Design of a 3D-printed Accessible and Affordable Robotic Arm and a User-Friendly Graphical User Interface

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Abstract. This paper presents the design, manufacturing and software integration of a 3D printed robotics arm. The robot design is made of a rotational base combined with a 5 degrees of freedom arm with a gripper. An intuitive and user-friendly Graphical User Interface is also implemented and integrated with the robotic device. Preliminary tests are performed showing that the system has the potential to be used in different contexts and applications, as well as manufacturing environments where pick and place tasks could be performed in a low-cost fashion.

Keywords: 3D printed prototyping, 3D printed robotics, human robot interface, intuitive interface, user-friendly human robot interaction.

1 Introduction

Since the 1960s there has been concern surrounding automation and robots' effect on the manufacturing industry. One of the biggest worries is the impact on workers' jobs. Automation is the *substitution of work activities undertaken by human labor with work done by machines, with the aim of increasing quality and quantity of output at a reduced unit cost* [1]. As technology continues to improve, automation will increase. In the upcoming five years, officials in Zhejiang, an eastern province of China known for its manufacturing industry, are planning to allocate approximately 500 billion Yuan (i.e. $ 82 billion) to facilitate the transition of 5,000 companies annually from human labor to automated systems [2].

Based on findings from the International Federation of Robotics, it has been noted that several nations, including Brazil, Republic of Korea, Germany, China and the USA, have witnessed a growth in paid employment. In contrast, Japan has encountered a decrease in employment [3]. The rise in automation not only leads to job displacement but also supports new employment opportunities. The global robot industry alone generates around 170,000 to 190,000 jobs. Additionally, there is a need for support staff and operators, which contributes to a similar number of job opportunities. Apart from direct employment, robotics also plays a role in job creation and preservation in some other scenarios. For example, there are tasks that can only be effectively performed by robots, ensuring precise and consistent production while maintaining cost-efficiency.

Also, robotics can be employed in situations where the current working conditions are unsatisfactory or even illegal in developed countries, providing an alternative means of operation [4]. Opponents of the automation boom argue that the rapid technological progress occurring is eradicating jobs that were traditionally held by the middle class. While elevator operators and highway toll collectors have already been replaced by robots and automated systems, the impact of automation extends beyond low-skilled positions. It is encroaching upon higher-skilled job roles as well, raising concerns about the potential for substantial job losses among human workers in the long run [5]. According to the Organization for Economic Co-operation and Development in 2019, it was projected that around 14% of existing jobs could be at risk of disappearing due to automation. Additionally, automation was predicted to have a significant impact on approximately 35% of jobs [6].

Automation, particularly using robotics, often involves the replacement of human labor with automated systems, resulting in the displacement of workers from their place of work. Therefore, the effective effect of automation vs employability is under discussion and may have an effective impact on jobs [7].

The literature shows that there is debate on whether robots' effect on the manufacturing industry is positive or negative. Workers are concerned about being replaced by robots, however there is evidence that shows the increase in automation can support jobs.

In this context, we want to provide the design of a robotic system which could support human activity and manufacturing, according to the following motivations:

- To make robotics technology more accessible and affordable for individuals, hobbyists, and small businesses.
- To enable the development of new applications and uses for robot arms, such as in education, research, and industry.
- To encourage innovation and experimentation in the field of robotics, by providing a low-cost platform for designers and engineers to build upon.
- To reduce the cost and complexity of existing robot arm designs, making them more practical and efficient.
- To help advance the field of robotics by providing a platform for researchers and developers to test and refine their ideas and algorithms.

We also aimed at taking inspiration from the biological system and, in particular, form the human arm, an articulated structure performing a wide range of movements through the shoulder, elbow and wrist joints [8].

2 Materials & Methods

This section presents the *Design of the Robotic Arm* (Section 1), the *3D Printing Manufacturing Process* (Section 2) and the implementation of the *Software Interface* (Section 3).

