DESIGN AND DEVELOPMENT OF AN IOT-ENABLED CONTROL SYSTEM FOR ROBOTIC EXTRUSION IN ADDITIVE MANUFACTURING

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Additive manufacturing, the Internet of Things (IoT), and robotics are key pillars of Industry 4.0, enabling the creation of connected and intelligent manufacturing systems. Despite the development of robotic additive manufacturing, the field of open and low-cost extrusion head control solutions for industrial robots remains relatively unexplored. This study focuses on the design and development of an IoT-based control system for an extrusion unit used in robotic FDM/MEX additive manufacturing. The proposed approach utilizes a compact hardware architecture based on the Arduino platform, ensuring seamless integration of sensors and actuators and implementation of a real-time control algorithm. The control logic was implemented and experimentally verified on a robotic assembly with an ABB IRB 120 industrial robot, monitoring the stability of the hotend temperature, the consistency of the material flow, and the quality of the printed test geometries. The results confirm the feasibility of using low-cost IoT devices for precise control of robotic extrusion and demonstrate sufficient process repeatability for laboratory and research applications. The study also points to the potential for further development towards scalable and flexible solutions, with future research focusing on systematic control optimization, improved data connectivity, and architecture preparation for industrial deployment.

KEYWORDS

Additive Manufacturing, IoT, Extruder Control, Robotics, Industry 4.0, Robotics Additive Manufacturing-

1 INTRODUCTION

Industry 4.0 is based on the rapid development of digital technologies such as the Internet of Things and cyber-physical production systems. Today's manufacturing is extremely dynamic, and companies must constantly adapt to new technological and market requirements. Traditional rigid manufacturing systems are therefore gradually being replaced by modular and adaptive solutions [Patel & Chen, 2022]. The focus is no longer on single-purpose machines, but on flexible equipment capable of rapid reconfiguration.

One of the pillars of this transformation is the robotization of production processes, which brings high flexibility in terms of positioning and programming. However, the technology that the robot performs must also be flexible [Fragapane et al., 2020]. A typical example is additive manufacturing [Dehghan et al., 2025]. Unlike conventional technologies, it does not require moulds, special fixtures, or tools, no cutting forces are generated during the process, and it is possible to quickly produce a custom part directly according to requirements [Höse et al., 2023].

There are many classic 3D printers for plastics or metals on the market, using various technological principles [Sniehotta, 2020]. However, if we want to print larger parts, parts with unusual orientations, at an angle, or non-planar without the need for supports, we reach the limits of conventional Cartesian systems. The solution may be a larger gantry, additional positioning, or the use of an industrial robot [Alhijaily et al., 2023].

Industrial robots have so far been most used for handling or welding, but in recent years, robotic additive manufacturing applications have also been increasingly appearing [Bartoš et al., 2021]. However, the available commercial solutions are mainly geared towards large-format 3D printing, where robots with medium to high load capacities (50–300 kg) and a working range of over 2 meters are used, together with pellet extruders providing high volume flows (in grams to kilograms per hour).

However, if a company or laboratory needs a compact, flexible, and space-saving system designed to print smaller parts using MEX (Material Extrusion) technology directly on the robot's work surface, the market offering is very limited [Romancik et al., 2024]. In such cases, it is necessary to design and create a custom solution. However, this requires a reliable extruder control system capable of operating in real time and connecting all technical components to the robot itself [Meibodi et al., 2023].

However, standard extruder heads from 3D printers are firmly connected to microcontroller-type control boards that control axes, temperatures, and fans. Their architecture is not adapted for direct communication with industrial robots via digital or analogue signals in real time, which significantly limits their integration into robotic systems.

For full control, it is therefore necessary to design a system that can directly control all technological parameters of the extruder while ensuring seamless integration with the robotic platform. Such a system will enable precise coordination between the extruder and the robotic manipulator, which is essential for creating complex geometries or non-planar printing. In laboratory conditions, a simple IoT device can be effectively used for this purpose, offering flexibility and sufficient variability for experimental research.

There are various solutions available – from microcomputers such as Raspberry Pi or Orange Pi, through industrial IoT platforms (e.g. Revolution Pi – RevPi Core), to integrated PLC systems (Siemens LOGO!, S7-1200, S7-1500, Allen-Bradley, Omron, etc.) [Ashima et al., 2022].

Current research in robotic additive manufacturing focuses primarily on topics such as path generation, motion planning, process options, and case studies. However, this paper focuses on the integration of control via the Arduino platform, which is an open control system with good availability, easy configurability, and the ability to communicate via various buses. [Fucile et al., 2023; Habibi & Ziadia, 2021].

This article therefore focuses on this less explored area and analyses the possibilities of integrating an extruder via the Arduino platform. This platform is an open control system with good availability, high variability, customization options, and support for communication via various industrial and non-industrial buses, making it a suitable candidate for experimental verification of the print head control concept for robotic additive manufacturing.

The aim of this work is to verify the possibilities of designing and implementing a functional printhead control system for robotic additive manufacturing, which allows real-time adjustment and monitoring of key process parameters such as temperature, feed rate, cooling intensity, and other technological variables. At the same time, it examines whether such a system can ensure stable implementation of the MEX process and enable the creation of physical components using an industrial robot.

The main outcome and contribution of the paper is a proposal for a control architecture for a robotic additive manufacturing system based on an IoT platform, which provides flexible extruder control and opens opportunities for further research in the field of robotics and additive technology integration.

2 BACKGROUND

Robotic Additive Manufacturing (RAM) is a modern approach that combines the flexibility of industrial robots with the precision and development potential of additive technologies [Urhal et al., 2019]. Traditional Cartesian 3D printers are limited by their working volume and material deposition direction, while the integration of a robotic manipulator allows material to be deposited in multiple axes. This improves surface quality, layer adhesion, and overall geometric accuracy of the part [Pini et al., 2025].

