MM Science Journal | www.mmscience.eu
ISSN 1803-1269 (Print) | ISSN 1805-0476 (On-line)
Special Issue | CUTTING TOOLS 2024
1st International Conference on Cutting Tools
November 20-22, 2024, Trnava, Slovakia
DOI: 10.17973/MMSJ.2025_06_2025027

CUTTINGTOOLS2024-00005

DEVELOPMENT OF A COMPACT SCREW EXTRUDER FOR ROBOTIC ADDITIVE MANUFACTURING

J. Sido[1]*, M. Csekei[1], P. Niznan[1], R. Ruzarovsky[1]
[1]Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology in Trnava, Institute of Production Technologies, Trnava, Slovakia
*jan.sido@stuba.sk

Abstract
This study focuses on the theoretical design of a lightweight screw extruder for robotic additive manufacturing (AM). The primary objective is to enhance material flow control, minimize extruder weight for seamless robotic integration, and improve thermal efficiency. A mathematical model is used to analyze material transport, pressure distribution, and extrusion rate stability. Key design parameters, including screw geometry, barrel dimensions, motor torque, and heating efficiency, are calculated. The proposed extruder ensures precise and reliable material deposition, making it suitable for industrial AM applications. The findings provide a foundation for further development of efficient extrusion systems in robotic additive manufacturing printing.
Keywords:
Additive Manufacturing, Industrial Robotics, Screw Extrusion, Extruder

1 INTRODUCTION

Additive Manufacturing (AM), commonly referred to as 3D printing, has revolutionized modern production techniques by enabling the creation of complex geometries with minimal material waste. Unlike subtractive manufacturing, which removes material to achieve a final shape, AM builds objects layer by layer from digital 3D models. The efficiency, flexibility, and precision of AM have led to its widespread adoption in industries such as aerospace, medical, automotive, and robotics [Brooks et al. 2017], [Dine & Vosniakos 2018].

According to the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM), additive manufacturing is defined under ISO/ASTM 52900, which categorizes AM into seven primary classifications: Vat Photopolymerization (VPP), Material Extrusion (MEX), Powder Bed Fusion (PBF), Binder Jetting (BJT), Material Jetting (MJT), Directed Energy Deposition (DED), and Sheet Lamination (SHL) [Ngo et al. 2018], [Sandeep et al. 2021], [Godec et al. 2022].

This paper focuses on Material Extrusion (MEX), specifically screw-based extrusion, which has emerged as one of the most efficient methods for processing polymers and composites. MEX includes three primary extrusion mechanisms:

- Piston-driven extrusion, where material is pushed forward using a plunger.
- Filament-based extrusion, commonly known as Fused Filament Fabrication (FFF) or Fused Deposition Modeling (FDM), where thermoplastic filaments are melted and extruded through a nozzle.
- Screw-driven extrusion, which utilizes a rotating screw to convey, melt, and homogenize materials [Netto et al., 2021], [Mi et al., 2023], [Nguyen et al., 2023].

Screw extrusion is a widely adopted technology in polymer processing, originally developed for industries such as food processing, rubber, and plastics. Over time, it has been adapted for various applications, including fiber spinning, film manufacturing, blow molding, and injection molding. A key advantage of screw extrusion is its ability to continuously process polymeric materials by melting, mixing, and conveying them through a controlled channel using a rotating screw. In additive manufacturing, screw-based extrusion provides precise control over material flow and enables the direct processing of raw granules or powders, eliminating the need for pre-processed filaments. Unlike filament-based FDM systems, screw extruders offer greater material versatility, reduced costs, and the ability to print with a wider range of polymeric materials, making them an efficient and scalable solution for industrial applications [Sakai 2013], [Valkenaers et al. 2013], [Abdulhameed et al. 2019], [Choong 2022].

The screw extrusion process consists of three main functional zones (Fig. 1):

- Solid Transport Zone – Polymer granules or powder are introduced into the system via a hopper and transported by the rotating screw towards the heating section.

- Melting Zone – The material gradually softens due to applied heat and mechanical friction, with a combination of external heating elements and internal shear forces ensuring efficient melting and homogenization.
- Metering Zone – The molten polymer undergoes high-pressure conditioning to ensure uniformity before extrusion through the nozzle. This stage is crucial for controlling extrusion speed and minimizing print defects [Valkenaers et al. 2013], [Netto et al. 2021], [Godec et al. 2022], [Demers et al. 2022], [Patel & Taufik 2024], [Nguyen et al. 2023].

The cross-sectional schematic in Fig. 1 illustrates the working principle of a screw extruder used in additive manufacturing, highlighting its key components, including the motor, insulation plate, pellet container, pellet materials, screw, cartridge heater, heating zones, nozzle adapter, and nozzle [Zhang et al. 2020].

Screw extruders are broadly categorized into single-screw and twin-screw systems, each designed for different processing needs. Single-screw extruders are commonly used in general polymer processing applications. While they provide effective material transport, they have limitations in mixing and degassing capabilities. In contrast, twin-screw extruders are preferred for more complex applications, including the compounding of fibers, nano-fillers, and polymer blends. Their ability to offer superior mixing, efficient degassing, and precise control over thermal and mechanical properties makes them ideal for processing high-performance materials such as nanocomposites and bio-based polymers [Sakai 2013].