2.1 Robotics Arm Design

The proposed design of the Robotic Arm consists of an articulated system with a set of rotational joints between the links of the robot. Precisely the project aims at designing a *6 actuated degrees of freedom robotic arm* with a *base*, an anthropomorphic *shoulder*, an *elbow*, a *wrist* - performing twist and rotation - and an opening and closing *gripper*. Some parts of this design are taken from *Giovanni Lerda's Kauda*, a printable and open-source robotic arm [9]: in particular, the base joint is taken from this source as it allows full 360-degree rotation, whereas the remaining design of the arm has been developed with the *Autodesk Fusion 360* software. This is a 3D CAD and CAM software widely used in a variety of manufacturing industries.

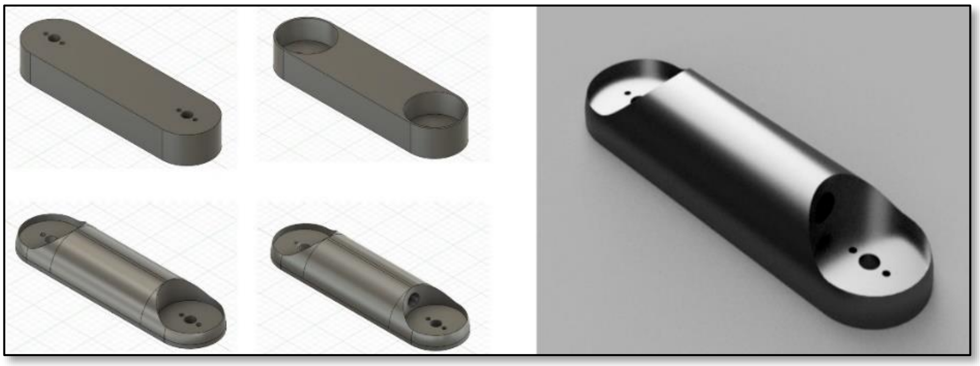

Fig. 1. Design and rendering of the parts with the Autodesk Fusion 360 software (left and right panels, respectively).

To design each component, a sketch that defines the basic outline and shape of the part can be initially prepared. Then, extrude tool can be applied to turn the 2D sketch into a 3D part. After this, features are added such as holes, and fillets to finalize the part and refine it. Once the part is finished it can exported as an STL file (i.e. *STereolithography*) for manufacturing. This process is shown for one component in the Figure 1 (left panel) where a final rendering of the section is also shown in the same Figure 1 (right panel). Due to the nature of the 3D printing process, once the part is exported, the STL file has to be manipulated with a slicing software. This further step is shown in the Figure 2 (left panel). The slicing software, which allow the preparation of the instruction for the 3D printer (i.e., the G-Code) is *Cura Slicer*. This slicer allows the user to set up a variety of parameters such as the height of the layer of materials, the infill density, as well as to optimize the speed of the printing.

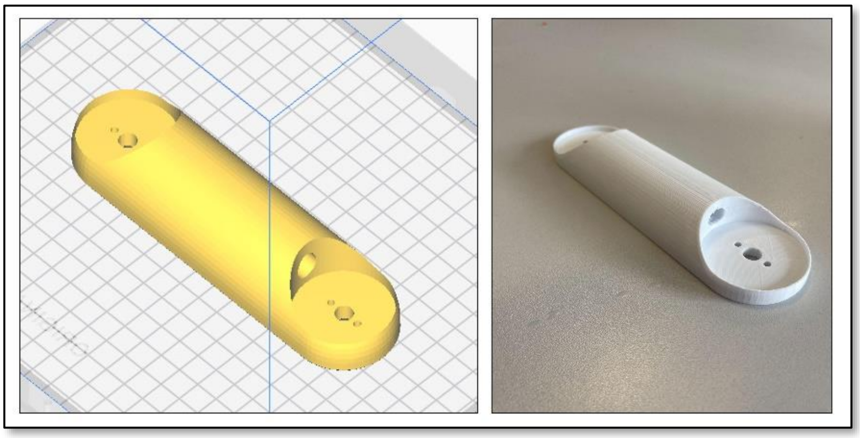

Fig. 2. Preparation with *Cura Slicer Software* and manufacturing of the part (left and right panels, respectively).

