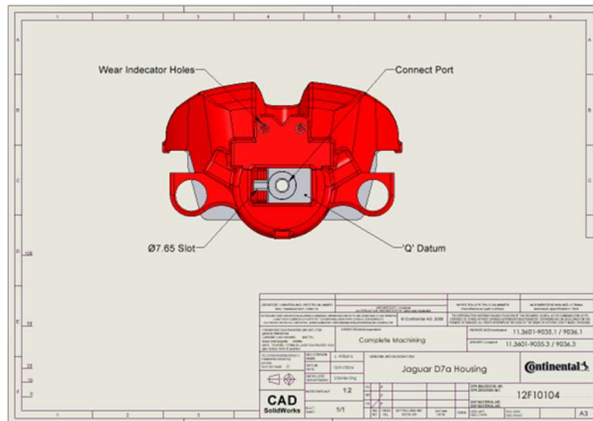


Figure 14 - Additions to Opp.10

Moving production to the automated cell means losing the capabilities of the 5-axis machine currently being utilised to manufacture the housings. This 5-axis machine is needed to produce the compound angle of the bleed port. However, the 'connect port', 'Q' datum and wear indicator holes (Figure 14) are on a parallel plane with the bore details, meaning they can be machined on a 4-axis CNC. To machine the bleed port on the 3-axis CNC in the automated cell, a new fixture that holds the housing at the correct orientation will need to be designed and fabricated. Moving the order of operations is

necessary if a finished part is to be produced in the automated cell. To achieve this, new tooling requirements must be met, and new CNC programs must be developed.

Machine	Operation
AMS Gemini Max (Op.10)	Mill Recess & Plate Holes, Bore Details, Disc Clearance, Bush Holes, Mill 'Q' Datum & Ø7.65 Slot, Drill & Tap Connect Port, Drill & Tap Wear Indicator Holes
STAMMA (Op.20)	Drill & Tap Bleed Port

Table 1 - New Machining Operation

3.2 Tooling Requirements

In response to the change in the sequence of machining operations, a thorough inventory check will be conducted to assess the availability of existing tools and their compatibility with the relevant CNC machines. This will identify tooling requirements and highlight absent tooling. In this case, new tools will be designed for the required machining operation.

3.2.1 AMS Gemini MAX

Operation	Tool Description	Tool Identification
Mill 'Q' Datum	Ø16 End Mill	ST 5009
Rough Ø7.65 Slot	Ø6.0 End Mill	New Tool Required
Mill Ø7.65 Slot	Ø7.65 End Mill	New Tool Required
Drill M6 Wear Indicator Hole	M6 Form Drill	New Tool Required
Tap M6 Wear Indicator Hole	M6 tap	ST 5900
Drill M10 connect port.	M10 Form Drill	New Tool Required
Tap M10 connect port.	M10 Tap	ST 5901

Table 2 - AMS Gemini Max Tooling Requirements

Analysing the additional operations added to the AMS Gemini Max has highlighted that four new tool designs are required. Two AMS Gemini Max machines, both twin spindles, are in the cell. The

components needed to construct these new tools can be taken from direct stores or redundant tooling, eliminating the need for external purchases. Please refer to the appendix for technical drawings (Figures 50 to 53) illustrating the specifications and dimensions of the tool assemblies.

Tool No.	Operation.	Tool Assy.	Tool Description.	Tool Number.	Qty.	SAP number.	Vendor.	Min. Stock.	No. Req'd.	Stock Available.	Comments.
1	M11 Guide Rail form. (2 places)	ST 5009	016 Carbide Endmill.	SP4035 HMR 160NN6-E	2	7-800006-236-900	Kennametal Ltd.	6	2	6	Same as London Tax
			016 HSK-A100 Hyd. Chuck & Chp.	HSK100AHC16100M	2	7-800006-245-900	Kennametal Ltd.	2	2	2	
			Coolant Pipe.	95.11.027.005	2	7-800006-027-800	Gewefa Ltd.	20	2	42	
2	M11 Ø18 Slot.	ST 5013	018 Carbide Endmill.	12T11006	2	7A-0023-2745-2-00	Komet Ltd.	4	2	7	Same as London Tax
			032 HSK-A100 Milling Chuck.	HSK100AHPMC3213SM	2	7-310126-183-000	Kennametal Ltd.	2	2	2	
			032-18 Reducing Collet.	32MHC 180M	2	7-310126-184-000	Kennametal Ltd.	2	2	4	
			Coolant Pipe.	95.11.027.005	2	7-800006-027-800	Gewefa Ltd.	20	2		
3	M11 Ø18 Slot & Spring Clip Groove.	ST 5014	018 Form Insert (322.1021.0207)	6-151849-010-000	2	7A-0023-2999-6-00	Horn U.K. Ltd.	6	2	11	
			Carbide Bar.	M322.0016.00A	2	7A-0023-2999-7-00	Horn U.K. Ltd.	4	2	6	
			016 HSK-A100 Hyd. Chuck & Chp.	HSK100AHC16100M	2	7-800006-245-900	Gewefa Ltd.	2	2	1	
			Coolant Pipe.	95.11.027.005	2	7-800006-027-800	Gewefa Ltd.	20	2		
4	M11 Disc Clearance Ø340.	ST 5006	R4 Milling Insert.	1722249	12	7-800005-939-100	Kennametal Ltd.	1200	16	1244	
			R1.2 Milling Insert.	60292181	12	7-800006-244-500	Kennametal Ltd.	300	12	319	
			Milling Cutter Ø240	60292190	2	7-800006-244-600	Kennametal Ltd.	4	2	4	
			HSK-A100 Shell Endmill Adaptor.	1722248	2	7-800005-978-900	Kennametal Ltd.	2	2	5	
			Coolant Pipe.	95.11.027.005	2	7-800006-027-800	Gewefa Ltd.	20	2		
5	Ø59.6 Bore & Chamfer.	ST 5106	Ø59.6 Bore Tool & Chp HSK-A100.	1B03000101750X	2	7A-0023-3367-4-00	Komet Ltd.	2	2	1	3 on order.
			Drill Insert (WCHX0804PN)	W01 42600.906115	4	7A-0023-3105-0-00	Komet Ltd.	70	8	66	
			Chamfer Insert.	SCMT 09T304	2	7A-0023-3105-1-00	Komet Ltd.	40	8	64	
			Coolant Pipe.	95.11.027.005	2	7-800006-027-800	Gewefa Ltd.	20	2		
6	Piston Face, & Boot Groove.	ST 5202	HSK-A100 Special Adaptor.	1B03000101756X	2	7A-0023-3375-6-00	Komet Ltd.	2	2	4	Same as London Tax
			Face Insert (SOEX120508)	W83 44010.087615	4	7A-0023-3385-1-00	Komet Ltd.	100	6	108	
			Boot Groove Insert.	6-081654-188-000	3	6-081654-188-000	Komet Ltd.	80	6	78	
			Coolant Pipe.	95.11.027.005	2	7-800006-027-800	Gewefa Ltd.	20	2		

Figure 15 - Inventory Report

In addition to the new tool designs, the inventory check (Figure 15) has highlighted that tooling purchases must be made. Three additional boring tools are required; while one is currently available in stock and two are being used in the current machining operation, a total of six tools will be necessary to support the machine effectively. This requires two twin spindle machines and two spare tools; therefore, three more boring tools are required. Notably, having two spares is imperative for the twin spindle machines to minimise downtime in unexpected cases of tool damage.

3.22 STAMMA-530

Operation	Tool Description	Tool Identification
M10 Bleed Port	Form Drill	HH 1793
M10 Bleed Port	M10 x 1 Tap	HH 1797
M10 Bleed Port	Ø4.0 Drill	HH 1635
M10 Bleed Port	Port Wash Tool	HH 1775

Table 3 - STAMMA Tooling Requirements

A similar assessment was conducted for the STAMMA-530, yielding different findings. No new designs or purchases are required; existing tools with the correct dimensions and thread specifications are required to complete the machining operations.

3.3 CNC Programs

With the tooling requirements identified, the next crucial step in the integration process was the development of CNC programs tailored to the specific machining operations carried out on the AMS Gemini MAX and STAMMA-530 machines. Each program underwent iterative refinement to optimise speed, feed rates, spindle speeds, and tool paths. The programming process began with creating detailed part models within CAD software, such as AutoCAD and SolidWorks, to accurately represent the geometry of the machine fixtures and the Jaguar housings; this provides essential geometrical data for tool path optimisation. Subsequently, CIMCO software was utilised to write the machine-readable G-code manually.

3.31 AMS Gemini Max CNC Program

The AMS Gemini MAX presents a unique challenge due to machining operations requiring eighteen unique tools. Writing a CNC program for a diverse toolset requires meticulous planning to optimise machine movements; careful consideration was also given to the sequence of machining operations within the CNC program. See Figure 59 in the appendix for the detailed program.

3.32 STAMMA-530 CNC Program

In contrast to the AMS Gemini MAX, the STAMMA-530 only utilises four tools due to its three-axis capabilities. The program was developed carefully, considering the dimensional specification of the new fixture design (Figure 60). It capitalised on the machine's basic capabilities while ensuring efficient execution of the machining operation. Despite its simplicity, the program also underwent careful validation to ensure accuracy and efficiency.

3.4 End Effector

3.41 Gripping Location

Before delving into the design of the gripping mechanism, suitable locations to grip the housing will need to be determined. These housings fall into the FN3 category, which refers to the housing design and how it is located for machining. As the technical drawing (Figure 47 & Figure 48) outlined, the initial machining operation required the housing to be located on three points: one flat, one 'v' shaped, and one domed. The gripping mechanism must not interfere with these location points.

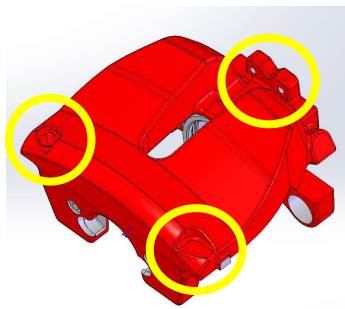


Figure 16 - FN3 Datums

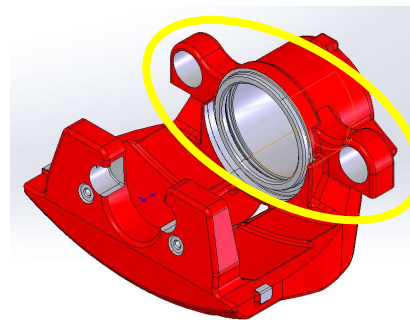


Figure 17 - 'W' & Bush Hole Datums

The location for the second operation differs from the first. The housing is located on machined surfaces carried out during the first operation. These datums are referred to as the 'W' face and 'bush holes', illustrated in Figure 17. The gripping mechanism must accommodate the datum points for both operations while maintaining a secure hold on the housing. Given the irregular geometry of the casting, options for gripping locations are limited. However, a thorough assessment has identified suitable gripping points behind the bore. Two flat locations at the bottom of the castings (illustrated in Figure 18) serve no function in manufacturing or brake usage, making them ideal for gripping. A flat surface on the top of the casting (Figure 19) used for clamping offers another suitable gripping location.

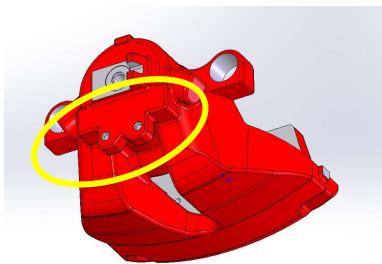


Figure 18 - Gripping Location (Bottom)

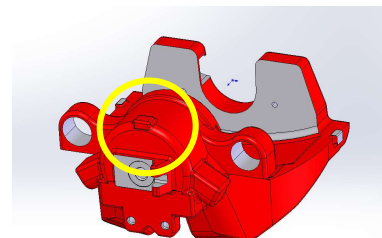


Figure 19 - Gripping Location (Top)

3.42 End-Effector Design

With a suitable location determined, the design process can begin. The end-effector can be divided into two main sections, the first being the section that directly fastens to the robot. It consists of an adapter designed to fit the specifications of the robot. Attached to this adapter is a spacing block, which houses two Schunk grippers; these are essential components to the end-effector as they deliver the gripping force required to hold the housings. The second section of the end effector comprises jaws that are responsible for clamping onto the housing. These jaws are designed to utilise the flat surfaces to ensure a secure hold during transportation. Additionally, the end-effector has been designed to manipulate two components simultaneously, aligning with the requirements of the twin spindle CNC machines.

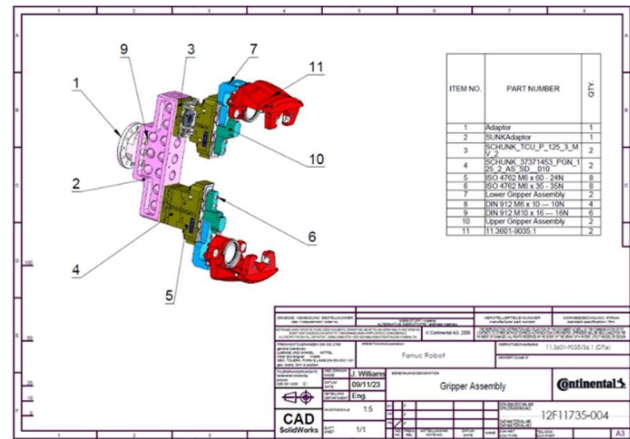


Figure 20 - End-Effector Assembly

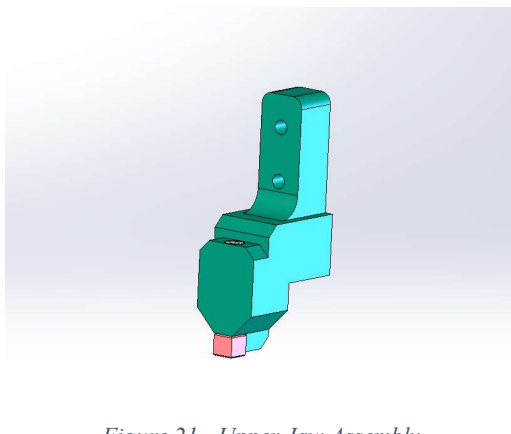


Figure 21 - Upper Jaw Assembly

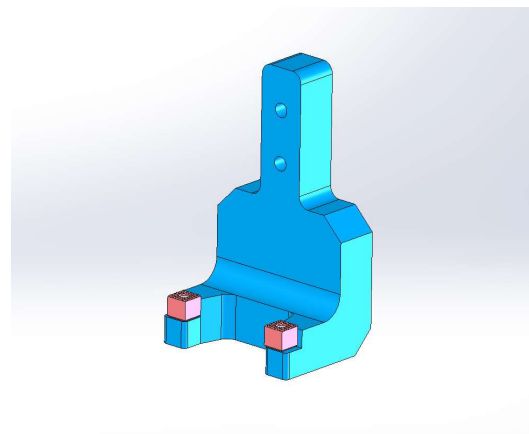


Figure 22 - Lower Jaw Assembly

The upper jaw assembly (Figure 21) consists of the main body equipped with a tungsten carbide gripping pad designed to contact the upper section of the housing. The lower jaw assembly (Figure 22) utilises two of the tungsten carbide gripping pads to secure the lower section of the housing. These three locations will ensure a consistent and secure hold on the housing. Figure 23 demonstrates the compatibility between the end-effector design and the fixture used to machine the first operation. The upper and lower jaw designs have enough fixture clearance to load and unload the housings safely.

