DEVELOPMENT AND OPTIMISATION OF A ROBOT ARM SYSTEM FOR ADDITIVE MANUFACTURING APPLICATIONS

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ABSTRACT

The paper presents the development of a new platform that represents a robotic arm system, useful and appropriate for the Additive Manufacturing applications. The main objective of this work was to explore the feasibility of integrating the off-the-shelf (COTS) Additive Manufacturing technologies and the six-degree-of-freedom industrial robotic arm, achieving a 3D Additive Manufacturing system which is able to perform six-degree fused deposition printing. The authors investigated the materials suitable to be used and performed more experiments with the aim to find the right configuration of the printing system. Finally, the technical issues reported during the experimental programme have been solved, the system being prepared to carry out workpieces with more complex shapes and more types of polymers.

KEYWORDS: additive manufacturing applications, 3D printing platform for additive manufacturing, FDM, robot arm

1. INTRODUCTION

The present research presents the possibility of using an extruder placed on the robot to print Fused Deposition Modelling (FDM) polymers. FDM is a process that uses 3D printer extruder nozzles. The process is achieved by extruding a material through a nozzle to form an object. The FDM process uses the motion of the portal system to control where the material is deposited on the two-dimensional plane.

By depositing vertically these planes, a 3D printed part is carried out. The extruded material must be heated to flow through the extruder. Due to its less expensive, friendly platform and open-source movement, the FDM technique is frequently used method for conventional 3D printing. If it is necessary to generate multi-plane motion in order to increase the layering capability, a serial link manipulator or robot arm can be used as a platform.

The industrial robot arms are a very used platform used in all the manufacturing industries (automotive, naval, civil engineering). The flexibility of their movement is what determines to be used in so many different applications including welding, assembly, pick and place, product inspection, testing, and other applications. Usually, the industrial robot arm has freedom of movement depending on the number and types of joints that have been connected. The main advantage of industrial robot arms is their relatively high degree of freedom (DoF). Because of DoF, a serial arm with 6 DoF can perform multi-planar movements in their working environment, compared to the conventional machine-type 3D printer portal, run into 3 DoF that are only capable of making planar layering [1], [2], [6].

Developing a robot arm system for Additive Manufacturing (AM) applications involves integrating robotic technology with 3D printing capabilities. This integrated system can be used for the deposition of material, layer by layer, and automated production of complex geometries. Some key steps regarding the development of such system are described below:

Requirements Analysis: determine the specific requirements of your additive manufacturing application. Consider factors, such as the desired build volume, material compatibility, printing speed, accuracy, and the complexity of the parts to be printed.

Robotic Arm Selection: choose a suitable robotic arm, based on the application requirements. Consider factors like payload capacity, reach, precision, and the number of degrees of freedom. Collaborative robots (cobots) are often preferred due to their flexibility and ability to work alongside humans.

End-Effector Selection: select an appropriate end-effector or tool head for the robotic arm that can perform additive manufacturing tasks. This may involve choosing a 3D printing extruder or other specialized equipment required for the specific AM process, such as laser sintering or powder deposition.

System Integration: integrate the robotic arm with the AM tool head. This involves developing or customizing the necessary hardware and software

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interfaces to ensure seamless communication and control between the robotic arm and the 3D printing system. Collaborative robots often have built-in safety features and user-friendly programming interfaces, simplifying integration efforts.

Motion Planning and Path Generation: develop algorithms for motion planning and path generation to enable the robotic arm to move precisely and deposit material accurately during the 3D printing process. These algorithms should optimize the toolpath for efficient printing while considering the factors, such as support structures, layer bonding, and overall print quality.

Material Handling and Supply: implements a system for managing the supply of additive manufacturing materials, whether it's filament, powder, or liquid resin. This may include automated material loading, unloading, and monitoring mechanisms to ensure a continuous printing process.

Process Monitoring and Quality Control: integrates sensors and monitoring systems to track the printing process in real-time and implements quality control mechanisms to detect and address any issues during the printing process. This can include monitoring factors, such as temperature, material flow rate, deposition quality, and potential defects.

Safety Considerations: ensure proper safety measures to protect operators and equipment. Collaborative robots should have safety features like force sensing, collision detection, and emergency stop functionality. Implement appropriate safeguards to prevent accidents and mitigate risks associated with the AM process.

