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DEVELOPMENT OF FGF 3D PRINTER

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Abstract: *The paper presents the development of a 3D printer based on Fused Granulate Fabrication (FGF) technology with a working space dimension of 500x500x500 mm. The printer was developed in the Student Workshop of the Faculty of Mechanical and Civil Engineering in Kraljevo as part of student activities and the completion of graduate work in the Mechanical Engineering study program. The conceptual design was based on a comparative analysis of existing technical solutions for 3D printers and their advantages and disadvantages. Based on the drawn conclusions a number of requirements were formed which need to be implemented in a new technical solution. The development included the following activities: defining the kinematic structure of the machine, detailed design, machine control based on the Arduino platform, specification of mechanical parts and electronic components, as well as configuring and entering the basic control program.At the end of the paper, the appearance of the constructed 3D printer is presented, along with one of the test examples used to evaluate the machine's performance.*

***Key words**: Development, Additive technologies, 3D printer, Fused Granulate Fabrication-FGF.*

1. INTRODUCTION

Within the Mechanical Engineering study program at the Department of Manufacturing Engineering of the Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac (FMCE), a Student Workshop has been established. In this workshop, students implement their practical projects. One of the projects realized in this workshop is the development of a 3D printer that uses plastic granules as its input material.

1.1. Student workshop

The Student Workshop at FMCE was established in 2018 as a collaborative initiative between professors and students. Its purpose is to encourage creatively and engineering-talented students to practically implement their ideas using modern technologies.

The goal is for students to independently design and create various micro and mini machines and systems with the assistance of mentors and professors, either in their free time or as part of their project assignments and graduate work.

So far, three different types of modern mini CNC machines have been successfully created, fully automated and computer-controlled:

1. CNC laser for engraving wood and softer materials with a working space dimension of 400x500 mm;
2. Upgraded FDM (Fused Deposition Modeling) 3D printer with a working space dimension of 320x320x450 mm. Students addressed all the disadvantages observed in the use of an existing 3D printer, significantly improving the quality of 3D printing;
3. CNC machine for 3-axis bending of wire with a diameter of up to 2 mm.

The students' task in the development of these machines was to design and manufacture all components that could be produced using the existing equipment available at FMCE. Other components, such as linear mechanical elements and electronics, were purchased as standard components. Commercially available solutions based on the Arduino platform were utilized for machine control.

The development of this FGF 3D printer was driven by the need of the Student Workshop for increased productivity, the production of larger-sized components, reduction in printing material costs, as well as the recycling of existing scrap parts created using FDM technology. Based on these requirements, the development and construction of an FGF (Fused Granulate Fabrication) 3D printer with a working space dimension of 500x500x500 mm were initiated.

1.2. Fused Granulate Fabrication

Fused Granulate Fabrication (FGF) technology belongs to the group of additive technologies, where plastic granules are used as the input material, similar to the ones utilized by plastic injection molding machines (Figure 1) [1].

The working principle of the FGF process is based on the application or deposition of molten material from the extruder (Figure 2). The granules are initially fed into the extruder body through the feed funnel (1). More precisely, they are directed onto a helical screw (2), after which the granules melt through the heated casing (3). At the bottom of the casing, in the nozzle zone, the necessary pressure is generated by the rotational movement of the helical screw, sufficient to extrude the molten material through the nozzle (4). The material is deposited onto the printing bed according to the pre-generated code (5), and then the

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object is formed layer by layer (6). The drive of the helical screw, ensuring the supply of the required material through the nozzle, is obtained from the drive system (7), consisting of a motor, gearbox, and coupling [3].

Fig.1. The material used by FGF 3D printers [2]

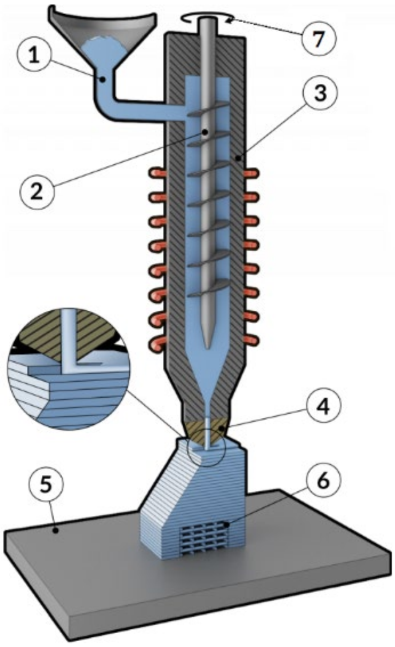

Fig.2. FGF method principle [3]

The fundamental characteristics directly influencing the quality of the finished part are [4]:

- Size and geometry of the granules;
- Maintenance of the specified moisture level in the granule material;
- Temperatures in the heating block and extruder head to achieve a continuous material flow;
- Speeds of the helical screw to achieve the required thickness of the applied material layer;
- Synchronization of all movement speeds to achieve the required shape and dimensions of the finished part;
- The control system that directly affects undesired vibrations during high-speed printing.