Robotic systems enable the production of large-scale components from polymers, composites, and metals while maintaining acceptable investment costs and high precision [Felsch et al., 2017].

Current developments are moving towards intelligent multi-robot cells (C-RAM) that use sensors, digital twins, and adaptive real-time process control [Rescsanski et al., 2025].

Material Extrusion (MEX), which includes FDM and FFF technologies, is one of the most widely used methods of additive manufacturing of thermoplastics [Hrbackova et al., 2019]. The process involves extruding molten material through a nozzle and depositing it layer by layer, enabling the creation of functional prototypes, tools, and structural parts [Urhal et al., 2019].

MEX technology includes three basic types of extrusion mechanisms (Fig. 1): piston extruders, screw extruders using granules, and the most widespread filament extruders, in which the filament is transported by feed rollers into a heated zone [Gibson et al., 2010; Godec et al., 2022; Miclette et al., 2022].

However, in robotic integration, the technical problem shifts from the mechanical feeding of material to the precise control of process parameters and their synchronization with the robot's movements.

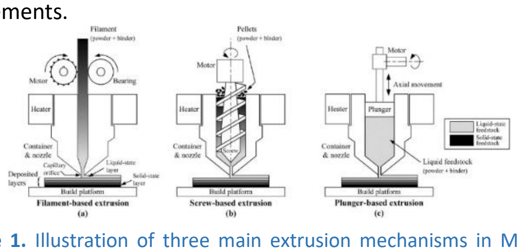


Figure 1. Illustration of three main extrusion mechanisms in MEX: a) filament-based, b) screw-based and c) plunger-based [Miclette et al., 2022]

From a hardware perspective, the robotic MEX system consists of mechanical and control architecture: an industrial robot with a controller, an extrusion head with a stepper motor or gearbox, a hotend heating element, temperature sensors, and cooling fans [Nayyeri et al., 2023].

The software part includes trajectory generation, robotic path simulation, [Badarinath & Prabhu, 2021].

The synchronization of these two layers is crucial for the quality of the final product, especially when printing at an angle or along curved surfaces, where fibre orientation is critical for mechanical, thermal, or electrical properties. The path program, such as G-code, is then transformed into a robotic language such as RAPID [Zhang et al., 2018].

However, integrating a robot with an extruder poses several technical challenges. Standard extruders usually do not have a suitable flange attachment to the robot, many robotic programming environments do not support direct control of external motors, and robot control systems often do not provide sufficient options for controlling the extrusion process. For this reason, it is necessary to supplement the robotic cell with its own modular and open extrusion head control system.

Arduino is an open platform that, when supplemented with communication modules (e.g., Wi-Fi), sensing elements (thermistors, thermocouples, RTDs, current measurement), and actuators (heating cartridges, stepper motors, fans), functions as a full-fledged IoT endpoint [Galadima, 2014]. It enables data exchange with edge or cloud services and executes control policies in real time as IoT platform. An Internet of Things (IoT) device is a physical object embedded with sensors and technology that allows it to connect to the internet, enabling communication with other devices and people from anywhere at any time [Singh et al., 2022].

Compared to PLCs or microcomputers such as Raspberry Pi, it provides a simpler, affordable, and flexible platform suitable for experimental research. Its disadvantages include lower reliability and the absence of industrial certifications, which may limit its use in demanding operating environments.

Controlling the extrusion head requires accurate temperature measurement using contact sensors (NTC thermistors, K/J thermocouples, RTD PT100/1000, or silicon sensors), which provide feedback for regulating the hot-end temperature [Goumopoulos, 2018].

The material is fed by a NEMA 17 or NEMA 23 stepper motor, whose discrete stepping allows for precise control of the flow and speed of extrusion [Virgala et al., 2015; Wolf et al., 2024]. Although these components work reliably in conventional 3D printers, in robotic applications it is crucial to synchronize them with the multi-axis movement of the robot.

Despite the rapid development of RAM, scientific literature in this field still focuses mainly on trajectory generation and process applications, while the issue of extrusion head control – in particular open control architecture, adaptive parameter setting, and connection to sensors – remains insufficiently researched [Lopes de Aquino Brasil & Carmo Pena Martinez, 2025].

Commercial robotic MEX solutions often use closed control systems that do not allow experimentation with new control strategies, extrusion head types, or real-time feedback control.

This creates a need for a dedicated experimental platform with open hardware and software architecture.

Such a system will enable the control algorithm to be linked to temperature, flow, and extruder load sensing, support the testing of new control strategies, and provide scope for optimizing trajectories and extruder head design.

The result is a flexible research platform for intelligent robotic additive manufacturing with the possibility of further expansion with multi-axis extrusions, multi-material heads, or hybrid robotic-measuring systems.

3 MATERIALS AND METHOD

Based on the identified challenges in the field of robotic additive manufacturing, an experimental system was designed that allows for detailed examination of extrusion head control in connection with an industrial robot.

The goal was to create an open, modular, and fully configurable platform that would enable the verification of process parameters, testing of control strategies, and implementation of printing using MEX technology in a robotic environment.

3.1 *Architecture of the robotic system for additive manufacturing*

The proposed architecture consists of hardware and software layers. The hardware part consists of an industrial robot with a control unit, an experimental extrusion head with an integrated stepper motor, a heating element, and temperature sensors, as well as a separate control module based on the Arduino platform, which provides real-time temperature control, filament feed control, and actuator control.

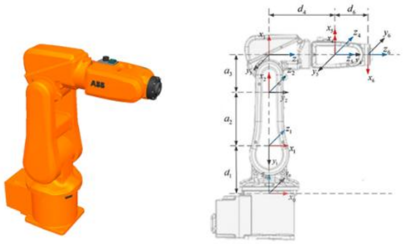
The software layer includes tools for generating trajectories, simulating robotic movements, and exchanging data between the robotic system and extrusion control.

