Modular robotic arm for automation of SMME industrial press

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Abstract. Small South African manufacturing companies, endeavouring to benefit from Fourth Industrial Revolution (4IR) technologies, specifically automation, are restricted by exorbitant costs and the lack of know-how associated with automation. This project aims to develop affordable modular automation blocks that can couple with each other, using the OpenStructures grid, to provide customisable degrees of freedom tailored for specific automation applications. The cost of development is recovered, and the cost of maintenance is reduced through the reuse of these blocks over different automation applications. A key measure of effectiveness is a standardised mechanical and electrical interface for each block.

1 Introduction

Many South African Small, Medium, and Micro Enterprises (SMMEs) in the manufacturing industry rely on labour to operate old machinery. The need to automate these processes to improve throughput and quality, cannot be fulfilled due to the substantial capital expenditure required [1, 2]. This project focused on the creation of Modular Operational Blocks (MOBs) that can be assembled in various configurations, to provide SMMEs with an automation solution that is low-cost, easily maintainable, produced in South Africa, and which has local support. As an initial application, the blocks have been used to develop a robotic arm that automates the process of placing a part in a press, triggering the press, and then removing the pressed part.

The project began with an analysis of Commercial Off the Shelf (COTS) robotic arms and COTS robotic actuators that met the mentioned needs.

Three robotic arms were investigated and evaluated for the following:

- Local support in South Africa
- Quick and easy repairs
- Scalable architecture and software
- Realtime monitoring
- Ease of programming [9]
- Cost
- Technical specifications

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Five [3,4,5,6,7] robotic actuators were investigated and evaluated for the following:

- Local support in South Africa
- Cost
- Availability
- Technical specifications

The analysis revealed that there are no local producers of robotic arms or actuators. Some suppliers [6] have local agents with low-cost systems; however, maintenance and repair does not always occur locally. Some actuators and robotic arms [8], not available in South Africa, could be purchased directly from international suppliers, but import duties and courier costs were too high. The available actuators [6] are scalable, but cost and space constraints were an issue. The lack of local support [8] in South Africa, availability, and cost, contributed to the decision to develop a local solution of low-cost MOBs that could be configured for different automation solutions such as pick and place and welding. The aim is to eventually commercialise the MOBs and subsequent automation solutions, with local support for maintenance and repair.

In the next sections the design of the modular robotic arm will be explained in detail, the results section will cover the laboratory tests and field test done on the arm, and future improvements from the findings done in the laboratory and field tests will be discussed.

2 Design

In the application environment where the robot arm was tested, human operators are presently used to manually insert, actuate, and remove parts from a 60-ton press. The press poses a potential safety hazard to the operator. Improper use of the press and a lack of focus by operators, has in the past resulted in damage to the tool die in the press. Hence, a need exists to automate the process of inserting a metal part into a press, actuating the press, and removing the pressed part from the press. It is expected that automation of the process will alleviate the issues listed above.

2.1 System Requirements

Analysis of the press and the operating environment resulted in the following list of design requirements.

1. The volume in which the system needs to operate must not exceed 400 mm x 130 mm x 240 mm (LxWxH).
2. The price of the system must be as low as possible.
3. The system needs to pick and place metallic, ferromagnetic parts weighing less than 100g.
4. A separate system will ensure that the parts are located at a fixed pick-up point.
5. Ease of programming by technicians.

The above requirements formed the basis of developing a system architecture.

2.2 System Architecture

Analysis of the press resulted in the concept design as shown in Fig 1. The envisaged robotic system would only require 2 Degrees of Freedom (DOF) to pick up and place the part in and out of the press. A vertical linear movement is required to pick up and drop, and an angular movement is used to move the part into and out of the press. A second linear movement could have been used to move the part in and out of the press, but due to the space constraint in the press, position of the part pick up point and limited mounting areas for the robotic system, the angular movement was selected.

