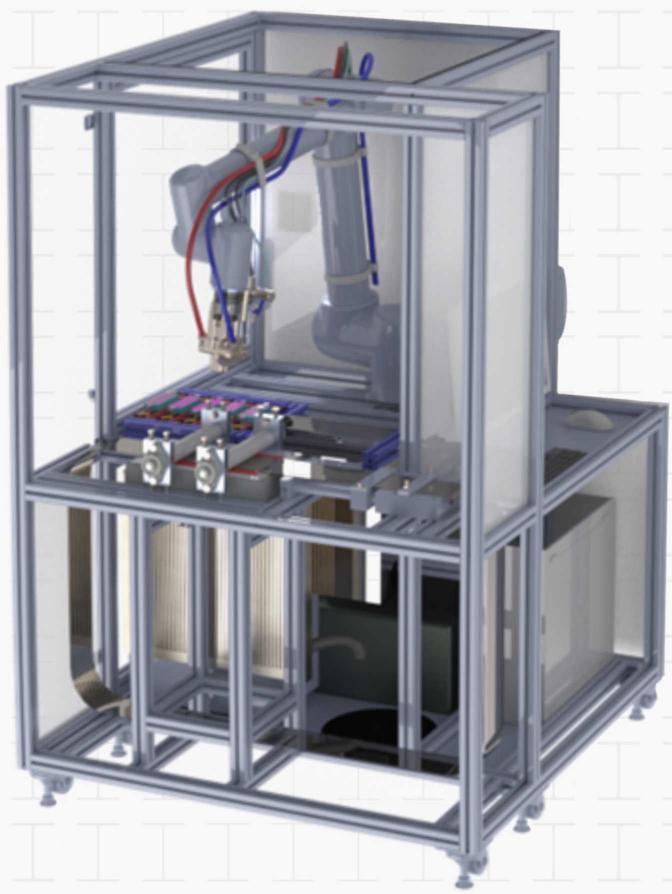
IMPERIAL COLLEGE LONDON
DEPARTMENT OF MECHANICAL ENGINEERING
ME3 DESIGN MAKE AND TEST PROJECT

DMT GROUP 8B
ULTRAMAN: ROBOT & TRANSMISSION

A NOVEL **ULTRA**-PRECISION AUTONOMOUS **MAN**UFACTURING PROCESS SIMULATOR WITH SMART FUNCTIONAL BLOCKS



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Executive Summary

The current industry standard for tribological testing, pin-on-disc testing, is extremely limited in replicating the hot stamping process, inspiring the development of a novel testing method by the Metal Forming and Modelling Group using a UR10 robot arm. However, this approach is labour-intensive and is still limited. ULTRAMAN aims to automate this testing and add additional functionality to significantly improve accuracy and autonomous runtime.

To achieve this, critical functionalities of the robot and transmission sub-assembly are needed, as identified in the QFD: accurate sample feeding, automated operation, adaptability and operator usability within a given budget criterion. The realisation of these requirements can be tied to the following individual systems of the robot and transmission sub-assembly that fulfil these criteria: precision feeder, stability anchors, control system, power circuitry and assembly integration. Thorough testing was conducted on all of these systems along with integration testing. The strip feeder transmission system exceeded the desired sample feeding accuracy of 2 ± 0.1 mm during all testing providing proper calibration protocols were followed. Stability was provided for flat plates but failed for rolled workpieces. The closed-feedback force control for the UR10 during testing did not work to specification due to issues with vibration and surface finish, requiring further adaptation. The control systems successfully integrated and controlled the robot, transmission, functional blocks and data acquisition systems for autonomous operation.

The ULTRAMAN successfully met most of its key requirements, demonstrating improved accuracy and automation in tribological testing. The system exceeded the planned budget by 17%, which was justified by the project's innovative nature. Future improvements should focus on enhancing the robot force control, extending autonomous run time, and improving the feeding mechanisms. Future recommendations include integrating actuators into the central system, adding safety panes, and considering additional sensor implementation to further enhance performance and reliability.

Version History

Version	Date	Author(s)	Revision Details
1.0.0	21/05/2024	M.S.	Structure drafted in LaTeX based on Blackboard template. Cover artwork added and customised document style.
2.0.0	30/05/2024	K.J-D.	First draft of super project overview
2.1.0	01/06/2024	All	Project description and testing protocols and statistical analysis techniques drafted
2.2.0	03/06/2024	All	Product description and super-project overview reviewed and changed
3.0.0	03/06/2024	All	Preliminary testing results incorporated into results sections, known limitations and predicted performance included
3.1.0	04/06/2024	All	Super-group testing results included, executive summary, discussions, conclusion and recommendations finalised. First complete draft
3.2.0	04/06/2024	All	Peer review of all sections, stylistic and content amendments
3.2.1	04/06/2024	All	Final linguistic changes and improved figures and pictures

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1 Super-Project Overview

Metal forming is a manufacturing technique extensively utilised to shape metals into functional products and components. However, despite its integral role in the automotive, aerospace, and construction industries, metal forming's advancement is still severely limited by the current inefficient pin-on-disc or largely hand-operated testing setups.

This super-project aims to improve the precision, efficiency, and safety of the industry standard for metal forming testing by automating much of the testing process with the assistance of a robotic arm and smart functional blocks to simulate the die-lubricant-metal interactions. More specifically, the super-project aims to achieve the following objectives:

1. Simulate the hot stamping manufacturing processes.
2. Characterise tribological interactions between metal blanks and tooling materials.
3. Implement data-driven continuous friction testing to replicate multi-cycle serial manufacturing.
4. Ensure precise and adaptable motion, alongside temperature and load control during testing.
5. Enable autonomous pin polishing, cleansing, lubrication, and blank feeding.

To efficiently realise these objectives, the super-project was divided into three sub-assemblies, each performing different roles in the super-assembly, namely: Structure & Heating, Transmission & Robotics, and Functional Blocks.

The Structure & Heating sub-assembly comprises a robust, portable test frame equipped with an integrated contact heater. The test frame features a modular construction achieved using an aluminium-extrusion skeleton with acrylic shielding in between. This modular design enables seamless adaptation for supporting and integrating with the other two sub-assemblies. Additionally, the airtight enclosure formed by the acrylic shielding enhances the effectiveness of the air filtration system, capturing lubricant fumes emitted during testing. Integrated with the frame, the contact heater is constructed from ceramic and steel, ensuring its capability to sustain at least two hours of continuous testing at 550°C. This closely mimics real manufacturing conditions for aluminium and steel, thereby validating the accuracy of testing results.

The Transmission & Robotics sub-assembly, which is the focus of this report, consists of a modified AF-4C pneumatic strip feeder, a UR-10 robotic arm, and accompanying subsystems to support their functionality. The strip feeder ensures precise linear movement of blanks, while a pair of high-temperature ceramic press-rollers apply downward force to fully secure the blank. This mechanical setup is seamlessly integrated with the robotic arm through a Python-based central control system, utilising a network of Ethernet and power connections. This integration enables the robotic arm to collaborate with the feeder, automating simulated testing procedures such as scratching, grinding, and dipping, all while maintaining data logging capabilities for at least two hours.

The Functional Blocks sub-assembly consists of the pin sample holder, pin sample grinding, and lubrication modules. The holder module secures the pin sample to the UR-10 robotic arm, ensuring efficient cooling with leak- and corrosion-resistant design for temperatures up to 600°C. The grinding module maintains a consistent speed to process the pin sample abrasively, minimising contamination and preventing galling. The blank lubricating module is integrated into the main control system via Arduino for pinpoint timing during automated test cycles and evenly dispenses lubricant onto blanks using a specialised nozzle with precision of $\pm$ 1 mm. The pin lubricating system provides as an alternative to blank lubrication, applying powder lubricant to the pin every six seconds, and accommodating various lubricants for adaptability in chosen testing conditions.