The methodology includes the design and implementation of an extrusion head control module, integration of the communication interface between the robot and the extruder, and experimental verification of printing using a robot-controlled MEX process. The system designed in this way allows the relationship between extrusion process parameters, robot movement, and the quality of the printed part to be examined, while also creating space for further technical improvements in the field of robotic MEX technology.

3.2 *ABB IRB 120 industrial robot*

Specifically selected materials and methodological procedures were used to examine the possibility of integrating our own extruder system with a robotic manipulator.

The ABB IRB 120 industrial robot was selected as the robotic platform, which meets the requirements of experimental laboratory research with its compact design, low weight, and suitable working space, Fig. 2.



Joint i	ϑ_i	d_i	a_i	α_i
1	ϑ_1	d_1	0	$-\frac{\pi}{2}$
2	$\vartheta_2-\frac{\pi}{2}$	0	a_2	0
3	ϑ_3	0	a_3	$-\frac{\pi}{2}$
4	ϑ_4	d_4	0	$\frac{\pi}{2}$
5	ϑ_5	0	0	$-\frac{\pi}{2}$
6	ϑ_6	d_6	0	π

Figure 2. ABB IRB 120 [Nezzi et al., 2025]

It is a 6-axis robot with a maximum payload of 3 kg, a reach of 580 mm, and an approximate weight of 25 kg, making it a suitable tool for testing low-load additive technologies.

Figure 3. Connection of the print head to the adapter plate of an industrial robot via a designed holder

Since the extrusion head must be firmly and precisely mechanically connected to the robot flange, a special adapter was designed and 3D printed that meets the requirements of ISO 9409-1 for attaching tools to the end of a robotic arm, Fig. 3.

This adapter ensures compatibility between the robot and the extruder and allows for secure and repeatable mounting during experiments.

3.3 *MEX extruder*

The KINGROON All Metal (Fig. 4) model was chosen as the extrusion unit, which was controlled by a designed IoT device as part of the experiment. This extruder uses a NEMA 17 stepper motor, which ensures accurate filament feeding and stable material flow during printing. The all-metal construction of the hotend without a PTFE insert in the heat-exposed zone allows higher operating temperatures to be achieved, which expands the range of processable materials.

Figure 4. Kingroon All metal extruder with hotend

The nozzle is heated by a 50 W, 24 V heating cartridge, which ensures fast and stable attainment of the set temperature. Temperature measurement is performed using a standard NTC 100 kΩ thermistor. The MK8 nozzle with a diameter of 0.4 mm is suitable for most common filaments and, if necessary, can be easily replaced with a different size depending on the required detail or printing speed.

The extruder also includes two cooling circuits: a 24 V type 5015 fan directing air onto the extruded material to promote rapid solidification, and a 24 V 3010 cooling fan designed to stabilize the temperature conditions of the hotend. Although not strictly necessary for the extrusion process itself, they significantly contribute to reducing the risk of delamination, process stability, and consistent print quality.

The proposed control system is universal and compatible with screw-based extruders, as these use similar design elements – heating zone, temperature sensors, actuators, and motor drive – but with a different material transport mechanism.

3.4 *ARDUINO platform as the control system*

The extruder is controlled by the Arduino UNO R4 WiFi microcontroller platform, which combines a Renesas RA4M1 32-bit microcontroller (R7FA4M1AB3CFM#AA0) and an ESP32-S3-MINI-1-N8 communication module for Wi-Fi connectivity.

The RA4M1 microcontroller is based on a 48 MHz Arm® Cortex®-M4 core and has 256 kB of flash memory, 32 kB of SRAM, and 8 kB of EEPROM. The RA4M1 operates at a supply voltage of 5 V, while the ESP32-S3 operates at 3.3 V; communication between the two microprocessors is therefore implemented via a TXB0108DQSR bidirectional logic converter.

Figure 5. Arduino UNO R4 WiFi used as a control platform

The UNO R4 WiFi platform includes several integrated peripherals that enable efficient signal processing and extrusion process control. The most important ones include a 14-bit AD converter for accurate measurement of analogue quantities (e.g., temperature sensors), a 12-bit DAC, and an integrated operational amplifier (OPAMP) suitable for modifying or filtering analogue signals, Fig. 5.

The equipment also includes a USB 2.0 Full-Speed module for programming and communication with a PC, and a Capacitive Touch Sensing Unit (CTSU) enabling capacitive touch inputs when needed.

In terms of communication options, the board supports several industry-relevant protocols, including UART (pins D0 and D1), SPI (pins D10–D13 and ICSP connector), two I²C interfaces (pins A4/A5 and Qwiic connector), and a CAN interface on pins D4 and D5, which, however, requires an external transceiver.

These communication options enable connection to sensors, actuators, and add-on modules, while the platform provides sufficient performance and flexibility to control the extruder in a robotic application and opens opportunities for future integration of IoT functionality.

The TMC2209 controller, a high-performance micro stepping driver from Trinamic designed for precise control of bipolar stepper motors, is used to control the extruder's stepper motor. The driver supports a peak output current of up to 2.0 A (RMS approx. 1.4 A) and allows micro stepping up to a resolution of 1/256 steps, ensuring extremely smooth and precise motor operation. The TMC2209 operates with a motor supply voltage range of 4.75–29 V and accepts a logic voltage of 3.3–5 V, making it compatible with the Arduino UNO R4 WiFi platform and other control systems [Arduino, 2025].