2.2 Arm Manufacturing

In order to manufacture the arm the parts were 3D printed. The *Prusa MK 3D Printer* works by building up layers of material to produce a three-dimensional object, as shown in Figure 3 (left panel). The 3D printer uses *PolyLactic Acid* (PLA) filament to build the object. PLA is an extensively used material with ecological benefit since it is a thermoplastic obtained from renewable sources [10].

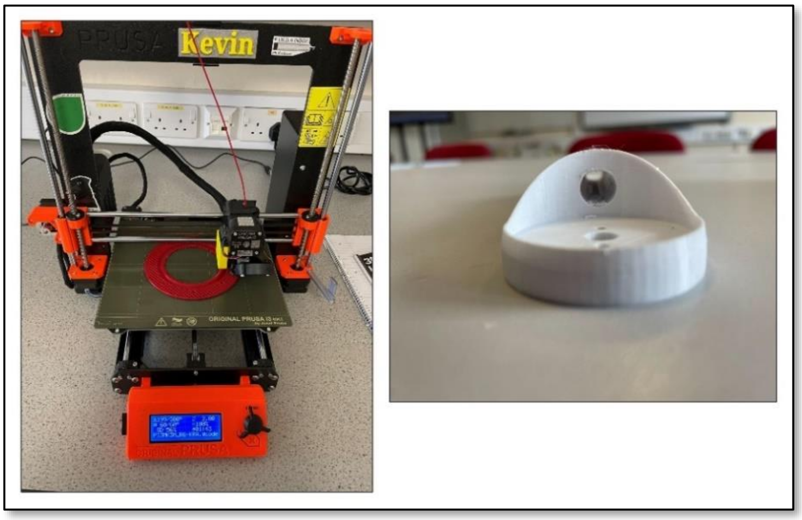

Fig. 3. Manufacturing of the Robotics Arm parts with the *Prusa MK 3D Printer* and PLA material.

Once the 3D printing of the object is completed, the part may require a further sanding, polishing, or painting phase, in order to improve the quality of its surface. The result of this process is, for example, the arm section shown in Figure 2 (right panel) and Figure 3 (right panel).

Once all the parts are printed, the arm can then be assembled: first step requires to assemble the motors with the parts. Then ball bearings are added to the base joint as it is shown in Figure 4. After this step, the limbs are assembled as well.

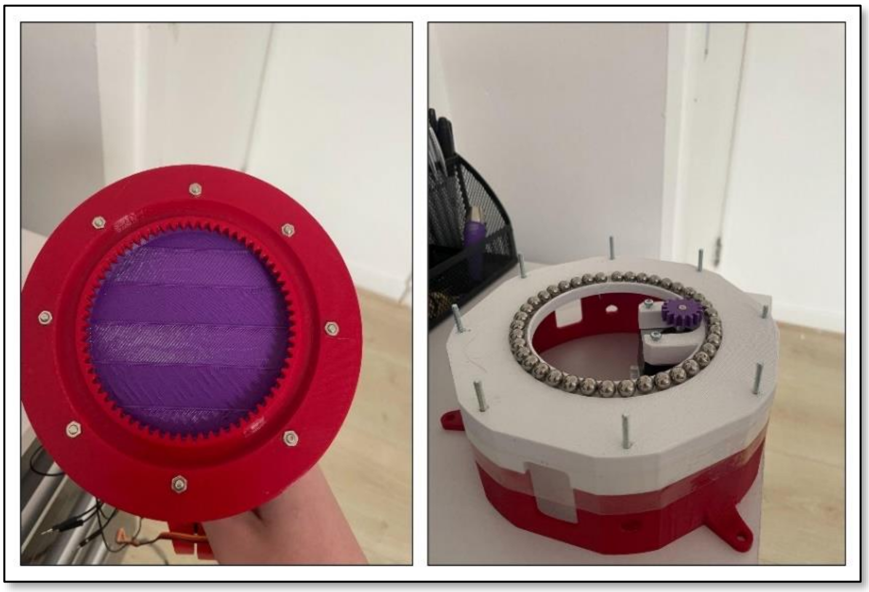

Fig. 4. Manufacturing of the *base joint* and integration with the ball bearings.