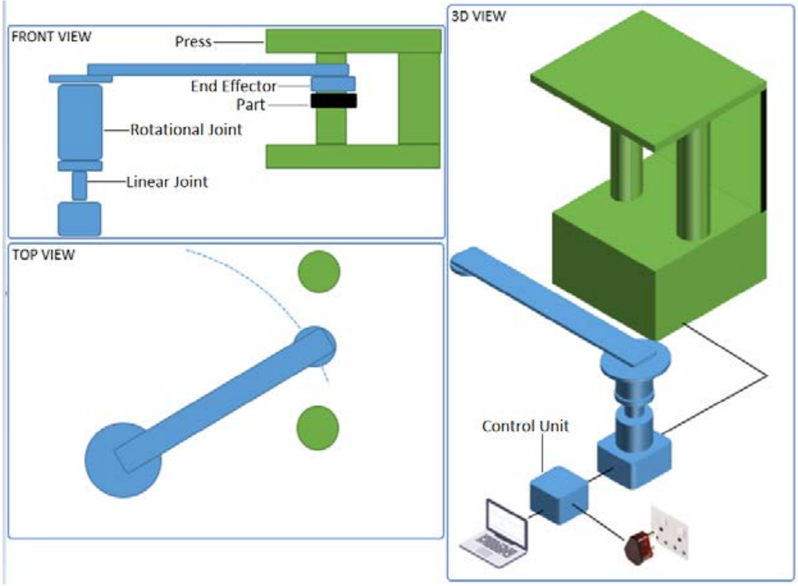

Fig 1: Initial Concept Design

The COTS robotic actuators listed in Table 1 were investigated to determine industry best practices for developing such systems.

Table 1: Robotic actuator comparison

	Motor and gear	**Brake**	**Absolute encoder**	**Integrated Controller**	**Voltage**	**Communication**
Robotis Dynamixel Pro Series [3]	Yes	No	Yes	Yes	24 V	RS-485
Harmonic Drive IHD [4]	Yes	Yes	Yes	Yes	24 V, 48 V	CANopen, ethernet, etherCat
ETH ANYdrive [5]	Yes	No	Yes	Yes	48 V	CAN, CANopen
Robolink Rotary Axis [6]	Yes	Yes	Yes	No	24 V, 48 V	RS-422 encoder CAN - controller
RDrive [7]	Yes	No	Yes	Yes	48 V	CANopen

From the evaluated actuator manufacturers, as shown in Table 1, the communication options to interface to their products vary between CAN (Controller Area Network), RS-485, or Ethernet. Due to its high throughput, low wire count, and robustness in automotive and industrial spaces [10], CAN bus was selected to connect the MOBs in this solution.

To minimise development time and cost, COTS components were used where possible. Each MOB is powered by 24 V, this voltage was chosen as industrial systems typical use 24V [11].

Analysis of the requirements, constraints and literature review resulted in a physical system architecture as shown in Fig 2.

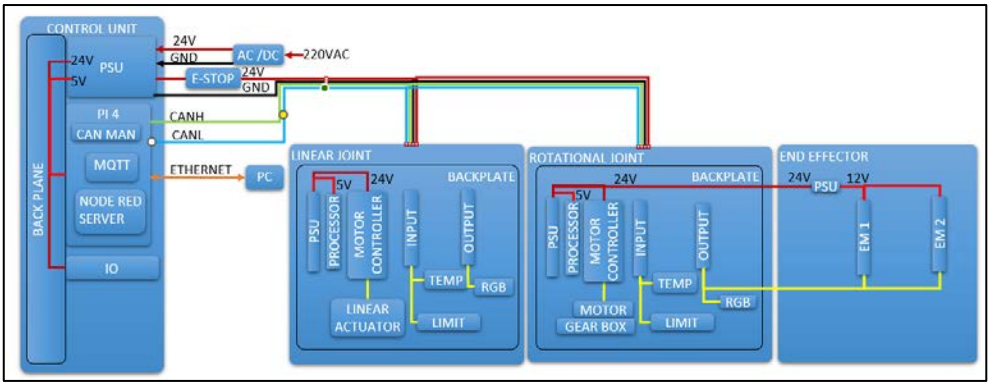

Fig 2: System architecture block diagram

The system architecture comprises the following MOBs:

- Control Unit (CU) controls the other MOBs.
- Linear Joint (LJ) allows movement in the vertical direction.
- Rotational Joint (RJ) allows angular movement.
- End Effector (EE) allows pick up and placing of the part.