This 3D printing process has several advantages over the FDM process [2]:

1. As the input material 3D printer uses plastic granules, which are more accessible and cost-effective than filament in wire form, eliminating the step of converting granules into wire;
2. Commonly used materials often contain certain additives that directly impact the mechanical properties of the finished part;
3. It is more productive than the FDM process due to a higher influx (flow) of molten material and thicker print layers;
4. Recycled granules obtained from parts produced by plastic injection molding or 3D printing can be utilized.

2. METHODOLOGY OF 3D PRINTER DEVELOPMENT

The development of the FGF 3D printer was carried out through 7 phases:

- Phase 1: Conceptual product development,
- Phase 2: Detailed machine design,
- Phase 3: Procurement of materials and finished components,
- Phase 4: Elaboration of manufacturing and assembly technology,
- Phase 5: Parts fabrication and product assembly,
- Phase 6: Development and programming of the control system, and
- Phase 7: Product testing.

As Phase 2 (detailed machine design) was the most crucial and extensive, the subsequent part of this chapter will provide a more detailed explanation of its activities.

2.1. Analysis and Selection of Conceptual Solution

At the beginning of the design process, an analysis of existing conceptual solutions for 3D printers was conducted (Figure 3).

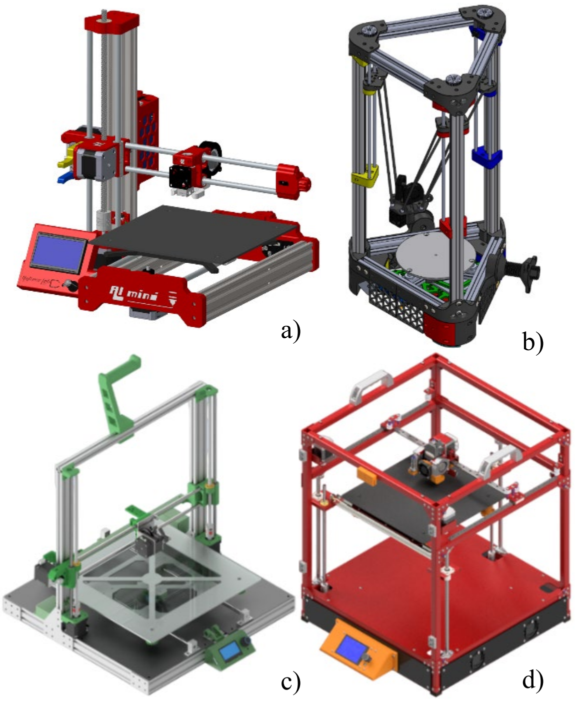

Fig.3. Overview of Conceptual Solutions for 3D Printers: a) Cantilever type, b) “Delta” type, c) “Prusa” type i d) “CoreXY” type [5,6]

Based on a comparative analysis, incorporating both theoretical assumptions and empirical/experiential facts, certain conclusions were drawn regarding the selection of technical-technological and geometrical solutions for each of the fundamental sub-assemblies or modules of the machine. The adopted concept is illustrated in Figure 4.

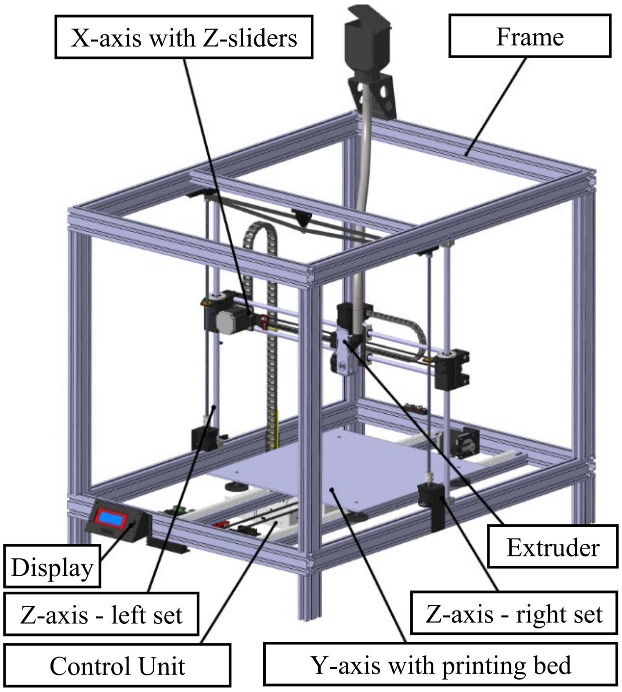

Fig.4. Representation of the Adopted Machine Concept[1]

