Manufacturing and Evaluation of the Open-Source AR3 Robot Arm for Educational Uses

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At the CSIR, a Learning Factory has been established to teach about the fundamentals of robotics and other Industry 4.0 disciplines. The Learning Factory makes use of the Annin Robotics AR3 robot arm: a low-cost robot designed for small automation processes, ideal for educational purposes. The AR3 robot was chosen based on its low cost and open-source implementation. The robot was built at the CSIR mainly from machined aluminium parts and 3D printed covers. To test the functionality of the robot, the AR3 open-source user interface was used. The robot may not be as precise as industrialized robots, but it provides similar functionality in a convenient format.

Keywords—Learning Factory, Robotics, Open-Source, Repeatability

I. INTRODUCTION

The Learning Factory at the CSIR represents a realistic manufacturing environment for education, training, and research [1]. The learning factory consists of a number of Industry 4.0 disciplines aimed at introducing learners to these various disciplines and it has been designed to develop their theoretical and practical knowledge in various disciplines at different workstations in the Learning Factory.

The Learning Factory consists of the following workstations: system integration, artificial intelligence, big data, additive manufacturing, cloud and edge computing, internet of things, cyber-security, augmented reality, simulation, and robotics.

The Robotics Practical Workstation is used to teach learners the basics of robotics, the various applications of robotics, pick-and-place, assembly, and the use of different grippers. The low-cost, open-source Annin Robotics AR3 robot arm [2] was selected to meet the needs of this practical workstation.

II. SELECTION AND MANUFACTURING

A. Selecting the robot

The AR3 robot was chosen to be a part of the Learning Factory because of its low cost and open-source implementation. The robot arm comes with a user manual explaining the components needed and the assembly of the mechanics and the electronics of the robot and how to install the necessary software [2].

The open-source nature of the robot's mechanical allows for the robot parts to either be purchased from Annin Robotics as a kit without the 3D printed cover or manufactured in-house as the CAD models are made available for download [2].

Depending on the intended use of the robot arm, its control software can be downloaded as a stand-alone executable file, or a folder containing the robot's source code, written in

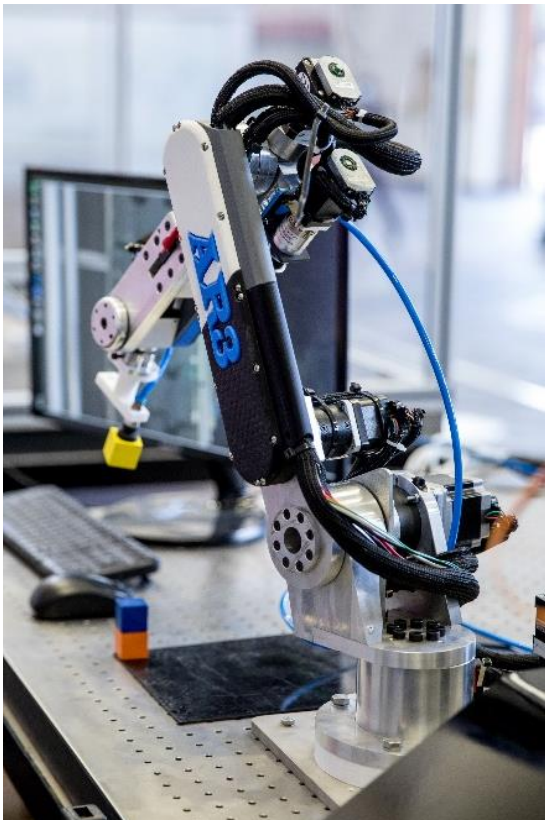

Fig. 1. AR3 Robot Arm

Python, can be downloaded separately. Having the source code allows for the user to manipulate the functionality of the control software to better suit the robot arm's intended use.

A. Manufacturing

The robot consists of a mechanical, electrical and software section. The manual explains how to manufacture, assemble and test each section [2].

1) Mechanical components

The mechanical components of the AR3 can be 3D printed or machined from aluminium. The robot was built from about 75% aluminium parts and 25% 3D printed parts and covers. The aluminium parts were machined in the workshop at the CSIR using the computer-aided design (CAD) models. The fully assembled robot arm is depicted in Fig. 1 with a suction cup used for moving test blocks around. Fig. 2 shows a CAD model of the robot arm with the robot's joints labeled and joint directions indicated.