These different MOB elements combine into a robotic arm system as shown in Fig 3.

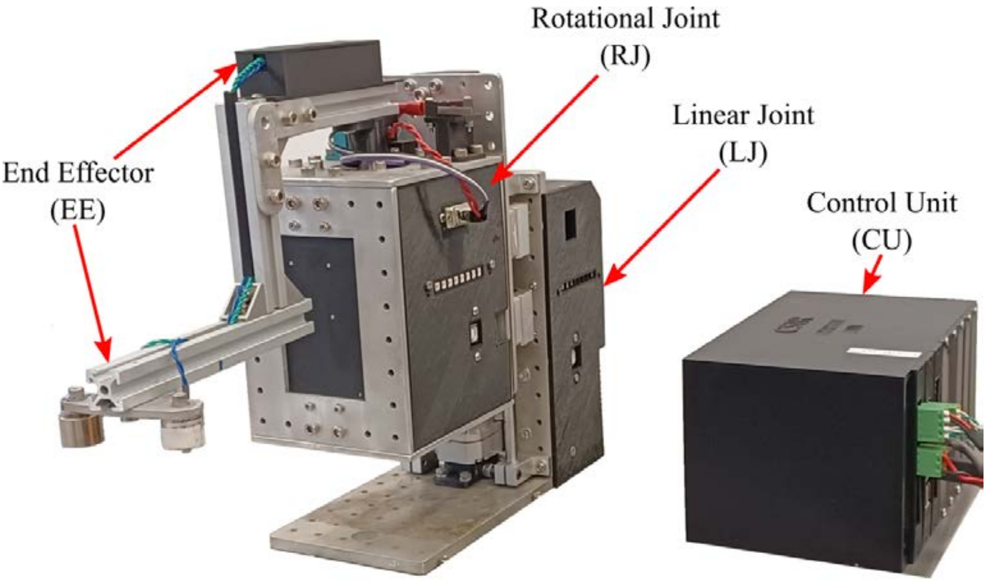

Fig 3: Assembled robot arm using MOBs.

The following sections detail the mechanical, electronic and software components of the system architecture.

2.3 Mechanical Architecture

OpenStructures (OS) [12] is an open, modular construction system where designs are based on:

- a common grid of 40x40mm,
- external diameters are in multiples of 20mm,
- part dimensions are multiples of 20mm,
- mounting holes (favouring M2.5, M5 and M10) are positioned at a multiple of 20mm from each other.

This allows for different designs to connect to each other and facilitates ease of repair, modularity, modifications, and reuse, thus resulting in reduction of maintenance costs and the recovery of development costs. The MOBs developed in this project comply to the OS grid.

Fig 4 shows the rotational joint mounted to linear joint's OS based mounting plate using M5 cap-screws. During integration, it was discovered that the rotational joint's movement needed to be limited to prevent damage. Limit switches, that were retrospectively added, were connected to the OS grid on the rotational joint. This demonstrates how the OS grid can easily facilitate modifications. Covers for the rotational joint and linear joint were 3D printed and attached using M5 cap-screws to the respective joint's OS grids.

Aluminium extrusions were used to connect the end effector to the rotational joint's shaft. This was achieved using a 3D printed shaft mount, based on the OS grid.