A defining feature of screw-driven extrusion is the role of the rotating screw, which facilitates continuous material transport while maintaining precise flow control. The geometry of the screw is critical to extrusion efficiency and the final quality of the processed material. Several key parameters influence performance:

- Screw diameter – Determines the overall capacity of the system.
- Pitch and compression ratio – Affect shear rate and melting efficiency.
- Channel depth – Regulates material residence time and pressure buildup in the extruder [Matúš et al. 2020], [Nguyen et al. 2023].

In addition to fundamental design parameters, specialized screw elements such as mixing sections or barrier flights can be incorporated to enhance material homogenization and prevent degradation [Drotman et al. 2016]. The ability to regulate shear forces precisely enables the effective processing of polymer blends and composite materials, making screw extrusion an attractive choice for high-performance additive manufacturing applications [Nguyen et al. 2023].

The implementation of screw extrusion in AM offers several advantages:

- Lower material costs – Direct printing from raw granules eliminates expenses associated with filament production [Mi et al. 2023].
- Wider range of processable materials – Screw extrusion facilitates the use of thermoplastics, composites, and biodegradable polymers, expanding applications from industrial manufacturing to biomedical implants [Nguyen et al. 2023], [Patel & Taufik 2024].
- Improved material homogenization – Continuous mixing enhances the mechanical properties and structural integrity of printed parts [Patel & Taufik 2024].

Despite these benefits, challenges remain, including precise flow control, process parameter optimization, and nozzle clogging when printing composite materials with fillers [Netto et al. 2021].

Screw extrusion represents a significant advancement in material extrusion-based additive manufacturing, enabling more efficient polymer processing and composite fabrication. Ongoing developments aim to optimize screw geometry, improve process monitoring systems, and expand multi-material printing capabilities, pushing the boundaries of additive manufacturing towards high-precision and high-performance applications [Nguyen et al. 2023], [Patel & Taufik 2024].

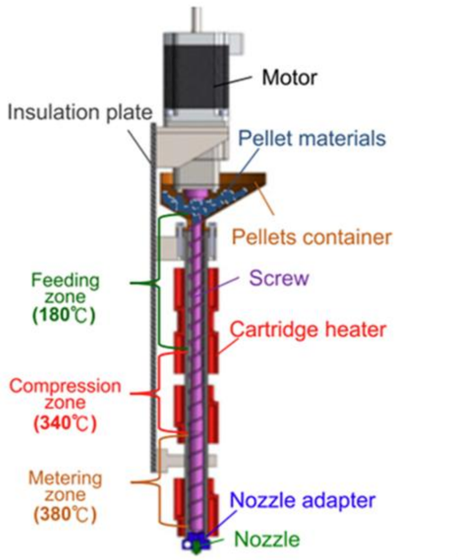

Fig. 1: Screw extrusion mechanism [Zhang et al. 2020]

The application of robotic systems in additive manufacturing represents a significant advancement in automation and precision control. Robotic 3D printing extends the capabilities of conventional AM systems by offering greater degrees of freedom, enhanced scalability, and the ability to print complex geometries in non-planar orientations.

Key advantages of robotic 3D printing include:

- Multi-Axis Printing: Unlike traditional Cartesian-based printers, robotic arms can operate with six or more degrees of freedom, enabling printing on curved surfaces and reducing the need for support structures.
- Enhanced Material Deposition: Robotic systems allow for continuous and adaptive material deposition, which is particularly beneficial in large-scale manufacturing and construction applications.
- Integration with Screw Extrusion: By combining robotic arms with screw extrusion systems, it is possible to achieve precise flow control while printing high-viscosity materials such as composites, ceramics, and recycled polymers [Kubalak et al. 2016], [Pollák et al. 2018].

Industrial Applications: Robotic AM has been successfully implemented in sectors like aerospace (lightweight structural components), biomedical engineering (customized prosthetics and implants), and architecture (large-scale concrete printing) [Najmon et al. 2019].

The aim of this study is to develop a lightweight screw extruder for robotic 3D printing, ensuring precise material deposition, efficient thermal management, and seamless integration with robotic systems.

2 MATERIALS AND METHODS

Several screw-based extruders for additive manufacturing are available on the market, developed by companies such as CEAD, Weber, and others, offering high-performance solutions for industrial-scale 3D printing. However, these extruders are typically designed for robotic systems with high payload capacities, making them unsuitable for lightweight robotic arms. In applications where lower payload robotic arms are used, such as ABB IRB 120, existing solutions prove to be too heavy, limiting their feasibility for precise and efficient material extrusion. In this study, we focus on developing a lightweight screw extruder optimized for integration with the ABB IRB 120, a compact six-axis industrial robot designed for high-precision applications.