It should be noted that the whole robot can also be 3D printed but problems were encountered with the strength of the 3D printed parts. Parts that were 3D printed were not printed according to the 3D printing assembly manual. The parts were

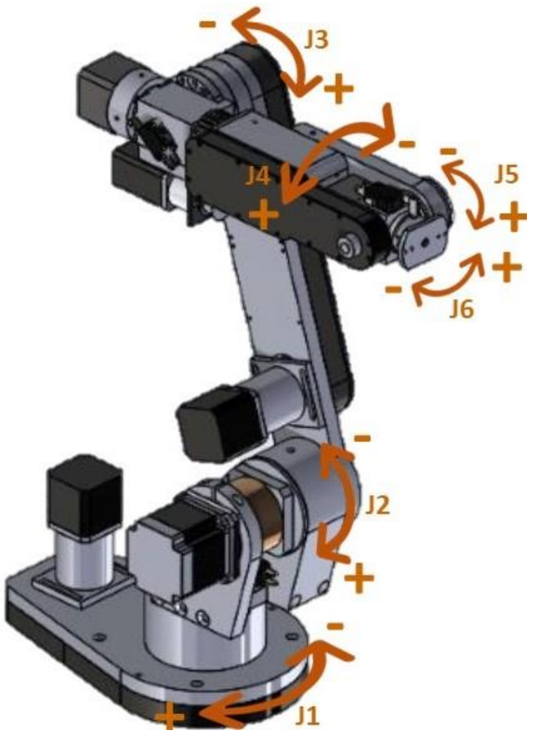

Fig. 2. AR3 schematic with joint directions

printed with the default printer settings and only once the strength problems were encountered was the manual referred to for reference. All the covers and the robot control box were 3D printed along with a joint 4 timing hub and the 60-tooth timing hub pulley. The structural components were machined from aluminum using the CAD model that was bought to manufacture the robot.

The robot was assembled in the lab, and although the manual provided is detailed, some insight and engineering experience are required if parts are to be machined.

During the assembly, it was identified that the robot has minor backlashes on the joints. This leads to the inaccuracy of the positioning because the encoder for that joint does not detect the backlash movement and therefore the inaccuracy is not accounted for.

In addition, it was noted that it is important to follow the manual and assemble the mechanics and electronics together as some of the limit switch mounts are not easily accessible if the robot is fully assembled, limit switches for joints 1, 2 and 3.

Using Fig. 2 as a reference of the robot's joints and joint directions, the following problems were encountered while building the robot:

- The J4 timing hub is a complex part to machine. To overcome this problem the part was 3D printed.
- The J1 and J3 motor mounts were 3D printed with a 25% infill. The motor mounts are used to provide tension to the motors to keep the chain tensioned. It was noted that J3 showed signs of deflection when the motor was tensioned. The manual states it should be printed at least at 50% infill, so deflection is expected.
- The 3D printed motor mounts also experienced wear of threads during tension since these were made of plastic.
- Over time it was noted that the grub screws began to slip on the motor shafts. The problem was encountered when some joints began to slip more than usual, and the problem was investigated. This may be because no threadlocker was used.
- There were tension issues on the chain and sprockets. This was due to sprockets not being concentric and other issues from the motor mounts.
- The linear rods need to be handled with care when they are cut to size as this might lead to bent rods. This will then lead to non-smooth sliding of the J5 carrier.
- The bolt and screw sizes are not in metric units, leading to unexpected friction caused by either the length or the head of the screws.
- When broaching the keyway, the position of the keyway must be at the exact position shown on the drawing. Failure to do so might lead to the tension ring not tripping the limit switch when it is expected to do so.

Some potential solutions to the problems encountered are:

- Ideally purchasing the kit with the AR3 aluminum structural components, hardware components and CAD combo. This will solve all of the issues that were encountered with machining the various parts and the screw lengths.
- The design has recently been updated to solve the concentric sprocket issue. A belt pulley is now used.
- To further improve the design, through keyways were used with the parts machined but this fix may not be needed if the kit is purchased from Annin Robotics directly.

2) Electrical components

The electronic manual is very descriptive and gives clear details on all the electrical wiring needed [2]. In the manual, a bill of materials is given for the wiring and electrical parts needed. Instructions for all the connections that need to be made are also provided.

The control box design, depicted in Fig. 3, does not account for the wiring of an end-effector for the robot arm, such as an electric gripper. The cluttered control box makes troubleshooting difficult if problems are encountered. The local wire gauge is different from the one suggested, so it was difficult to place all the wires in the box properly.