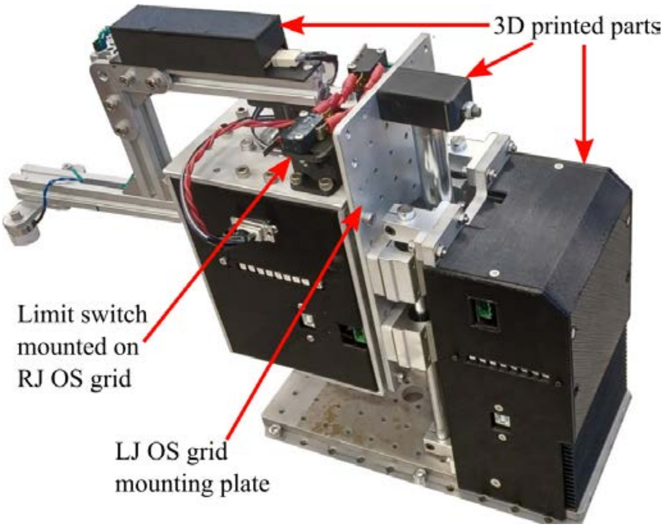

Fig 4: Rotational joint mounted to linear joint on OS grid.

2.4 Electronics

The design of the electronics, as with the rest of the system, was driven by the need for low-cost, availability of electronic components, modularity, maintainability, and reliability. To achieve modularity and reduce costs, a standardised electrical interface, comprising only 4 wires, was defined. The first pair of wires carry power (24V and Ground), and the second pair of wires carry the CAN communication interface, Fig 2. This allows MOBs to be daisy chained together for power and communications. MOBs can be added and removed as required.

Referring to Fig 2, the chain begins with an AC-DC converter module that takes 220VAC and provides 24VDC to the Control Unit. The Control Unit comprises modular electronic blocks which include a Power Supply Unit (PSU), Central Processing Unit (CPU) with a CAN interface module, shown in Fig 5, and a 24V Input/Output (IO) module.

Ease of maintenance of the Control Unit is achieved using a backplane design. Each electronic block plugs into the backplane, Fig 6. In the event of failure, the faulty electronic module is easily replaced. The backplane also improves the reliability of the Control Unit, as this approach eliminates the use of wires to interconnect the electronic blocks. Wires interconnecting blocks, creates a disorderly arrangement that has proven to hinder repairs and introduce faults during the repair process. The backplane utilises PCIe x4 connectors, which were selected for their low-cost, high pin count and availability. The electronic blocks are built onto separate PCIe cards that plug into the backplane. PCIe has a cost advantage in that the PCIe cards use the PCB edge to connect, and not an additional connector. It should be noted that the PCIe implementation is purely for mechanical and electrical interfacing and does not comply to the PCIe standard [13].

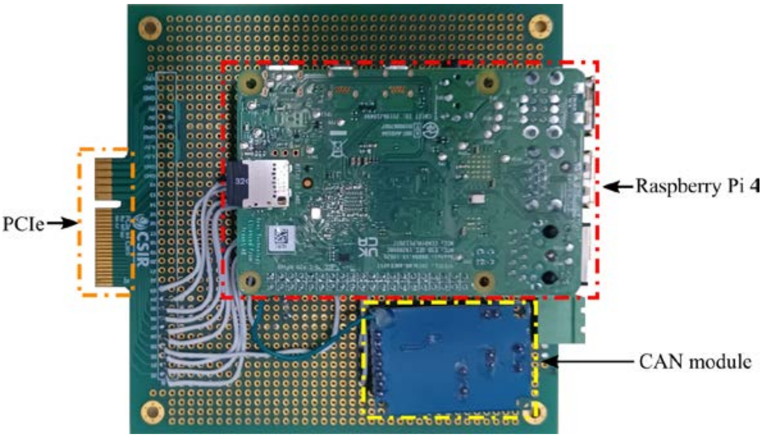

Fig 5: CPU with PI4 and CAN module on PCIe plugin card

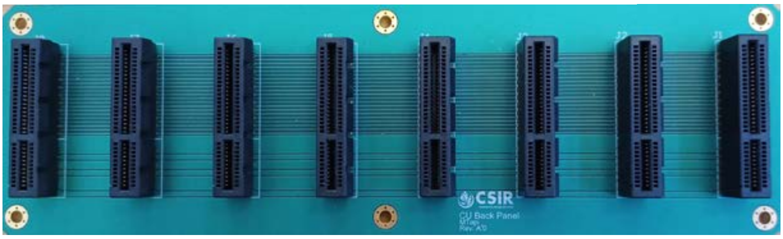

Fig 6: Control Unit backplane using PCIe connectors.