Item	Quantity	Unit Price (€)	Total price (€)
Switching PSU S-360-12 (12V/30A)	1	25.0	25.0
TMC2209 stepper driver	1	6.0	6.0
IRF520 MOSFET module	1	2.5	2.5
KINGROON Extruder	1	18.0	18.0
Arduino UNO R4 Wi-Fi	1	22.0	22.0
Breadboard (full size)	1	3.0	3.0
Resistor 220 Ω	2	0.05	0.1
Hook-up wire (5 m)	1	3.0	3.0
Dupont jumper wires (set)	1	3.0	3.0
Total cost			82.60

Table 1. Component Cost Summary

The IRF520 MOSFET module is used for switching and controlling DC loads with higher voltage and current. It is a simple and effective solution for controlling external components using low-voltage logic signals from microcontrollers such as Arduino, ESP32, or Raspberry Pi. The module allows switching of loads at voltages up to 24 V and currents of approximately 1–2 A, depending on the conditions. It is based on the IRF520 N-channel MOSFET, which acts as an electronic switch – when a HIGH logic level (≈5 V) is applied to the control electrode "gate," the transistor opens and allows current to flow through the load. The module includes a three-pin control connector (SIG, VCC, GND) for connection to a microcontroller and screw terminals (V+, V–, GND) for connecting the power supply and controlled load.

Non-solderable contact fields (breadboards) are used to assemble and test prototype solutions, enabling quick and flexible implementation of circuits using components and connecting wires without the need for soldering. This approach is suitable for research and experimental applications, as it allows for easy wiring adjustments and quick verification of different control system variants.

The complete list of components used in the development process is presented in Table 1. This table includes both the unit cost and quantity of each component to enhance clarity, transparency, and reproducibility of the experiment.

By providing detailed information on the hardware materials and their economic aspects, the table supports the replication and verification of the experimental setup in future research.

3.5 Methodological framework of the experiment

The experiment was designed as a multi-stage methodological process aimed at verifying the functional feasibility of a proprietary extrusion module integrated with an ABB IRB 120 robotic manipulator. The methodology was designed to enable gradual verification of individual subsystems, their mutual coordination, and subsequently also assessment of the system's ability to perform basic robotic MEX printing.

In the first phase, the methodology focused on preparing a hardware prototype and verifying the basic functionality of the extruder control system. The aim of this phase was to create a stable basis for temperature control and material feeding, which is necessary for its subsequent integration with the robotic manipulator. The goal was to ensure that all control blocks worked consistently in isolated mode, without the load of robotic movement.

In the next phase, the methodological framework focused on the implementation of regulatory mechanisms, the calibration of key parameters, and the definition of relationships between the inputs and outputs of the extrusion process. These tasks represent a necessary step towards integrating the control module into the robotic work process under precisely defined conditions and ensuring reproducibility.

The third part of the methodological procedure was devoted to the integration of the extrusion module with the robotic manipulator. At this stage, the focus was on harmonizing the timing, orientation, and synchronization between the robotic program and the extrusion control, with the robotic movement being used without extruding material. The purpose was to confirm that the extruder control framework is compatible with the kinematics and dynamics of the robotic system.

In the final phase, the methodology included the preparation and definition of test geometries, which serve as a standardized basis for experimental verification of the entire system. Their task was to create controlled conditions for assessing the alignment of the robot speed, the temperature regime of the extrusion head, and the extrusion speed. These geometries allow the analysis of the system's behaviour for different types of trajectories and create a bridge between the methodological framework and the subsequent "Results" section, where the actual behaviour of the prototype is evaluated.

This methodology ensures a consistent and controllable procedure that creates conditions for an objective assessment of the functionality of the integrated robotic MEX system, clearly separating the preparatory, calibration, and integration phases of the experiment from the evaluation of the results achieved. In contrast, existing robotic additive manufacturing systems rely on tightly integrated control architectures [Kubalak et al., 2016; Ribeiro et al., 2019]. The proposed solution adopts a simpler control framework, enabling easier modification for experimental applications.

4 RESULTS

This chapter presents the results of the design, implementation, and experimental verification of a robotic MEX system that combines a proprietary IoT-controlled extrusion module and an ABB IRB 120 robotic manipulator.

The results reflect the individual stages of development – from hardware and software design, through integration with the robot, to robotic printing tests and evaluation of the quality of the created geometries.

The experimental procedure was designed to enable gradual verification of the system's functionality: from basic hardware and control algorithm activation, through synchronization of extrusion with robotic movement, to printing test samples without significant defects.

This methodological framework made it possible to identify key parameters affecting extrusion stability and coordination with the robotic trajectory.

The proposed robotic system is designed as a modular mechatronic platform connecting three functional units – the ABB IRB 120 robot, the extrusion head with local control, and the IoT communication module.

The architecture designed in this way enabled independent but time-coordinated control of extrusion and robot movement, creating suitable conditions for the implementation of robotic additive manufacturing.

Part of the development was the design and implementation of a complete extruder control system that integrates power circuits, control algorithms, and a communication interface for cooperation with the robot.

The result is a functional control unit capable of stable temperature control, precise filament feeding, and reliable synchronization with the robotic program during the implementation of extrusion trajectories.

4.1 Hardware Architecture and Initial System Commissioning

In the first step, a hardware prototype was assembled on a solderless breadboard, connecting an Arduino UNO R4 WiFi, a TMC2209 driver, an IRF520 MOSFET module, a hotend temperature sensor, and fans.

After the basic connection, the control logic was activated: verification of the temperature reading from the thermistor, switching of the heating cartridge using a PWM signal, and basic rotation of the stepper motor in both directions at low speeds.

At this stage, we worked without filament to eliminate wiring errors and unwanted overheating.

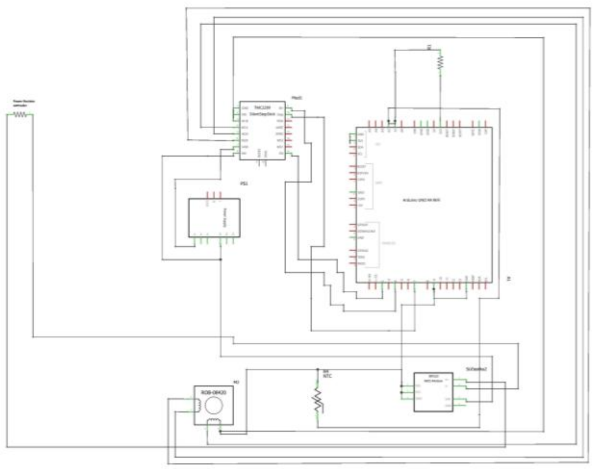


Figure 6. Electrical circuit diagram of the designed control system

The Arduino UNO R4 WiFi microcontroller platform regulates temperature, controls the stepper motor, and turns on the fans. The extruder stepper motor is controlled by a TMC2209 controller with microstepping, while the heating element and fans are switched via an IRF520 MOSFET module.