Testing and Optimization: conduct thorough testing of the robotic arm system for additive manufacturing applications. Optimize the system by fine-tuning parameters, improving accuracy, and addressing any performance issues that arise during testing.

Scalability and Flexibility: design the system with scalability and flexibility in mind to accommodate future needs and potential changes in the additive manufacturing process. Consider the possibility of integrating multiple robotic arms or expanding the system for larger-scale production.

Throughout the development process, it's essential to collaborate with experts in robotics, additive manufacturing, and automation to ensure the successful integration and optimization of the robot arm system for additive manufacturing applications.

It is important to know that the specific details of developing a robot arm system for additive manufacturing can vary depending on the chosen technique (e.g., FDM, SLA, SLS) and the desired application. It is recommended to ask for the support of the experts in both robotics and additive manufacturing to ensure the successful development and integration of such a system [7], [8]. Besides, it is necessary to apply various standards and guidelines to ensure safety, quality, and compatibility, such as follows:

- ISO 10218: this international standard specifies the safety requirements for industrial robots. It covers areas, such as robot system design, integration, and operation, including the considerations for collaborative robots (Cobots).
- ISO/ASTM 52900: this standard provides guidelines for additive manufacturing processes. It covers aspects, such as terminology, process control, design, post-processing, and quality assurance for additive manufacturing systems.
- ASTM E2500: this standard outlines the requirements for the qualification, verification, and validation of the robotic systems. It includes considerations for the system design, installation, commissioning, and operational performance.
- ISO 13849: this standard addresses the safety of machinery and provides guidelines for the design and implementation of safety-related control systems. It specifies requirements for the functional safety of the robotic systems, including risk assessment and performance levels.
- ANSI/RIA R15.06: this standard is specific to the industrial robot safety in the United States. It provides guidelines for system integration, safeguarding, and operational practices, including considerations for collaborative robot systems.
- ISO 12100: this standard focuses on the general principles of machinery safety, including risk assessment and risk reduction. It provides guidance on hazard identification, risk assessment, and risk reduction measures for machinery, including robotic systems.

In conclusion, it is crucial to consult these standards and any other applicable local regulations to ensure compliance, safety, and quality. Additionally, it is recommended to involve experts in robotics, additive manufacturing, and safety engineering to address the specific requirements and challenges in your application.

2. MATERIALS

The material used in the experiments was Polyethylene Terephthalate Glycol (PETG) that is a thermoplastic material which has increasingly become popular in various industries due to its unique properties. Here are some of its principal properties:

Transparency: PETG is transparent, allowing for clear visibility through the material. This property makes it a popular choice in industries such as packaging and signage.

Impact Resistance: PETG has an excellent impact resistance, making it less likely to crack or break when subjected to sudden or high-impact forces. This property makes it a popular choice in industries, such as transportation, where materials are exposed to constant vibrations and impacts.

Chemical Resistance: PETG is resistant to many chemicals, including acids, alkalis, and alcohols. This property makes it a popular choice in industries, such as medical and laboratory, where materials must withstand exposure to various chemicals.

Flexibility: PETG is flexible and can be easily formed into various shapes and sizes. This property makes it a popular choice in industries, such as packaging, where materials must be flexible and able to conform to different shapes and sizes.

Recyclability: PETG is highly recyclable, making it an environmentally friendly option. It can be recycled into various products, such as clothing, carpet fibers, and packaging materials.

Overall, the combination of these properties makes PETG a versatile material with a wide range of applications in various industries. PETG offers several important advantages over other commonly used 3D printing materials, like PLA and ABS. One of the key advantages of PETG is the excellent layer adhesion, which means that the layers of the 3D print stick well together and do not easily separate or delaminate. This makes PETG an ideal material for creating strong and durable parts that can withstand stress and strain.

PETG is also highly resistant to impact and deformation, which makes it a good choice for creating functional parts and prototypes that need to be able to withstand wear and tear. Additionally, PETG is resistant to chemicals and moisture, which makes it suitable for creating parts that will be exposed to harsh environments.