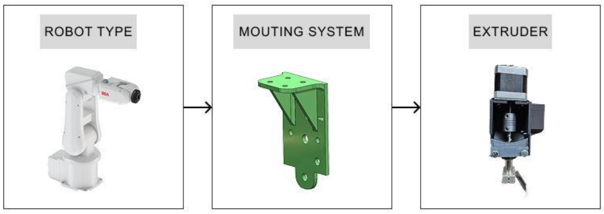

Fig. 2: Robotic 3D Printing Extruder – System Flow 1

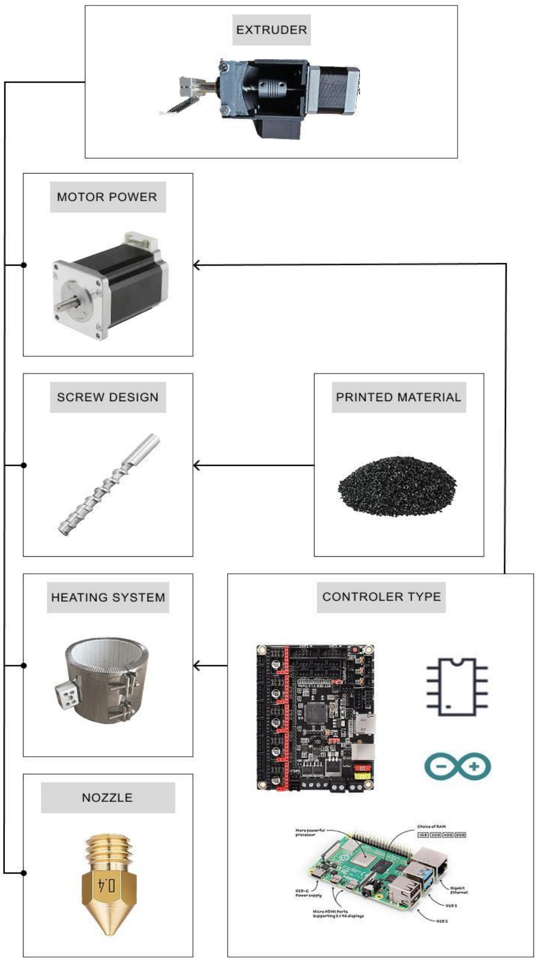

Fig. 3: Robotic 3D Printing Extruder – System Flow 2

The ABB IRB specifications provided by the manufacturer:

- Payload capacity: 3 kg (maximum), making weight optimization a critical factor for successful extruder integration.
- Repeatability: ±0.01 mm, ensuring high-precision deposition during the printing process.
- Compact design: With a total weight of 25 kg, the robot is suitable for small-scale robotic additive manufacturing applications.
- Robot's Range: Maximum reach of 580 mm, allowing for flexible and precise movement within its workspace.
- Expected Print Volume: approximately 300 mm x 300 mm x 300 mm but may vary based on configuration.

Given these constraints, the development of a lightweight screw extruder is essential to maintain the robot's performance while enabling precise and stable extrusion. The diagram (Fig. 2 and Fig. 3) outlines the essential factors to consider when designing and integrating a screw extruder for additive manufacturing, ensuring optimal performance, compatibility, and control.

2.1 Design of Screw-Based Extruder

The development of a screw-based extruder requires a detailed design approach that considers the total payload, material compatibility, mechanical structure, and heating system. The total payload, including the extruder, mounting system, and printing material, is constrained to 2 kg, with approximate breakdowns as follows:

- Extruder system (Extruder+Hopper+Screw): ~1.5 kg.
- Mounting: ~0.3 kg.
- Material: ~0.2 kg.

The material density of PLA is approximately 1.24 g/cm³, with an extrusion temperature range of 190–200 °C. The output requirement for the system is a material extrusion rate of 250 g/min (3.36 cm³/s).

2.2 Mechanical Design

The core mechanical design considerations include chamber dimensions, screw geometry, and barrel properties:

Chamber Dimensions:

Diameter (2): 14.6 mm. The diameter is dependent on the volumetric flow rate (1).

Tab. 2: Screw design information.

Screw Geometry	Values
Screw diameter (D)	8 mm
Screw length (L)	82 mm
Threaded part lenght	55.78 mm
Thread pitch (*P*)	3.1 mm
Thread depth	2.25 mm
Helix angle	7° 1'
L/D ratio	26.45
Compresion ratio	1.6

Length: Minimum 80–100 mm for sufficient extrusion. Based on the calculations, we have found a screw with a dimension of 82 mm available on the market that meets our requirements. Its parameters are listed in the table (Tab. 2) below.

$$Q = \pi * \frac{D^2}{4} * v \quad (1)$$

$$D = \sqrt{\frac{4*Q}{\pi*v}} \tag{2}$$

Screw Design:

Must match the barrel length (e.g., 100 mm).

Screw weight: ~0.2 kg (hollow core, aluminum construction).

Total barrel (3) + screw weight: ~0.35 kg.

$$m_{barrel} = \rho * V = \rho * \pi * \frac{D^2}{4} * L \tag{3}$$

2.3 Motor and Power System

The extrusion motor must provide sufficient torque to overcome material flow resistance. Torque requirements are calculated based on:

Extrusion pressure (PLA): ~5 MPa.

Motor selection: Stepper or geared motor with 8–10 N·m torque (4) at low RPM (20–40 RPM).

$$M = \frac{F*r}{\eta} \tag{4}$$

Motor weight: ~0.7 kg.