The system is powered by an S-360-12 switching power supply (12 V DC / 30 A), with local voltage levels adapted to the requirements of individual components. Based on the proposed architecture, a complete control circuit was assembled from the components listed in Table 1 and processed into a detailed electrical diagram (Fig. 6).

The diagram was then implemented in the form of a physical prototype consisting of an Arduino UNO R4 WiFi microcontroller, a TMC2209 controller, an IRF520 MOSFET module, a temperature sensor, and cooling fans.

During assembly, correct power distribution, common ground reference, and separation of the power and logic parts were ensured to minimize interference.

After assembly, the hardware was gradually brought to life. First, the continuity of the power and signal lines was verified, followed by testing of the communication links between the microcontroller and peripheral modules.

After power-up, preliminary measurements were performed, which confirmed the correct operation of the switching elements, stable temperature sensing, and reliable communication with all control components, Fig. 7.

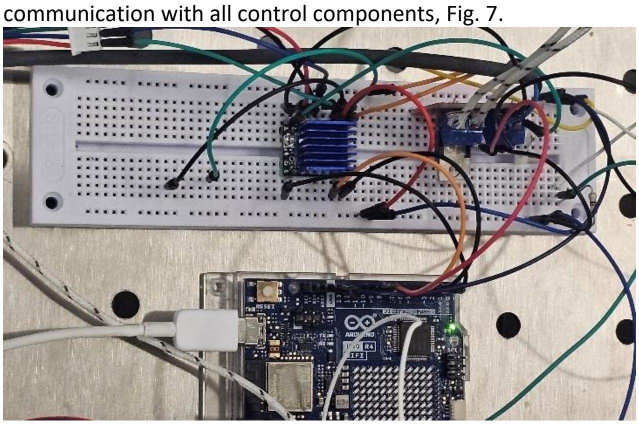


Figure 7. Prototype wiring of the extruder control module using an Arduino board and breadboard-mounted power electronics

4.2 Development and implementation of control software and IoT for the extrusion module

In the second step, a control algorithm for hotend temperature control was designed and implemented. Based on measurements of the dynamic response of the system (start-up times, stabilization behaviour), the control parameters were gradually adjusted to ensure stable maintenance of the set temperature within the tolerance required for the filament used.

At the same time, the stepper motor was calibrated to accurately determine the number of steps (or microsteps) required per unit length of extruded filament. This step created the conditions for parametric adjustment of the extrusion speed in later stages of the system.

The control software was implemented on the Arduino UNO R4 WiFi platform and integrated with the Arduino IoT Cloud environment.

To ensure seamless operation, several libraries were integrated into the program, including ArduinoIoTCloud.h and Arduino_ConnectionHandler.h for cloud connectivity, AccelStepper.h for stepper motor control, and Thermistor.h for processing the analog signal from the NTC temperature sensor.

Several libraries were incorporated to ensure the functionality of the system:

- #include <ArduinoIoTCloud.h>
- #include <Arduino_ConnectionHandler.h>
- #include <AccelStepper.h>
- #include <MultiStepper.h>
- #include <thermistor.h>
- #include "thingProperties.h"
- #include <Wire.h>

Cloud-based synchronization between the device and the dashboard is achieved through property definitions. Each variable is declared as a read/write property, which automatically triggers specific callback functions when updated via the IoT dashboard. The corresponding code structure is shown in the following snippet (Fig. 8).

```
ArduinoCloud.addProperty(heating_temp, READWRITE,
ON_CHANGE, onHeatingTempChange);
ArduinoCloud.addProperty(speed, READWRITE,
ON_CHANGE, onSpeedChange);
ArduinoCloud.addProperty(temp, READWRITE,
ON_CHANGE, onTempChange);
ArduinoCloud.addProperty(kurenie, READWRITE,
ON_CHANGE, onKurenieChange);
ArduinoCloud.addProperty(tlacidlo, READWRITE,
ON_CHANGE, onTlacidloChange);
```

Figure 8. Configuration of Arduino IoT Cloud properties used for controlling the extrusion module. Each parameter (heating temperature, extrusion speed, measured temperature, heating enable signal, and push-button input) is mapped to a cloud variable with READ/WRITE access and an associated callback function that handles value changes in real time

The initialization sequence ensured the configuration of hardware pins, establishment of a Wi-Fi connection, and activation of serial diagnostics. After starting the main loop, continuous synchronization with the cloud platform took place, as illustrated below on Fig. 7.

The control logic executed in the main loop ensures continuous synchronization with the cloud platform while managing temperature and feeding speed in real time.