The following problems were encountered while building the robot:

- The wiring is cluttered and hard to troubleshoot.
- The wire diameters specified could not be obtained.
- The gripper's wiring was not considered in the design of the robot control box.

- Motor on joint 4 (J4) gets extremely hot.

Some solutions to the problems encountered:

- By creating a printed circuit board for the wiring in the robot controller box, it would be simpler to connect the wires.
- Wiring for both pneumatic and electric grippers should be considered. This can be done by using the -5V and +5V if the gripper runs on 5V, and one of the Ethernet connections can be used for the control signal.

3) Software

The robot arm comes with its own control software, which includes a graphical user interface (GUI) [2] with video tutorials available online [3]. As all the source files are provided, this allows for the user to make modifications of the software as needed.

Modifications to the GUI were made for this application to make programming the robot simpler for the learners as part of the Learning Factory. The modified GUI is depicted in Fig. 4. In Fig 4. the display for each angle joint displays the current angle of each axis. If the buttons used to jog the robot are increased with the + sign or decreased with the – sign the angles will update on the joint angle display. The gripper buttons are used to turn the gripper suction on and off. The programming buttons are used to program the robot and the location data is displayed in the programming window.

If the robot is jogged to the required location the "Teach New Position" button can be used to save the location. The new position will be loaded into the programming window. The location can be updated later using the "Modify Position" button by jogging the robot to a new location, selecting the position to be modified in the programming window and clicking the "Modify Position" button. A position can be removed from the programming window by selecting it and clicking the "Delete" button.

The green arrow is used to play the whole program in the program window. The FWD button is used to step through the code line by line and the REV button is used to reverse the step through line by line.

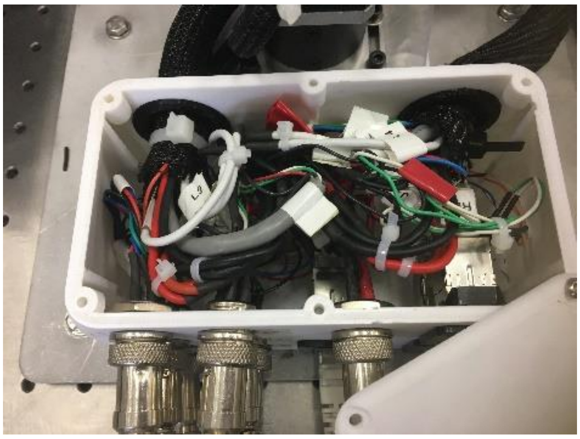

Fig 3. AR3 robot control box wiring

B. Integration and testing

To interface the GUI and the robot, the Teensy 3.5 and Arduino Mega micro-controllers are used to control the robot and the gripper, respectively. The software needed to program both micro-controllers is provided [2].

Once software was loaded onto the Teensy and Arduino Mega micro-controller, the robot was tested in the following stages:

- First power was connected and the robot was observed to see if no power issues are observed.
- Each axis J1 to J6 was jogged in positive and negative directions about 5 degrees and observed if it worked as expected.
- The system was then powered off and manually moved to its home position.
- The system was powered on and calibrated manually