2 Project Description

2.1 Product-Design-Specification (PDS) Review

Based on end-user input, the broader aims of the super-group product were discretised into PDS requirements more specific to the Transmission & Robotics sub-assembly. These requirements cover aspects from 'ease-of-cleaning' to 'noise levels', but from Quality-Function-Deployment (QFD) assessments, the following PDS highlights were identified as most important to user benefit realisation:

1. **Precision:** linear sample feeding precision of 2 $\pm$ 0.1 mm onto a stable flat testing surface.
2. **Autonomy:** up to 2 hrs of autonomous grinding, lubrication, and scratching manoeuvres complete with data collection.
3. **Adaptability:** tolerates variations in sample thickness (0.5-1.5 mm) and temperature (up to $550°$C for Aluminium/Steel testing).
4. **Usability:** system is intuitive to use (UI), safe to operate (no exposed hazards), and portable (2 x 1.4 m footprint).
5. **Cost:** total cost within subassembly project budget of £1400.

It should be noted that discrepancies in the above values from the original PDS are owe to changes requested by the team (on the grounds of unforeseen logistical challenges) approved by the client.

In the following sections, the fulfilment of the above five highlights will be justified through an examination of their relationship to the manufactured product, as well as a review of the total spending. The numbering of these highlights will be referenced in the section below for conciseness.

2.2 Performance Verification

This section assesses the performance of the final product according to the identified critical functionalities. To facilitate rigour in the examination process, the product will be divided into the following functional aspects, and their contributions to the PDS critical functionalities will be scrutinised in turn:

1. **Precision Feeder:** mechanism(s) responsible for the linear movement of the sample.
2. **Stability Anchors:** mechanism(s) responsible for the stability and flatness of the sample..
3. **Control System:** software aspect of the mechatronics, centring on communication protocols.
4. **Power Circuitry:** hardware facet of the mechatronics, focusing on the electrical network..
5. **Assembly Integration:** the internal layout and external compatibility considerations.

2.2.1 Precision Feeder - Figure 1

With the aid of a journal article by Cetinkaya, a pneumatic strip feeder was chosen as the linear transmission, as opposed to mechanically actuated feeders [1]. In [1], the author compared the surface damage between the two feeder archetypes, and concluded that pneumatic feeders were the most practical for factory usage due to convenience and only a minor difference in surface scratch width (0.02 mm vs 0.04 mm). The AF-4C model from Henli was chosen due to its translational tolerance of $\pm$ 0.08mm. As shown in the testing section below, this contributed to the fulfilment of Critical Functionality 1 (Precision). Initially, in the PDS it was stated that blank thicknesses should be between 1 and 2 mm, but due to cost constraints the strip feeder chosen only enabled blank thicknesses of up to 1.5 mm, satisfying the updated Critical Functionality 3 (Adaptability). The end user of the ULTRAMAN agreed that this reduction in thickness capability was justified.

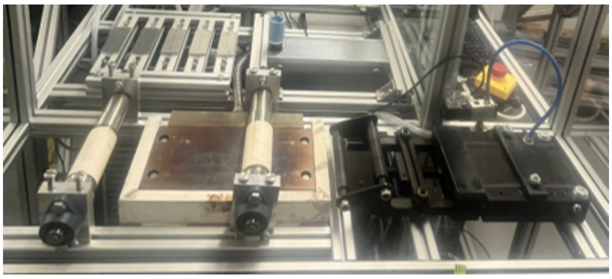


Figure 1: Pneumatic strip feeder and press roller sub-assembly

2.2.2 Stability Anchor - Figure 1

During the automated testing operation using the UR10 robot, it is crucial that the metal blank is rigidly secured against movement from the scratching or bowing of the sample as this could affect the accuracy of the collected data. Therefore, in addition to the horizontal constraints of the pneumatic strip feeder, two press rollers were used to apply a vertical force of 94.18N on the test sample. This normal force applied to the metal blank during testing was calculated to be sufficient in ensuring the stability of the metal blank in all directions during testing while maintaining enough compliance for feeding, satisfying Critical Functionality 1 (Precision). Additionally, the rollers also assist with uniform heating on the contact heater, preventing the formation of hot spots. Due to complexity, size requirements, and cost restraints, it was decided to use a passive clamping system rather than an actuated one which would be needed for the previously ideated and discarded screw clamp or jaw clamp designs.

2.2.3 Control System

The control system is one of the primary contributors to the fulfilment of Critical Functionality 2 (Autonomy). Through the employment of actuator-specific communication protocols within a centralised Python control framework, the system reliably coordinates the UR10 arm, the pneumatic actuators, and the PC to perform collaborative manoeuvres (e.g. lubrication).

For the UR10 arm, autonomy is manifested through its automated data logging and execution of complex work cycles. The UR native language - URScript - is only capable of storing joint positions to be followed and is unsupportive of exporting output or altering routines without extensive manual work. This was amended by coupling URScript with Python through the Real-Time-Data-Exchange (RTDE) protocol library, which allows real-time data exchange at 125 Hz with minimal wiring (for details on the programme design, Appendix C provides a detailed analysis of the control system architecture). In turn, this facilitates the use of Python to extract testing data (force, position, time, etc.) into CSV files, and to generate complex work cycles such as shuffling scratching, dipping, and grinding movements via the non-linear execution of URScript positioning commands.

For the pneumatic actuators connected to the feeder and sprayers, autonomy was manifested through remote actuation of custom toggling routines with no minimal input. Similar to the UR10, the valves - which respond to High/Low voltage levels across - need to be integrated into the digital framework. This is done via serial communication with an Arduino that provides the voltage needed, with the toggling routines stored on the Arduino executable with the call of a custom function on the Python end. Altogether, this allows the precise timing-based toggling routines to be triggered with only a function call. Together, the UR10 and the pneumatic actuators are centrally controlled via the main Python script framework. This allows the timing between different actuator functions to be lined up precisely and reliably (the PC's internal clock of 18.2 Hz is of sufficient timing resolution), such as the on/off spray controls upon arriving at certain UR10 waypoints to achieve complete autonomy that also maximises time/movement efficiency to achieve work cycles of <6s/scratch. More detail on programming is shown in Appendix C.

In summary, the implementation of the centralised Python control system enables the autonomous operation to be sustained as long as needed ($>$ 2 hours, assuming the material sample is sufficiently fed and stored) in conjunction with the Power Circuit mentioned next. Future improvements that could be considered include integrating all other actuators (heater - currently standalone PID controlled; fan - currently always on; etc.) into the system to achieve further performance/efficiency improvements, adding safety panes to robot movements to improve Critical Functionality 4 (Usability), and the consideration of sensor-use to improve reliability of coordination, allowing for preventive maintenance rather than reactive maintenance of the system, and preparing the ULTRAMAN system for integration with the factories of the future [3].

2.2.4 Power Circuitry

In order to control the movement of the pneumatic strip feeder, an Arduino Uno was used with a 5V DC to 220V AC relay to control a 220V AC solenoid valve. Using the code shown in Appendix C, signals can be sent to the solenoid valve thus controlling the movement of the pneumatic strip feeder.

To protect the wiring insider from detaching from its connections due to vibrations moving components in the design, jump wires were soldered to the relay and the Arduino pins, and connection blocks were used to join wires together at the node points as shown in Figure 1 to guarantee Critical Functionality 4 (Usability).

The circuitry elements were contained in a thermoplastic junction box which was used to hold the Arduino Uno, relays, and AC-DC converter used for Group C. The junction box is IP65 rated meaning that it is dust-tight, and it safeguards wiring against contaminants and moisture, an important consideration as the project deals with lubricants, thus ensuring Critical Functionality 4 (Usability) was fulfilled. Compression glands (IP68 rated) keep a tight seal around wiring going to and out of the junction box and ensure a dust and moisture-free environment for the circuitry inside the junction box. To prevent electric shocks to the user, if any wires were to be exposed, the pneumatic strip feeder and the main frame were grounded.