The measured temperature is corrected, compared with the desired setpoint, and used to control the heating element through a MOSFET switch, Fig. 9.

```
void setup() {
  pinMode(heating_control_pin, OUTPUT);
  pinMode(podavanie_pin_EN, OUTPUT);
  stepper1.setMaxSpeed(50000);
  Serial.begin(9600);
  delay(1500);
  initProperties();
  ArduinoCloud.begin(ArduinoIoTPreferredConnection);
  setDebugMessageLevel(2);
  ArduinoCloud.printDebugInfo();
}
```

Figure 9. Initialization procedure of the extrusion control module. The setup routine configures output pins for heating and filament feeding, sets the maximum stepper motor speed, initializes serial communication, registers IoT Cloud properties, and establishes the connection to the Arduino IoT Cloud. Debugging output is enabled to provide runtime information during system startup

Simultaneously, the stepper motor speed is governed by the speed variable, and the extrusion process is enabled or disabled by the digital control variable tlacidlo (button) as illustrated on Fig. 10.

```
void loop() {
  stepper1.setSpeed(speed);
  stepper1.runSpeed();
  temp = therm1.analog2temp() + korekcia;
  if ((kurenie == 1) & (heating_temp > temp)) {
    digitalWrite(heating_control_pin, HIGH);}
  else {digitalWrite(heating_control_pin, LOW);}
  if (tlacidlo == true) {digitalWrite(podavanie_pin_EN,   LOW);}
  else {digitalWrite(podavanie_pin_EN, HIGH);}
  ArduinoCloud.update();
}
```

Figure 10. Main loop controlling motor speed and temperature regulation. It also handles filament feed and cloud synchronization

This software architecture provides a robust and modular foundation for IoT-based control of thermal and mechanical subsystems. The integration of cloud connectivity enables remote access and monitoring, while the modular code structure supports future scalability and the incorporation of advanced control algorithms.

Overall, the developed software demonstrates reliable operation of the heating and feeding control processes, establishing a suitable framework for further research focused on intelligent extrusion management and temperature regulation in experimental setups.

The implemented software provides a flexible and reliable solution for real-time control of the heating and extrusion processes within the designed system. By combining cloud connectivity, sensor feedback, and modular control logic, the program ensures precise operation and easy reconfiguration for various experimental conditions. This software layer serves as a critical component of the overall system, enabling further research on intelligent process optimization and integration of adaptive control strategies.

Functional tests confirmed that the implemented combination of hardware and software ensures reliable and stable operation of both the thermal and mechanical subsystems. Temperature control showed stable behaviour when changing the setpoint, and the stepper motor demonstrated smooth control across the entire range of set speeds. Cloud communication was consistent and provided reliable real-time feedback.

The results achieved confirm that the proposed control architecture provides a robust basis for the subsequent integration of the extruder with the ABB IRB 120 robotic arm and for the implementation of the experimental printing tests presented in the following sections.

4.3 Integration of the extruder with the robotic system

In the third step, the extruder was mechanically integrated with the ABB IRB 120 robotic manipulator. A 3D-printed adapter compatible with ISO 9409-1 was designed to attach the extrusion module, enabling repeatable, accurate, and stable connection of the tool to the robot flange.

The KINGROON All Metal extruder used is equipped with a NEMA 17 stepper motor for filament feeding, a heated nozzle with a 50 W / 24 V heating element, an NTC 100 kΩ temperature sensor, and a pair of cooling fans designed to stabilize the hotend temperature and cool the extruded material.

After mechanical integration, "dry" trajectory tests were performed without extrusion. These tests served to verify the correctness of the robotic program, geometric reach, tool orientation, and time coordination between the robot's movement and the extruder control unit.

Only after these tests were successfully completed were synchronization commands for controlled extrusion inserted into the robotic program.

Communication between the robotic system and the extrusion module takes place via digital inputs and outputs. The robot generates synchronization signals defining the start and end of extrusion, while the local control logic on the Arduino platform controls the hotend temperature and filament feed rate according to preset parameters.

The communication architecture of the system is based on a simple but reliable signal flow between the ABB IRB 120 robot and the external extruder control module.

The robot sends digital control signals (DI/DO) to the Arduino UNO R4 WiFi microcontroller, which determine the start, end, and enable of extrusion, Fig. 11.

Arduino then controls the process variables via power modules: the TMC2209 driver generates step and direction pulses for the NEMA 17 motor, while the IRF520 MOSFET module switches the heater and fans.
Temperature feedback from the thermistor is processed by the microcontroller's analogue input, which allows for nozzle temperature control.

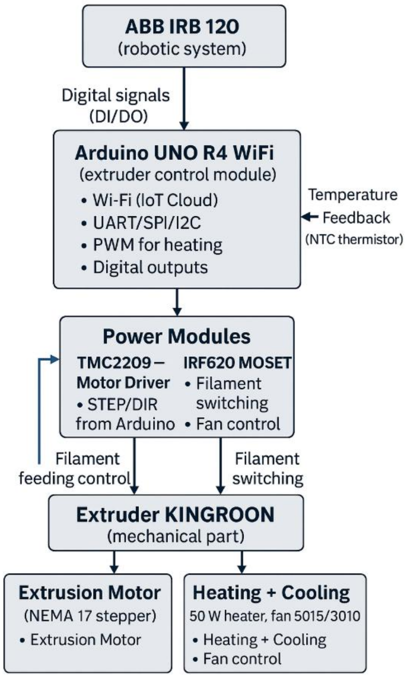


Figure 11. Architecture of the extruder control system integrated with the ABB IRB 120 robot. The diagram illustrates the signal flow between the robotic controller, Arduino-based extrusion module, power electronics, and the mechanical extruder components, including motor control, heating, cooling, and filament switching

Communication with the IoT Cloud takes place via the ESP32-S3 Wi-Fi module, enabling system monitoring and remote management.
Synchronization between the robotic program and the extrusion system was also implemented. The Arduino control unit received commands to start and stop extrusion via digital signals, with stepper motor operation and temperature control running independently but coordinated in time with robotic movement. During testing, there were no significant signal delays or communication instability, confirming the suitability of the modular IoT approach even when integrated into a robotic application.
This communication method ensured reliable coordination of the robot's movement with the extrusion process, which was essential for subsequent printing tests.

4.4 Software environment and generation of production paths

Trajectory generation for robotic MEX printing was implemented in the ABB RobotStudio environment using the 3D Printing PowerPack extension, which allows the creation and optimization of extrusion paths directly from 3D models. This solution provides an integrated toolchain for converting geometric data into robotic movements and enables synchronization between robot motion and extrusion control.
The 3D models intended for printing were imported into RobotStudio in standard STL format. Fig. 12.
The 3D Printing PowerPack module enabled automatic layer creation and path generation for individual contours, internal fills, and transitions. A simple parametric strategy was chosen for the test objects, which included:
- contours around the perimeter of the object,
- single-layer lines to assess the consistency of extrusion,
- basic 2.5D shapes to verify spatial coordination.