Returning to the chain, the PSU receives the 24V and then outputs the 24VDC with the CAN signals on a single connector. The 24VDC out of the PSU is bridged via an Emergency Stop (E-Stop) button, so that in the event of the E-Stop being triggered, power is removed only to the MOBs downstream and communication to the Control Unit is maintained. The 24VDC out of the E-Stop together with the CAN interface connects to the linear joint MOB and then to the rotational joint MOB, as depicted in Fig 2.

Each MOB has an internal power supply unit that is used to convert 24V to 5V for powering their processing module, the CAN interface module and RGB LED strip. The stepper motor controller is supplied with 24V.

The processing module, for each joint MOB, is a microcontroller that interfaces to the CAN controller module, the stepper motor controller, limit switches, and the RGB LED strip. The RGB LED strip is used to provide feedback to the user. This allows the user to visually monitor the various joint statuses such as its CAN, temperature, limit switches, homing, and heartbeat statuses.

Additionally, the rotational joint is used to control the two electromagnets located on the end effector.

The next section details the software design.

2.5 Software

The following sections break up the software of the system into two aspects – namely the embedded software and the control software. The embedded software is the software that executes on the microcontroller to control the individual joints, while the control software executes on the CPU of the control unit and is responsible for the control of the overall system.

2.5.1 Embedded Software

The embedded software is responsible for the control of the individual joints and provides three main functions. The first function is to listen for commands sent from the control unit, via the CAN bus, and respond accordingly. If the control unit were to send a command requesting the joint to move to a new position, the embedded software would detect this and move the actuator accordingly. The embedded software also allows for the control unit to request information from the joint as well as change certain joint settings, such as its speed and acceleration, as a percentage of their maximum.

A second function provided by the embedded software is continuous feedback of its current state. Each joint sends the control unit its current state information at a rate of 4Hz. This continuous feedback contains information on the temperature of the microcontroller, temperature of the motor, position of the motor, and whether the motor is in motion. By each joint automatically providing continuous feedback to the control unit, it removes the need for the control unit to probe each joint for its basic state information.

The third function provided by the embedded software is feedback of the joint states to the user via the RGB LED strip. The software continuously flashes one of the LEDs, known as the heartbeat LED, to indicate to the user that the joint is functioning normally. It provides temperature feedback by turning the temperature LED green when the motor temperature is within normal operating temperatures and then red when it is too hot. It provides feedback on the functioning of the CAN communication module by turning the CAN status LED green when it is functioning normally, orange when it encounters a send error, and red when it fails to initialise. It also provides feedback on the joints homed state and limit switch states.

2.5.2 Control

The CPU runs a native Raspbian operating system which hosts a Node-RED [14] server, Mosquitto MQTT broker [15] and an MQTT based CAN Manager (CANMAN). The CANMAN is written in Python [16] and manages the low-level interfacing to the CAN module. It publishes CAN data received from the linear joint, rotational joint, and end effector to various MQTT topics. It subscribes to MQTT command topics published from Node-RED and relays these commands to the respective MOBs.

Using the Graphical User Interface (GUI), Fig 7, the user can perform the following functions:

- Monitor statuses of the control unit, rotational joint, and linear joint.
- Manually control the position, speed, and acceleration of each joint.
- Manually enable the two electromagnets on the end effector.
- Run automated pick and place sequences.