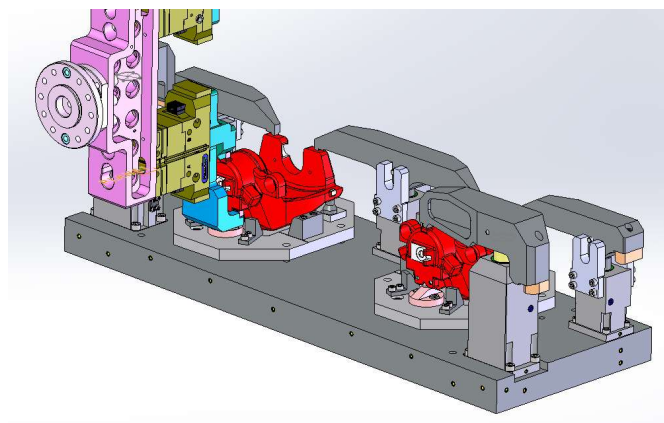


Figure 23 - First Operation Fixture Clearance

3.5 Loading Table

The loading table is a critical component in the cell setup. It is where the operator will place the housing, which is comprised of twelve individual nests, as displayed in Figure 25. The loading nest is comprised of a base plate with three location points resembling those on the machining fixture.

These three locations serve as the datum points for the housings, resulting in narrow tolerances in the casting process. Positioning the casting on these locations will minimise variability and ensure the housings' accurate alignment on the loading table. Precise alignment during loading is essential in this cell's overall performance and contributes to improved quality control by minimising variations. The nest is located on the table, and two dowels and two bolt holes are used to secure it; the two dowels will ensure the precise alignment of the nest and, in turn, the housing.

Another key feature is including a hole in the centre of the nest designed to accommodate a proximity sensor. This sensor provides feedback to the system to determine whether a housing is present or absent. This feedback is essential to the system to determine if a casting is present to pick up and load the CNC machines.

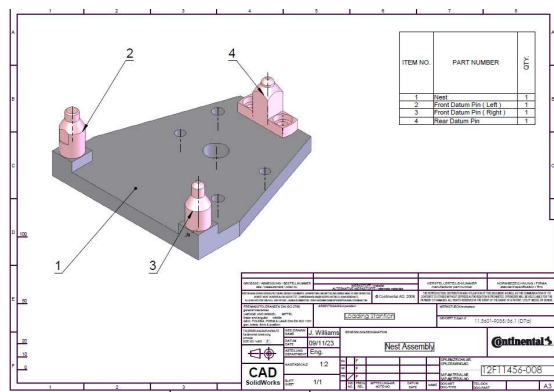


Figure 24 - Nest

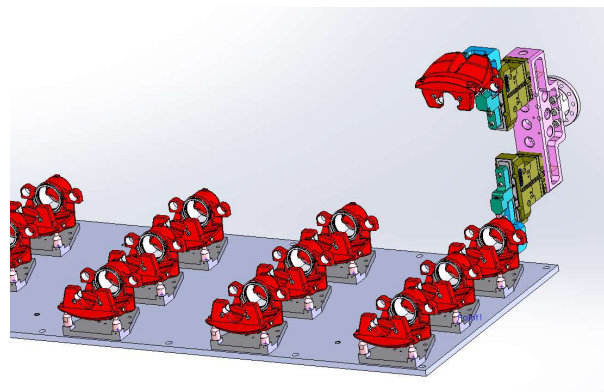


Figure 25 - Loading Table

The nest's design is also optimised to ensure compatibility with the end-effector. Altering the transparency of the lower jaw reveals where the tungsten carbide grippers contact the housing and the clearance with the nest and datum pins, illustrated in Figure 26. In addition to the twelve loading nests, there will also be four nests within the cell to act as a 'set down' table for when the robot is completing other tasks.

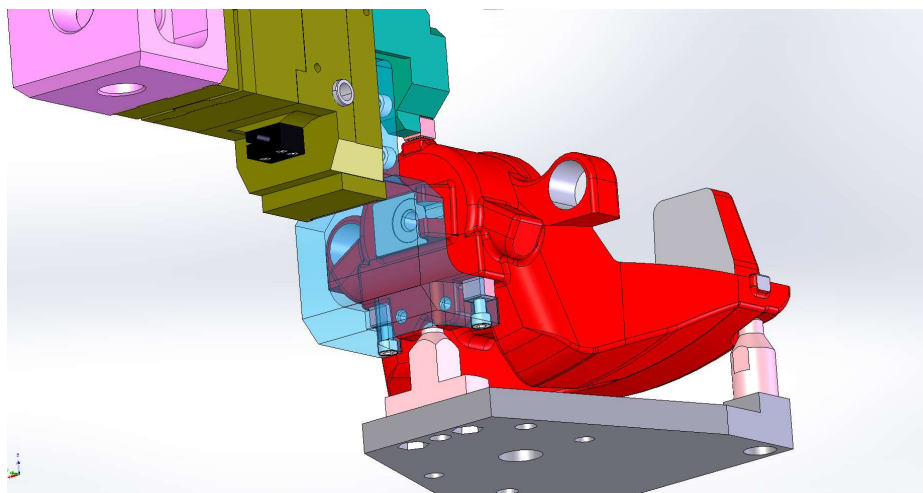


Figure 26 - End-Effector and Nest Clearance

3.6 Connect Port Fixture

The final phase of the design section was to develop a fixture to machine the housings 'bleed port' feature. The fixture is designed to produce two housings per machining cycle, one left-hand and one right-hand. Utilising hydraulic clamping mechanisms will ensure a secure hold on the housings at the correct orientation, as depicted in Figure 27.

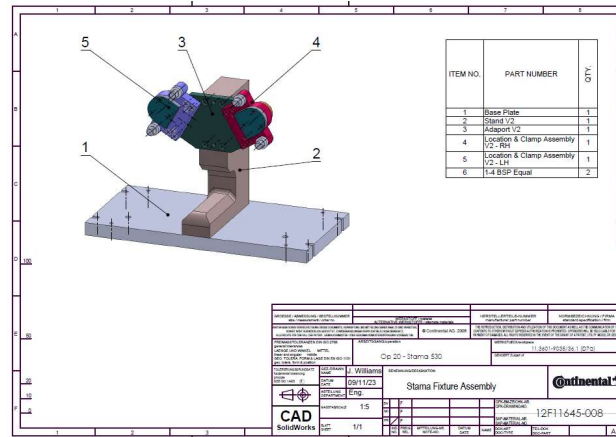


Figure 27 - 60° Port Fixture B.O.M.

Figure 27 illustrates the five main components of this fixture. Also, figures 28 and 29 visually represent how the end-effector loads the housings onto the fixture. The fixture and end-effector design have been coordinated to ensure sufficient clearance and compatibility.

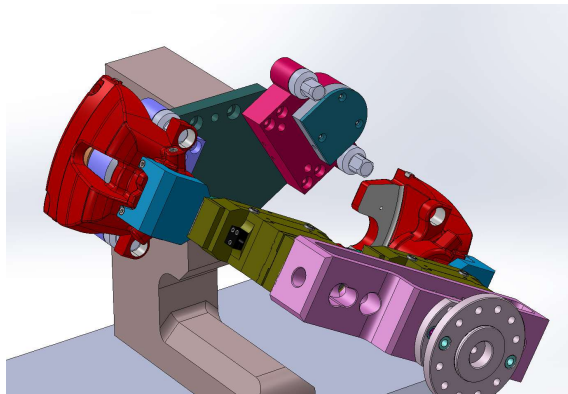


Figure 28 - Fixture Loading

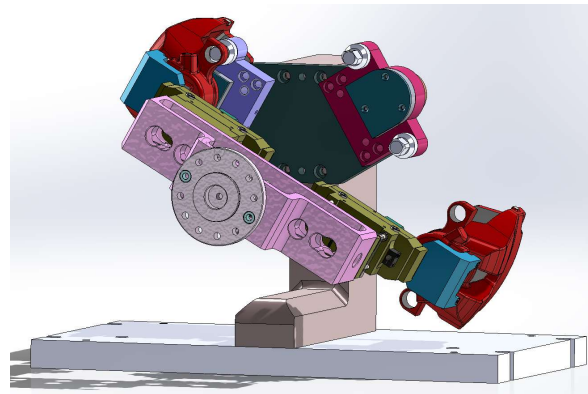


Figure 29 - Fixture Clearance

It is important to note that the fixture design specifies the required dimensions; however, a third-party specialist will develop the hydraulic clamping system's intricacies. Collaborating with experts will ensure reliable and efficient clamping mechanisms.

3.7 Robot Program

Following the completion of the cell design, the next step involves developing a program for the robot, illustrated in Figure 54 of the appendix. At this stage, an offline program can be produced, laying out the robot's movements and operations sequence. This preliminary program sets up the initial actions of the robot without the need for any physical installation. However, it is important to note that the program will be fine-tuned once all the cell components are installed and operational. In summary, the robot program is a crucial component in the efficiency of the cell, and a preliminary program developed before installation can help optimise movements and sequences.

4. Project Analysis

The project analysis evaluates the actions taken to integrate Jaguar production with the automated cell. Focusing on the end-effector, loading nests, projected cell output, and cost considerations, this analysis aims to provide insights into the project's success and lead to recommendations for further improvements.

The following key objectives will guide the analysis:

- Evaluate end-effector design and for functionality and efficiency.
- Perform FEA analysis to assess the structural integrity of the gripping jaws.
- Assess the effectiveness of the loading nests through prototyping.
- Use Arena discrete event simulation to project cell output and identify potential bottlenecks.
- Consider cost impletions and feasibility.

Addressing these key objectives will help us understand the new manufacturing process and identify areas for improvement or refinement. This analysis will then serve as the foundation for recommending further work and improvements.

4.1 End-Effector Design

The end-effector design plays a crucial role in the cell's overall performance. The jaw design is based on the Jaguar specifications, Figures 47 & 48, and the Shank specification, Figure 62, so compatibility with these two components is essential. The dimensions of the Schunk gripper and the 6mm travel per finger have completely influenced the dimensions of the jaws. Based on the various specifications, the total weight of the end-effector can be calculated. The master data sheet for Jaguar, Figure 49, states that the weight of an unmachined housing is 5664g, and the weight of the end-effector with no payload has been calculated using SolidWorks mass properties, Figure 50, and is 18876.6g. This gives the maximum weight of the end-effector as 30204.6g, the end-effector carrying two unmachined components. The Fanuc robot specification, Figure 63, states that the maximum carry capacity at the wrist is 70kg, which is more than double what this project requires. All appropriate specifications can be found in the appendix.

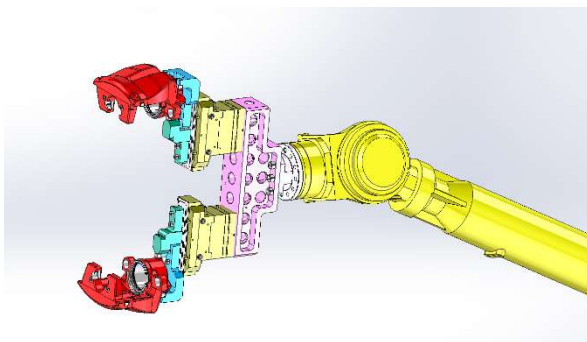


Figure 30 – End Effector Design

Regarding material, P20 low-carbon tool steel was chosen for the main body of the jaws. The tool steel is nitride-hardened. This material choice was influenced by previous and successful gripper designs and its excellent machinability. However, the salt bath nitride case hardening may be excessive considering the application of the jaws; a more conventional case hardening technique may be more cost-effective whilst producing similar results. In addition to the main body, serrated tungsten carbide gripping pads have been

chosen to contact the housing due to the excellent hardness and durability of the material. Past uses of other metals, such as steel, have proven unsuccessful for this application due to the wear of serrations, which usually results in components being dropped.

In addition to its core functions, the end-effector design is compatible with all CNC fixtures and loading nests within the cell. This, in turn, ensures a smooth workflow due to the robot's efficient loading and unloading of components.

4.2 FEA and End-Effector Performance

A comprehensive understanding of the jaw's performance and structural behaviour will ensure the efficiency and robustness of the design. To gain insights into the jaws' physical performance, an FEA analysis of the jaws under static load and fatigue loading was carried out.

The aims of the analysis are:

- Identify the distribution of stresses and deformation under an applied gripping force exceeding that of the specified Schunk gripper, highlighting potential areas of structural weakness.
- Evaluate the structural integrity of the jaws under a static load.
- Predict the gripper's fatigue life after being subjected to the cyclic loading of the initial static load.
- Assess areas susceptible to damage through fatigue failure.

This exploration of static and fatigue analysis aims to provide an understanding of the jaws' structural behaviour and potential insights for design refinement. The FEA analysis was carried out using SolidWorks simulation and SI units.

4.21 Static Load Analysis

Firstly, the model for this experiment has been simplified. The simplification assumes the Schunk gripper is completely rigid; this assumption has been made to focus the study on the jaws, not the purchased Schunk gripper. Secondly, the force applied by the Schunk gripper is 3,040N per finger, which can be found in Figure 64 of the appendix. This analysis will use a closing force of 10,000N per finger to scrutinise the model thoroughly by highlighting the weakest areas of the structure, illustrated by the purple arrows in Figure 31. Identifying the fixed geometry is also essential to the success of this analysis; these fixtures serve as the boundary conditions for the study. The holes that fasten the jaws to the Schunk gripper will be fixed for the analysis, displayed using green arrows in Figure 31. The material properties for this analysis are displayed in Table 4.

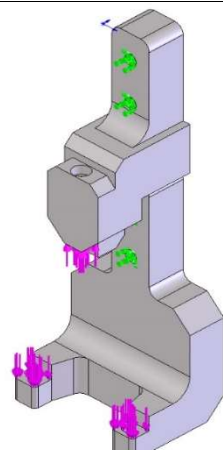
Name:	Plain Carbon Steel	
Model type:	Linear Elastic Isotropic	
Default failure criterion:	Max von Mises Stress	
Yield strength:	2.20594e+08 N/m²	
Tensile strength:	3.99826e+08 N/m²	
Elastic modulus:	2.1e+11 N/m²	
Poisson's ratio:	0.28	
Mass density:	7,800 kg/m³	
Shear modulus:	7.9e+10 N/m²	
Thermal expansion coefficient:	1.3e-05 /Kelvin	

Figure 31 - Applied Force & Fixed Geometry

Table 4 - Material Properties

The serrated tungsten carbide gripping pads have been excluded from this experiment. Firstly, due to the tungsten carbide's excellent strength, hardness, and rigidity (Cavallo, 2023), and to focus the evaluation on the performance of the jaws. Since the carbide pads are the surface that comes into contact with the workpiece, the force has been applied to the regions where the pads would be situated on the jaws. Furthermore, the lower jaw features two contact areas, distributing the 10,000N load evenly across

these regions. In contrast, the upper jaw has a single contact area, resulting in the entire 10,000N load being applied to this location.

The stress analysis presented in Table 5 focuses on the von Mises stress, which predicts materials' yielding under complex loading (Ishchuk, 2022). Understanding this stress is critical to understanding the jaws' structural response to the load.