Since all components are powered by mains, it was crucial to establish a layout for all the components that require power. As described in the manufacturing review, the contact heater would require its own plug, directly connected to mains due to its 13A and 3000W power usage which is all that mains provide. All other components fall under the power available from mains: 30W monitor, 20W router, 300W PC, 500W UR10, 30W control box (including solenoid valves), and 110W nozzle sprayer (for group C). For convenience and to add another safety layer, having an extension cable for the PC, monitor and router separated from the rest of the components was deemed most effective. An additional safety level was an emergency stop used if the valves started to malfunction, as shown in Figure 2.

The design of the control box and the layout of how each component is powered were specifically designed to validate the completion of safe autonomous operation, thus fulfilling Critical Functionality 2 (Autonomy) and Critical Functionality 4 (Usability).

2.2.5 Assembly Integration

The initial layout of components was planned in CAD and approved by the super-group in previous gateways to minimise the footprint of the sub-assembly of the overall project to meet the sizing requirements of 1.5 x 0.8 m. During the physical assembly process, further care was made to verify no sub-optimal routing leading to collisions with other subsystems or the acrylic safety panes via testing of individual movements, and electrical safety was prioritised by having emergency switches all within proximity and wiring all discreetly situated within the assembly storage area.

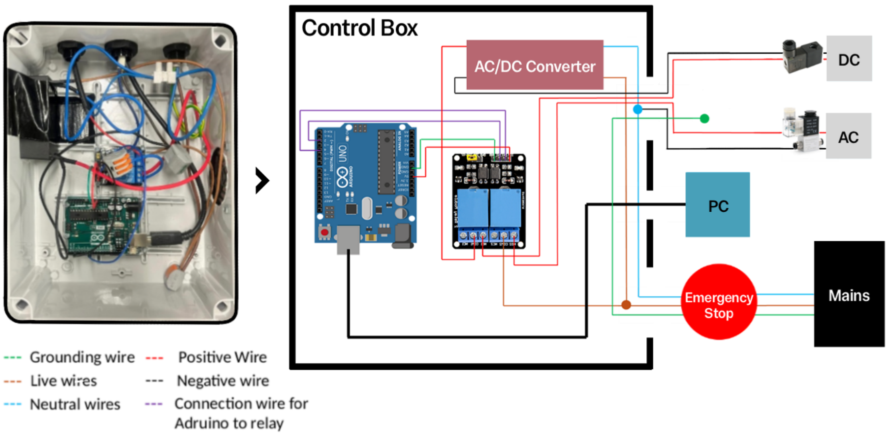


Figure 2: Control Box Schematic

Overall, the above usability considerations (Critical Functionality 4) for the end-user primarily in the aspects of portability and safety were present throughout the assembly process and allowed the project to seamlessly coordinate with the rest of the super-project, as discussed in the upcoming testing sections.

2.3 Spending Evaluation

During the preparation for the manufacturing review are budget was set to £1400 due to a more accurate list of parts being developed, and, due to high-temperature requirements shown in the PDS, unconventional materials would need to be bought and to implement contingencies where it may be important to pay more for delivery services to ensure an adequate lead time. Consequently, the pneumatic strip feeder had a total projected cost of £508.25, the press roller mechanism had a total projected cost of £457.79 and the mechatronics system totalled £117.10, as shown in Table 1. This amounted to £1083.51 and an extra £300 was requested as a contingency for issues that were encountered during manufacturing.

Throughout the manufacturing and assembly process, various factors led to increased project expenses. These included the need to purchase expedited courier services, manufacturing errors, and unused components for the final assembly. Consequently, the total spending reached £1613.24, as detailed in Table 1. The cost performance index (CPI) for this project was 0.867, which is considered acceptable given the project's unique nature. Since this project lacked a template or previous version for comparison, expenses increased to ensure a successful project within the time constraints were justified.

Table 1: Projected Budget and Actual Spending for Various Subsystems

Subsystem	Projected Budget	Actual Spending
Pneumatic Strip Feeder	£508.62	£773.38
Press Rollers	£457.79	£592.39
Mechatronics	£117.10	£201.00
Testing Metal	£0.00	£46.57
Contingency	£316.49	£0.00
Sum	£1400.00	£1613.34

A comprehensive breakdown of expenditure is provided in Table 4, located in Appendix A.

3 Accuracy Test

3.1 Aims

This test addresses the 'ultra-precision' aspect of the ULTRAMAN project. According to the Product Design Specification, the distance between scratches on the tested sample must be maintained at 2 ± 0.1 mm. This requirement is the most critical performance criterion that sub-group 8B is responsible for. The primary aims of this test are:

1. To validate strip feeder synchronicity with UR10 robot arm.
2. To validate that scratches produced by the UR10 robot arm are parallel.
3. To validate whether the required distance of 2 ± 0.1 mm between scratches is met
4. To assess any trends in accuracy and precision as the operation continues
5. To determine the optimal operating pressure for the AF-4C strip feeder.

3.2 Background & Justification

The AF-4C strip feeder was identified as the primary variable influencing the distance between scratches, as it controls the translational movement of the sample. Additionally, the UR10 robot arm, with a precision of $\pm$ 0.1 mm, and the stickiness of the sample at high temperatures were also considered.

However, since the UR10 robot arm operated in a direction orthogonal to the direction between the scratches, any positional error in its movement does not affect the spacing between the scratches. This makes the robot arm theoretically infinitely precise in maintaining the required distance between scratches. Furthermore, in real operation, the sample was thoroughly lubricated, minimising the effect of metal stickiness at high temperatures. Thus, it was reasonable to assume that friction arising from temperature effects would not significantly affect the accuracy of the distance between scratches.

The manufacturer claims that the AF-4C strip feeder operates with a tolerance of $\pm$ 0.08 mm which needed to be independently verified. Pilot testing showed that while the strip feeder was rated for the compressed air intake at 4.5 bar, it was functional at much lower pressures due to the relatively low force demands of the application compared to typical industrial uses. Operating the strip feeder at pressures of 4.5 bar and above was also found to cause damage to the surface finish of the tested samples due to the high clamping force. The end user expressed that maintaining the surface finish of the tested sample, while not the most important consideration, was ideal for examination and study after testing. In addition, operating at lower pressures would result in reduced vibrations in the aluminium extrusions and a safer structure for the ULTRAMAN. This motivated the need to determine an optimal operating pressure for the strip feeder that satisfied accuracy requirements while minimising surface damage to the samples.

3.3 Preliminary Testing

Two preliminary tests were conducted before the sub-system accuracy test, which required the majority of the ULTRAMAN to be assembled — a process that was still underway. These preliminary tests allowed for the early validation of individual functions, providing time for necessary adjustments. The first test focused on the strip feeder's accuracy, while the second assessed the synchronicity of the UR10 and AF-4C strip feeder.

3.3.1 AF-4C Preliminary Accuracy Test

The first preliminary test aimed to independently verify the stated tolerance of the AF-4C, a specification critical in ensuring accurate scratch spacing. The requirement of 2 mm spacing between scratches also needed to be calibrated and checked. To do this, an aluminium blank with dimensions 500 mm x 100 mm x 0.5 mm was prepared and a section was covered with marking blue. The strip feeder was initially calibrated by using vernier callipers to measure the distance between the nylon gasket and the edge of the moving clamp and using the adjustment screw to set this distance to 2 mm. The blank was inserted into the strip feeder, a vertical line was scribed at the starting position, and 10 cycles of blank translation were carried out. A line was then scribed at the ending position, and the distance between the two lines was measured using callipers and an alignment block. From the stated tolerance of $\pm$ 0.08 mm, the line spacing should have been measured at 20 $\pm$ 0.8 mm.

Table 2: Results of Preliminary AF-4C Testing

	Distance (mm)			
	Run 1	Run 2	Run 3	Target
Iteration 1	30.4	30.4	30.3	20.0 $\pm$ 0.8
Iteration 2	20.0	20.2	20.3	

Table 2 shows the collected data. The first iteration of testing revealed high precision but low accuracy, indicating a calibration issue rather than a problem with the strip feeder's function. Consequently, a second iteration was performed using a 2 mm slip gauge from the student teaching workshop to set the distance between the nylon gasket and the moving clamp edge, effectively resolving the calibration issue. This preliminary testing confirmed that the stated accuracy was not only met but also conservative.