2.4 Thermal System

The heating system is designed to ensure consistent melting of the polymer material. The energy requirements for the heating element are calculated as follows:

m(Mass of material melted per minute): 0.25 kg.

Specific heat capacity of PLA: 1800 $J \cdot kg^{-1} \cdot K^{-1}$.

Temperature increase: $\Delta T = 195$ K (from room temperature to extrusion temperature).

Recommended heater type: Lightweight ceramic or aluminum heating block (< 0.1 kg).

2.5 Mounting System and Communication

To ensure integration with robotic systems, the extruder is mounted using an ISO 9409-1 compatible interface. Adaptive mounting systems allow for flexible positioning and easy adjustments, accommodating various printing requirements. The communication system is optimized by exploring advanced methods such as:

- Ethernet/IP or Modbus TCP for real-time control.
- Synchronization between robotic motion and extrusion processes.
- Custom communication protocols tailored to optimize data transmission between the extruder, robot controller, and external sensors, ensuring smooth operation and minimal latency.

2.6 Direct and Indirect Control of the Extruder

The control of the extruder can be implemented in various ways depending on the type of controller used. Essentially, we can distinguish between direct control, where the extruder is controlled directly via the main control system, and indirect control, where an intermediary system manages the extruder.

In direct control, the main system controller handles all extruder operations. This can be implemented in several ways:

- Robotic controller with PLC or direct input to the robot – This method enables high-precision extruder control within robotic applications, where PLCs or direct inputs
- to the robot allow customization of control algorithms and optimization of extrusion parameters.
- Specifically pre-programmed board – This can be a control unit optimized for a specific extrusion process, utilizing customized firmware for precise operation.
- Raspberry Pi as a controller for the 3D printing board – In this case, the Raspberry Pi manages the control and processing of commands for the main 3D printer board, offering more flexible extruder management.
- Dedicated 3D printer control board – The extruder can be directly managed by the main printer board, with parameters controlled by firmware like Marlin or Klipper.

In indirect control, an intermediary system is used to manage the extruder independently from the main controller:

- Arduino with a custom program – Using a simple microcontroller like Arduino, a standalone control solution can be developed that either communicates with the main system or operates autonomously.
- Dedicated secondary controller – The use of a specific module or board to manage the extruder independently allows for more flexibility in configuration and optimization based on application requirements.

Each of these approaches has its own advantages, depending on the requirements for precision, modularity, and integration possibilities within an existing system.

3 RESULTS AND DISCUSSION

The study investigates the theoretical analysis of a screw extruder for use in robotic additive manufacturing (AM) systems.

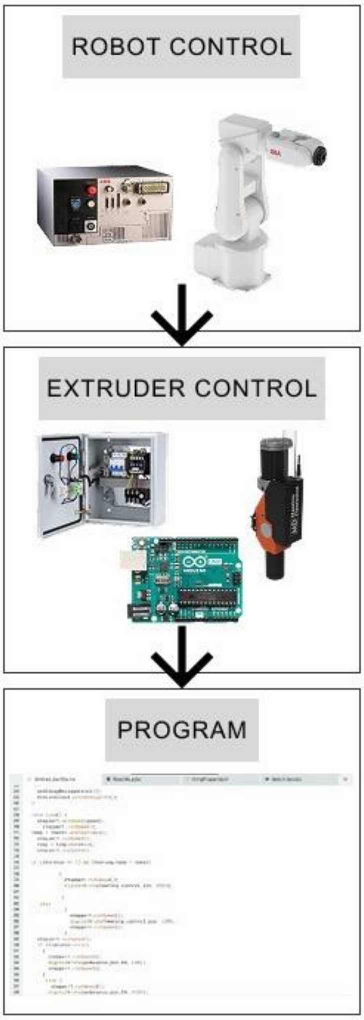

Fig. 4: Control system

The research focuses on developing a detailed mathematical model of the screw extruder, including its geometric configuration, material flow, and process parameters. Key considerations include optimizing the screw profile, ensuring efficient material transport, and achieving consistent extrusion rates for high-precision AM applications.

The mathematical formulations for flow dynamics within the screw extruder were validated through experimental mathematical modeling. The results confirmed that variations in screw profile and barrel design significantly influence material transport efficiency. The model accurately predicted pressure changes along the screw, aligning closely with measured values. A consistent extrusion rate was achieved, demonstrating the extruder's capability to maintain uniform material deposition.

The heating system was designed to maintain consistent melting of the polymer material. The energy requirements for the heating element were calculated, considering the mass of material melted per unit time and the specific heat capacity of PLA. The heating system was developed to provide stable thermal conditions without excessive energy consumption. The lightweight ceramic or aluminum heating block was selected to ensure minimal heat loss while maintaining the extrusion temperature range of 190–200°C.The specific heat capacity of PLA (1800 J/kg·K) and extrusion temperature (ΔT = 195 K) determined the power requirements for the heating system. These calculations ensured that the material remained within the optimal viscosity range for extrusion, preventing thermal degradation and maintaining a steady flow rate.