Depicted in blue, most stress levels in the model are observed at $1.171\text{e}+04\text{N/m}^2$, which is roughly half of the material yield strength. These areas raise little concern in terms of structural integrity. In opposition, the maximum stress value was recorded with a magnitude of $5.311\text{e}+08\text{N/m}^2$, depicted in red. These regions are barely visible on the model preview but are present.

Most stress levels recorded are around $3.187\text{e}+08\text{N/m}^2$ in concentrated areas. The simulation has provided a yield strength of $2.206\text{e}+08\text{N/m}^2$; this means that the areas illustrated in green and yellow would plastically deform under this load. However, it is important to note that this simulation has been conducted with a load of approximately three times what would be typical.

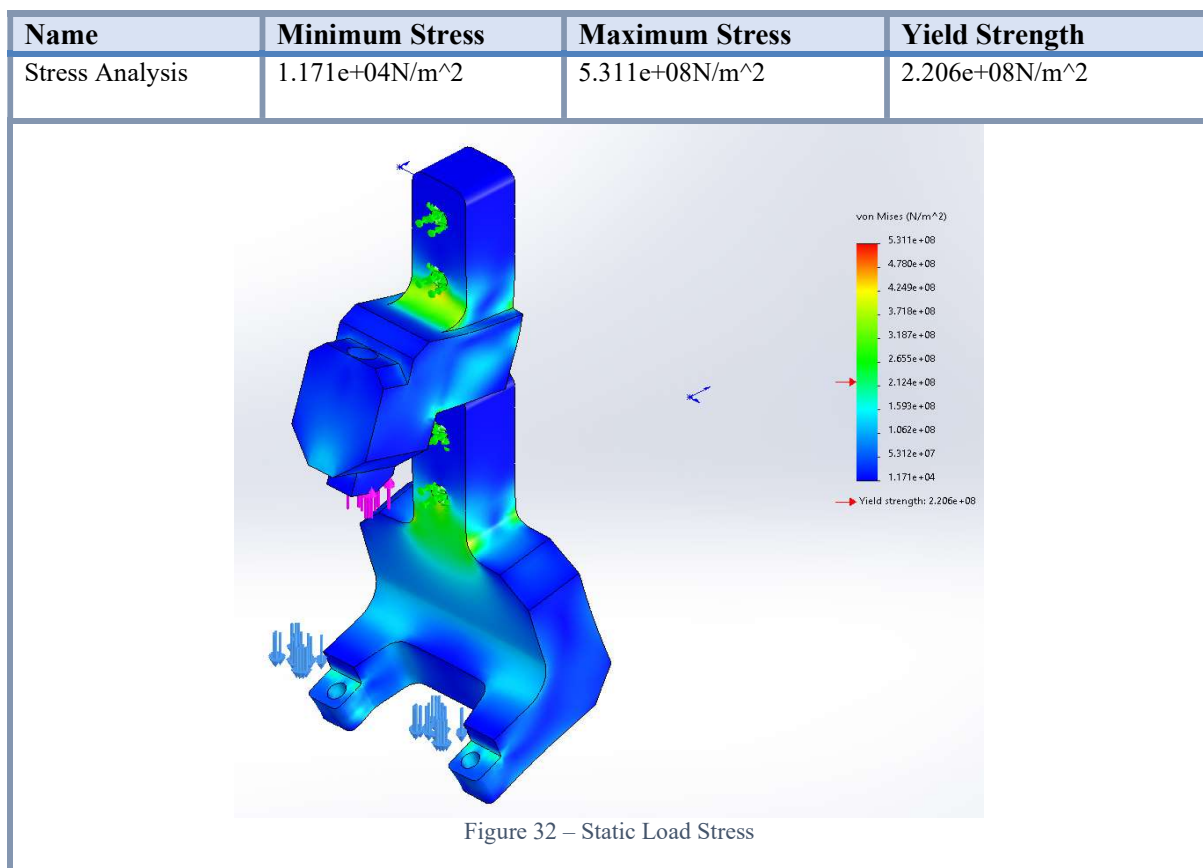


Table 5 - Stress Analysis

In conclusion, the stress analysis of the jaws provides valuable insights into their structural behaviour under load. While most stress levels remain manageable, this study has identified areas of concern. These regions are relatively few but indicate potential vulnerabilities that warrant further investigation. Moreover, the simulation's use of excessive force underlines the importance of interpreting these results correctly.

Addressing the identified stress concentrations will be essential for ensuring the structural integrity and performance of the jaws in practical applications. However, plastic deformation would not occur under the 3040N load because the stress does not exceed the yield strength, illustrated in Figure 64 of the appendix.

The results of the displacement analysis, shown in Table 6, provide crucial information regarding the structural deformation of the jaws under static load. At the minimum displacement of 0mm, visualised in blue, the jaws are experiencing negligible deformation. Conversely, the maximum displacement, visualised in red, is 0.3494mm.

The regions exhibiting the maximum deflection are the points where the jaws contact the workpiece. These locations are also the furthest section of the jaws from the fixing holes, resulting in increased leverage. Consequently, these are the areas experiencing the most significant deflection. In summary, the displacement observed in Figure 34 offers insights into the extent of the deformation. However, it's important to note that the deformation is anticipated, and the relatively small amount indicates the robustness of the jaw's design.

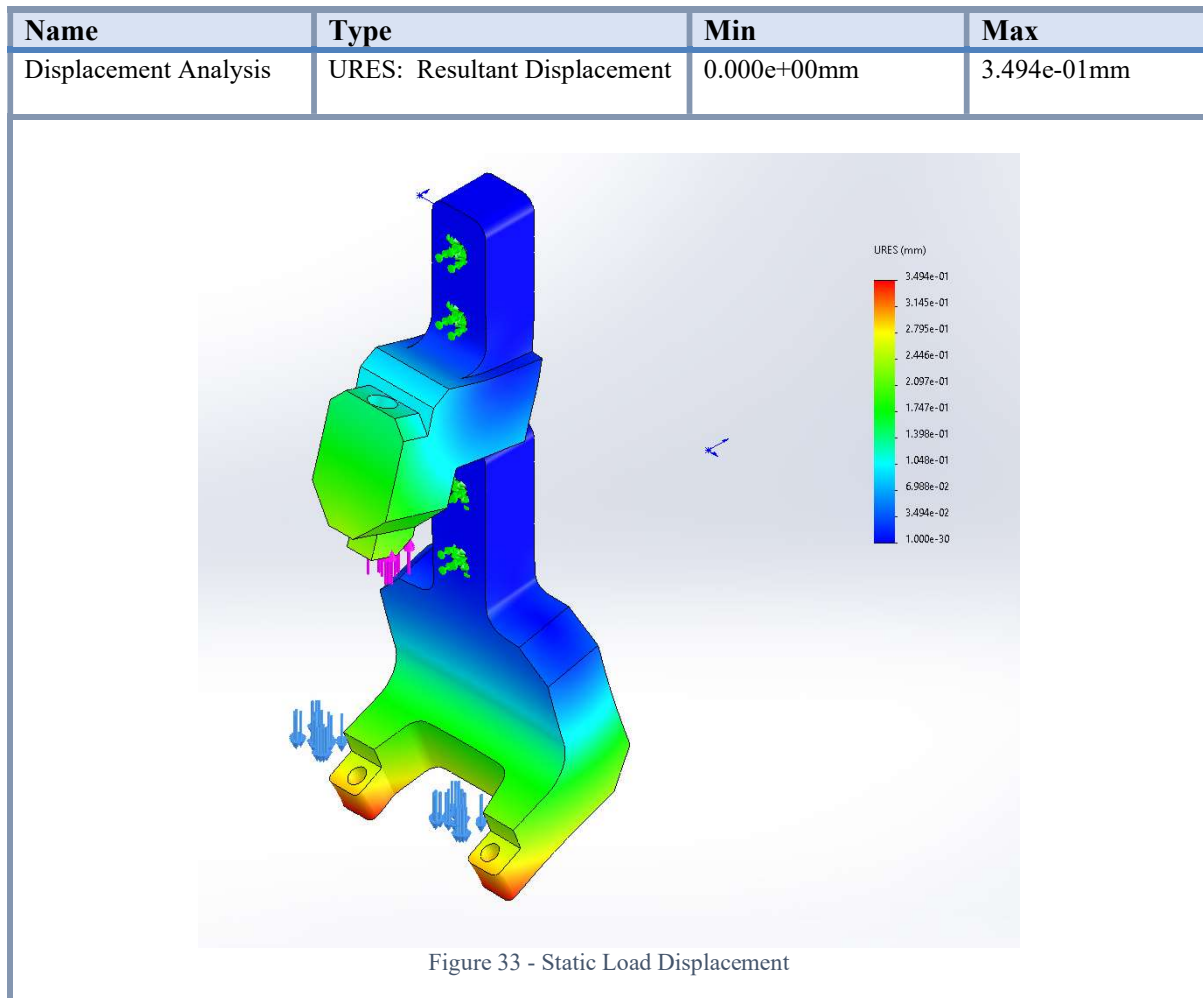


Table 6 - Displacement Analysis

Excessive displacement could pose challenges when handling the workpiece, especially when loading the CNC machines. Misaligned workpieces in the machines can produce defective parts or, in extreme cases, damage to the tooling and machine. The 0.3494mm deflection on the lower jaw and the 0.07354mm deflection on the upper jaw amount to a total deflection of 0.42294mm across the gripping device. With a nominal distance of 89.5mm between the contact areas of the jaws, this slight deflection underscores the design's robustness and should ensure reliability when loading the CNC machines.

The strain analysis results in Table 7 represent the jaws' deformation from stress; the findings are displayed as a ratio. The maximum strain value is $8.157\text{e-}08$, which is manageable when considering factors such as material properties and design requirements. Concentrated in identical areas to the stress, this strain analysis has highlighted where failure is most likely to occur. To prevent a failure, the material selection could be reviewed, or alternatively, modifications can be made to the model's design.

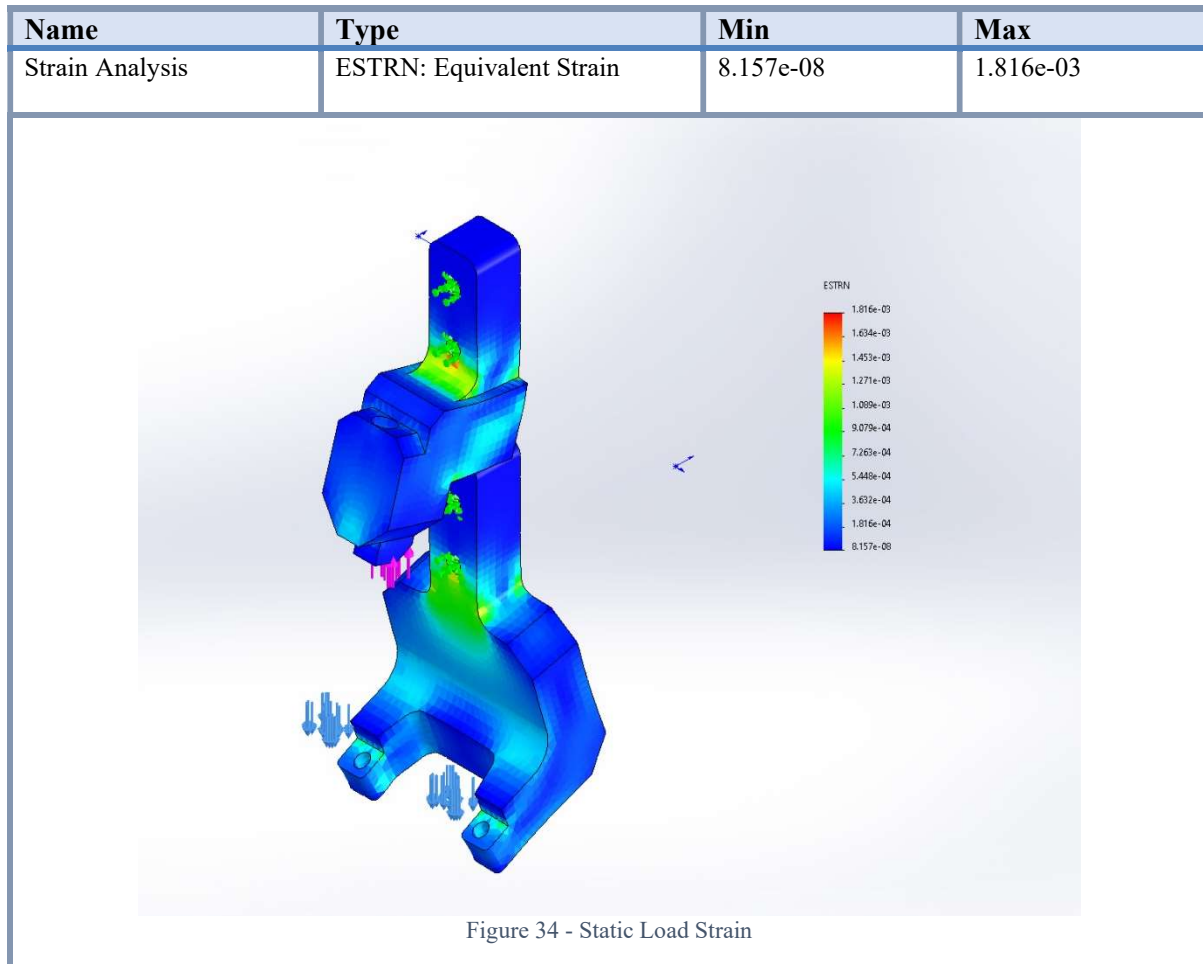


Table 7 - Strain Analysis

The static load analysis provided an understanding of the performance and structural behaviour of the jaws' design. It has highlighted the weakest areas of the end-effector, which can inform design adjustments to strengthen the components. However, the jaws will be repetitively subjected to this static force for prolonged periods. These findings provide a solid foundation for the subsequent fatigue analysis, representing a more realistic simulation of the jaws' endurance and durability.

4.22 Fatigue Analysis

The fatigue analysis builds on the static load analysis, utilising the same material properties and model. This study aims to analyse the life cycle of the jaws; a crucial aspect of fatigue analysis is determining the number of cycles to simulate. This study adopted an approach of 100,000,000 cycles for this simulation; this figure significantly overestimates the actual lifespan of the jaws and serves the purpose of testing the jaws until failure. This approach allows for a comprehensive assessment of the jaws' fatigue resistance and durability under extreme conditions, aiding in identifying potential failures and indicating areas for improvement in the design.