To investigate an 'optimal pressure' this test was then repeated at an intake pressure of 2 bar. Accuracy was maintained at this lower pressure, but the tractive force of the strip feeder was seen to be noticeably lower. After considering the additional loads of the two-press roller and the likeliness of thermal expansion and blank sticking, it was decided that the recommended pressure of 4.5 bar was to be used.

3.3.2 UR10 & AF-4C Synchronicity Test

To ensure the system ran smoothly, all its moving parts needed to function accurately and reliably. A focus for the sub-group was testing the synchronisation between the UR10 robot arm and the strip feeder's movement. It was essential that the strip feeder remained stationary whenever the UR10 robot was scratching the metal blank and that it only performed a single 2 mm movement per vertical scratch.

During the initial test, the strip feeder's movement appeared erratic compared to the UR10 robot. This issue was traced back to the Arduino not receiving the complete data packet when it sent a command to operate the pneumatic strip feeder. To resolve this, the code was modified to keep the connection to the Arduino open until all command data was transmitted. This change ensured reliable communication with the strip feeder, resulting in a synchronised system. No quantitative data was taken during this test, but a video was recorded and inspected frame-by-frame to ensure synchronicity.

3.4 Sub-System Accuracy Test

3.4.1 Method and Setup

The ULTRAMAN was operated at reduced functionality, using only the strip feeder and UR10 control codes. UR10 interaction with the functional blocks, the lubrication spray, the PID heater, cooling systems and other subsystems were disabled .

An aluminium rolled sample, 1 m in length, was prepared and fed through the press rollers and the strip feeder. The pressure regulator valve was set to 4.5 bar and the UR10 and Arduino code were executed to begin testing. 50 scratches were produced for data processing.

Photographs of the tested sample were taken using an overhead camera setup, courtesy of the Mechanics of Materials research group with assistance from PhD student Peter Hanna.

3.4.2 Data Processing and Interpretation

The photographs of the tested sample were processed using ImageJ software. Preparing the photographs for processing involved converting the images to grayscale, enhancing contrast, thresholding and removing noise to create a binary image where the scratches were white, and the background was black as shown in Figure 3. A custom macro was then recorded to automate the detection of the scratches and measure the distance between them. From this the sample mean and variances at each three pressure settings were computed using python.

$$\bar{x} = \frac{1}{50}\sum_{i=1}^{50} x_i \quad s^2 = \frac{1}{49}\sum_{i=1}^{100}(x_i - \bar{x})^2$$

Confidence intervals for the mean scratching distance were constructed using the Student's t-distribution with 49 degrees of freedom, at 90%, 95%, and 99% confidence levels (Table 3):

$$\mathsf{CI} = \bar{x} \pm \ t_{\frac{\alpha}{2},49} \cdot \frac{s}{\sqrt{50}}$$

If these confidence intervals fall within 2 ± 0.1 mm, we fail to reject the hypothesis that the accuracy of the scratching process meets the specified requirements, and the test is said to be passed at the given confidence level.

Given that the testing produces only 50 scratches, while the actual operation involves up to 1200 scratches, it was also crucial to determine if any trends in accuracy emerged as the procedure continued. Although accuracy and precision requirements may be met in a sample of 50 scratches, even a slight decline over time could become significant by the 1200th scratch, potentially leading to a substantial underperformance of the required 2 ± 0.1 mm accuracy

To investigate this, an ordinary least squares regression was performed on the scratches produced at a scratching pressure of 4.5 bar to analyse the relationship between the error in the scratch distance and the scratch number. The resulting R^2 coefficient was then examined to assess the significance of these trends.

3.4.3 Results and Discussion

Figures 4a and 4b show the results of our sub-group test looking at the scratching accuracy of the UR10 robot arm and pneumatic strip feeder transmission. The scratch spacing is shown to be slightly out of the required tolerance of 2 ± 0.1 mm, with values centring around 2.128 mm. The tolerance of $\pm$ 0.1mm was adhered to however, which again suggests a minor calibration error that was only revealed due to the increased accuracy in scratch spacing measurements from using ImageJ, as opposed to the caliper measurements in the preliminary strip feeder accuracy test. This was subsequently corrected for the super-project test by iteratively making minute adjustments to the distance screw and measuring a set of 10 scratches. Recommendations were also made to not rely on the distance locking mechanism of the strip feeder, and instead to recalibrate the distance every time to improve accuracy.

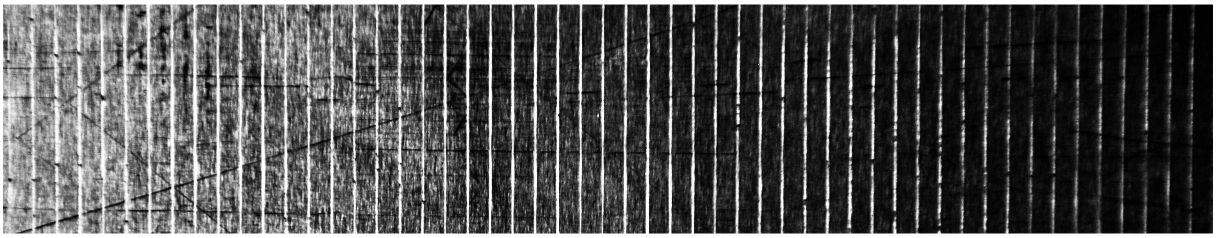
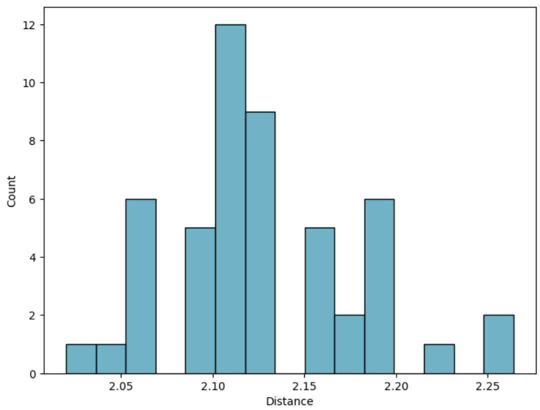


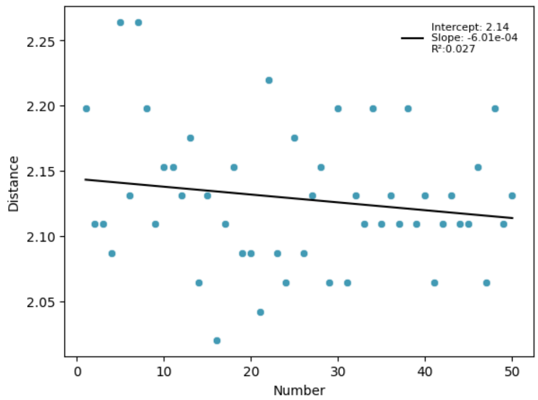
Figure 3: Photograph of Tested Sample processed using ImageJ. Scratches Parallel as Required.

Table 3: Sample Statistics and Confidence Intervals

Sample Mean and Variance		$\bar{x}$ Confidence Intervals		
$\bar{x}$	s^2	90%	95%	99%
2.128	2.833e-3	[2.116, 2.141]	[2.113, 2.144]	[2.108, 2.149]



(a) Distribution of scratch spacing



(b) OLS Regression Analysis of Scratch Spacing and Scratch Number

Figure 4: Statistics and Machine Learning Visualisations

An R^2 coefficient of means only 2.7% of the variance in scratch distance can be explained by scratch number. Therefore, it can confidently assumed there is no significant trends that would affect accuracy later in operation.

One important limitation of this test was the discovery of excess bowing of the 0.5 mm thick aluminium roll workpiece. This led to vertical deviation of the UR10 head, rendering the initial scratch data invalid. This bowing likely occurred due to an underestimate in stiffness and was rectified by switching to a 1 mm thick flat aluminium workpiece. This new workpiece maintained planar contact with the testing surface, allowing for the collection of useful scratch data. Despite this improvement, the ability to use rolls of blanks remains a crucial part of meeting the original PDS requirement of 8-hour autonomous testing. Methods of incorporating rolls of blanks are discussed further in the Conclusions and Recommendations section.