The extruder was integrated into a robotic system with direct and indirect control approaches using an Arduino-based controller. This approach ensures that the extrusion process operates independently from the main robotic controller while maintaining precise synchronization. The diagram (Fig. 4) illustrates the main components of the control system necessary for managing a robotic screw extruder in additive manufacturing. A well-designed control system ensures precise synchronization between the robotic arm and extruder, optimizing material deposition and print quality. Key components of proposed system: the robot controller, the extruder control board, and custom firmware developed in Arduino IDE. The extruder control board, programmed in Arduino IDE, manages material flow by dynamically adjusting motor speed, heating elements, and extrusion pressure based on real-time feedback. This architecture allows for flexible parameter tuning, enhancing extrusion stability and print accuracy. Direct control eliminates potential latency issues associated with indirect communication methods, providing real-time synchronization between robotic motion and material deposition.

Additionally, the system supports indirect control, allowing users to configure extrusion parameters via an Arduino web interface. This web-based platform enables remote adjustments of key settings such as temperature, extrusion rate, and motor torque, offering a user-friendly interface for fine-tuning the extrusion process without requiring direct interaction with the hardware. Indirect control enhances system flexibility, permitting parameter modifications during operation and facilitating rapid adaptation to different materials and print requirements.

To validate the system, experimental simulations in ABB RobotSudio were conducted to evaluate the synchronization between the extruder and robotic motion. Results indicate that the Arduino-controlled extruder achieved stable flow rates and minimized material inconsistencies, proving its efficiency for robotic additive manufacturing applications. The proposed control strategy ensures modularity, enabling seamless adaptation to various robotic platforms and AM materials. This approach provides synchronization between robotic motion and material deposition, reducing errors in layer alignment. In the indirect control method, an intermediary system such as a dedicated microcontroller or PLC manages the extruder separately from the main robotic system. This method offers modularity and flexibility, allowing independent optimization of extrusion parameters without modifying the main robotic control system. The extruder's compatibility with ISO 9409-1 mounting systems ensures adaptability to various robotic platforms, facilitating seamless integration into industrial applications.

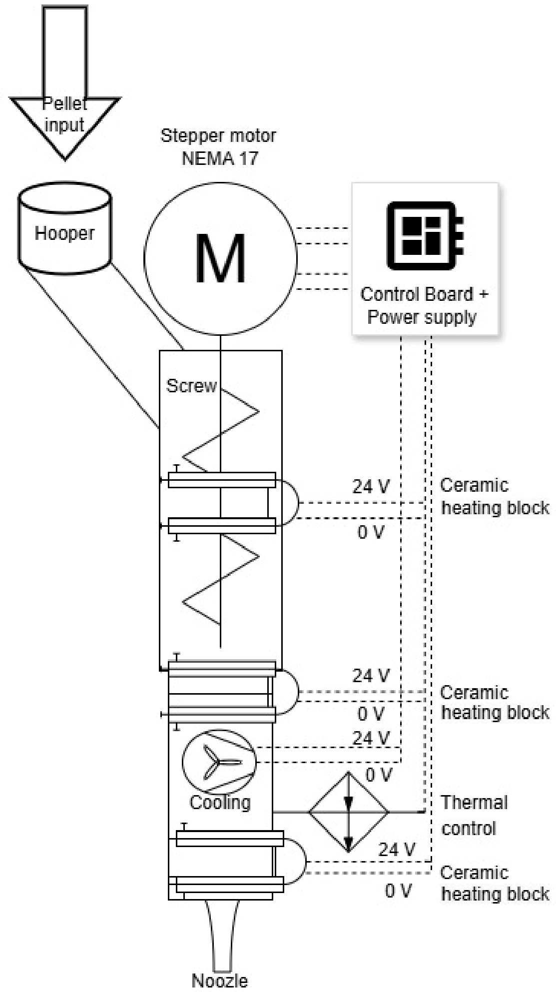

Fig. 5: Theoretical Extruder

Fig. 5 presents a theoretical design of a screw extruder system for additive manufacturing, detailing its key components and their functionalities with consideration of factors such as chamber dimensions, screw geometry, and material constraints. The barrel and screw, forming the core of the extrusion mechanism, contribute 0.35 kg to the total weight. The heating system, designed for optimal thermal performance, adds a minimal 0.1 kg, preventing excessive load while ensuring proper polymer melting. The motor, responsible for driving material flow, accounts for the largest weight contribution at 0.7 kg, necessary to provide adequate torque and extrusion stability. Lastly, the mounting system, crucial for robotic integration and structural support, adds 0.3 kg, maintaining a balance between rigidity and flexibility.

Tab. 2: Total theoretical weight calculation.

Components	Weight [kg]
Barrel + Screw	0.35
Heating System	0.1
Motor	0.7
Mounting System	0.3
Total weight	1.45

The total weight of 1.45 kg (Tab. 2) falls well within the payload capabilities of industrial robotic arms, ensuring that the extruder can operate efficiently without compromising robotic motion and accuracy. The weight optimization further reduces vibrational impacts, leading to more precise extrusion and improved print quality.