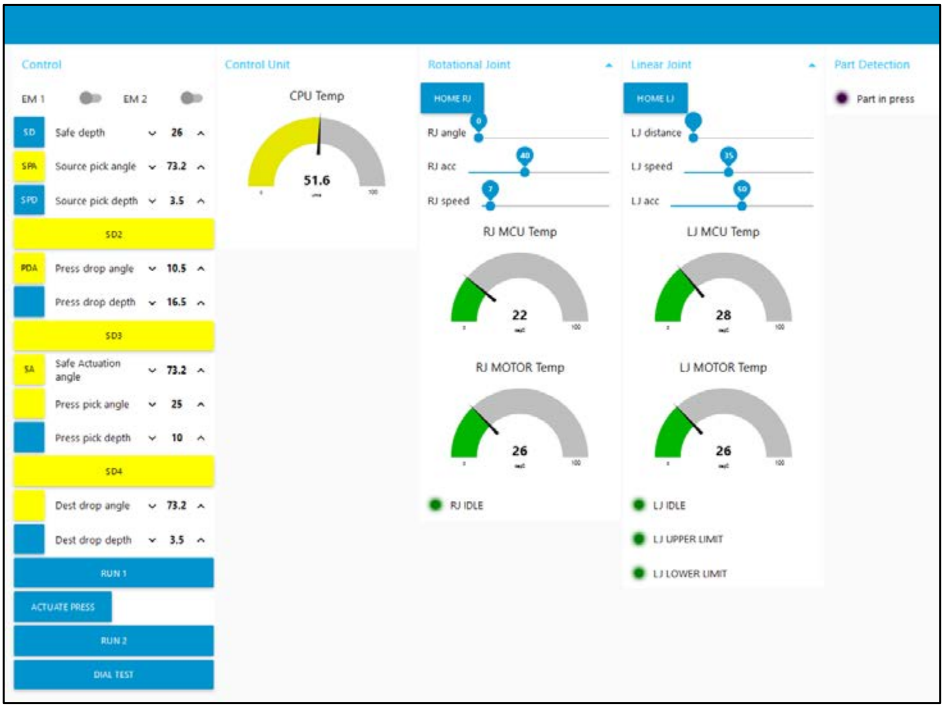

Fig 7: Node-RED Graphical User Interface (GUI) with monitoring and control.

Fig 8 shows a sample of the graphical programming interface of Node-RED, in this case, the graphical code for the "ACTUATE PRESS" button in the GUI, Fig 7. The drag and drop and low-code features of Node-RED addresses the need for ease of programming the system.

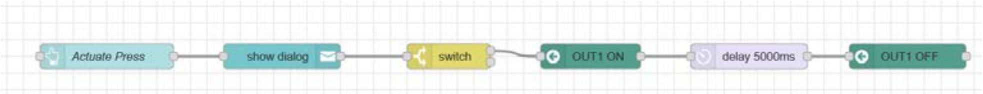

Fig 8:Node-RED flow for "ACTUATE PRESS" button.

3 Testing and Results

The following sections detail the verification of the system in a laboratory and validation of the system in the operational environment. The system was initially tested in the laboratory for repeatability and accuracy, as shown in Fig 9 a. It was then integrated into the press and tested for functionality, as shown in Fig 9 b.

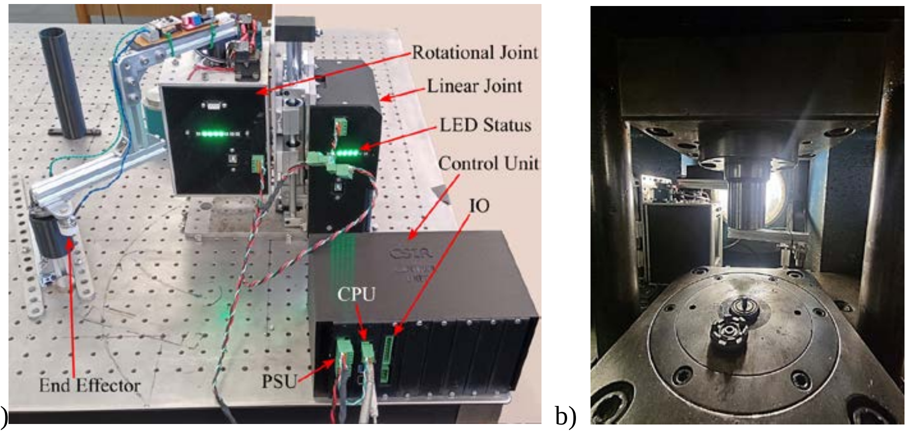
a) b)