4 Endurance Test

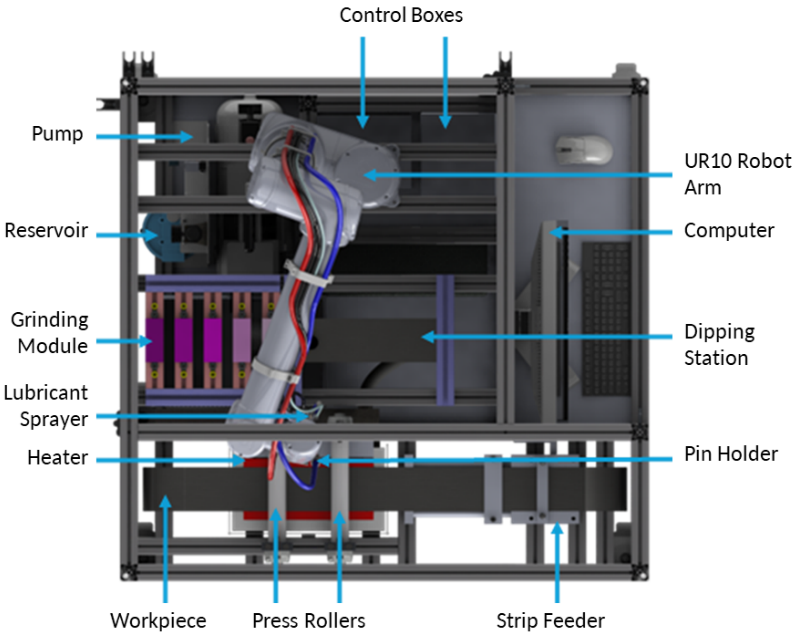


Figure 5: Top-Down render of ULTRAMAN with core components labeled

4.1 Aims

The super-project test was built upon many successful sub-assembly tests to ensure that each individual system functioned independently and safely. The ULTRAMAN endurance test's primary objective was to collect friction force data using the load cell integrated into the UR10 robot arm, as this is the data that is most useful to the end users. To collect this data, all of the individual systems shown in Figure 5 needed to work together seamlessly. Therefore, a core part of the super project test was the overall system integration. The most relevant metrics that quantify the level of integration between the sub-groups apart from the friction for data were temperature changes, vibration measurements, and cycle times. Throughout the process, additional metrics such as airflow within the case, lubrication actuation, and any other necessary observations were monitored through visual inspection.

4.2 Justification

The key purpose of the ULTRAMAN system was to provide an autonomous, lights-out simulation of the hot metal stamping process. Our meaningful super-group test reflects this purpose by combining the functionality of 8A's frame and heating, 8B's transmission, blank constraint and UR10 robot arm control, and 8C's functional blocks, including a grinding module, plate lubrication, pin lubrication and pin cooling. By starting the system and letting it run for as many consecutive cycles as possible, the data collected was able to be analysed to check whether it was suitable for extrapolation to a significantly longer period.

Another important purpose of ULTRAMAN was to aid Dr Xiao Yang with her research in the performance of lubricants as part of the metal-forming group. Our system aims to automate her current manual testing setup as described in [5], and therefore justification of our super-group test is provided since one of our key aims is to gather force data and compare it to her previous testing to ensure the ULTRAMAN system would be useful to her future data collection. However, since our testing setup is novel compared to her manual setup, some deviation in the data collected is expected.

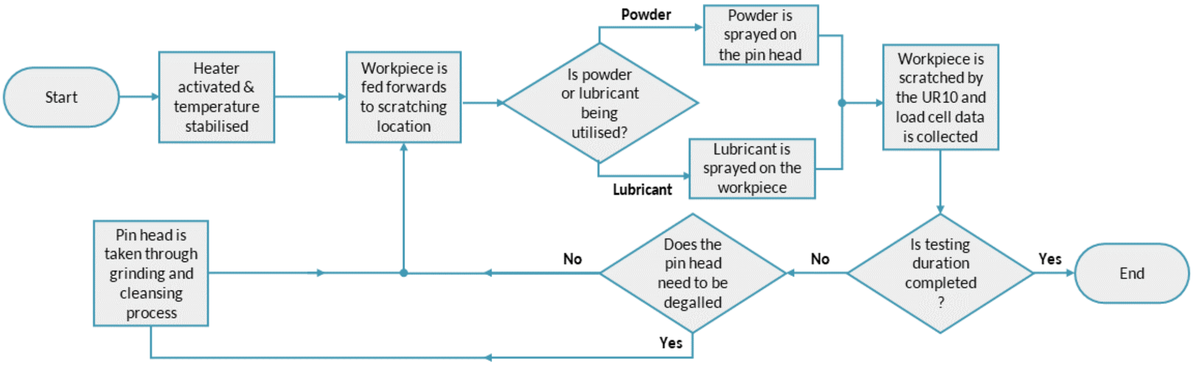


Figure 6: Working Cycle Flow Chart of ULTRAMAN system

4.3 Method

The super-group testing method is outlined as follows: First, the heater was turned on and the temperature was monitored using the control box until it reached the target temperature of $550°$C. The temperature next to the radiator was predicted to be near-ambient and was measured next. Using the strip feeder, the aluminium workpiece was fed onto the top surface of the contact heater. The working cycle as outlined in Figure 6 was then initiated, and the required metrics were measured. These include measuring the lubricant spray timing with a stopwatch, visually inspecting the lubricant spray location, and measuring the friction force on the workpiece using the integrated load cell in the UR10. Planarity was inspected both using a spirit level and visually, ensuring that the angle between the testing surface and pin head did not exceed $3.7°$ (as calculated from the overall CAD model) in order to avoid collision. The duration of the working cycle between scratch movements was measured with a stopwatch, and at the end of the final scratching process, the pin head was visually inspected. This inspection was carried out post-grinding to ensure that any galling during the process had been removed. The correct sensors required for measurement of the outlined key metrics are defined in [2]. Kalsoom et al. also detail the integration of these sensors into a smart factory setup, which is something that should be recommended for implementing improved real-time data acquisition into future iterations of the ULTRAMAN system.

4.4 Known Limitations

The most significant limitation known prior to the super-group test was the inability to run the system autonomously for eight hours continuously. Before testing we realised it would be unfeasible to store the 10 m of blanks required to conduct eight hours of testing, and instead manual feeding every two hours was required. However, due to time constraints, additional manufacturing, and assembly difficulties, our ability to safely increment our length of test up to two hours was compromised, leading to a final testing time of 20 minutes. A future test for the full run time would be a better form of verification for the PDS requirement of autonomous operation.

Another limitation of the test was the vibrations induced by the UR10's movement. These affected the force readings on both the grinding module and the scratching significantly, necessitating the manufacture of four stabilising extrusions before testing could continue. The extrusions provided the required rigidity to somewhat reduce the vibrations but at a significant time cost.

Certain metrics such as air quality and air-cooling speed could also have been quantified with the proper equipment (e.g. air purity monitors and pitot tubes respectively), but unfortunately, these were unable to be acquired. An LEV (Local Exhaust Ventilation) system was also present during testing for safety reasons, making the flow data acquisition difficult.