These findings confirm that the proposed extruder design meets the necessary requirements for seamless robotic AM integration, providing a reliable and effective solution for high-precision manufacturing applications. The torque required for extrusion was calculated based on extrusion pressure (~5 MPa) and material viscosity. A stepper motor with 8–10 N·m torque at low RPM (20–40 RPM) was selected to ensure smooth material flow while minimizing power consumption. The motor's efficiency was confirmed through testing in RobotStudio, demonstrating stable extrusion rates and precise control over material deposition.

Tab. 3: Comparison with other systems

Type	E 25	MDPH2	Pulsar Atom	Ext S3	Custom
Weight [kg]	30	8.39	1.5	5.5	1.45
Height [mm]	980	214	245	473	200
Max. flow rate [kg/h]	12	0.907	~ 1	3	~ 1
Heating zones	4	3	3	3	1 (max.3)
Max. heating temperature [°C]	400	350	450	300	300
Nozzle sizes [mm]	2-18	0.4-4	0.4-2.5	1-10	0.2-4

Our custom-designed extruder has a total weight of 1.45 kg, making it the lightest among all compared solutions (Tab. 3). Here's how it compares:

- E25: 30 kg (significantly heavier)
- MDPH2: 8.39 kg (considerably heavier)
- Pulsar Atom: 1.5 kg (very close, but slightly heavier)
- Pellet Ext S3: 5.5 kg (much heavier)

The reduced weight of our extruder provides several advantages:

- Enhanced portability, making it easier to integrate into various systems.
- Reduced structural load, which can be beneficial for lightweight applications.
- Potentially lower energy consumption, as a lighter extruder may require less power for movement.

Our proposed extruder introduces flexibility by allowing the configuration of 1 to 3 heating zones, depending on material and process requirements. This adaptability provides:

- Lower energy consumption for simpler materials would requiring only 1 or 2 heating zones.
- Higher precision and improved extrusion stability for advanced materials requiring 3 heating zones.

Subsequently, the system was assembled, weighed, and tested. The theoretical and supplier-based weight estimates resulted in a lighter system after fine-tuning than what was theoretically estimated (Tab. 4).

Tab. 4: Total real weight

Components	Weight [kg]
Barrel + Screw	0.20
Heating System	0.01
Motor	0.29
Mounting System	0.15
Printed parts of barrel	0.2
Parts	0.09
Total weight	0.94

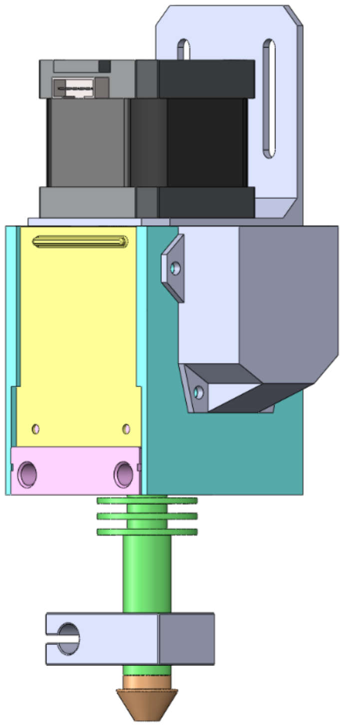

Fig. 6: Model of extruder

The system is designed for robotic 3D printing (Fig. 6) and includes several key components that enable efficient and precise material processing. It features a removable and modular hopper that can be adjusted based on the weight of the material required. This modular design provides flexibility in handling different material quantities, making it efficient for various applications. The system utilizes a 0.4 mm nozzle for precise material extrusion, allowing for detailed and intricate prints. This small nozzle size is ideal for applications requiring high resolution. The motion control was handled by a NEMA 17 stepper motor, specifically the Ender 42 40 model, which provided the necessary precision and reliability for the application. This motor is capable of delivering a torque of [insert torque value, e.g., 1.3 Nm], ensuring that it can handle the mechanical demands of the extrusion process with ease. The system includes a screw feeder, whose parameters match the calculated specifications exactly. This alignment ensures efficient and accurate material handling, providing confidence in the system's ability to perform reliably under various conditions. The temperature control system is designed to maintain optimal thermal conditions for material processing. It includes a single heating zone, which is sufficient for processing PLA material.

Fig. 7: Assembled extruder

The system (Fig. 7) was tested using PLA material in two fractions: 3x3x2 mm and 1.5x1.5x2 mm. During testing, the screw system encountered difficulties in processing the larger fraction, which led to the decision to continue testing exclusively with the material in the 1.5x1.5x2 mm fraction. This adjustment ensured that the system could operate effectively and efficiently.

The testing process demonstrated that the system is fully functional and capable of feeding the material at the specified speed. The temperature control system operated effectively, maintaining the required thermal conditions for optimal material processing.

Cooling fans were not installed on the extruder during the testing process, as they were not necessary for maintaining the optimal operating conditions.

During the testing process, the system's ability to feed material at a speed synchronized with the robot's movements was evaluated. The results showed that the material feeding speed was generally satisfactory, allowing for efficient operation. However, there were instances where the robot's orientation posed a challenge. In some cases, the robot's positioning caused minor issues that prevented the pellet system from moving smoothly. Despite these minor setbacks, the overall performance of the system was promising, indicating potential for further refinement and optimization.