Finally, in order to control the robot and the joint actuators, a *low-cost Arduino board* is selected and connected to a breadboard interface between the robot controller and the actuators. The electronics are wired up and connected to the Arduino, as shown in Figure 5. Then the breadboard is connected to 6 different motors, namely one *gripper actuator* and other *5 motors*, performing the movement of the *base* and of the robotic arm, namely the *shoulder*, the *elbow*, the *wrist's twist* and the *wrist's rotation*.

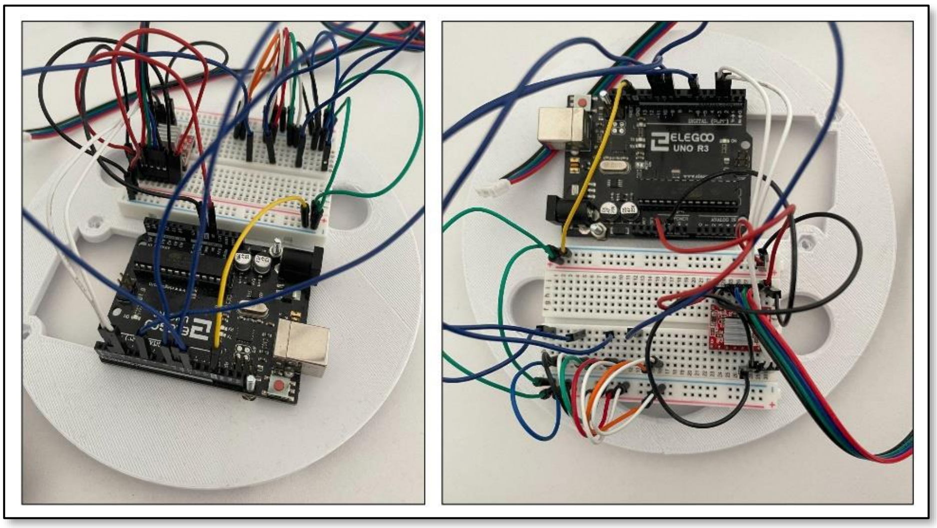

Fig. 5. Integration of the Arduino board and of the breadboard within the base.

2.3 Software Implementation

To control and move the robotic arm, a software interface has been designed in *Java Programming Language* with the *Processing* programming environment. Processing is a software environment which allows the design of *Integrated Development Environment* (IDE) for animations, and interactive applications. This IDE has been adopted because it is supported by several libraries and functions that simplify the process of designing a *Graphical User Interface* (GUI) with elements such as buttons, sliders, and drop-down menus.

Serial communication is a straightforward method of transferring data. The *Processing.serial.* library* allows the Processing IDE to send and receive information to and from microcontrollers, sensors, and other devices. The library supports several data formats, such as the communication of numerical values and strings.

According to this features, a GUI has been designed as it is shown in Figure 6: this interface is characterized by 6 controlling sliders for the 6 different motors of the robotic arm. For each motor there is a slider which allows the user to set the angular displacement of each motor. The angle is also returned to the user and displayed. For the stepper motor there are also two buttons which control these motors in both their directions. The color of these buttons go into grey when the button is pressed in order to inform the end-user.