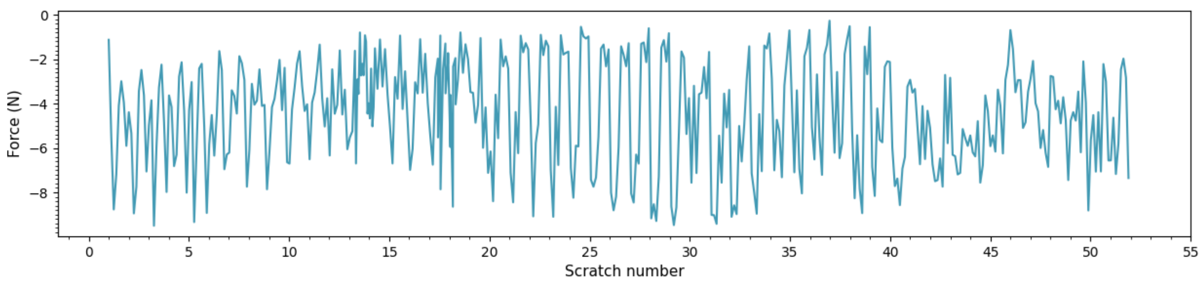
4.5 Predicted Performance

Previous natural frequency calculations led to a minimum value of 5.78 revolutions per second before resonance occurred for a mass resting on two aluminium extrusions, a value that was unlikely to be achieved by the UR10 robot arm. However, due to changes in frame geometry, longer beams were used, leading to vibration becoming a potential issue again due to a decrease in angular velocity required to reach resonance. This was confirmed during the initial startup of the UR10 in the frame as some vibration was noticed visually.

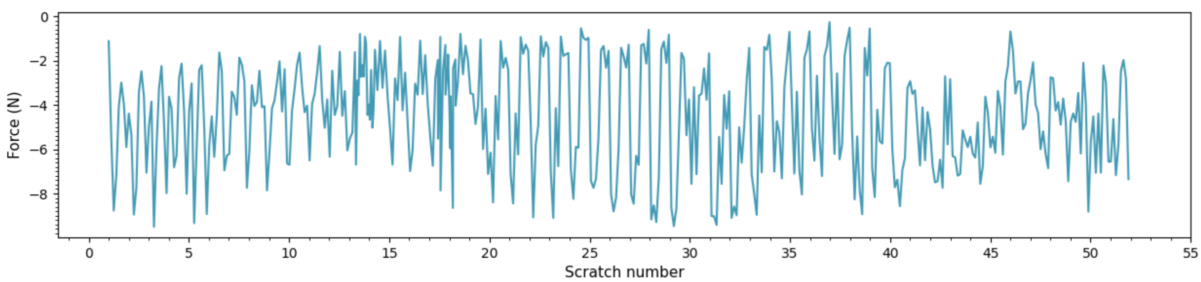
The temperature of the underside of the heater was calculated to be $225°$C using a SolidWorks heat transfer simulation. $50°$C was deemed to be the temperature limit on the outside of the aluminium extrusion frame, as this is the lowest temperature that can sustain burns if touched for a prolonged period of time.

Due to the novelty of the ULTRAMAN system, it is expected that the load cell friction force data will differ at least slightly from Dr Yang's previous tests. However, the general trends should be similar, and therefore comparison is useful to predict the performance of the ULTRAMAN system. To provide another source of predicted friction data, coefficient of friction values were collated from a journal article by Trzepieciński et al. [4]. The authors used 6-series aluminium rather than 5-series aluminium and used slower sliding speeds of 10 and 20 mm/min. However, their coefficient of friction values of 0.13 – 0.16 for engine oil-lubricated aluminium workpieces provided a good baseline to compare our results to for validation.

4.6 Results and Discussion



(a) Normal Force Data



(b) Friction Force Data

Figure 7: De-sampled Dry Scratching Data from Load Cell

Figure 7a shows a graph of normal force against the scratch number. The normal force is a parameter set on the UR10 control panel and was targeted to be a constant 6N throughout the test. As shown in Figure 7a, rather than staying at a constant 6 N, the normal force deviated between an upper bound of 12.13 N and a lower bound of 1.71 N, averaging out at 5.38 N. Previous verification of the normal force remaining constant at 6 N during Dr Yang's table-mounted test setup suggests frame vibration as a possible cause of this deviation from the expected result. The frame vibration would affect the immediate normal force of the pin, causing the UR10 to update its vertical position to attempt to maintain 6 N of vertical force. However, the slight delay between the onset of vibration and the UR10's response would likely have led to further vibrations, resulting in variations in the recorded normal force data. Further testing is therefore recommended after the implementation of additional frame stabilisation in the form of extra reinforcing extrusions or specialist dampeners. It is also important to note a systematic error may have occurred during the test, shifting all force data by a constant value. Minor misalignment of a selection of aluminium extrusions resulted in a slight difference in height between the testing platform and the strip feeder platform. This difference in height puts a constant stress on the metal blank which could effectively result in a resistive force on the scratching area, affecting the force readings.

The key result of a friction force against scratch number graph is shown in Figure 7b. From Dr Yang's previous experiments, the friction force is assumed to increase with the scratch number due to increased galling on the pin's surface [5]. Our collected data shows no clear trend in friction force with the scratch number, alluding to limitations in the ULTRAMAN system in its current state. Notably, the graph shown is under dry sliding conditions, due to an issue with the lubricant spraying system. In standard conditions, this would lead to a further increase in galling due to flash-heating of the pin surface, a trend not reflected in our collected data. It is therefore assumed that conditions outside of the direct robot-transmission interface contributed to inaccuracies in the testing data. Possibilities include excess vibration and workpiece defects, both of which are investigated in more detail below.

Additionally, defects in the metal blank are another potential cause of the deviations between the measured and predicted friction force readings. As stated earlier, the clamping pressure of the pneumatic strip feeder creates small scratches and other defects on the surface of the workpiece. Initially, it was thought to solve this problem in the design phase by positioning the strip feeder after the testing stage to pull rather than push the blank. This results in the majority of damage occurring after scratching, meaning the testing is unaffected. However, due to the limited testing material available for use, testing material was used repeatedly, meaning a damaged testing surface was used. Surface roughness of the metal surface can have a major impact on the force readings obtained by the load cell on the UR10 robot arm as there is no consistently smooth surface for the pin the scratch during operation. To fix this for future operation, it is important to ensure that a sufficient stock of metal blanks exists for testing and to ensure that the metal blanks are inspected to adhere to surface roughness guidelines.

A final issue occurred towards the end of the ULTRAMAN endurance test. Testing at the maximum temperature of $550°$C involved leaving the workpiece stationary on the contact heater for a minimum of 20 minutes to ensure the temperature had stabilised. This led to the thermal expansion of the blank, which was previously calculated to be 0.08 mm using Hooke's law with a thermal expansion coefficient of $\alpha_{Al} = 23 \times 10^{-6}\,$°C^{-1}. This was thought to be accounted for by the use of compliant press rollers that were free to rise up as the blank expanded. However, minor misalignment during assembly led to the raising of the testing surface, removing the clearance for the rollers to rise up. This in turn led to the workpiece fusing to the testing surface, rendering all data at the highest temperature meaningless. This can be resolved relatively easily by manufacturing bolts with an extra 10 mm of clearance and moving the blank intermittently during the heating-up process to reduce the possibility of sticking.

5 Conclusions and Recommendations

A novel tribological testing machine for the hot stamping process was designed, manufactured and tested over the course of this year. The ULTRAMAN system aimed to build upon the manual testing setup of Dr Yang to gather frictional force data from a pin scratching on a metal blank. Our responsibility of the transmission and robot arm control met the key requirement of a scratching accuracy of 2 $\pm$ 0.1 mm whilst also facilitating the multitude of other processes involved in a full working cycle, including pin grinding and both powder and liquid lubricant application. Two custom press rollers were made, providing sufficient constraint to have a flat testing surface as required in the PDS.

URScript - RTDE and Arduino - C communication protocols were consolidated in a central Python control system to automate data collection and coordinate collaborative manoeuvres involving multiple actuators, seamlessly integrating the work of all three sub-groups. Safety precautions including grounding and insulation-layering were incorporated into the power network design to provide safety to all personnel whilst ensuring performance for all electrical components.

A 17 % increase in spending over the initial budget limit was justified by the innovative nature of the design and lack of previous benchmarks for costing comparison.