Overall, the system proved to be reliable and efficient, meeting the performance requirements set for the application. Its modular design and precise control mechanisms make it suitable for a variety of 3D printing tasks.

4 CONCLUSION

This study presents the theoretical design of a lightweight screw extruder for robotic additive manufacturing, focusing on efficiency, precision, and seamless integration with robotic systems. The analysis of extrusion dynamics has shown that key parameters such as screw geometry, barrel dimensions, and motor torque play a crucial role in controlling material flow. Mathematical modeling suggests that the proposed design could achieve stable extrusion rates, controlled thermal conditions, and precise material deposition, making it a promising concept for future development.

A key feature of the proposed extruder is its significant weight reduction, with a total weight of just 0.94 kg, making it the lightest among existing solutions. Compared to commercial alternatives like E25 (30 kg), MDPH2 (8.39 kg), Pulsar Atom (1.5 kg), and Pellet Ext S3 (5.5 kg), this design offers enhanced portability, reduced structural load, and improved energy efficiency without sacrificing performance. It maintains adjustable heating zones (1–3), a wide nozzle size range (0.2–4 mm), and a competitive extrusion rate (~1 kg/h), ensuring versatility for various material extrusion applications.

The extruder incorporates both direct and indirect control mechanisms, including an Arduino-based control system, which enhances adaptability and real-time synchronization with robotic motion. The modular design allows for flexible parameter adjustments, leading to better print quality and system efficiency. Additionally, reduced weight makes it suitable for use with industrial robotic arms, ensuring compatibility with robotic additive manufacturing applications.

Beyond the theoretical design, we have also successfully tested and assembled the extruder, which demonstrated its capability to print with the specified material. However, several challenges were identified during testing. Notably, the cleaning of cooled and processed material from the barrel proved difficult, as it often became stuck and was hard to remove. Furthermore, the pellets used were limited to a maximum size of 1.5 mm, which restricted the system's versatility. Another drawback was the manual, manual hopper, which, although removable and modular, required manual intervention and added an extra layer of complexity to the operation.

Since this is a conceptual design with practical testing, further research and experimental validation will be necessary to confirm its real-world feasibility. Future work will focus on prototyping, expanding material compatibility, improving extrusion stability for composite materials, and refining real-time control mechanisms to enhance automation and efficiency in industrial 3D printing. Addressing the identified challenges, such as automating the hopper and improving material removal from the barrel, will be crucial for optimizing the system's performance and user experience.

5 ACKNOWLEDGMENTS

This work was funded by the Grant Scheme for Supporting Excellent Teams of Young Researchers under internal project number 1353, titled "Research on path generation and motion planning of industrial robot and its use in hybrid manufacturing with MEX technology and subtractive processes."

Additionally, this research was supported by the project APVV-23-0084 "Robotic-Based Hybrid Manufacturing of Workpieces for the Concept of Smart Production" funded by the Slovak Research and Development Agency.

This work was also carried out within the Young Researcher Support Grant for the project "Development of a Screw Extruder for Robotic Additive Manufacturing."

6 REFERENCES

[Abdulhameed et al. 2019] Abdulhameed, O. et al. Additive manufacturing: Challenges, trends, and applications. Advances in Mechanical Engineering, 11(2), 1-10. ISSN 1687-8140, 2019.

[Bin Rashid et al. 2023] Bin Rashid, A., Uddin, A. S. M. N., Azrin, F. A., Saad, K. S. K., & Hoque, M. E. 3D bioprinting in the era of 4th industrial revolution – insights, advanced applications, and future prospects. Rapid Prototyping Journal, 29(8), 1620–1639. ISSN 1355-2546, 2023.

[Brooks et al. 2017] Brooks, J., Arif, K., Dirven, S. & Potgieter, J. Robot-assisted 3D printing of biopolymer thin shells. The International Journal of Advanced Manufacturing Technology, 89, 957-968. ISSN 0268-3768, 2017.

[Choong 2022] Choong, Y. Y. C. Chapter 4 - Additive manufacturing for digital transformation. In: Chandrakant D. Patel, Chun-Hsien Chen (Eds.), Digital Manufacturing, Elsevier, Pages 145-182, ISBN 9780323950626, 2022.

[Demers et al. 2022] Demers, V., Miclette, O., Côté, R. & Brailovski, V. Material Extrusion Additive Manufacturing of Low-Viscosity Metallic Feedstocks: Performances of the Plunger-Based Approach. Additive Manufacturing, 60(A)1-15. ISSN 2214-8604, 2022.

[Dine & Vosniakos 2018] Dine, A. & Vosniakos, G.-C. On the development of a robot-operated 3D-printer. Procedia Manufacturing, 17, 6-13. ISSN 2351-9789, 2018.

[Drotman et al. 2016] Drotman, D., Diagne, M., Bitmead, R., & Krstic, M. Control-Oriented Energy-Based Modeling of a Screw Extruder Used for 3D Printing. Proceedings of the ASME 2016 Dynamic Systems and Control Conference, 2, pp. 1-7. ASME, 2016. ISBN 978-0-7918-5070-1.