Fig 9:Arm performing pick and place operation in a) the lab b) with the press at SMME.

3.1 Laboratory Tests

To verify the correct functionality of the MOBs the following tests were conducted in the laboratory: payload test, degrees of movement for the rotation joint, height movement for the linear joint, and the repeatability and accuracy of the MOBs.

3.1.1 Payload Test

The end effector is fitted with two electromagnets that are 20mm in diameter and capable of picking up 2.5kg each. In future applications this can be a limiting factor. The robot can be fitted with a stronger electromagnet or a different gripper as the need arises.

The centre of the electromagnet was modified with a guide pin to centre the part during pick up. The modification of the electromagnet resulted in a maximum pick-up weight of 290g, more than sufficient for the specified 100g pick up weight requirement and the actual 32g weight of the part.

3.1.2 Repeatability and Accuracy Test

ISO 9283 [17] and ANSI/RIA R15.05 [18] are the two standards used to determine the accuracy and repeatability of an industrial robot where repeatability is defined as the ability of a robot to reach a known point consistently [19] and accuracy is defined as the error difference between the specified point and the achieved point [20].

Positional accuracy (A_p) [17] and positioning repeatability (PR) [17] from ISO 9283 are defined as equations A_p and PR. The positional accuracy is calculated with equation 1, $\bar{x}$ is the mean of the positions in the x-direction and x_c is the commanded position:

$$A_p = \sqrt{(\bar{x} - x_c)^2} \qquad (1)$$

The positional repeatability, equation 2, is calculated with the following four equations:

$$PR_l = \bar{l} + 3S_l \qquad (2)$$

$$\bar{l} = \frac{1}{n}\sum_{i=1}^{n} l_i \qquad (3)$$

$$l_i = \sqrt{(x_{ai} - x_c)^2} \qquad (4)$$

$$S_l = \sqrt{\frac{\sum_{i=1}^{n}\left(l_i - \bar{l}\right)^2}{n-1}} \qquad (5)$$

$\bar{l}$ is the mean positional repeatability and n is described as the number of times the robot was moved to the same position.

The experimental setup was as follows: a dial indicator with a 0 – 25mm displacement range and a 0.01mm resolution was used to measure the movement of the robot in both the linear and rotational direction. The robot was programmed to move left and right and up and down 100 times and trigged a camera to take a snapshot of the dial indicator in position. Fig 10 shows the experimental setup.

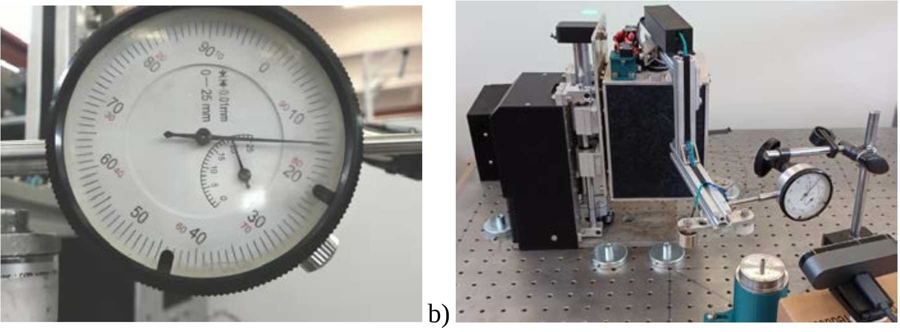
a) b)

Fig 10: Measurement test setup a) photo of dial indicator b) photo of full experiment

Table 2, shows the results of the pose repeatability and pose accuracy and movement range of the linear joint and rotational joint.