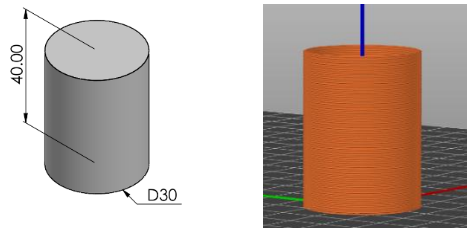


Figure 12. View the 3D model of the part as an STL model and a model from Slicer

The 3D Printing PowerPack module enabled automatic layer creation and path generation for individual contours, internal fills, and transitions. A simple parametric strategy was chosen for the test objects, which included:
- contours around the perimeter of the object,
- single-layer lines to assess the consistency of extrusion,
- basic 2.5D shapes to verify spatial coordination.
In the case of robotic printing, it was necessary to define the orientation of the extrusion head in such a way as to minimize singularities and range limitations in the ABB IRB 120 workspace. Although 3D printing traditionally uses G-code, in the robotic application it was necessary to convert it to RAPID language. PowerPack automatically converts extrusion instructions (e.g., start of extrusion, application speed, end of extrusion) to:
- MoveL and MoveJ motion commands,
- TCP orientation control,
- signal commands for starting and stopping extrusion.
The process also includes automatic path linearization, which ensures smooth layer deposition and prevents sudden changes in robot acceleration.
After generating the path, each trajectory was verified in RobotStudio in fully virtual mode, Fig. 13. The simulation made it possible to identify potential collisions, exceeding the robot's movement limits, and unwanted rotations that could negatively affect the smoothness of extrusion.
The following were verified in particular:
- correct orientation of the nozzle relative to the substrate,
- continuity of the path without sudden interruptions,
- correct timing of extrusion signals,
- placement of the object in the optimal part of the workspace.

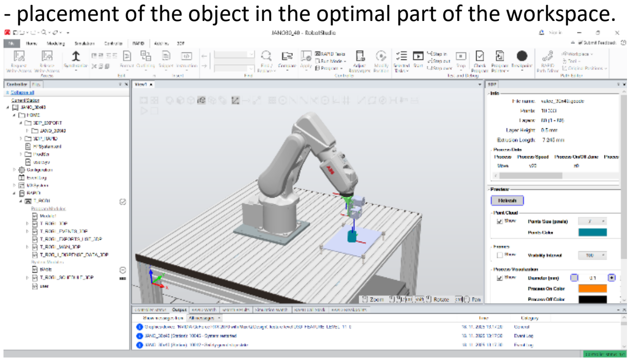


Figure 13. View of a robotic station created in ABB RobotStudio with 3D Printing Power Pack during process debugging and simulation

The resulting program was exported in the form of a RAPID script. Signal commands for starting extrusion were synchronized with the digital outputs of the robot control unit. These signals then controlled the Arduino, which controlled the stepper motor and temperature regulation.
This architecture enabled:
- direct synchronization of motion and extrusion,
- independent control of temperature and material feeding,

- reproducible experiments with different speeds and trajectories.
The use of RobotStudio with 3D Printing PowerPack proved to be suitable for the rapid preparation of MEX paths and significantly reduced the time between the design of the test geometry and its implementation. Automated conversion to RAPID eliminated manual intervention in the program code and enabled direct integration with the designed extrusion control, Fig. 14.

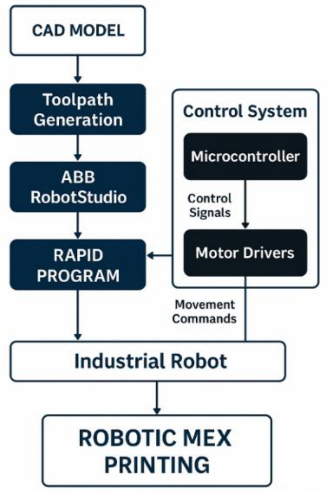


Figure 14. Workflow of the robotic MEX printing process, illustrating the transformation from a CAD model through toolpath generation and ABB RobotStudio programming to a RAPID program executed on an industrial robot. The control system, consisting of a microcontroller and motor drivers, supplies additional movement commands to coordinate the extrusion process.

4.5 *Verification of robotic integration and testing of trajectories for the MEX process*

After successful mechanical and signal integration of the extruder with the ABB IRB 120 robotic manipulator, the experiment focused on verifying the coordinated behaviour of both subsystems during real motion sequences.
The aim was to confirm that temperature control, filament feeding, and robot movement are stable and mutually coordinated under conditions typical for additive manufacturing using the MEX method.
For this purpose, test trajectories representing the basic elements of the process were defined in the ABB RobotStudio environment: single-layer lines, flat walls, and simple contours.
The robotic manipulator then performed these paths in real time, with the extruder responding to synchronization signals generated by the robot's control program.
During the tests, the stability of the hotend temperature, the uniformity of filament feeding, and the smoothness of robotic movement, especially in curved sections of the trajectory, were monitored.
Attention was also paid to the dynamics of movement, specifically the speeds and accelerations of the arm, which can affect the consistency of extrusion.
The results confirmed that the system exhibits stable behaviour even when the robot's speed changes, with no significant delays between the start of extrusion and the movement of the tool.
The coordination between the robot's digital signals and the local logic on the Arduino remained consistent during the tests, with no disruptive communication failures.
Verification of the interaction between the robot and the extrusion module thus demonstrated that the proposed architecture is functionally ready for subsequent printing experiments.
The findings also provided an initial overview of how process parameters and trajectory shape affect the quality of the deposited material in a robotic MEX environment and created a basis for optimizing printing tasks.