For future development of the ULTRAMAN system, the key area for improvement is the overall autonomous run time of the system. The original aim of lights-out 8-hour operation was not met due to difficulties in infeeding and outfeeding the required 10 m of material. Moving from metal blanks to metal rolls aids in the initial storage of this material due to reduced space requirements. However, as outlined in the super-group testing section, bowing became a major issue. A potential solution to this problem would be to implement a 3-roll bender both before and after the working section and transmission. The purpose of these would be to flatten and re-coil the metal roll respectively. Calculations, a full CAD model and fully checked engineering drawings were drafted for a custom 3-roll bender that would fit into the existing frame, with a selection of these shown in Appendix B. Time and cost constraints prevented from manufacturing and implementing these components, but all details will be passed on to assist with the future improvement of the ULTRAMAN system.

6 References

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[2] Tahera Kalsoom et al. "Advances in Sensor Technologies in the Era of Smart Factory and Industry 4.0". In: *Sensors* 20 (23 Nov. 2020), p. 6783. ISSN: 1424-8220. DOI: 10.3390/s20236783.

[3] Mohsen Soori, Behrooz Arezoo, and Roza Dastres. *Internet of things for smart factories in industry 4.0, a review*. 2023. DOI: 10.1016/j.iotcps.2023.04.006.

[4] Tomasz Trzepieciński et al. "Friction Behaviour of 6082-T6 Aluminium Alloy Sheets in a Strip Draw Tribological Test". In: *Materials* 16 (6 2023). ISSN: 19961944. DOI: 10.3390/ma16062338.

[5] Xiao Yang et al. "Experimental and modelling studies of the transient tribological behaviour of a two-phase lubricant under complex loading conditions". In: *Friction* 10 (6 2022). ISSN: 22237704. DOI: 10.1007/s40544-021-0542-0.

Appendix A: Expenditure

Table 4: Detailed Purchase Records

Item	Supplier	Date purchased	Total price	Budget remaining
AF-4C Pneumatic strip feeder	Henli	23/02/2024	£623.75	£776.25
AR35540 Alumina tubes	Liling Zen Ceramic	01/03/2024	£100.92	£675.33
12V/24V Electrical Wire 2 Core Cable	Amazon	06/03/2024	£26.99	£648.34
Arduino Uno REV3	Amazon	06/03/2024	£25.06	£623.28
Cat 8 Ethernet Cable [3]	Amazon	06/03/2024	£23.99	£599.29
5V Relay Board	Amazon	06/03/2024	£8.29	£591.00
Breadboard jumper wires	Amazon	06/03/2024	£9.99	£581.01
Stainless Steel 303 Round Bar (⌀18) [8].	Metals4u	13/03/2024	£51.20	£529.81
Aluminium Flat Bar (101.6 x 31.7 x 100) [2]	Metals4u	18/03/2024	£30.70	£499.11
Stainless Steel 303 Round Bar (⌀41.3) [2]	Metals4u	18/03/2024	£127.48	£371.63
Stainless Steel 304 Round Tube (⌀45) [4]	Metals Supermarket	18/03/2024	£43.92	£327.71
Tube Push-in Fitting	RS Components	18/03/2024	£27.87	£299.84
AC/DC Converter	RS Components	18/03/2024	£12.37	£287.47
IP65 Thermoplastic Junction Box	RS Components	18/03/2024	£17.05	£270.42
USB 2.0 A to B Lead	Amazon	21/03/2024	£3.99	£266.43
Emergency Stop Push Button	RS Components	22/03/2024	£21.49	£244.94
Push Button Enclosure	RS Componets	22/03/2024	£12.35	£232.59
230V Emergency Safety Stop Switch	Sinolec	23/03/2024	£32.28	£200.31
Aluminium Flat Bar (101.6 x 31.7 x 100) [4]	Metals4u	22/05/2024	£73.44	£126.87
2 Hole Flange Bearing Unit [4]	RS Components	04/05/2024	£146.56	-£19.69
Bronze Pneumatic Silencers	RS Components	04/05/2024	£56.38	-£76.07
Steel Compression Spring	RS Components	04/05/2024	£15.25	-£91.32
IP68 Nylon Cable Glands	RS Components	04/05/2024	£4.19	-£95.51
Nylon Compressed Air Pipe	RS Components	04/05/2024	£59.71	-£155.22

Continued on next page

Table 4: Detailed Purchase Records (Continued)

Item	**Supplier**	**Date purchased**	**Total price**	**Budget remaining**
M10 x 50 bolts [8]	ME Stores	30/05/2024	£1.40	-£183.09
Nyloc Nuts [8] ⌀10	ME Stores	30/05/2024	£0.56	-£183.65
Steel Washers ⌀10 [8]	ME Stores	30/05/2024	£0.48	-£184.13
Gaff Tape	ME Stores	30/05/2024	£4.15	-£188.28
Double Sided Tape	ME Stores	30/05/2024	£3.00	-£191.28
304 Stainless Steel Foil Roll (1000 x 100 x 0.5)	Amazon	31/05/2024	£21.58	-£212.86
M10 Spring Washers	ME Stores	03/06/2024	£0.48	-£213.34

All implied dimensions in mm.