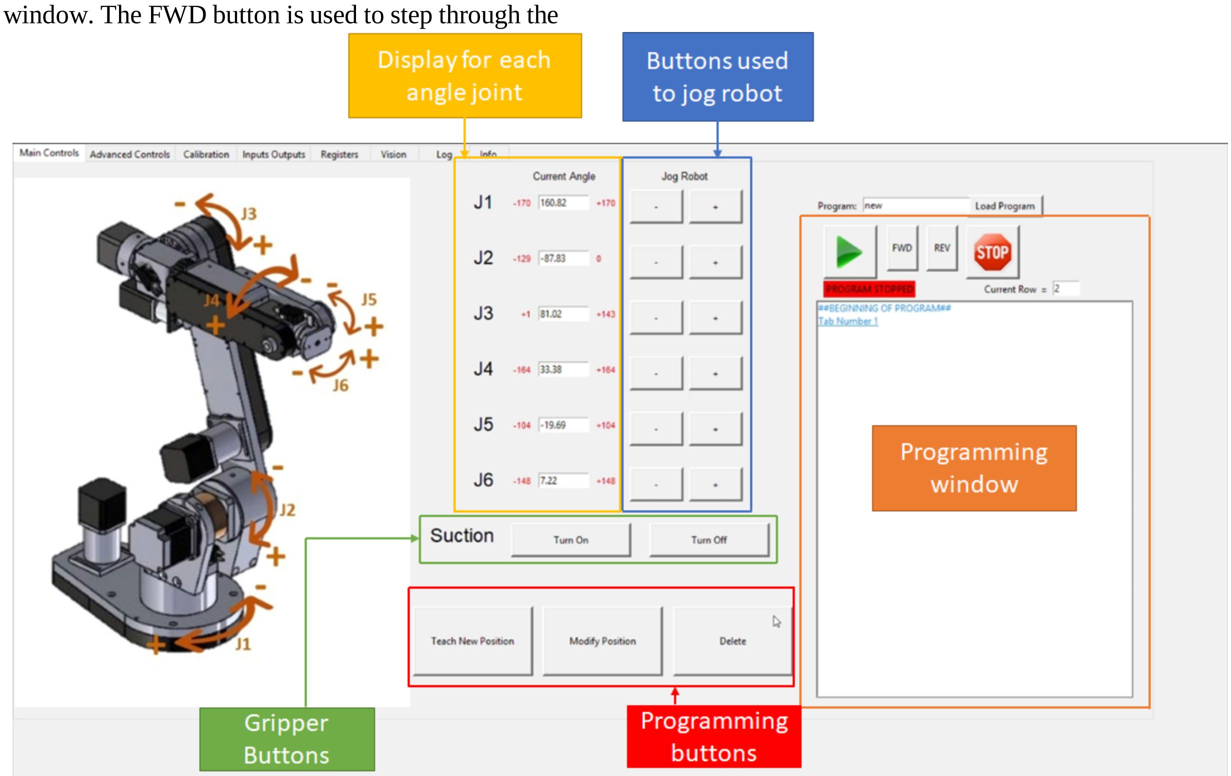

Fig. 4. Modified AR3 control software user interface

- All the limit switches were tested by calibrating each axis separately and the limit switches were activated manually before the robot hit them to see if they all worked. The emergency stop button was kept close in case any problems occurred. Joint J5 was not tested manually for calibration as the limit switch cannot be reached manually.
- Once everything worked as desired, the system was auto-calibrated.
- After successfully auto-calibrating the robot, it could then be used.
- The gripper was configured to the correct pin on the Arduino Mega micro-controller to be controlled via a vacuum pump and solenoid.

III. Testing and Results

To test the if robot performed as specified in the manual, the criteria tabulated in Table I was used.

The AR3 has the following specifications reported by Annin Robotics: a payload of 1.9 kg, a horizontal reach of 629 mm and a repeatability of 0.2 mm. Table I shows the degrees of movement of each axis of the arm.

Table I is used to form a comparison of the specifications given by Annin Robotics and the specifications that were measured from the AR3 Robot that was built at the CSIR.

ISO 9283 [6] and ANSI/RIA R15.05 [7] were the two standards used to determine the repeatability of the robot. In industrial robotics, repeatability, more specifically referred to as pose repeatability (PR), is the ability of the robot to return repeatedly to the same position from the same direction [4, 5].

Due to the complexity of the ISO 9283 to measure *x*, *y*, and *z* co-ordinates along the 5-point routine that the robot needs to move along, it was decided to measure the repeatability of each axis using the ISO 9283 PR equations [6]. $\acute{x}$ is the mean positions attained in each axis direction, x_j is the position the robot was expected to reach, and n is the number of times the experiment was repeated.

$$PR_l = \acute{l} + 3S_l \quad (1)$$

$$\acute{l} = \frac{1}{n}\sum_{j=1}^{n} l_j \quad (2)$$

$$l_j = \sqrt{\left(x_j - \acute{x}\right)^2} \quad (3)$$

$$S_l = \sqrt{\frac{\sum_{j=1}^{n}\left(l_j - \acute{l}\right)^2}{n-1}} \quad (4)$$

TABLE I. AR3 SPECIFICATIONS FROM ANNIN ROBOTICS

Properties		Annin Robotics Specifications
Repeatability (mm)		0.2
Degrees of movement (°)	Axis 1 rotation	+170° to -170°
	Axis 2 arm	0° to -129°
	Axis 3 arm	+1° to +143°
	Axis 4 wrist rotation	+164° to -164°
	Axis 5 wrist bending	+104° to -104°
	Axis 6 wrist turning	+148° to -148°