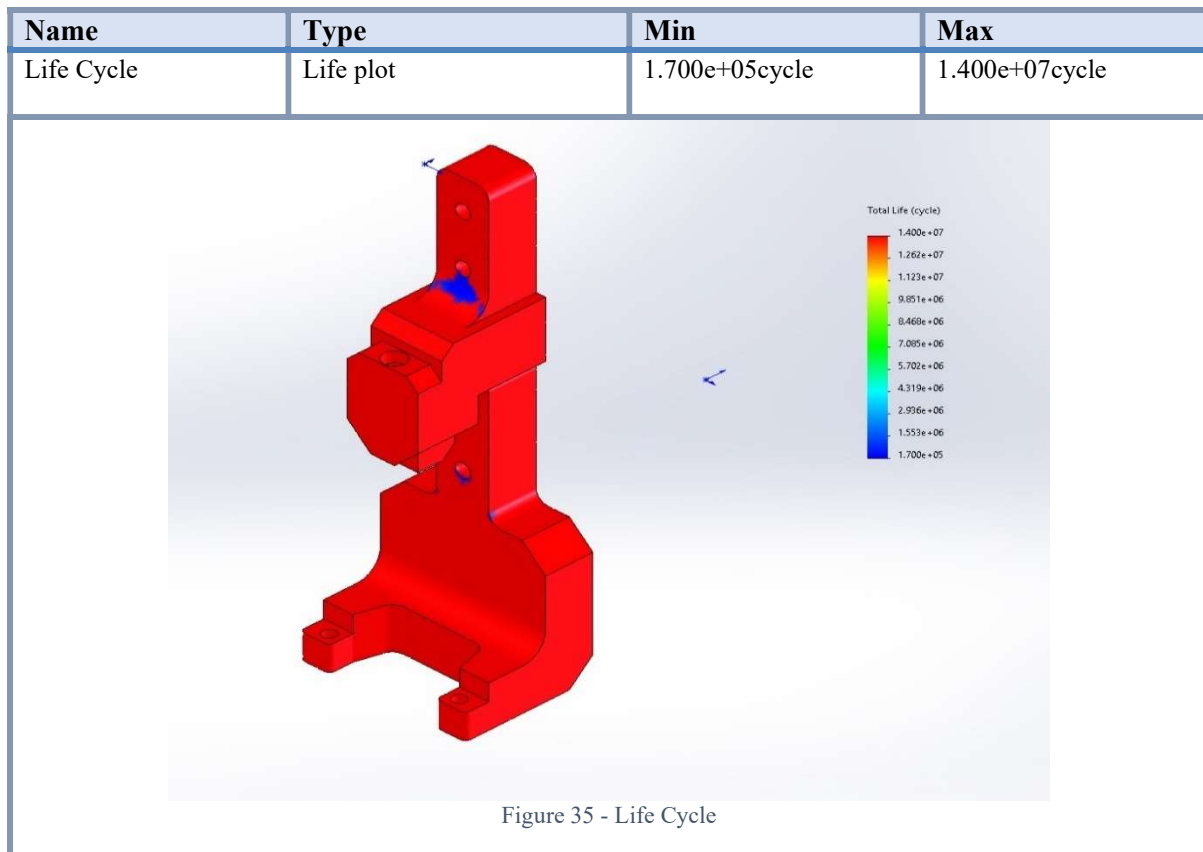
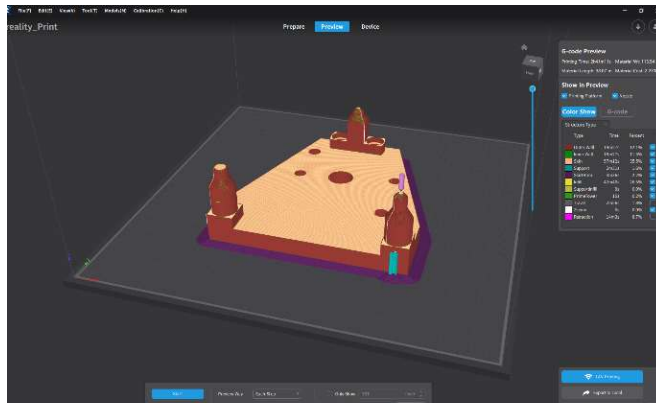


Table 8 - Life Cycle Analysis

Table 8 illustrates the fatigue analysis of the design. It uses the 10,000N static load analysis to simulate fatigue and identify the areas likely to fail. The predicted output of the cell can be multiplied by the number of times the robot handles individual parts to estimate the life cycle requirement. Assuming the robot operates continuously for twenty-four hours, it would handle housings 2400 times, and this figure can then be halved to estimate the value per jaw. Over three years of continuous production, each jaw would clamp approximately 876,000 times. However, this estimation is high as it doesn't consider interruptions, like maintenance; it serves the purpose of thoroughly scrutinising the design.

Most of the model is depicted in red (Figure 35), indicating a life of 1.400e+07 (14,000,000) cycles, far exceeding any estimation of the model's life. Conversely, the minimum cycles, shown in blue, suggest a fatigue life of 1.700e+05 (170,000) cycles. Using similar estimations, this would equate to roughly 141 production shifts. Although this figure doesn't accurately reflect the jaw's lifespan, the study has pinpointed a concentrated section of the top jaw vulnerable to fatigue. This area features a change in cross-section and is where the jaw is expected to be weakest. Additionally, the lower jaws show signs of fatigue failure at the neck of the jaw, which is where the model is expected to be weakest. These locations would be suitable considerations for a redesign to enhance the structural integrity of the jaws.

The loading nest serves as a critical component in the make-up of the automated cell, facilitating the precise position of the workpieces for the robot to handle. Maximising the effectiveness and reliability of this component will contribute to the overall productivity of the cell. This loading nest analysis evaluates the component's functionality through the development of a prototype. This prototype has proved the usability and dimensional accuracy of the nest. However, it has also highlighted potential



flaws, most notably concerns regarding the operator misloading the housing. This flaw works in conjunction with the proximity sensor setup, which is another poor design of the cell; it is still possible for a misloaded housing to trigger an appropriate signal on the sensor. This potentially misaligned part could be transferred to the CNC machine, where it would again be placed incorrectly; this can have huge implications and is sure to cause damage to both the machine and tooling.

A discrete event simulation was employed to validate the cell output, as depicted in Figure 37. The simulation model simplifies the actual operations; for instance, the block labelled 'load Max 1' represents the robot unloading finished components onto the set-down table and then loading raw material from the table onto the machine, which takes approximately fifty-one seconds. The simulation assumes twelve components, six for each hand, entering the cell, mimicking the operator's loading table. An additional twelve will be added when the twelve components have left the table; this process will be repeated for a given amount of time, in this case, eight hours. To simulate the robot's operation, the model uses a 'seize' block to allocate the robot resource to each operation, ensuring its singular use at any given time. Simulating an eight-hour shift produces a total output of 174 parts.

Furthermore, the simulation assesses resource utilisation as a percentage in Figure 37. A simulation analysis determined that the robot utilisation is 26.75%, indicating that it is idle for approximately 73.25% of the time. Applying this rate to an eight-hour shift reveals that the robot remains inactive for around 5.86 hours, leaving only 2.14 hours of active operation. This data highlights a significant portion of time when the robot is not engaged in productive tasks, identifying potential areas for optimisation to enhance efficiency and productivity within the operational environment.

Figure 10: Simulation of the two-robot system. The figure is divided into three main sections. The top-left section shows a sequence of events: 'Left Part Arrives' (green box) leads to 'Assign Type 1' (green box), then 'Left' (orange box), then 'Assign 5' (green box). This leads to 'Robot Status (Red = Busy)' (red circle). Similarly, 'Right Part Arrives' (green box) leads to 'Assign Type 2' (green box), then 'Right' (orange box), then 'Assign 7' (green box), also leading to 'Robot Status (Red = Busy)'. The bottom-left section shows a sequence: 'Set Down In' (green box) leads to 'Stand Down Table' (orange box), then 'Load Stamma' (green box), then 'Stamma Process' (green box), then 'Dispose 4' (green box). The top-right section shows a more complex flow: 'Max In' (green box) leads to a 'Routing By Type' (yellow diamond). This branches into two paths. The top path goes through 'Load Max1' (green circle), 'Clone Release Signal 1' (green box), 'Max 1 Process' (green box), and 'Assign 6' (green box). The bottom path goes through 'Signal 1' (green box), 'Robot Move from Max1 to Pick Up' (green box), 'Release 1' (green box), and 'Dispose of Signal 1 Entities' (green box). The bottom path also branches into another path: 'Signal 2' (green box), 'Robot Moves from Max2 to Pick Up' (green box), 'Release 2' (green box), and 'Dispose of Signal 2 Entities' (green box). The bottom path also branches into a third path: 'Load Max2' (green circle), 'Clone Release Signal 2' (green box), 'Max 2 Process' (green box), and 'Assign 8' (green box). The bottom path also branches into a fourth path: 'Max Out' (green box). The bottom-right section shows a summary table with the following data: Parts Completed: 174.00, Robot Util: 26.75, Max1 Util: 81.87, Max2 Util: 81.73, Simulation Time: 8.00, Stamma Util: 36.25.

4.5 Cost Evaluation

[illegible]

In addition to these purchases, the loading nests have been produced in-house, totalling approximately £48.00 for twelve units. These loading nests represent a significant cost saving. A previous integration

with this cell used new plates and location pins, costing £3,600 (Figure 38). Using additive manufacturing and reusing location pins has resulted in a 98.67% reduction in spending for this area compared to a similar project.

50	Table Jigs - Design	£400.00	2	£800.00
51	Table Jigs - Manufacture	£300.00	12	£3,600.00
52	Gripper Fingers - Design	£400.00	4	£1,600.00
53	Gripper Fingers - Manufacture	£1,500.00	2	£3,000.00
54	Robot Programming	£400.00	2	£800.00
55	Commissioning	£400.00	5	£2,000.00

Figure 38 - VW Loading Nest Cost

5. Recommended Further Work

This section aims to build on the project analysis and literature survey by recommending further improvements to enhance the cell's efficiency or cost-effectiveness. With continuous technological improvements, it is crucial to identify areas for enhancement to stay competitive in the industry. The following key objectives will ensure successful recommended improvements:

- Explore design improvements for the end-effector and loading nests.
- Enhance the efficiency of the robot's movements.
- Maximise productivity in the cell by scrutinising the cell.

Addressing these objectives will ensure the latest improvements and best inform the manufacturing operations practice, optimising overall efficiency.

5.1 Enhanced Design Opportunities

The FEA revealed some areas of concern on the upper jaw, indicating susceptibility to fatigue. In response, conceptual modifications have been made to reinforce the vulnerable regions, as illustrated in Figure 39 and Figure 40. Before manufacturing, these design modifications must be validated by repeating an FEA under identical conditions. This iterative process of analysis and refinement can be repeated until a satisfactory design is reached. Strengthening the design would add weight, with the total weight of the end-effector being less than half of the robot's maximum carrying capacity before the modifications. However, a topology study could be used if weight becomes a concern.

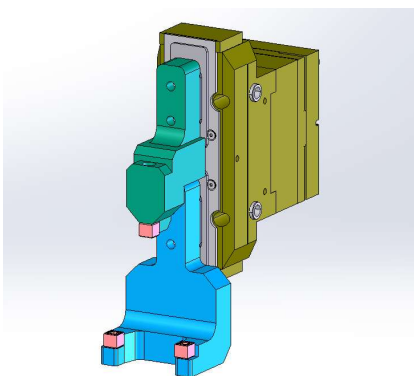


Figure 39 - Original Design

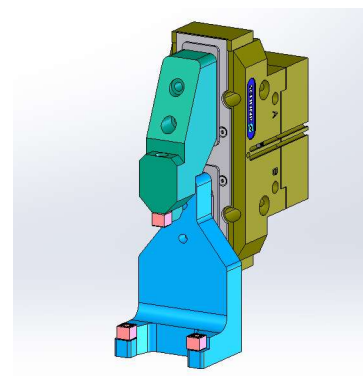


Figure 40 – Conceptual Design

A critical evaluation of the loading nests has highlighted the need for design improvements. Implementing guides will improve the ergonomics of the nest by making the loading easier for the operator, as illustrated in Figure 41 and Figure 42. Adding these guides may also improve the functionality of the proximity sensors, facilitating the correct loading of the housing. Finally, these guides also function as a poka-yoke, preventing the wrong component from being loaded onto the nest. These changes can be made cheaply because the nest is 3D printed, where complexity does not cost.

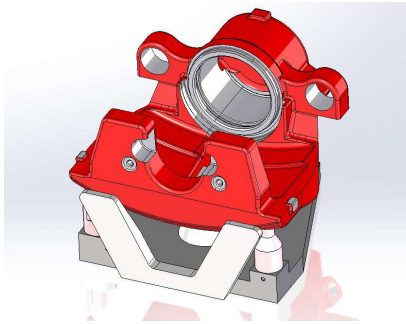


Figure 41 - Loading Nest Concept with Housing

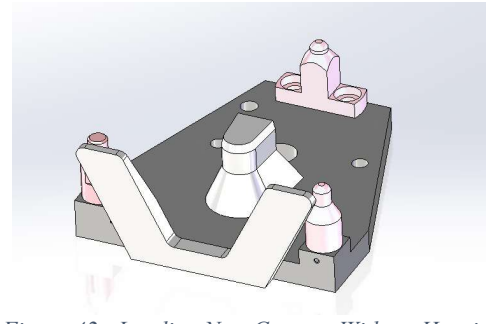


Figure 42 - Loading Nest Concept Without Housing

5.2 Cell Improvements

The current machining cycle for the first operation is significantly longer than the bleed port operation; the cycle time for the first operation drives the cell's production levels. A key recommendation to increase the cell's output would be to perform more machining operations on the STAMMA to utilise it better. However, the scope of the project has been constrained by the cell utilising a three-axis CNC machine; transitioning to a four-axis or five-axis machine would provide options to balance the machining operations of the CNC machines. Purchasing a new machine would prove to be a significant investment in the cell, or alternatively, moving an existing machine into the cell may interrupt the production of other platforms.

In addition, the robot also has significant idle time during the machining operations, as highlighted by the Arena model; optimising the robot's activities is essential in optimising the cell's output. Figure 43 demonstrates the current path the robot would take; firstly, the CNC machine will be unloaded, and then the housings will be placed on the set-down table; the robot then moves to the loading table to retrieve raw material that will be used to load the CNC machine. Figure 44 illustrates the proposed path, where the robot places raw material on the table when idle. Next, the robot unloads the CNC machine, places the machined housings on the set-down table and picks raw material from the same place to load the CNC machine. The machining cycle is fixed, so the cell can only benefit from loading the machines faster. Introducing a strategy where the robot utilises the set down to pre-position raw material could minimise the robot's idle time and improve the loading time.



Figure 43 - Current Path

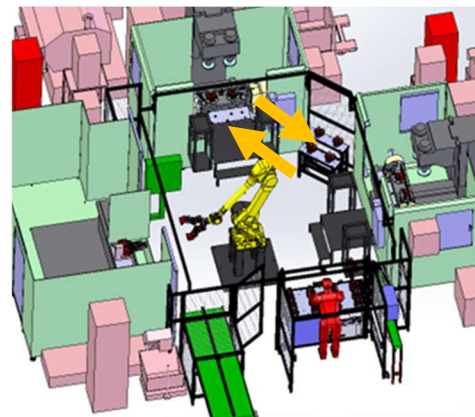


Figure 44 - Proposed Path

An Arena model was created to assess the impact of reducing the loading times for Max One and Max Two machines. Although accurately predicting the new loading times is challenging, halving it to 25 seconds resulted in notable improvements. The utilisation of Max machines increased to approximately 96%, indicating a more efficient use of these resources. Moreover, the cell's output rose from 174 to 182 parts, as shown in Figure 45. However, a discrepancy occurred regarding robot utilisation. The model indicates a reduction in robot utilisation following the decrease in loading time; this contradicts the actual operation of the cell. In reality, the robot would not remain idle but strategically engage in

tasks such as placing raw material near the intended machine. Consequently, the model's representation of reduced robot utilisation does not accurately reflect the practical scenario, highlighting the importance of accurately simulating models with real-world operations.