4.6 *Results of robotic MEX printing tests*

After successful integration of the extrusion module with the ABB IRB 120 robotic system, experiments were conducted to verify the system's ability to perform robotic MEX printing. Testing was carried out in successive steps, evaluating extrusion accuracy, process stability, and the quality of the printed geometries.
First, single-layer lines were tested to assess material flow consistency and application accuracy. After setting a stable hotend temperature and calibrating the feed rate, the extruder produced a uniform filament without interruption or excessive extrusion. Visual inspection confirmed the stable thickness of the extruded material throughout the entire path.
In the next phase, tests were carried out on simple shapes – thin-walled structures in the form of cylinders.
The robotic manipulator followed the trajectories generated in RobotStudio, with extrusion synchronized via the Arduino control module.
No significant defects such as gaps between fibers, width fluctuations, or delamination of layers were observed on the samples. The dimensions of the basic objects were within acceptable tolerances for laboratory experiments.
To verify dynamic behavior, lines were printed at different robot speeds. The system responded stably even during faster linear sections, with the extrusion process remaining consistent.
When changing the feed rate and industrial robot, the extrusion system demonstrated its ability to maintain a consistent material flow without clumping, interruptions, or local deformations.
Based on the experiments conducted, it can be concluded that the proposed system is capable of performing basic robotic MEX printing with sufficient repeatability and layer quality for further research.

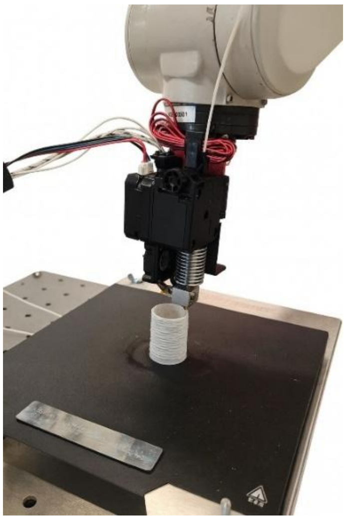


Figure 15. Experimental verification of the functionality of robotic MEX printing after integrating the extruder with the ABB IRB 120 robot, including tests of single-layer lines and simple thin-walled geometries to assess extrusion accuracy and process stability

The extrusion module controlled via Arduino UNO R4 WiFi in combination with the ABB IRB 120 robot created a functional platform that allows the study of the influence of process parameters, control settings, and motion trajectories on the quality of extruded parts.

5 DISCUSSION

The case study focused on verifying the possibility of integrating a proprietary extruder system controlled by an IoT microcontroller with an ABB IRB 120 industrial robot.

The primary objective was to validate the proposed hardware-software architecture, which was designed to ensure stable temperature control, accurate material feeding, and synchronization of extrusion with robotic movement.

The results of the experiments confirmed that the proposed system is functional and suitable for the implementation of basic robotic additive manufacturing based on the MEX process.

The control module was able to maintain a stable hotend temperature within the required tolerance, and the stepper motor ensured consistent filament feeding without significant fluctuations.

Communication between the extruder and the robot was stable, with no delays that would negatively affect print quality.

Initial print tests showed that the robot can reproduce predefined trajectories with sufficient accuracy, and the resulting samples were free of any significant visually observable defects, such as gaps between fibers, excessive extrusion, or delamination.

Although more complex trajectories required finer tuning of extrusion parameters and movement speed, the system demonstrated clear potential for further experimental expansion.

Overall, it can be concluded that the proposed platform fulfills its research purpose: it allows testing the interaction between extrusion parameters, robotic trajectory, and the quality of extruded parts, and provides a sufficiently open environment for future development of advanced control strategies in the field of robotic additive manufacturing.

The integration results confirm that the proposed extrusion module is fully compatible with the 6-axis robotic system and functionally ready for experimental testing of robotic MEX printing.

The experimental procedure defined in this way made it possible not only to verify the functionality of the proposed control architecture, but also to obtain initial insights into the influence of process parameters and robotic trajectory on the quality of printed parts in a robotic MEX technology environment.

The architecture designed in this way enables independent but coordinated control of robot movement and the extrusion process, while also creating space for future integration of more advanced communication (e.g., serial, Ethernet, or CAN).

6 CONCLUSIONS

The case study demonstrated that the combination of the ABB IRB 120 industrial robot and a proprietary extruder system controlled by an IoT microcontroller represents a viable and flexible approach to experimental robotic additive manufacturing based on MEX technology.

The proposed hardware and software architecture enabled stable temperature control, accurate material dosing, and reliable synchronization of extrusion with robotic motion, which was confirmed by a series of practical tests.

Experimental results have shown that the system is capable of creating simple and moderately complex geometries without significant optical defects, confirming its suitability as an open platform for academic and laboratory research. The functionality of control and communication, together with the successful integration of the motion and extrusion subsystems, creates a solid technical foundation for the further development of more advanced solutions in the field of robotic MEX technology.

Future research will focus primarily on the systematic calibration of the extrusion system in order to precisely define the relationship between the filament feed rate and the robot's movement speed along the trajectory.

This bond is essential for achieving consistent interlayer adhesion and eliminating defects associated with uneven extrusion during dynamic speed changes.

The next step will be to expand the communication interface between the robot and the extruder towards full-fledged two-way communication in real time. Such a solution will allow extrusion parameters to be changed dynamically, based on current speed, acceleration, or feedback from additional sensors.

There are also plans to expand the sensor equipment with flow sensors, nozzle pressure sensors, and optical sensors for deposited layers. The implementation of these elements will enable the creation of adaptive control algorithms capable of continuous process correction, further increasing the quality and repeatability of the resulting parts.

The aim of these steps is to build a fully modular, open, and experimentally oriented platform for robotic additive manufacturing that will enable extensive testing of trajectories, materials, control strategies, and their impact on the mechanical properties of printed components.

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