Another important advantage of PETG is its ease of printing. PETG has a low tendency to warp or shrink during printing, which means that it can be printed without the need for a heated bed or enclosure. PETG also has a wide printing temperature range and can be printed at higher speeds than many other 3D printing materials. Overall, PETG's combination of strength, durability, chemical resistance, and ease of printing make it a versatile and important material in the FDM 3D printing process.

PET-G (Glycol-modified polyethylene terephthalate) is a co-polyester that was made by a mixture of PET and glycol and the material was developed especially for 3D printing.

The PET-G filament has a lot of advantages and combines the advantages of ABS (strength, good temperature behaviour, durability) with those of PLA (easy to print) in a single material. Co-polyesters carry on their strength, clarity, and other mechanical properties even when the material is exposed to various chemicals that can affect other materials. Advantages: durable, high impact resistance, flexibility.

3. EXPERIMENTAL PART

The experimental part consists of developing a robot arm to print polymers. The experimental part took about 3 weeks to optimize the position and the necessary components of the plate that underlie the operation of the robot arm.

The optimization has been conducted in the direction of the electronic control. The part of the electronic controller was very much optimized because a lot of variants were tried before the final combination of the power controller, electronic processor board, and power source. In the first steps of this c study case, the components were much less, but as the study evolved, more components were needed on the PCB. The Arduino Mega has been changed two times because the electric controller didn't start, and for this reason different combinations of the parts were tried.

The extruder system has been composed from an extruder head, a motor to feed the extruder, a cooling fan, a heating element, a thermistor, and compressed air. The extruder controller has been composed from an Arduino Mega 2560 with a Ramps 1.4 extruder driver board. The extruder head system includes a thermal insulator, a heat block, and a nozzle. A 0.4 (mm) nozzle was used to feed a Polyethylene terephthalate glycol filament through the extruder head. A NEMA 17 stepper motor was used as the extruder feed motor to feed the Polyethylene terephthalate glycol filament. Rated current of 1.5 (A), step angle of 1.8 (degrees), and holding torque of 0.4 (Nm). To keep the filament melting only at the extruder heat block, a cooling fan was used to lower the thermal temperature of the insulator (this was the solution that the research team took in that stage of the research).

The present study represents the development of a robot arm that has an extruder that can print polymers. The experimental part of the work was quite difficult because there were problems in writing the code on the board as well as an erroneous alignment of the components, initially only one source was used, but as the research progressed it was concluded that two sources were needed. Another problem was the failure of some components such as the thermocouples, but by optimizing as much as possible, and modifying some positions on the board, it was possible to complete it.

After selecting the 3 parameters (filament speed, plate temperature, and temperature of the thermocouple, mounted directly on the extruder) and after reaching the optimal temperature, the extruder is ready to print the desired part. Speed and temperature are also adjusted according to the material used.

For the PETG, the optimum temperature is between 230 - 260°C, the working table temperature is 60°C, and the optimum speed is between 3.6 - 4.8 mm/s). The extrusion head system includes a thermal insulator, a thermal block, a thermocouple, a cooling fan, a stepper motor, and a 0.4 mm nozzle. The operating principle and phases are briefly presented below:

- initializing the robot, acting on the controller to command the electronic controller module;
- acting the microprocessor board to command the extruder heating module until the required temperature is reached;

- operating the support plate on which the part is moulded;
- operating the display module and setting the process parameters;
- starting the working cycle by initialising the software;
- positioning the robot and starting the extruder until the required viscosity is reached (10-15s time);
- adjusting the wire feed speed to reach the temperature or speed required by acting the potentiometer 1 or potentiometer 2, respectively;
- acting the system to start the 3D printing process.

In the figure 2, it is presented the block diagram of the process of making the plate that underlies the printing arm with the related circuits and components. Also, in figure 3, it can be seen the components positioning on the plate that underlies the operation of the robotic arm [3], [4], [5], [6], [16].