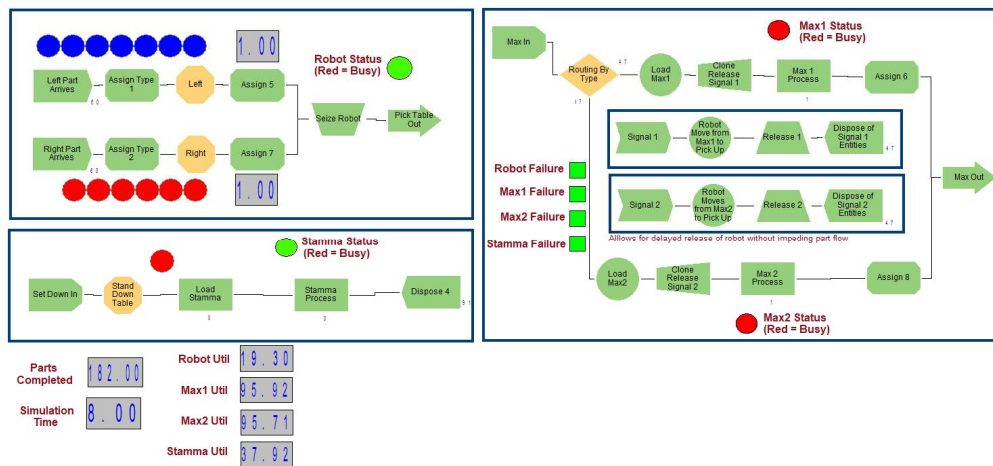


Figure 45 - Reduced Loading Times

A "strategic placement" process was introduced to validate the proposed improvements further. The process aimed at utilising the robot for 50 seconds, derived from the reduced loading times of 25 seconds per machine. Additionally, the cycle times for the Max machines were decreased by two minutes, while the STAMMA cycle time was extended by the same duration. The results presented in Figure 46 were compared with the original model to assess the impact on resource utilisation.

The improvements yielded promising results. Robot utilisation significantly increased from 26.75% to 43.92%, indicating a substantial improvement in its engagement with the cell. Similarly, the utilisation of the Max machines experienced a slight improvement, rising from approximately 92% to 94.65%. Moreover, the utilisation of the STAMMA machine improved substantially from 36.35% to 94.67%. The overall output of the cell also increased to 226 parts, a rise of 42 parts per shift, signifying a significant enhancement in productivity. Although these figures may not truly represent real-world outcomes, they indicate the importance of resource utilisation and simulation techniques while validating suggested improvements.

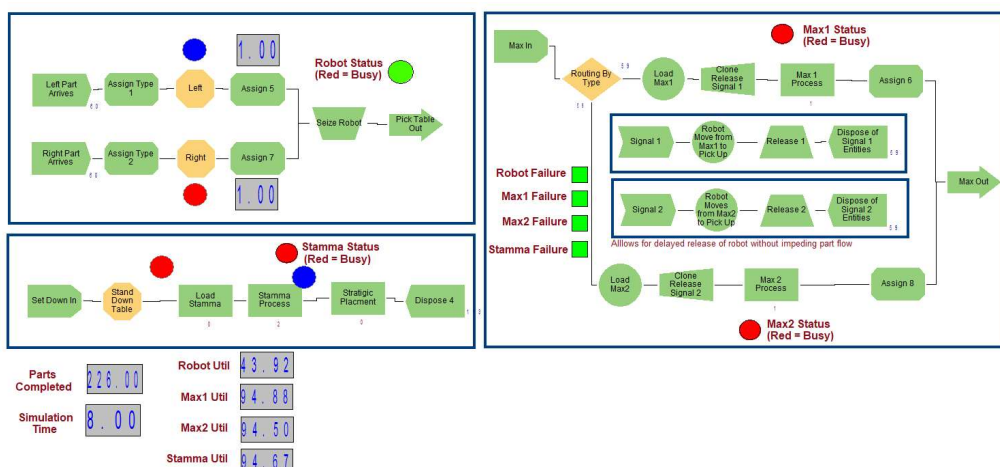


Figure 46 - Complete Cell Improvements

Considering alternative solutions to the improved nest design, integrating a vision system could greatly improve the loading process by eliminating the need for loading nests and proximity sensors. This

approach would allow the operator to place parts freely on the table while the robot identifies and retrieves them; it would also eliminate system failures associated with proximity sensors being triggered by debris. The benefits associated with implementing a vision system, covered in the research section, would directly apply to this cell, improving overall efficiency by reducing handling errors.

The STAMMA port fixture (£9,890.00) accounts for roughly half of the required investment. To reduce the required investment, running the first machining operations on the Gemini Maxes and removing the STAMMA operation would be possible, producing an unfinished component in the cell. The port operation can then be carried out on the 5-axis CNC machine, which is the process before integrating with the automated cell. This alternative order of operations could be carried out in two ways following the original machining process, as shown in Figure 4. This would offer unique benefits, such as reducing the cycle time on the Gemini Max due to the 'Q' datum and 'connect port' operations being moved back to the second machining operation. The downside would be that the pressure on the 5-axis CNC machine would not be resolved; with two machines feeding it, the pressure may even increase. Alternatively, carrying out the extra machining of the 'Q' datum and 'connect port' on the Gemini Max, as proposed by this project in section [3.1], is a viable alternative. This approach would require the 5-axis CNC machine only to carry out the 'bleed port' machining, significantly reducing the cycle time and relieving the pressures on the machine output. In addition, the production levels of Jaguar would increase compared to the current process. However, the cycle time for the first operation has increased, and the housings will now be produced on two CNC machines, increasing overall output. To justify these ideas, Arena simulations should be carried out as seen in the analysis of this project.

6. Discussion and Conclusions

Integrating the production of Jaguar housings with the automated cell is a significant advancement in manufacturing efficiency. This integration required meticulous planning and research across various areas, such as automation, tooling requirements, CNC programming, end-effector design, fixture design, projected cell output, and cost considerations. The core of the project's success was the strategic rearrangement of machining operations. To transition effectively to the automated cell, the capabilities of different CNC machines were identified and leveraged to produce optimal results. This involved careful examination of the existing capabilities and developing new fixtures that align with these capabilities and accommodate the altered operation sequence. This transition also highlighted the need to assess tooling requirements, comprehensive inventory checks and compatibility assessments, resulting in new tool designs. The new designs capitalised on existing resources where possible; however, new purchases were required.

The structural integrity of the end-effector was scrutinised through finite element analysis under static and fatigue loading conditions. This analysis identified weak areas in the design, and informed concepts were produced to enhance its durability and reliability. Optimising the loading nests also significantly enhanced the cell's overall efficiency. Conceptual modifications incorporating guides aimed to streamline the loading process, minimising the risks associated with incorrect part alignment. These design improvements were implemented cost-effectively using additive manufacturing; further adjustments can be made cheaply. The Arena simulation provided valuable information on the cell's projected output. Production requirements would easily be met after this integration, as the parts produced per shift would almost double. The current machining process would be made redundant, meaning there would be far less pressure on the 5-axis STAMMA. Jaguar housings were continually produced in one of the two working areas of this machine; moving production to the automated cell would allow for more flexibility in production across Continental. Looking ahead, the recommended further work presents challenges for enhancing efficiency within the cell. Exploring design refinements for the end-effector and loading nests will improve handling efficiency. Similarly, optimising the robot's movements using simulation software and introducing new technology to the cell, such as a vision system, offer avenues to explore and continuously improve the cell.

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Appendices

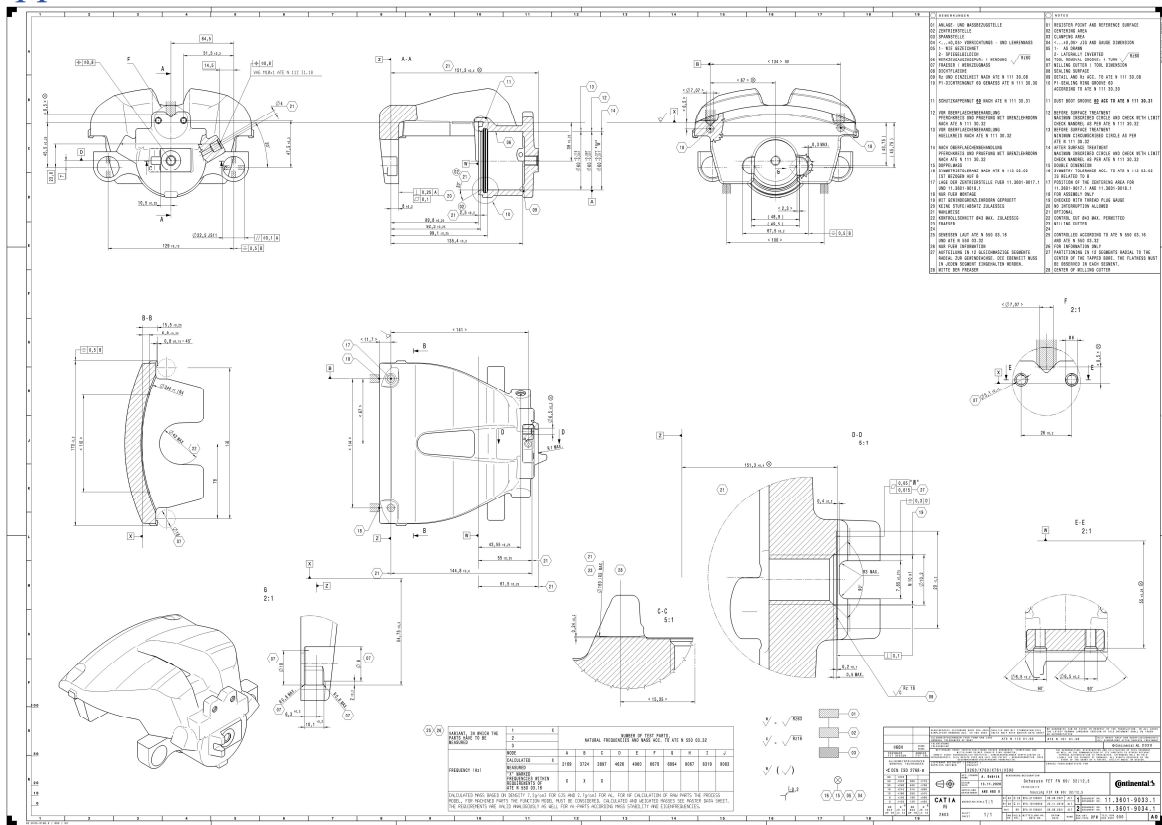


Figure 47 - D7a Technical Drawing (Sheet 1)

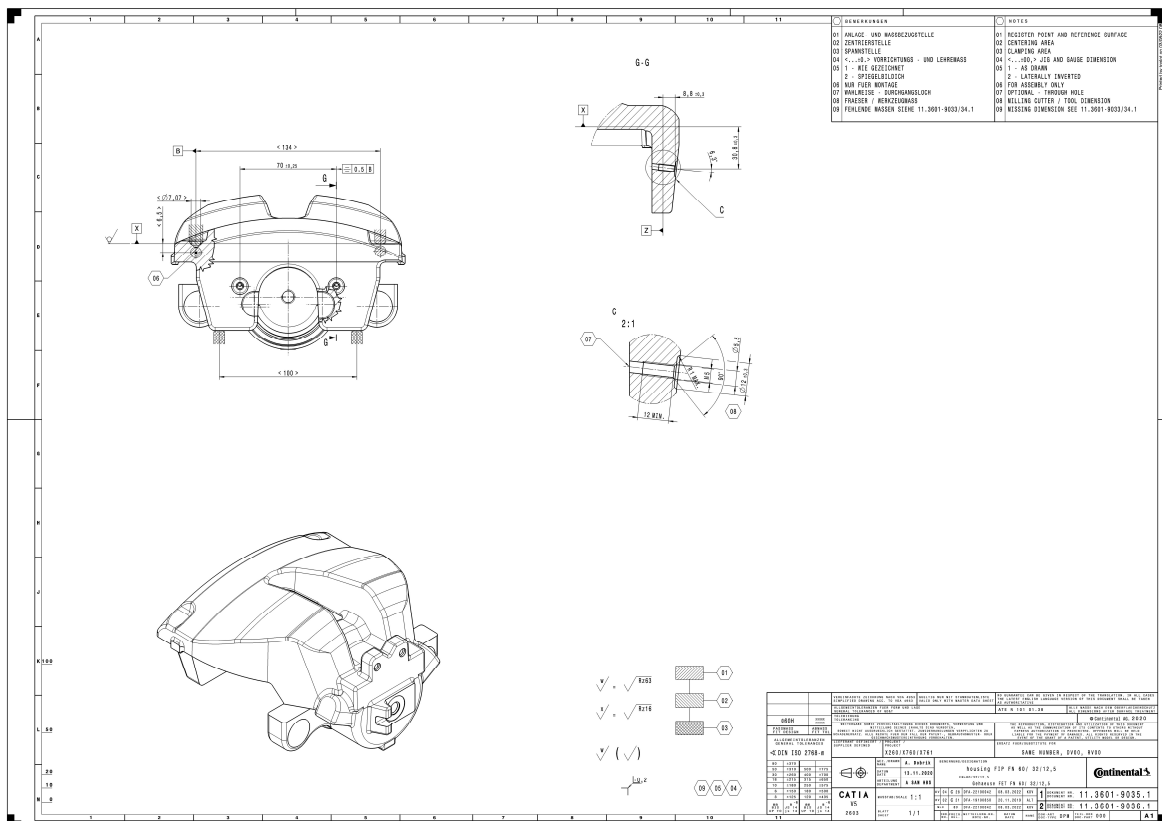


Figure 48 - D7a Technical Drawing (Sheet 2)

STAMMDATENLISTE / MASTER DATA SHEET



Administration										
W Merkmal nach ATE N 101 00.02/W Char. acc. ATE N 101 00.02										
1										
Material										
Oberflaeche cm2/Surface cm2										
1.041,600 cm2										
Gewicht (g) gerechnet/Weight (g) Calculated										
5664,000 g										
Tolerierungsgrundsatz/Tolerance Principle										
ATE N 101 01.38/ATE N 101 01.38										
Werkstoff/Basic Material										
WS002182 EN-GJS-500 ATE N 550 03.16										
"W"										
Qualität / Quality										
Prüfnorm/Check Standard										
TEVES										
CAD Modellart/CAD Model Type										
2D ProdZ. exakt;3D Solidm exak/2D ProdD. exact;3D Solidm exac										
Objekte / Objects										
Objektänderung/Object Change										
Keine Objektänderung/no Object change										
Materialrevisionsstand/Material Revisionlevel										
06										
Änderungsnummer Revisionsstand/Revision Level Change Number										
DFA-17101384										
FREIGABE / RELEASE					ES GILT DER URHEBERSCHUTZVERMERK D.ZEICHNUNG/D.3D MODELLS. DIESSES DOKUMENT IST RESTAUTEIL D.ZEICHNUNG/D. 3D-MODELLS/D.STUECKLISTE MIT GLEICHER DOKUMENT-NR.					
MLC	80	DFA-16101189	25.10.2017	ALT	THE COPYRIGHT NOTE OF THE DRAWING/3D-MODEL APPLIES. THIS DOCUMENT IS AN INTEGRAL PART OF THE DRAWING/3D-MODEL/PARTS LIST WITH THE SAME DOCUMENT NO.					
	07	DFA-14110606	27.06.2014	ALT						
	06	FRA-13112813	12.07.2013	SKB	BENENNUNG: Gehaeuse ROH FN 60/ 32/12,5 DESIGNATION: housing RAP FN 60/ 32/12,5					
ÄNDERUNG / CHANGE					ZUSATZBENENNUNG 1: ADDITIONAL DESIGNATION 1: FN+60/32/13					
06	08	C23	DFA-18101442	12.04.2019	ALT	ZUSATZBENENNUNG 2: ADDITIONAL DESIGNATION 2:				
06	07	C21	DFA-17101384	28.05.2018	SRce	Ersatz fuer SUB. POR				
05	06	C23	DFA-16101189	25.10.2017	ALT	HERSTELLT CREATED	Fakac	STAMMDATENLISTE NACH VDA 4953 MASTER DATA LIST TO VDA 4953		
05	05	C21	DFA-14110606		ALT	DATUM DATE	28.03.2019	DOK.-ART DOC.-TYPE DPM	BL. SH. 1	DOK-NR. DOC-NO. 11.3601-0415.9
RV	DV	FR. REL.	MITTEIL. NR NOTICE NO.	DATUM DATE	NAMEN NAME	ART. DEPT.	AMS	TEIL-DOK. DOC.-PART 000	VON OF 3	

82.9208-0002.4/800/00 DRUCKDATUM/PRINTDATE: 02.03.2021 DRUCKZEIT/PRINTTIME: 21:36:46

Figure 49 – Jaguar Specification

Mass properties of GripperAssembly
 Configuration: STANDARD
 Coordinate system: – default –

Mass = 18876.8 grams

Volume = 3261600.635 cubic millimeters

Surface area = 775816.616 square millimeters

Center of mass: (millimeters)

X = -35.183

Y = 34.145

Z = -67.214

Principal axes of inertia and principal moments of inertia: (grams * square millimeters)
 taken at the center of mass.