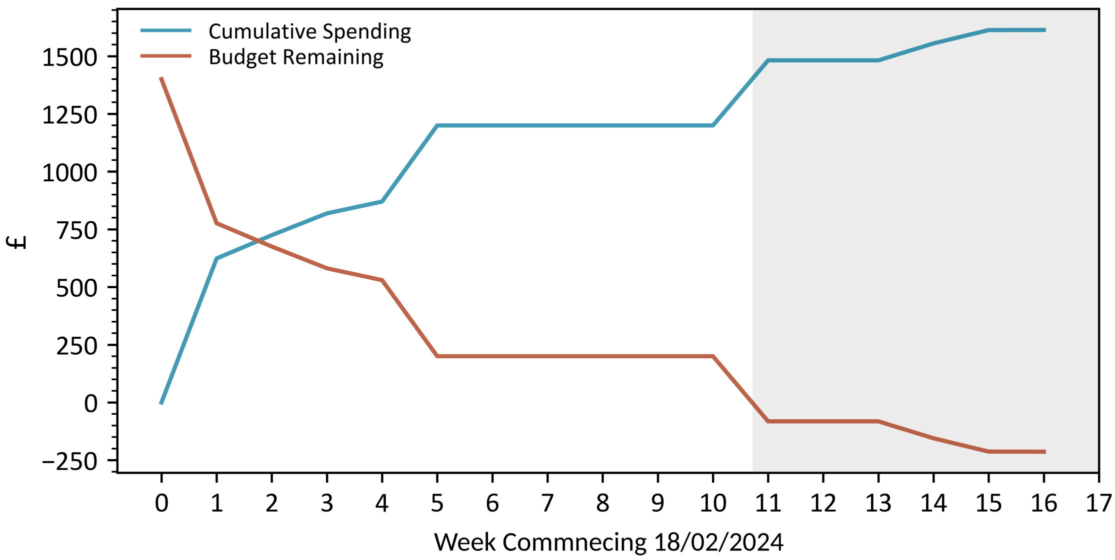


Figure 8: Cumulative Spending and Budget Remaining Over Time

Appendix B: Three Roll Bender

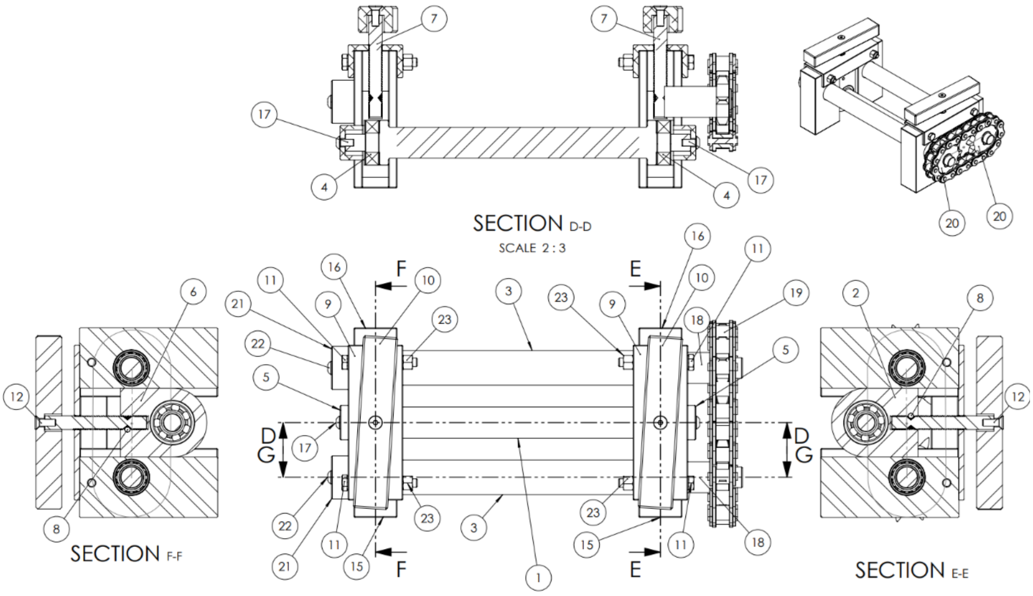
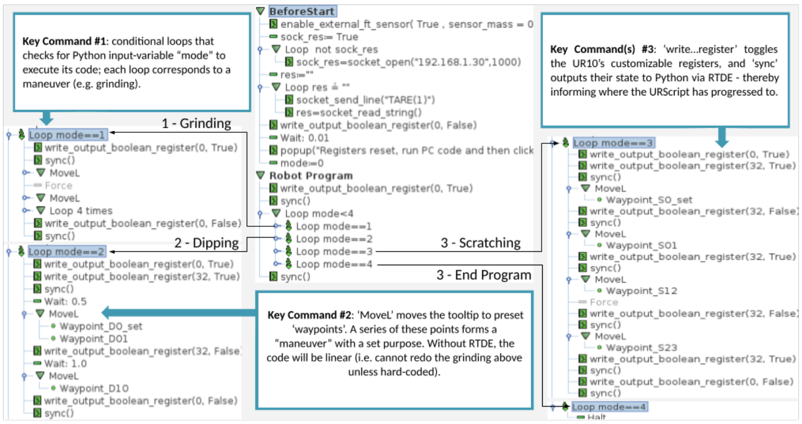


Table 5: Proposed manufacturing process for Three Roll Bender

3-ROLL BENDER	END CAP	2	1	FDM 3D Printer	ABS 3D Printing	Print part from CAD model
			2	"	Post-Processing	Examine part for flaws and deburr edges
	HANDLE	2	1	Mill	Set-up + Milling	Secure stock in mill and cut to external dimensions
			2	"	Marking + Drilling	Mark and tap centre drill hole
			3	"	Drilling	Drill central holes
			4	"	Workholding + Drilling	Flip workpiece and drill countersink
			5	Workbench	Chamfering	Chamfer all edges with file
	LEAD SCREW	2	1	Lathe	Set-up + Turning	Secure in chuck and face off both sides
			2	"	Turning	Turn outer profile
			3	"	Drilling + Reaming	Drill and ream the 5mm deep hole
			4	"	Drilling + Tapping	Flip piece and drill + tap the other side
	PIN	2	1	Lathe	Set-up + Turning	Secure in chuck and face off both sides
			2	"	Turning	Turn outer profile
	ROLL BENDER SUPPORT	2	1	Mill	Set-up + Milling	Secure stock in mill and cut to external dimensions
			2	"	Marking + Drilling	Mark and centre drill holes
			3	"	Drilling	Drill and ream holes
			4	"	Workholding + Milling	Flip workpiece and mill slot
			5	Workbench	Chamfering	Chamfer all edges with file
	ROLLER	3	1	Bandsaw	Cutting	Cut stock to length, leaving facing material
			2	Lathe	Set-up + Turning	Secure in chuck and tailstock, then face off both sides
			3	"	Turning	Turn outer profile
			4	"	Turning	Turn circlip grooves with grooving tool
			5	"	Drilling	Drill holes in ends of the shaft
			6	Mill	Workholding + Milling	Secure shaft on mill in jaws and mill out keyway
	SLIDERS	2	1	Mill	Set-up + Milling	Secure stock in mill and cut to external dimensions
			2	"	Milling	Mill outer radius using a rotary table
			3	"	Drilling	Drill and ream holes
			4	"	Workholding + Drilling	Reposition work piece, then drill and tap the M8 thread
			5	Workbench	Chamfering	Chamfer all edges with file
	TOP COVER	2	1	Bandsaw	Cutting	Cut profile stock to length
			2	Drill Press	Drilling	Drill and chamfer holes
			4	Workbench	Chamfering	Chamfer all edges with file

Appendix C: Programming†



User Input Variables

```
# ================================================================================
# User Inputs
lube_mode = 1 # 1 for sprayer, 2 for dipper
scratches = 3  # number of scratches expected (only for testing purposes)
leeway = 0.02  # leeway length at the end
length = (scratches * 0.002) + leeway  # total length of all blanks to be tested (in m)
```

These variables are inputted by the user prior program start (via user interface) which will influence the work cycle of the robot.

(See comments for purpose of variables)

Arduino Serial Communication

```
import serial.tools.list_ports
# Function to control the solenoid valves
def valve(command):
    print(1)
    serialInst.write(bytes(command, "utf-8"))
    # time.sleep(0.1)  # Small delay to ensure command is sent
    print('Written to Arduino, reading for response.')
    bytesReceived = False
    while bytesReceived == False:
        if serialInst.in_waiting > 0:
            response = serialInst.readline().decode("utf-8").strip()
            end = time.time()
            # print("Arduino Activation Time: ", end - start)
            print(response)
            bytesReceived = True
        if command == "exit":
            end = time.time()
            print("end:", end - start)
            serialInst.close()
            print("Program ended")
            bytesReceived = True
```

Importing the serial-commands library

Writing the 'command' number to Arduino

Arduino verifies that the actions has been carried out

[Arduino-C++ Code]

```
void loop() {
  if (Serial.available() > 0 ){
    String msg = Serial.readString();

    // strip feeder solenoid valve
    if (msg == "1"){
      digitalWrite(stripFeeder, LOW);
      delay(100);
      digitalWrite(stripFeeder, HIGH);
      Serial.println("Strip feeder activated");
    }
    // sprayer 1 solenoid valve
    else if (msg == "3"){
      digitalWrite(sprayer, LOW);
      Serial.println("Sprayer ON");
    }
    else if (msg == "4"){
      digitalWrite(sprayer, HIGH);
      Serial.println("Sprayer OFF");
    }
```

UR10 RTDE Communication

```
import rtde.rtde as rtde
import rtde.rtde_config as rtde_config

# initial grinding (mode 1)
watchdog.input_int_register_0 = 1
con.send(watchdog)
while True:  # Waiting for move to finish
    state = con.receive()
    con.send(watchdog)
    if not state.output_bit_registers0_to_31:
        print('Initial grinding finished.\n')
        break

while keepRunning and scratches > 0:  # Waiting for 1 scratch to finish
    # valve("3")
    state = con.receive()
    con.send(watchdog)
    if (state.output_bit_registers32_to_63 == 0) and done == 0:
        print('Force recording.')
        state = con.receive()
        forceXYZ = state.actual_TCP_force[:3]
        posXYZ = state.actual_TCP_pose[:3]
        force = np.append(force, forceXYZ)
        position = np.append(position, posXYZ)
        done = 1
        print(done)
```

Importing the RTDE library (by Universal Robots)

Writes the register_0/ 'mode' variable as input into the UR10 to switch between manoeuvre routines.

Reads the customizable register (0) state to determine whether the robot has finished the entire manoeuvre (in this case, grinding, since 'mode = 1').

Reads the customizable register (32) state to determine whether the robot has reached key locations.

In this case, this is a check for if the robot has begun scratching, and if yes, then begin to record force data into predefined arrays.

User Interface Design

To enhance the user experience during operation, a simple user interface was designed. The UI, showcased in Figma, demonstrates the basic functionality and user interactions.

[1]A complete repository of codes used in this project can be found on GitHub