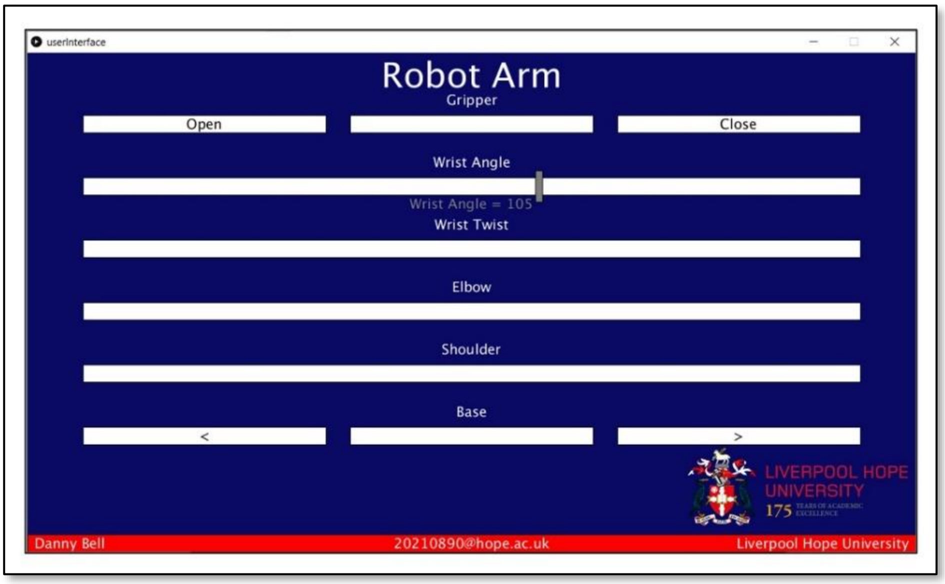

Fig. 6. The GUI for the control of the 6 actuators of the robot by means of sliding commands and interactive buttons; angular position of the actuator is also displayed.

The Arduino board is connected to 6 actuators, namely a *set of servomotors performing the arm movement* and a *stepper motor* controlling the rotation of the robotic base. The stepper motor requires the integration of a controller between the Arduino board and the robot itself. When a button is pressed on the GUI, an integer value is passed into the board by means of the communication protocol. The Arduino is programmed to read the integer and move the correct motor accordingly. An *A4988 motor driver* is used to interface the Arduino board with the microcontroller and the stepper motors.

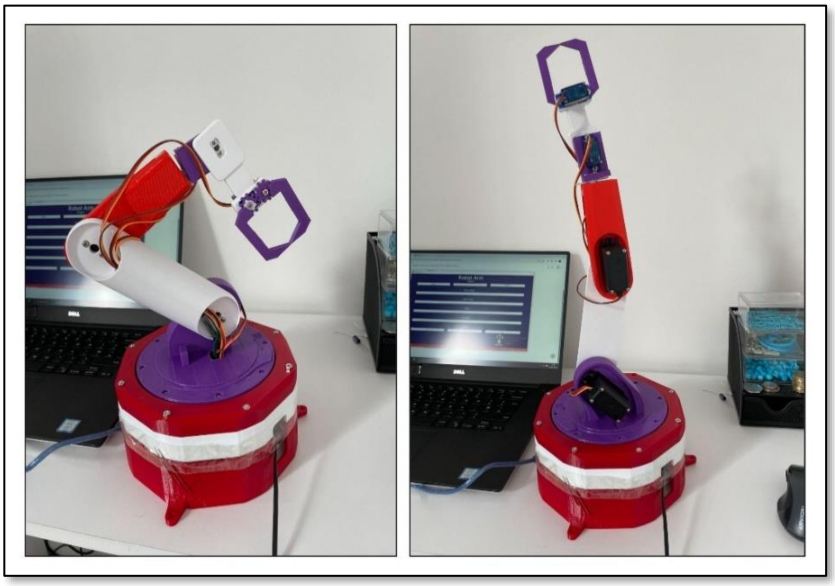

Fig. 7. The Robotic Arm

3 Results

A low cost 6 Degrees of Freedom robotic arm has been developed. The arm has been designed to be easy to assemble, and affordable, with a focus on using commonly available materials and 3D printed components. The final prototype is made of 5 servo motors and 1 stepper motor plus an Arduino board as reported in the Figure 7. The servo motors are attached to a series of 3D printed limbs, allowing an easy assembly and disassembly of the arm.