Ix = (0, 1, 0) Px = 159106139.253

Iy = (-1, 0, 0) Py = 282139566.678

Iz = (0, 0, 1) Pz = 427064874.976

Moments of inertia: (grams * square millimeters)

taken at the center of mass and aligned with the output coordinate system. (Using positive tensor notation.)

Lxx = 282139573.087 Lxy = 52340.782 Lxz = 64460.479

lyx = 52340.782 lyy = 159106161.927lyz = -10462.805

Lzx = 64460.479 Lzy = -10462.805 Lzz = 427064845.895

Moments of inertia: (grams * square millimeters)

taken at the output coordinate system. (Using positive tensor notation.)

lxx = 389427279.921lxy = 22625314.972 lxz = 44704221.785

lyx = 22625314.972 lyy = 267752085.585lyz = 43333446.61

lzx = 44704221.785 lzy = 43333446.61 lzz = 472440489.526

One or more components have overridden mass properties:

SCHUNK_0301032_MMS_22_S_M8_PNP<1><Default>@SCHUNK_TCU_P_125_3_MV_2<1><Default>
 SCHUNK_0301032_MMS_22_S_M8_PNP<1><Default>@SCHUNK_TCU_P_125_3_MV_2<2><Default>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<1><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<1>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<2><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<1>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<3><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<1>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<4><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<1>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<5><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<1>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<6><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<1>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<7><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<1>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<8><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<1>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<1><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<2>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<2><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<2>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<3><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<2>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<4><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<2>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<5><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<2>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<6><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<2>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<7><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<2>
 _SCHUNK_9939379_Zentrierhuelse_D10x6_65_27<8><Default>@SCHUNK_37371453_PGN_125_2_AS_SD_010<2>

Figure 50 - End-Effector Weight Calculation

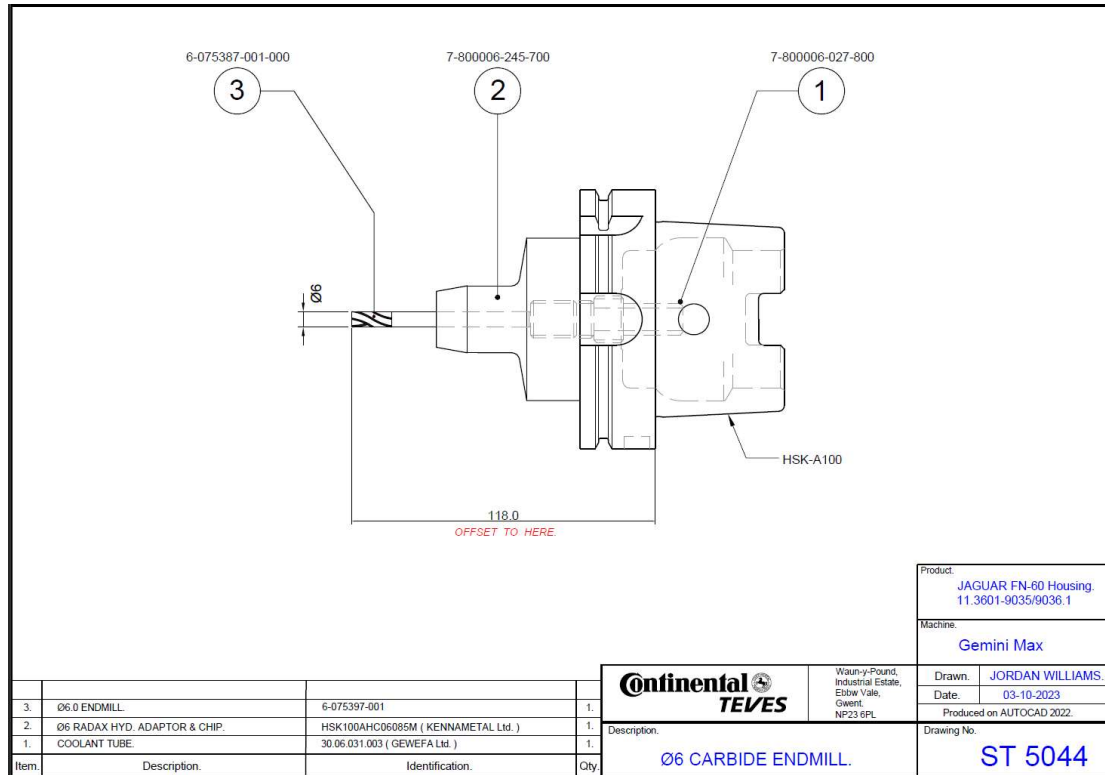


Figure 51 - ST 5044 (Ø6 Carbide Endmill)

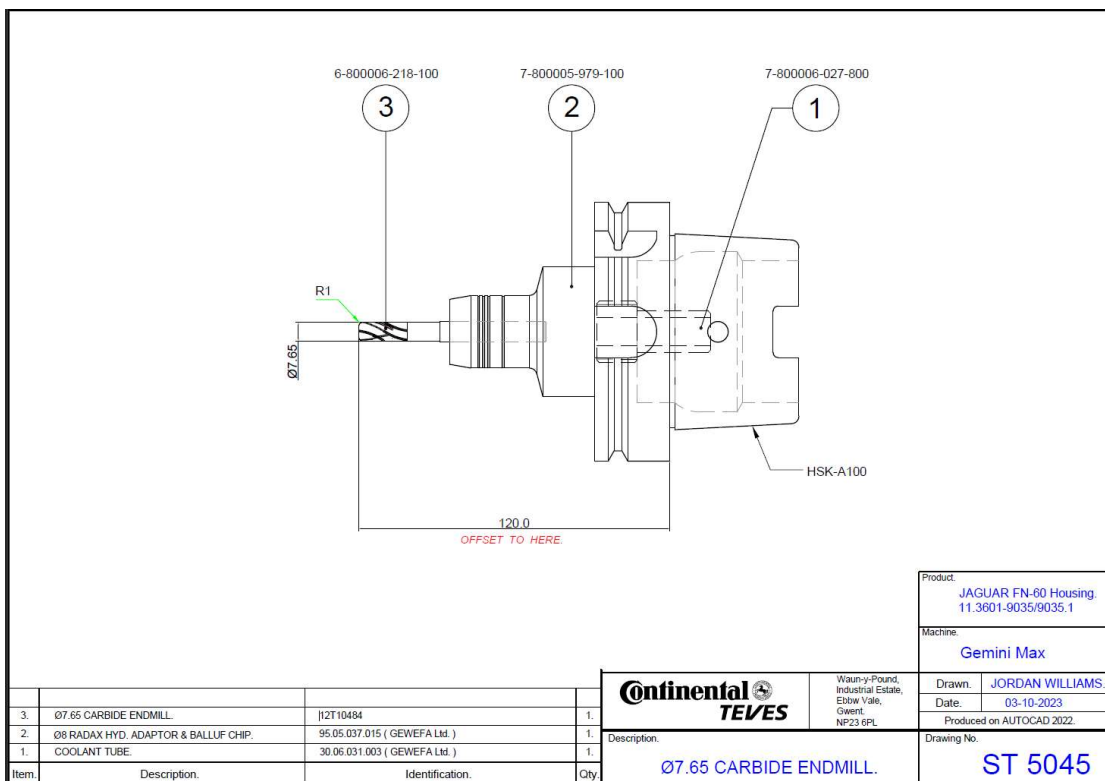


Figure 52 - ST 5045 (Ø7.65 Carbide Endmill)

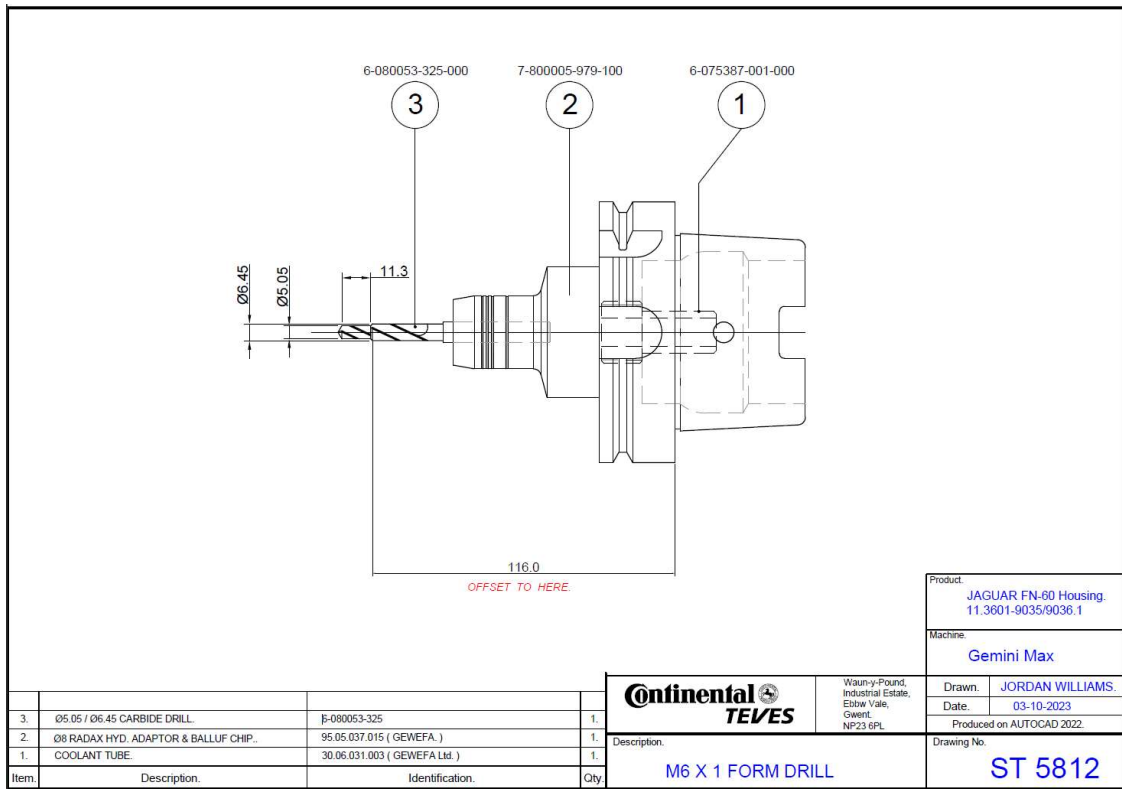


Figure 53 - ST 5812 (M6 Form Drill)

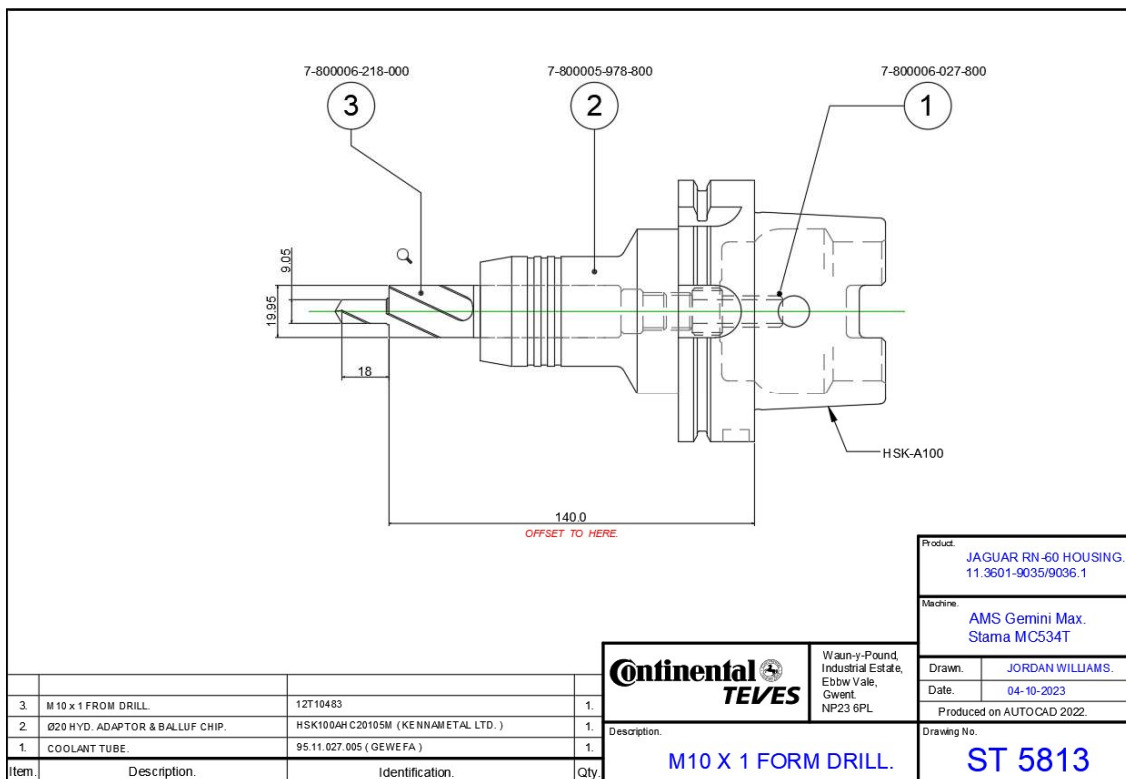


Figure 54 - ST 5813 (M10 Form Drill)