The final technical solution for the machine was adopted based on the following conclusions:

1. **Construction** – To meet the requirements of the project task, the construction needs to provide dynamic rigidity and stability for a working volume of 500x500x500 mm. Therefore, the "CoreXY" construction type was chosen as a technically acceptable solution.
2. **X-Axis Module** – The beam type identical to "Prusa" machines was selected as a technically acceptable solution.
3. **Y-Axis Module** – The kinematics of the printing bed should be independent of the kinematics of the X-axis module to ensure dynamic rigidity and stability. The technical solution applied in cantilever machines, as well as the "Prusa" type, fully meets the requirements of this project task
4. **Z-Axis Module** – Within the construction assembly, two symmetrically embedded vertical guides are installed to provide support for linear motion in the Z-axis direction and increase the rigidity of the construction. Linear bearings moving in the specified direction are implemented within the X-axis assembly.
5. **Control and Drive Elements** – From a control perspective, the "Arduino" platform was chosen as the most suitable solution. The drive elements consist of NEMA17 and NEMA23 stepper motors, manipulated through frequency stepper drivers ("Drivers").
6. **Extruder** – Based on the project task, the "**Pellet extruder v4**" from the manufacturer "**Mahor XYZ**" from Spain was selected (Figure 5). The basic technical characteristics of the chosen extruder are provided in Table 1.

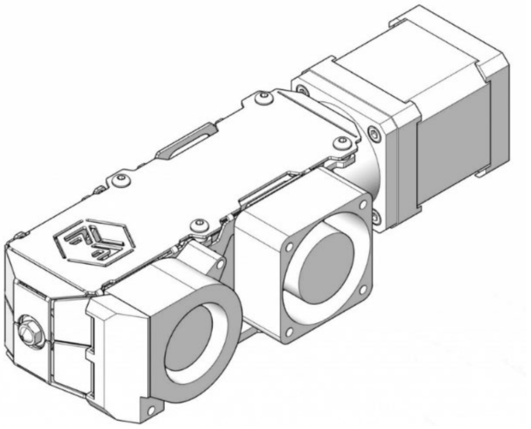

Fig.5. Pellet extruder v4 Mahor XYZ [7]

Table 1. Technical characteristics of Pellet extruder v4

Extruder drive	NEMA17 steper motor (1.7A)
Transmission	Planetary reducer 5:1
Possible materials for 3D printing	PLA, PETG, ABS, ASA, TPE, TPU, EVA...
Temperature probe	Termistor NTC 100k
Extruder cooling	Axial fan 24V
Printed part cooling	Centrifugal fan 24V
Extruder block heating	Tube heater 24V 50W
Nozzle diameter	0.8 mm
Helical screw	Helix diameter 10 mm with step 7.5 mm
Extruder weight	600 g

The machine is of a closed type (enclosed) for the following reasons:

- to eliminate any risk of injury caused by moving parts or heat;
- to reduce heat losses;
- to protect against dust and airflow;
- as well as to enhance the aesthetic appearance of the printer.

The machine's protection (enclosure) is made of a 2 mm thick steel sheet, while transparent surfaces are enclosed with Plexiglas (Figure 6).