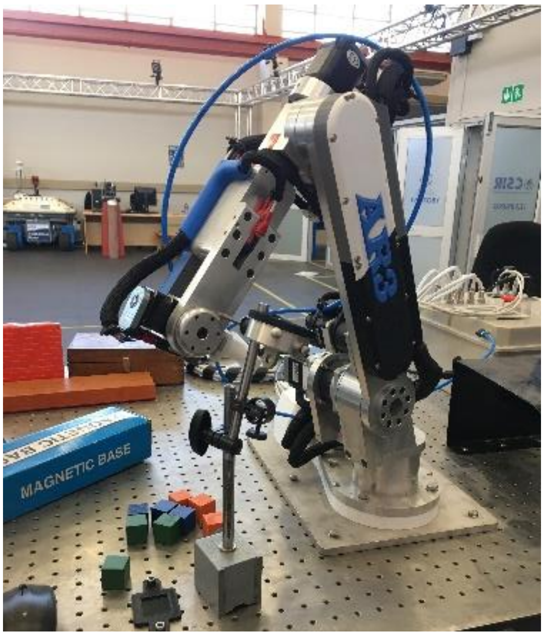

Fig 5. Test procedure setup

Table II indicates that the repeatability is not as accurate for the robot built as stated by Annin Robotics. Annin Robotics repeatability was not referenced by an ISO standard therefore not making it possible to perform an accurate comparison, however it can be noted the robot did not perform as well as expected.

Forward kinematics was used to observe where the end-effector would be using the Denavit-Hartenberg parameters given by Annin Robotics [3, 9]. The PR values were then used to determine the angle of deviation each axis could be off by using the cosine rule. The calculated angles are shown in Table II.

Forward kinematics was then preformed to determine where the end-effector could be in both the positive and negative directions. The *x, y* and *z* values for the ideal, positive, and negative values are shown in Table III.

TABLE II. POSE REPEATABILITY (PR) TEST RESULTS IN MM AND CORRESPONDING DEGREES

PR Results per axis		
Axis	**PR (mm)**	**PR (degree)**
1	2.33	2.95
2	0.33	0.44
3	1.01	1.93
4	0.22	0.44
5	0.34	0.85
6	1.11	3.97

TABLE III. PERFORMANCE OF AR3 USING FORWARD KINEMATICS

Axis	Forward Kinematics		
	Negative direction (mm)	**Ideal direction (mm)**	**Positive direction (mm)**
X	588.99	591.83	592.72
Y	-66.65	-36.25	-5.753
Z	181.11	169.77	158.47

IV. Review

The AR3 robot arm is used as part of the Learning Factory at the CSIR. The robot arm will be used to up-skill, educate, and give learners insight to industrial applications. The teaching cell gives learners access to a robot with 6 degrees of freedom, where the students can learn about robotics and different end effectors that can be used to perform a simple pick-and-place action using the robot. From this, the students learn the fundamentals of robotics that can be used in industry.

A. *Comparison to industrial robot*

The AR3 robotic arm is classified as a pre-programmed robot. Pre-programmed robots perform simple monotonous tasks in a controlled environment, for example, a mechanical arm on an assembly line.

As part of the Learning Factory, the ABB IRB1100-4/0.58 robot arm [8] is used in a small production line. This robot is a 6 degrees of freedom robot and has a reach of 0.58 m. To compare low-cost robot arms versus industrial robot arms, Table IV was generated.

The significant differences between the two robots are their payload, weight, and repeatability. The AR3 has a smaller working range in terms of each joint rotation around the given axis.

From Table IV, it can be concluded that the AR3 robot is a satisfactory low-cost robot that can be used to teach students and employees about robotics. The AR3 robot could also be used in a small production line to improve the production throughput.

TABLE IV. COMPARISON OF ABB IRB1100-4/0.58 AND AR3 ROBOT ARM

Specification	**ABB IRB110-4/0.58**	**AR3**
Reach (mm)	580	692
Payload (kg)	4	1.9
Number of axes	6	6
Repeatability (mm)	0.01	0.2
Robot weight (kg)	21.1	12.3
Enclosure weight (kg)	24	5.6
Max Power Consumption (W)	275	198

V. Conclusion

The robot did not perform as well as the suggested specifications. Compared to the industrial robot, it is not as precise and does not have the same repeatability. However, the repeatability can be overcome by using a larger gripper that is able to pick up larger items, yet still accounting for the inaccuracies.

The AR3 robot arm may not be as precise as other industrialized robots, but it provides similar functionality in a more user-friendly format. This is made possible by its low cost and open-source implementation which makes it more accessible than its more industrialized competition. Therefore, this makes the AR3 robot arm a satisfactory low-cost robot that can be used to teach students and learners about robotics and it could be used in a small production line to improve the production throughput.

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