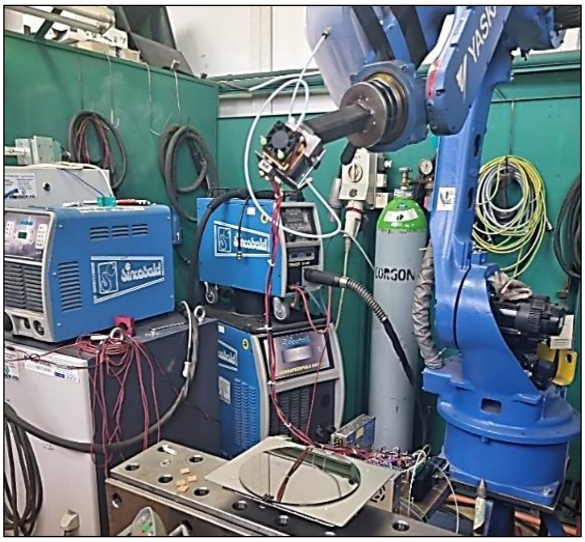

Fig. 1. Robot arm-based Additive Manufacturing system

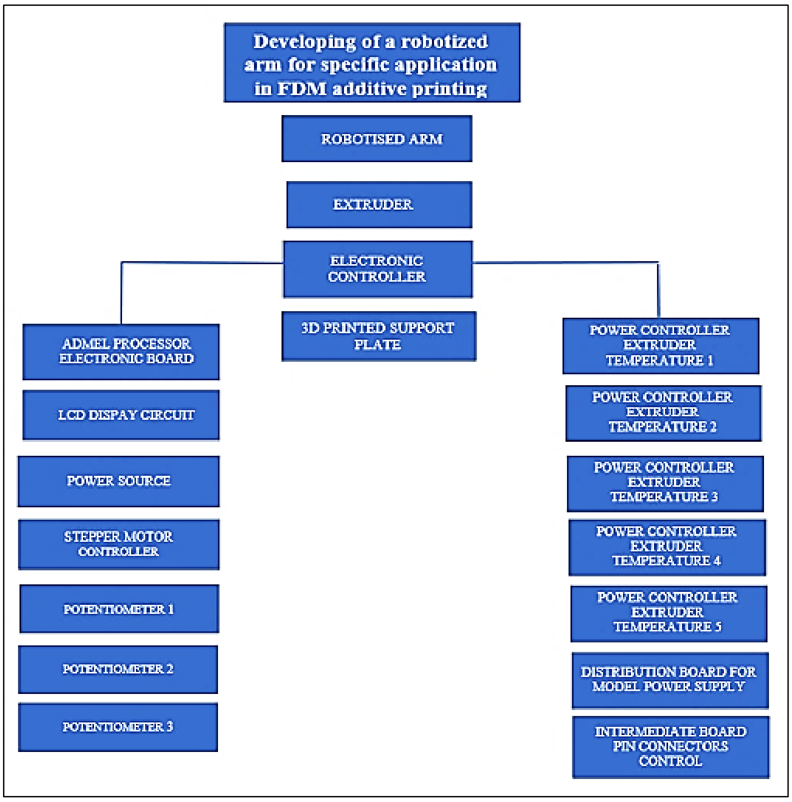

Fig. 2. Process block diagram

4. FUSED DEPOSITION MODELLING PROCESS

Fused Deposition Modelling Process (FDM) can be used for various extrusions, materials, and filament thickness. The 3D extruder is the part of the 3D printer that extrudes material in liquid or semi-liquid form to deposit it in successive layers. In some cases, the extruder serves only to deposit a bonding agent used to solidify a material that is initially in powder form.

The robotic arm is a mechanical device that resembles the human arm. The mechanical arms can be programmed to do various tasks. The robotic arms are often used to perform tasks that are either harmful to humans, unsafe, unpleasant, or highly repetitive.

The extruder: the high-temperature reflow kit was chosen due to the efficiency of printing materials that have higher melting points than the usual ABS and PLA materials. In this study the Polyethylene terephthalate glycol (PETG) material will be used for printing the samples and optimising the system developed. The toolkit includes a standard hot end for printing ABS and PLA for further studies.

Drive system: motor to feed the extruder during printing. The extruder is designed to fit it.

Electronics: Arduino Uno was chosen to control the fans, stepper motor and heating element.