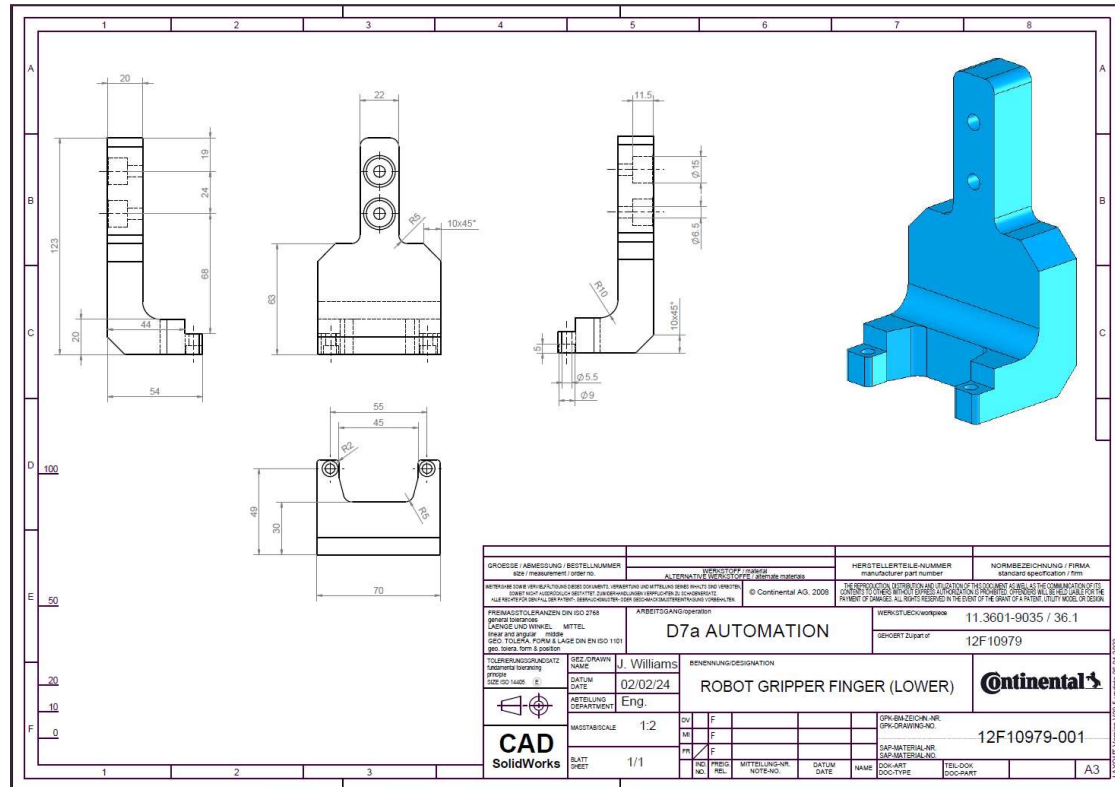


Figure 55 - Lower Gripper Finger (Technical Drawing)

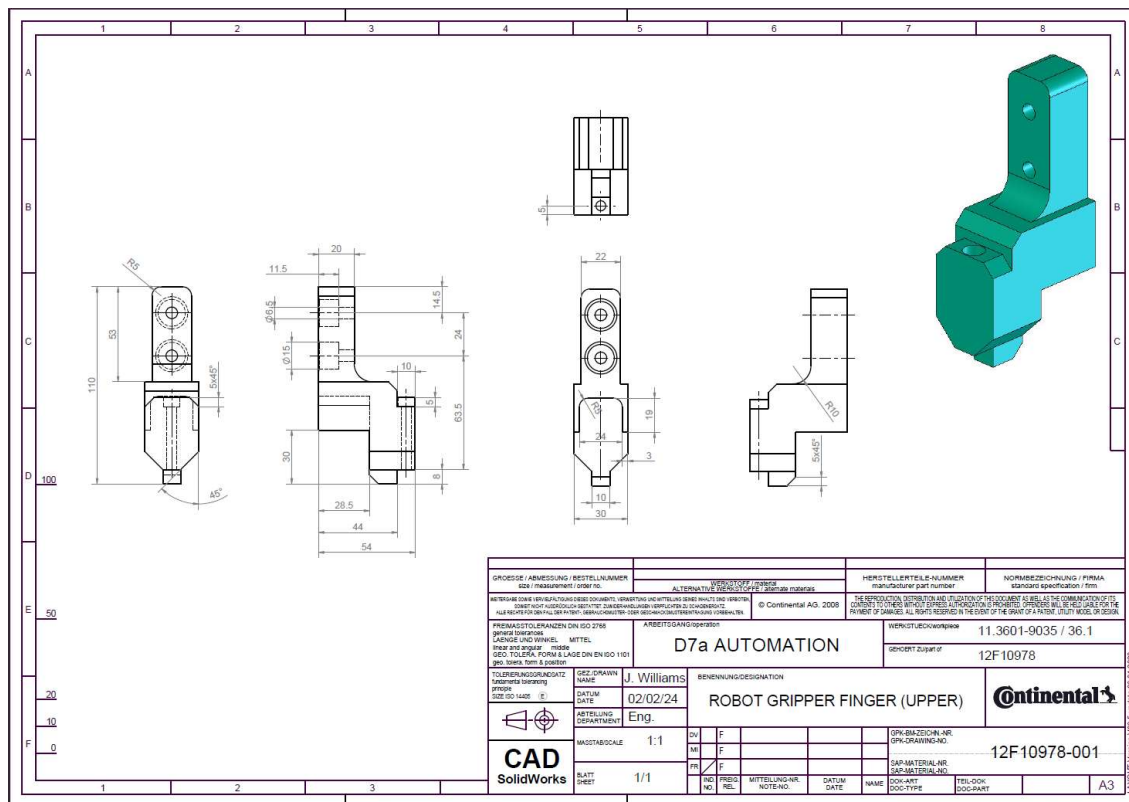


Figure 56 - Upper Gripper Finger (Technical Drawing)

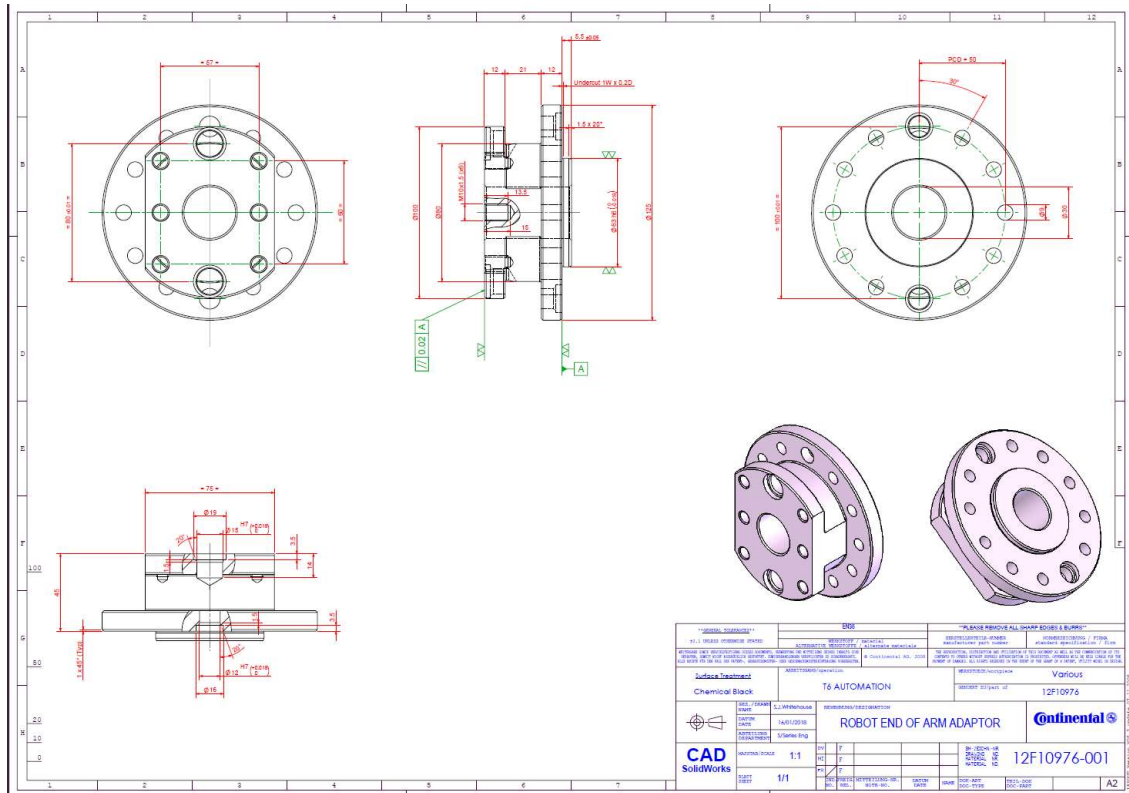


Figure 57 - Robot Adaptor (Technical Drawing)

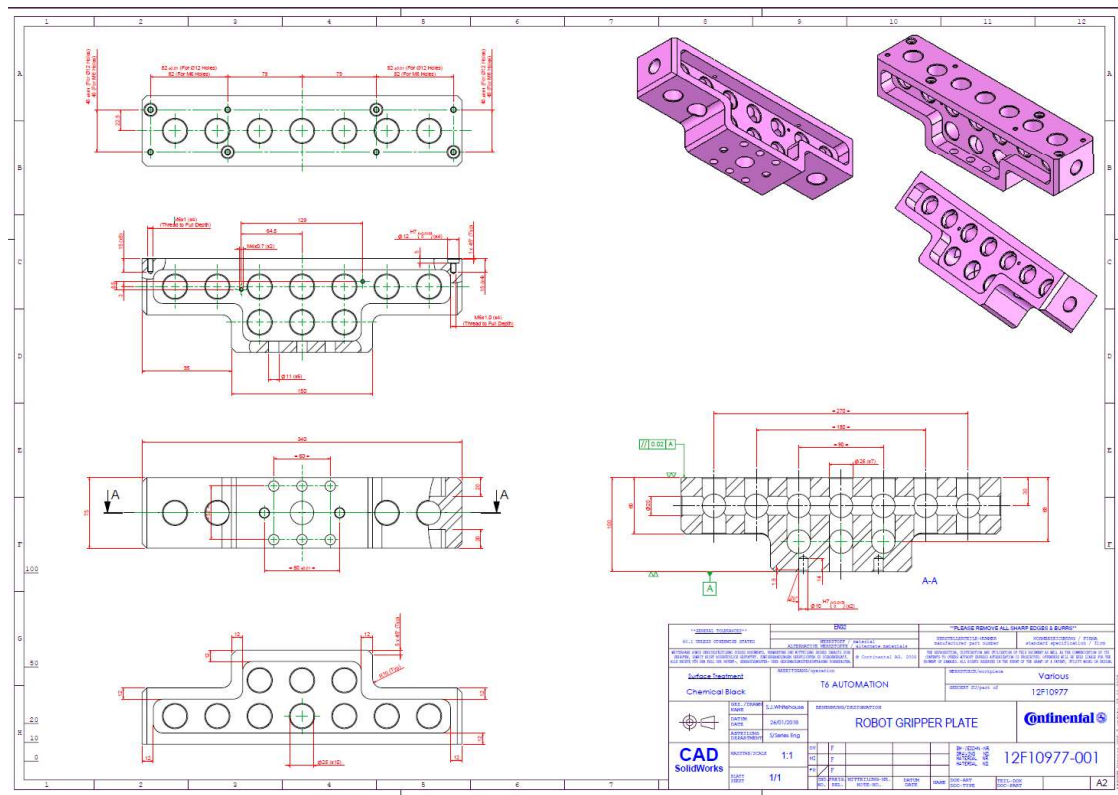


Figure 58- Gripper Plate (Technical Drawing)



Date:	Pages:	Filename:
25/03/2024 08:27:27	1	Y:\...\Uni\Major Project\Project\Programs\Gemini Max\11.3601-0417_0418.1 MP.nc

%
O6017(11.3601-0417-0418.1)
N10M98P7998(START TIMER)
(GEMINI MAX. 3)
(11.3601-0417/0418.1)
(RED JAGUAR FN+80 HOUSINGS)
(SUBS O1125 - O1137)
(J. WILLIAMS 25-01-2024)
(PROVEN PROGRAM)
(DOWNLOADED)(19-10-2019)
(CYCLE TIME 2 PARTS)(7 MIN 50 SECS)

(FIXT. CLAMP SEQUENCE NO. 3)
(ENSURE FLOW VALVE FULLY OPEN)

(#718=1 FOR 9035)
(#718=2 FOR 9036)
#718=1

N20G10L2P0X0Y0Z0B0
N30G17G21G40G80G94
N40G0G91G28Z0

N50M98P1125(ZERO OFFSETS)
N60GOTO#801
N70T02
N100M98P1126(MILL GUIDES ST5009 - T02)
N110M98P1127(MILL 18 DIA. SLOTS ST5013 - T03)
N120M98P1128(MILL 18 DIA. RECESS ST5014 - T04)
N130M98P1129(12 DIA. ENDMILL ST5015 - T05)
N140M98P1130(M5 FORM DRILL ST5803 - T06)
N150M98P1131(M5 TAP ST5903 - T07)
N160M98P1132(MILL DISC CLEARANCE ST5006 - T20)
N170M98P1133(59.6 DIA. BORE/CHAMF. ST5106 - T08)
N180M98P1134(BOOT GROOVE & FACE ST5202 - T09)
N190M98P1135(60.08 DIA. REAM ST5505 - T10)
N200M98P1136(SEAL GROOVE ST5306 - T11)
N210M98P1137(22.5 DIA. BUSH HOLES ST5705 - T12)
N215M98P1138(6.0 DIA ENDMILL ST5044 - T13)
N220M98P1139(7.65 DIA ENDMILL ST5045 - T14)
N225M98P1140(M6 FORM DRILL ST5812 - T15)
N230M98P1141(M6 TAP ST5900 - T16)
N235M98P1142(M10 FORM DRILL ST5813 - T17)
N240M98P1143(M10 TAP ST5901 - T18)
N245G0G91G28Z0
N250G91G28Y0
N255G91B-270
N260M5
N265M72
N270M98P7999(END TIMER)
N999M30
%

Figure 59 - AMS Gemini Max Program



Date:	Pages:	Filename:
25/03/2024 08:34:53	1	Y:\...Jordan Williams\Uni\Major Project\Project\Programs\Stama 530\STAMA PROGRAM.1
O6018(11.3601-0417-0418.1) N10M98P7998(START TIMER) (STAMA 04) (11.3601-0417/0418.1) (RED JAGUAR FN+80 HOUSINGS) (SUBS O1145 - O1148) (J. WILLIAMS 25-01-2024) (PROVEN PROGRAM) (DOWNLOADED)(19-10-2019) (CYCLE TIME 2 PARTS)(1 MIN 36 SECS) N20G10L2P0X0Y0Z0B0 N30G17G21G40G80G94 N40G0G91G28Z0 N50M98P1145(ZERO OFFSETS) N60GOTO#801 N70T02 N100M98P1146(M10 FORM DRILL ST1793 - T02) N110M98P1147(4 DIA DRILL ST1635 - T03) N120M98P1148(M10 TAP ST1797 - T04) N125M98P1149(PORT WASH - T05) N130G0G91G28Z0 N135G91G28Y0 N140G91B-270 N145M5 N150M72 N155M98P7999(END TIMER) N999M30		