Table 2: Summary of experimental results

	Linear Joint	Rotational Joint
Positional Accuracy	0.19 mm	0.19˚
Positional Repeatability	0.39 mm	0.20˚
Movement range	0 – 60 mm	0˚ - 160˚

From the table, the positional repeatability, accuracy, and movement range for each joint is sufficient to meet the requirements for the parts to be picked and placed. These compare favourably with the COTS robot arms.

3.2 Field Tests

The system was integrated into a press at the SMME premises. It was demonstrated that the system was able to successfully insert parts into the press and automatically actuate the press. Successful removal of the part was dependent on the following factors:

1. The part returned to the same height.
2. The part remained loose on the core rod i.e., it did not stick to the core rod located on the tool die.

The use of a feedback mechanism to measure the return height of the part to adjust the pickup height would be advantageous.

4 Future Research

The current system is a prototype that has been tested in the operational environment and is presently at Technology Readiness Level (TRL) 7 [22]. The aim of the next phase of the project is to develop a Minimal Viable Product (MVP) and get the system to at least TRL 8 by industrialising the current prototype.

The following improvements to the individual MOBs and the system are required to ensure that the MVP can operate efficiently and reliably in its environment and that each MOB can be used in other configurations.

A feedback MOB is required to provide distance information of the part in the press. This will allow the CPU to adjust the pickup depth of the part after press actuation. This could be incorporated into the end effector using a laser distance measurement sensor. The end effector could also be upgraded to incorporate a strain gauge to measure the force exerted when the end effector contacts the part in the press. This feature is also useful to detect whether the arm collides with other objects.

The system also requires a feedback, part detection MOB, to detect if the part is still in the press as the possibility exists that the part is not picked up. If a part is inserted onto another part already in the press, actuation of the press can destroy the tool die in the press.

The system presently requires that the linear and rotational joint be homed to known positions on startup. This requires user involvement via the GUI to manually move the joints into safe positions before homing can occur. The MOBs need absolute encoders to alleviate this issue. The backlash of the rotational joint can be improved by using a cycloidal gearbox as opposed to the current planetary gearbox.

The linear and rotational joint use a backplate for mounting of electronic modules, this can be improved by using the backplane approach as on the control unit, which would result in easier maintenance of these MOBs.

5 Conclusion

The project aimed to develop a pick and place, automation solution, for a SMME. The solution needed to ensure that it is maintainable, reconfigurable, low cost, easily programable and locally supported.

The development of MOBs in accordance with the OpenStructures approach allows for retrospective modifications and reconfiguration of MOBs.

Ease of programming was achieved using Node-RED, which provides a low code, rapid development environment at no cost, to develop dashboards and controls quickly and easily for the robot arm.

The architecture developed allows for scalability of MOBs in other application areas that would require additional DOFs, sensors, or feedback systems. The use of a standard electrical interface (CAN and power) and mechanical interface (OpenStructures) allow for easy maintenance, reuse, and integration.

One of the aims of the project was the production of a competitive, low-cost robotic arm that SMME’s can deploy within their production facilities. This aim has been achieved as the current material costs of the arm are approximately one third to one half that of low-cost, COTS systems.

The CSIR would like to acknowledge Sintered Metal Products for their support in providing access to their press machinery for field integration and testing.

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Rebuttal

All formatting issues were addressed i.e.

- Figure changed to Fig.
- Figure references not bolded.
- Space between measurement and units

Figure 1 labels legible.
Mechanical section changed to Mechanical Architecture section.
Results section changed to Testing and Results section.
References added to introduction.
Test results discussed.
As per the template, acknowledgment not added under a new section.
Conclusion section updated.