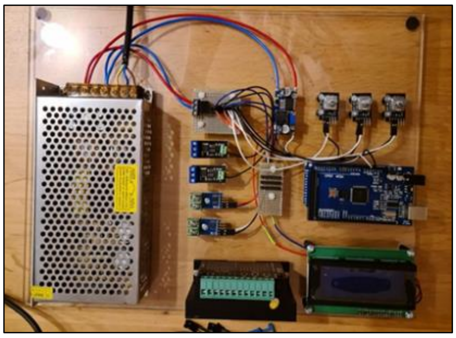

Fig 3. Main board

Fig. 4. Components on the main board

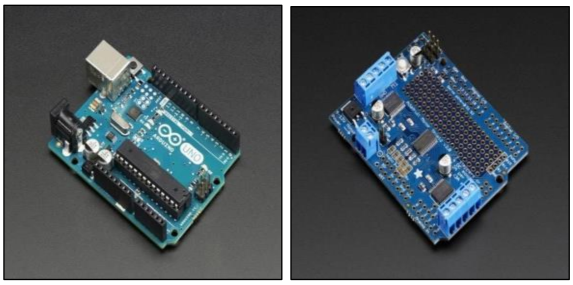

Fig. 5. Arduino Uno

The encoders are sensors that detects the angle of rotation or linear displacement, being used in devices that need to operate at high speeds and with high accuracy. The method of controlling the motor rotation by monitoring the motor speed and rotation angle with encoders is called feedback control (closed loop method).

- Encoder 1 for controlling the filament speed;
- Encoder 2 for controlling the extruder temperature;
- Encoder 3 used for controlling the table temperature.

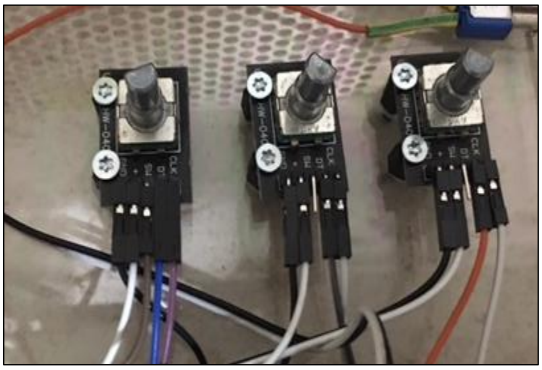

Fig. 6. Encoders

After several trials, the base/main plate, which is the basis of the robot arm operation, was found. The optimization process was quite difficult because of the technical issues related to the components, thermocouples and insufficient power supply. Finally, it was concluded that two current sources were needed.

The material used is Polyethylene terephthalate (PETG) that in generally is thermoplastic (as opposed to thermosetting). This characteristic is related to the way the plastic responds to heat. There are some variants of this material (such as certain types of polyester) that are thermosetting. Thermoplastics become liquid at their melting point (around 260°C in the case of PET). The PETG is a glycol-modified version of polyethylene terephthalate (PET), which is commonly used to produce water bottles. It is a semi-rigid material with good impact strength, but has a slightly softer surface, making it prone to wear. The material has an excellent thermal characteristic, allowing the plastic to cool efficiently with almost negligible deformation.

The advantages of 3D printing PETG is connected to the easy printing, as well as the availability in a wide variety of colours and transparency properties. There are several disadvantages, such as limited bridging possibilities, or spider-thin threads that may appear on the printed surface caused by the characteristics of the filament. In the figures 7 and 8, it can be seen the steps followed for the product optimization [13], [4], [15].

Table 1. PETG particularities

Features	
Durability	High
Material costs	Low
Strength	High
Flexibility	Low
Resistance	
Heat resistance	Medium
Chemical resistance	High
Fatigue resistance	High
Water resistance	High