Figure 60 - STAMMA-530 Program

```

1  /PROG D7a
2  /ATTR
3  OWNER          = MNEDITOR;
4  COMMENT        = "";
5  PROG_SIZE      = 1176;
6  CREATE         = DATE 15-11-23 TIME 14:01:38;
7  MODIFIED       = DATE //--// ;
8  FILE_NAME      = ;
9  VERSION        = 0;
10 LINE_COUNT = 59;
11 MEMORY_SIZE = 1708;
12 PROTECT        = READ_WRITE; 13 TCD: STACK_SIZE      = 0,
14     TASK_PRIORITY = 50,
15     TIME_SLICE    = 0, 16     BUSY_LAMP_OFF = 0,
17     ABORT_REQUEST = 0,
18     PAUSE_REQUEST = 0;
19     DEFAULT_GROUP = 1,*,*,*,*;
20     CONTROL_CODE  = 00000000 00000000;
21 /MN
22 1: LBL[1] ;
23 2: DO[41]=OFF ;
24 3: DO[42]=OFF ;
25 4: DO[43]=OFF ;
26 5: DO[44]=OFF ;
27 6: DO[45]=OFF ;
28 7: IF (DO[38]=ON AND DO[40]=OFF),JMP LBL[2] ;
29 8: IF (DO[40]=ON AND DO[38]=OFF),JMP LBL[2] ;
30 9: ;
31 10: ;
32 11: IF (DI[33]=ON AND DI[35]=OFF),CALL D7aPICKLOADTABLE ;
33 12: ;
34 13: ;
35 14: IF DI[34]=ON,CALL UNLOADCONVEYOR ;
36 15: ;
37 16: IF DI[37]=ON,CALL D7aPLACEMAX1 ;38 17: IF DI[38]=ON,CALL D7aPICKMAX1 ;
39 18: IF DI[39]=ON,CALL D7aPLACESDT1 ;
40 19: ;
41 20: ;
42 21: IF DI[41]=ON,CALL D7aPLACEMAX2 ;43 22: IF DI[42]=ON,CALL D7aPICKMAX2 ;
44 23: IF DI[43]=ON,CALL D7aPLACESDT2 ;
45 24: ;
46 25: ;
47 26: IF DI[45]=ON,CALL D7aPLACESTAMA ;
48 27: IF DI[46]=ON,CALL D7aPICKSTAMA ;
49 28: IF DI[47]=ON,CALL UNLOADCONVEYOR ;
50 29: ;
51 30: ;
52 31: IF DI[68]=ON,CALL D7aPICKREINTROM1 ;
53 32: IF DI[76]=ON,CALL D7aPICKREINTROM2 ;
54 33: ;
55 34: IF DI[75]=ON,JMP LBL[5] ;
56 35: ;
57 36: ;
58 37: JMP LBL[1] ;

```

Figure 61 - Preliminary Robot Program

Item	Qty.	Product description	GBP/unit net	GBP net sum
10	2 Piece	37371453 PGN+ 125-2-AS-SD 2-FINGER Universal 2-finger parallel gripper with large gripping force and high maximum moments thanks to multiple-tooth guide. Stroke per finger: 6.0 mm, 3040.0 N. Please note currently only 3 off available ex-stock Germany Shipping date: approx. 1 working week after receipt of order	538.30	1,076.60
20	4 Piece	0301478 IN 80/S-M8, PROXIMITY SWITCH PNP,CLOS.M 8X1,0X32 Shipping date: approx. 1 working week after receipt of order	30.53	122.12

Registered Office

Cromwell Business Centre
10 Howard Way
Interchange Park
Newport Pagnell
MK16 9QS
Great Britain

Tel. +44-1908-611127
Fax +44-1908-615525
info@gb.schunk.com
www.schunk.com

Registered in England,
No. 3488643
VAT No. GB 715 9191 21

Figure 62 – Schunk Gripper Specification

M-710 Series

Max. load capacity at wrist: 70 kg

Max. reach: 3123 mm

M-710C 50

Available robot versions:

M-710iC/12L, /20L	Long arm
M-710iC/20M, /45M	High inertia
M-710iC/50S	Short arm
M-710iC/50H	5-axis
M-710iC/50, /70	Standard model
M-710iC/50E	Offset wrist
M-710iC/50T, /70T	Top mount

Robot		Controller		Max load capacity at wrist (kg)	Reach (mm)	Controlled axes	Repeatability (mm)	Mechanical weight (kg)	Motion range (°)						Maximum speed (°/s)						J4 Moment/ Inertia (Nm/kgm²)	J5 Moment/ Inertia (Nm/kgm²)	J6 Moment/ Inertia (Nm/kgm²)	Average Power consumption (kW)	Protection						
Series	Version	Type	Version						Open or closed cabinet	Main cabinet	Sub-cabinet	J1	J2	J3	J4	J5	J6	J1	J2	J3					J4	J5	J6	Body standard/ optional	Wrist & J3 arm standard/ optional		
M-710	iC	12L	R-3008	-	•	•	•	12	3123	6	± 0.09**	540	360	225	434	400	380	720	180	180	180	400	430	22 0/0.65	22 0/0.65	9 8/0.17	2.5	IP54/IP67	IP67		
M-710	iC	20L	R-3008	-	•	•	•	20	3110	6	± 0.11**	540	360	225	432	400	280	900	175	175	180	350	360	400	39 2/0.88	39 2/0.88	19 4/0.25	2.5	IP54/IP67	IP67	
M-710	iC	20M	R-3008	-	•	•	•	20	2982	6	± 0.04**	530	360	225	435	400	280	900	175	175	180	350	360	400	39 2/0.88	39 2/0.88	19 4/0.25	2.5	IP54/IP67	IP67	
M-710	iC	40M	R-3008	-	•	•	•	45	3404	6	± 0.04**	570	360	225	440	800	250	800	180	180	180	250	250	240	204/0.28	204/0.28	122/0.05	2.5	IP54/IP67	IP67	
M-710	iC	50S	R-3008	-	•	•	•	50	1369	6	± 0.04**	545	360	169	376	720	250	720	175	175	175	250	250	355	204/0.28	204/0.28	122/0.11	2.5	IP54/IP67	IP67	
M-710	iC	50T	R-3008	-	•	•	•	50	1900**	6	± 0.07	410	**1)	261	491	720	250	720	**1)	175	175	175	250	250	355	204/0.28	204/0.28	122/0.11	2.5	IP54/IP67	IP67
M-710	iC	50H	R-3008	-	•	•	•	50	2053	5	± 0.15	540	360	225	440	234	720	-	175	175	175	175	720	-	150/4.3	48/2.5	-	2.5	IP54/IP67	IP67	
M-710	iC	50	R-3008	-	•	•	•	50	2050	6	± 0.04**	540	360	225	440	720	250	720	175	175	175	250	250	355	204/0.28	204/0.28	122/0.11	2.5	IP54/IP67	IP67	
M-710	iC	50E	R-3008	-	•	•	•	50	2050	6	± 0.07	560	360	225	440	720	380	720	175	175	175	250	240	340	204/0.28	204/0.28	98/3.3	2.5	IP54/IP67	IP67	
M-710	iC	70T	R-3008	-	•	•	•	70	1900**	6	± 0.07	410	**1)	261	491	720	250	720	**1)	120	120	120	225	225	225	294/0.28	294/0.28	147/0.11	2.5	IP54/IP67	IP67
M-710	iC	70	R-3008	-	•	•	•	70	2050	6	± 0.04**	560	360	225	440	720	250	720	160	120	120	225	225	225	294/0.28	294/0.28	147/0.11	2.5	IP54/IP67	IP67	

• standard ◊ on request - not available () with hardware and/or software option **1) depending on rail specification ** Based on ISO283

Figure 63 - Fanuc Robot Specification (Standard Model)

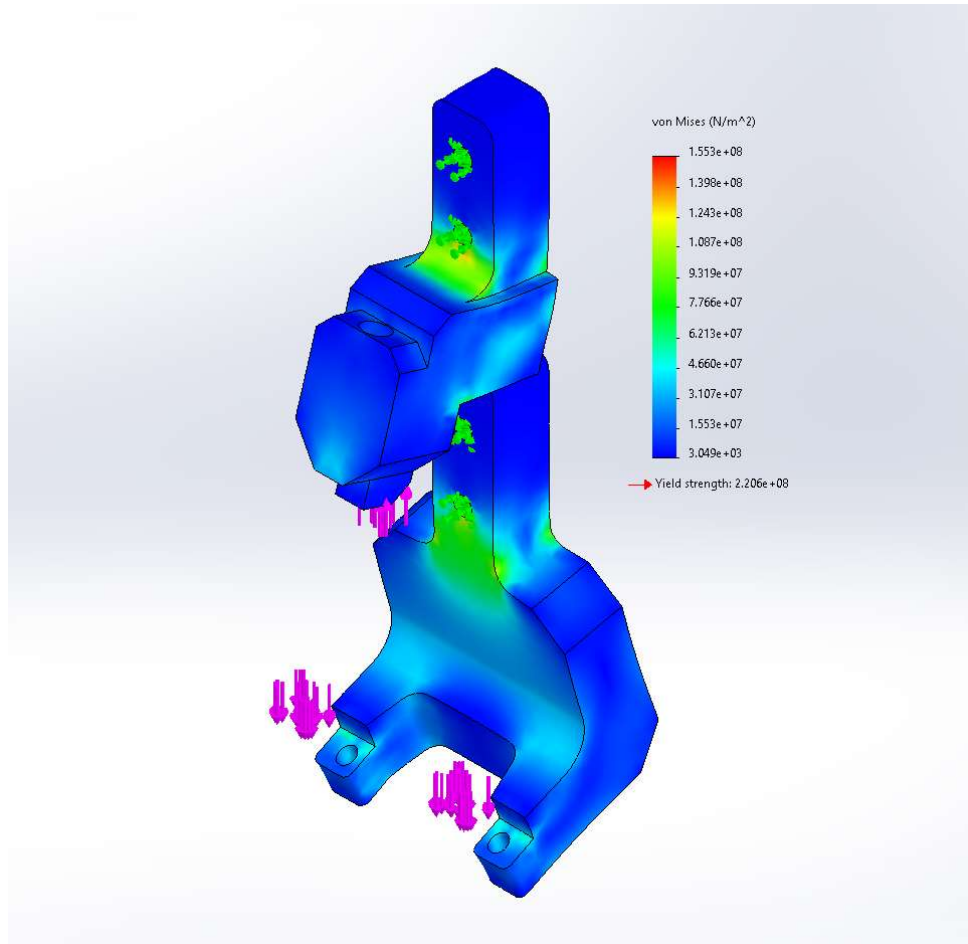


Figure 64 - Stress Analysis (3040N)

SEQUENCE OF OPERATION									
STEP NO.	WHO	DESCRIPTION	WHERE	CONFIRMED BY	TIME TAKEN (S)	CONCURRENT TO		SEQUENTIAL TO (DEFAULT IS CRITICAL PATH)	
						STEP NO.	DELAY (S)	STEP NO.	DELAY (S)
1	Machine	ROBOT MOVES TO MAX1			3	1		1	
2	Machine	UNLOAD MAX1 FX 1 GRIP 1			5	2		2	
3	Machine	UNLOAD MAX1 FX 2 GRIP 2			3	3		3	
4	Machine	MOVE TO SET DOWN TABLE 1			5	4		4	
5	Machine	PLACE FIX1 GRIP 1			3	5		5	
6	Machine	PLACE FIX2 GRIP 2			5	6		6	
7	Machine	ROBOT MOVE TO LOAD TABLE			3	7		7	
8	Machine	PICKGRIPPER 1			5	8		8	
9	Machine	PICKGRIPPER 2			3	9		9	
10	Machine	ROBOT MOVES TO MAX1			5	10		10	
11	Machine	LOAD MAX 1 FIX1 GRIP1			3	11		11	
12	Machine	LOAD MAX 1 FIX2 GRIP2			5	12		12	
13	Machine	MOVE MAX 1 SAFE			3	13		13	
14	Machine	MAX 1 CYCLE START			684	14		14	
15	Machine	ROBOT MOVES TO MAX2			3	15		15	
16	Machine	UNLOAD MAX2 FX 1 GRIP 1			5	16		16	
17	Machine	UNLOAD MAX2 FX 2 GRIP 2			3	17		17	
18	Machine	MOVE TO SET DOWN TABLE 2			3	18		18	
19	Machine	PLACE FIX1 GRIP1			3	19		19	
20	Machine	PLACE FIX2 GRIP2			5	20		20	
21	Machine	ROBOT MOVE TO LOAD TABLE			3	21		21	
22	Machine	PICKGRIPPER 1			5	22		22	
23	Machine	PICKGRIPPER 2			3	23		23	
24	Machine	ROBOT MOVES TO MAX2			5	24		24	
25	Machine	LOAD MAX 1 FIX1 GRIP2			3	25		25	
26	Machine	LOAD MAX 2 FIX2 GRIP2			5	26		26	
27	Machine	MOVE MAX 2 SAFE			3	27		27	
28	Machine	MAX 2 CYCLE START			708	28		28	
29	Machine	ROBOT MOVES TO STAMMA			3	29		29	
30	Machine	UNLOAD STAMA FIX 1 GRIP 1			5	30		30	
31	Machine	UNLOAD STAMA FIX 2 GRIP 2			3	31		31	
32	Machine	MOVE TO UNLOAD CONVEYOR			5	32		32	
33	Machine	PLACE GRIPPER 1			3	33		33	
34	Machine	PLACE GRIPPER 2			5	34		34	
35	Machine	MOVE TO SET DOWN TABLE 1			3	35		35	
36	Machine	PICK FX 1 GRIPPER 1			3	36		36	
37	Machine	MOVE TO SET DOWN TABLE 2			3	37		37	
38	Machine	PICK FX 1 GRIPPER 2			5	38		38	
39	Machine	ROBOT MOVE TO STAMA			3	39		39	
40	Machine	LOAD LH FIX GRIP 1			5	40		40	
41	Machine	LOAD RH FIX GRIP 2			3	41		41	
42	Machine	MOVE TO STAMA SAFE			5	42		42	
43	Machine	STAMA CYCLE START			120	43		43	
44	Machine	ROBOT MOVES TO STAMMA			5	44		44	
45	Machine	UNLOAD STAMA FIX 1 GRIP 1			3	45		45	
46	Machine	UNLOAD STAMA FIX 2 GRIP 2			5	46		46	
47	Machine	MOVE TO UNLOAD CONVEYOR			3	47		47	
48	Machine	PLACE GRIPPER 1			5	48		48	
49	Machine	PLACE GRIPPER 2			3	49		49	
50	Machine	MOVE TO SET DOWN TABLE 1			5	50		50	
51	Machine	PICK FX 2 GRIPPER 1			3	51		51	
52	Machine	MOVE TO SET DOWN TABLE 2			5	52		52	
53	Machine	PICK FX 2 GRIPPER 2			3	53		53	
54	Machine	ROBOT MOVE TO STAMA			3	54		54	
55	Machine	LOAD LH FIX GRIP 1			3	55		55	
56	Machine	LOAD RH FIX GRIP 2			5	56		56	
57	Machine	MOVE TO STAMA SAFE			3	57		57	
58	Machine	STAMA CYCLE START			120	58		58	
59	Machine	ROBOT MOVE TO HOME			3	59		59	

Figure 65 - Robot Timings