The base joint uses a stepper motor, which allows a full 360° rotation. The stepper motor embeds a gear on its shaft which engages with another internal gear connected with the base. Metal ball bearings help the arm to smoothly rotate. The shoulder and elbow joints use *MG996R Servo Motors*, which have a 180° rotation range and a torque of up to 11 kg/cm at 6 V thanks to metal gearing. The wrist joints and the gripper use *SG90 Servo Motors*, which also have a 180° rotation range with 1.8 kg/cm of torque. The control system of the robot arm is made of an Arduino board connected to a computer via USB, and a custom user interface developed in Processing. This interface allows the end-user to control the arm by means of sliders and buttons via serial communication.

Before testing the system, the arm has been calibrated to ensure that it correctly operates. The calibration requires setting the correct angles for each servo motor and checking that the arm moves smoothly. A 47 μF capacitor has been introduced in parallel with the power supply at this stage to stabilise the power and reduce electrical noise in the circuit, which in turn, could cause motor’s shaking.

The robot arm's performance has been evaluated through two types of tests or experiments. Firstly, the accuracy of the arm's movement has been tested, by asking the robotic arm to perform movements towards a specific points (or marks) within its workspace (i.e., movement accuracy test).

Table 1. Movement Accuracy Test Results

Trial	Distance from Base [mm]	Distance from Ref Marker [mm]	Percentage Error [%]
1	250	5	3.3
2	300	6	2.0
3	200	3	1.5
4	220	3	1.4

3.1 Testing Positioning’s Accuracy

The movement accuracy test has been performed by defining the test points, namely the specific points in space that the robot arm has to reach. The arm has been positioned at a designated starting point and calibrated in order to be ready to move.

Next the control software is used to move the arm towards each designated test point. The arm is moved slowly and precisely to ensure accuracy. After the robot arm has reached each test point, the actual arm position - in relation to the designated location - is recorded. A ruler is used to measure the distance between the end effector and the defined point.

Once the results are collected, they are analysed. The differences between the actual and designated positions are calculated and assessed. The testing process is shown in Figure 8 and the results are shown in Table 1.

This test has been designed in order to validate the performance of the arm, as well as to detect any possible issue in terms of movement capability. According to the results, the device shows a proper accuracy vs positioning towards the targets.

Fig. 8. Testing the Positioning's accuracy vs targeting marks.

3.2 Testing Manipulation Capability

We have then performed a second type of tests where the device has to move a different set of objects of different size and shapes. Here we have used a set of daily life objects such as a pen and small objects like a screw and a nut. The robotic arm has been positioned on a flat surface and then a set of moments are performed while grasping these objects. The movements of the device are controlled by means of the GUI and the grasping capability and manipulation capability are observed, then results are analysed to detect possible improvements vs the proposed design.

The outcome of these tests show that the proposed design could be used in a set of laboratory experiments where objects need to be moved and manipulated, provided that the weight of these objects is not too high vs the overall weight of the robotic arm [11].

4 Discussion & Conclusion

In this work we have presented a 3D printed design of a robotic arm which shows potential for the low-cost manufacturing of robotic devices [12, 13].

The arm has been integrated with a GUI in order to be used by non expert end-users on daily basis. The integrated system (i.e., hardware and software design) has been also tested to evaluate performance and capability.

There is room for improving the overall set-up in term of 'sensorization' on the system, given that a better set of transducer could be also integrated within the robot and combined with a suite of other software features, making the device more adaptable and reactive vs the environment. However, the proposed combination of 3D printed parts and low-cost hardware and software seems to be a significant benefit of this project [14].

A further set of tests should be considered in order to systematically validate the prototype. Integration of other human-robot interface could also be considered to make the system more ‘human-like’ [15-17].

Acknowledgments

This work was presented in Dissertation form in fulfilment of the requirements for the BEng in Robotics for the student Daniel Bell from the Robotics Lab, School of Mathematics, Computer Science and Engineering, Liverpool Hope University.

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