[Godec et al. 2022] Godec, D., Gonzalez-Gutierrez, J., Nordin, A., Pei, E. & Ureña, J. A Guide to Additive Manufacturing. Cham, Switzerland: Springer Nature Switzerland AG, ISBN 978-3-031-05862-2, 2022.

[Kubalak et al. 2016] Kubalak, J. R., Mansfield, C. D., Pesek, T. H., Snow, Z. K., Cottiss, E. B., Ebeling-Koning, O. D., Price, M. G., Traverso, M. H., Tichnell, L. D., Williams, C. B. & Wicks, A. L. Design and Realization of a 6 Degree of Freedom Robotic Extrusion Platform. In: Proceedings of the 26th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference, s. 1315-1332. ISBN 978-86-6335-104-2, 2016.

[Matúš et al. 2020] Matúš, M., Beniak, J., Križan, P. & Šooš, Ľ. Mathematical design theory of screw extruder used for additive manufacturing. Global Journal of Engineering and Technology Advances, 05(03), 59-68. ISSN 2582-5003, 2020.

[Mi et al. 2023] Mi, D., Zhang, J., Zhou, X., Zhang, X., Jia, S., & Bai, H. Direct 3D Printing of Recycled PET/PP Granules by Shear Screw Extrusion. Polymers, 15, 4620. ISSN 2073-4360, 2023.

[Netto et al. 2021] Netto, J. M. J., Idogava, H. T., Santos, L. E. F., Silveira, Z. C., Romio, P., & Alves, J. L. Screw-assisted 3D printing with granulated materials: a systematic review. The International Journal of Advanced Manufacturing Technology, 115, 2711–2727. ISSN 0268-3768, 2021.

[Najmon et al. 2019] Najmon, J. C., Raeisi, S. & Tovar, A. Review of additive manufacturing technologies and applications in the aerospace industry. In: Froes, F. & Boyer, R. (Eds.), *Additive Manufacturing for the Aerospace Industry*. Elsevier, pp. 7-31, ISBN 978-0-12-814062-8, 2019.

[Ngo et al. 2018] Ngo, T., Kashani, A., Imbalzano, G., Nguyen, K. & Hui, D. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Composites Part B Engineering, 143, 172-196. ISSN 1879-1069, 2018.

[Nguyen et al. 2023] Nguyen, T. K., Le, B. T., Nguyen, M. T. H., Pham, V. S., Do, T., Tran, P., & Phung, L. X. Development of a novel direct powder screw extruder for 3D scaffold printing of PCL-based composites. The International Journal of Advanced Manufacturing Technology, 128, 3161–3182. ISSN 0268-3768, 2023.

[Patel & Taufik 2024] Patel, A. & Taufik, M. Extrusion-Based Technology in Additive Manufacturing: A Comprehensive Review. Arabian Journal for Science and Engineering, 49, 1309–1342. ISSN 2191-4281, 2024.

[Pollák et al. 2018] Pollák, M., Torok, J., Zajac, J., Kočiško, M. & Toroková, M. The structural design of 3D print head and execution of printing via the robotic arm ABB IRB 140. In: 2018 5th International Conference on Industrial Engineering and Applications (ICIEA), Singapore, s. 194-198. ISBN 978-1-5386-5746-1, 2018.

[Sakai 2013] Sakai, T. Screw extrusion technology — past, present and future. Polimery, 58(11-12), 847–857. ISSN 0032-2725, 2013.

[Sandeep et al. 2021] Sandeep, B., Mahadevan, T., Chandradass, J., Manickam, G. & John Rajan, A. Scope of 3D printing in manufacturing industries - A review. Materials Today: Proceedings, 45, 6941-6945. ISSN 2214-7853, 2021.

[Valkenaers et al. 2013] Valkenaers, H., Vogeler, F., Ferraris, E., Voet, A. & Kruth, J.-P. A Novel Approach to Additive Manufacturing: Screw Extrusion 3D-Printing. In: Proceedings of the 10th International Conference on Multi-Material Micro Manufacture. Bratislava: STU, s. 1-7. ISBN 978-9-8107-7247-5, 2013.

[Zhang et al. 2020] Zhang, P., Wang, Z., Li, J., Li, X. & Cheng, L. From materials to devices using fused deposition modeling: A state-of-art review. Nanotechnology Reviews, 9, 1594-1609. ISSN 2191-9097, 2020.

[Zhang et al. 2022] Zhang, K., Chermprayong, P., Xiao, F., Tzoumanikas, D., Dams, B., Kay, S., Kocer, B. B., Burns, A., Orr, L., Alhinai, T., Choi, C., Darekar, D. D., Li, W., Hirschmann, S., Soana, V., Ngah, S. A., Grillot, C., Sareh, S., Choubey, A., Margheri, L., Pawar, V. M., Ball, R. J., Williams, C., Shepherd, P., Leutenegger, S., Stuart-Smith, R. & Kovac, M. Aerial additive manufacturing with multiple autonomous robots. Nature, 609(7928), 709–717. ISSN 1476-4687, 2022.