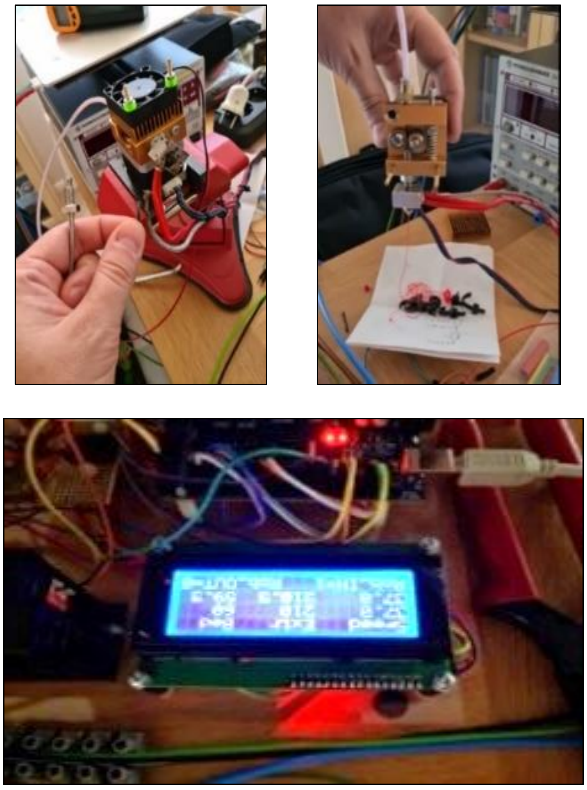

Fig. 7. Preparing and starting the 3D printing process

During the first experiments, the thermocouples failed and a supplementary source was needed to be added together with the first one. The first sample achieved has a square shape and was made by printing PETG layers, as figure 8 shows. The first printed sample showed a defect after the first 5 layers were deposited. Therefore, the studies need to be continued in order to improve the quality of the samples. The defect developed during the printing process has been caused by the cooling time between layers. Modifying the cooling time between the layers deposited, the quality was increased. Moreover, the next layers made possible the remelting and the removal of defects developed within the first layers the next layers covered the defect from the first layers [10], [11], [12].

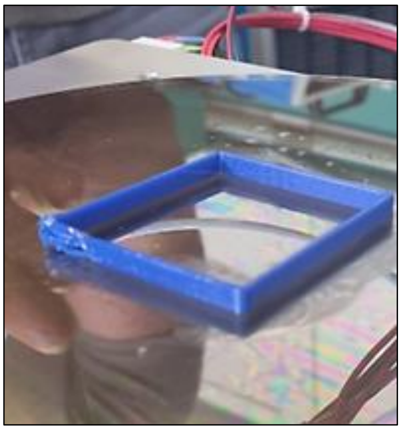

Fig. 8. Sample performed with the extruder robot arm

The printed sample, shown in figure 8, was performing by melting and depositing 20 layers. The future research will be focused on increasing the complexity degree of the samples, to perform more irregular shape and to extend the materials range. The main goal of this study was to realize the robot arm with the specific polymer extruder with the purpose of doing research studies on polymer printing on a robot [7], [8], [9].

6. CONCLUSIONS

The aim of the investigation was to develop and optimise a robot arm system that has been used for printing polymers materials. The extrusion head system includes a thermal insulator, a thermal block, a thermocouple, a cooling fan, a stepper motor, and a 4 mm nozzle. The GCode developed can control the robot arm movement, the coordinates in the working space, the orientation of the extruder head, the speed of the robot arm, the extrusion speed and volume during the printing process.

The system developed will be able to print more types of polymers (PLA, PET, PETG, ABS, etc.) with higher printing speed, better homogeneity and, consequently with increased quality [17], [18]. Based on the capabilities of the 5 or 6 DoF robot and on the features of the extruder, it is supposed that the system will be better than a professional printer.

In the experimental programme, several technical issues in writing the code on the board, as well as the improper alignment of the components, or the need of the second source led to the improvement step by step of the process. Optimization has been carried out in the direction of electronic control and part combinations on the PCB, some parts being replaced, and others had to be doubled to determine the final configuration. Another issue was the failure of some components, such as the thermocouples, but optimizing as much as possible, and modifying some positions on the board, the problems have been solved. Finally, the most important steps to be followed for a qualitative process are briefly described below:

- selecting the parameters (filament speed, worktable temperature, and temperature of the thermocouples, mounted directly on the extruder).
- setting the appropriate temperature, so that the extruder to print the required workpiece.
- Speed and temperature adjustments according to the material used.
- It was found that the PETG optimum temperature should be in the range of 230–260°C. Besides, the working table temperature should be 60°C, and the optimum speed must be 3.6 to 4.8 mm/s.

One of the future objectives will be focused on obtaining defect-free products. Moreover, future studies will be extended to other materials and other complex shapes, including lattice beam shapes, by taking into consideration the full capabilities of system developed in this research.

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