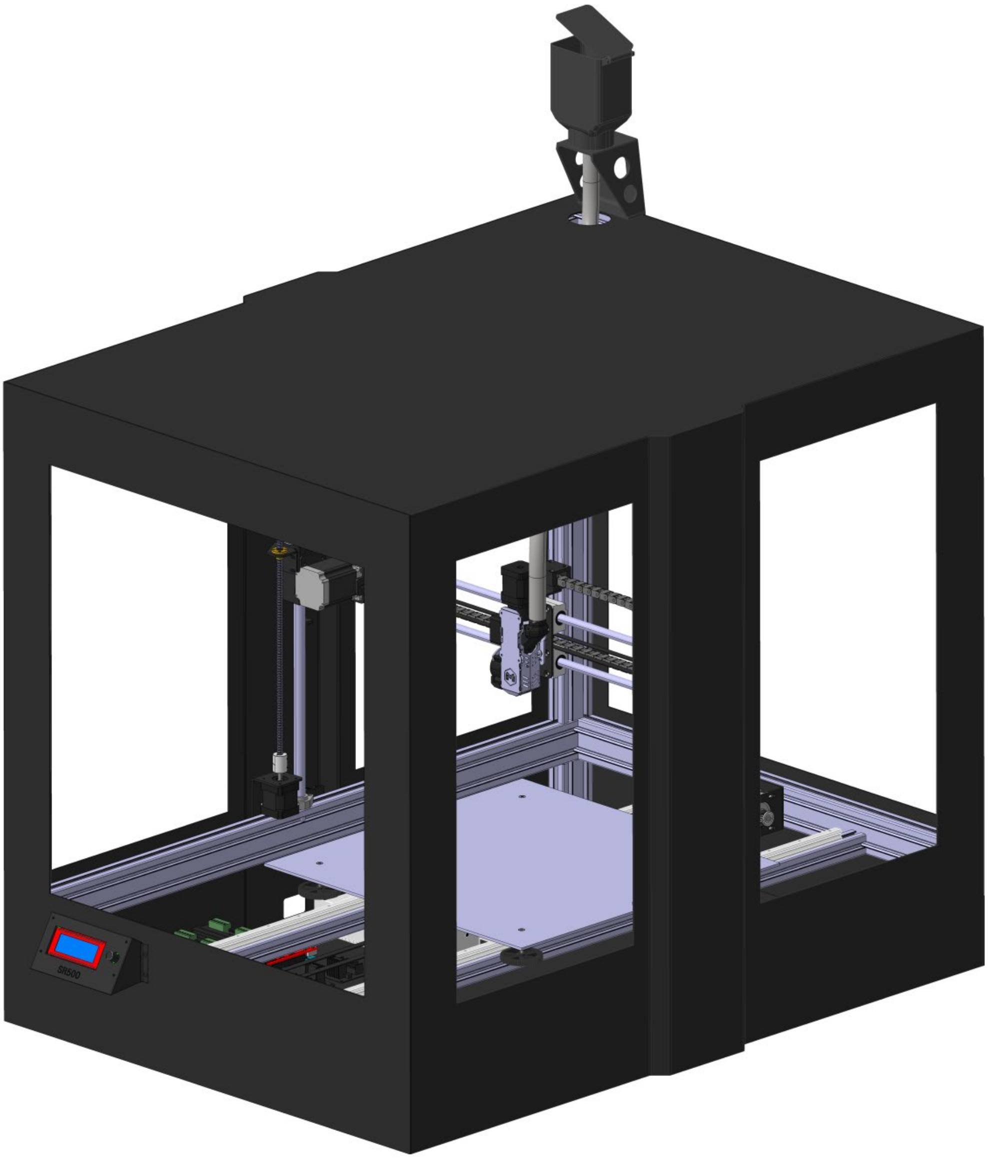

Fig.6. 3D model of the designed machine with enclosure [1]

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On the top of the machine, the granulate feed or storage, known as the reservoir, is clearly visible. From the storage reservoir, plastic is distributed to the extruder's input reservoir through a discharge hose. The reservoir's volume accommodates approximately 1 kg of granules, depending on the density of the granular material being used.

2.2. Presentation of the developed solution

The adopted solution consists of 5 modules:

1. Z-axis module with the supporting structure;
2. X-axis module with the extruder for applying molten material;
3. Y-axis module with the printing bed;
4. Peripheral equipment;
5. Control module.

Z-axis module with the supporting structure: The supporting structure is formed from aluminum profiles 3030 and 3060, connected with appropriate corner brackets and 3D-printed components. The structural design of the Z-axis module is illustrated in Figure 7.

X-axis module with the extruder: The technical solution for the X-axis module is realized using linear rails and linear blocks that enable movement along the X-axis, including the extruder for applying molten material (Figure 8). The X-axis comprises two induction-hardened linear rails with a diameter of 12 mm, ensuring precise movement and support for the X-slider during motion along the X-axis. At the ends of the linear rails, there are supports for the X gantry, serving as sliders in the Z-axis direction. The movement of the extruder along the X-axis is facilitated by a drive system consisting of a NEMA23 stepper motor and a timing belt transmission (HTD3M type).

Y-axis module with the printing bed: The technical solution for the Y-axis module with the printing bed is shown in Figure 9. The horizontal supports are made of aluminum profiles 3030, featuring HGR15CA-type linear rail guides and sliding bearings marked as HGW15CA, supporting the assembly of the printing bed. The movement of the printing bed along the Y-axis is facilitated by a drive system consisting of a NEMA23 stepper motor and a timing belt transmission (HTD3M type).

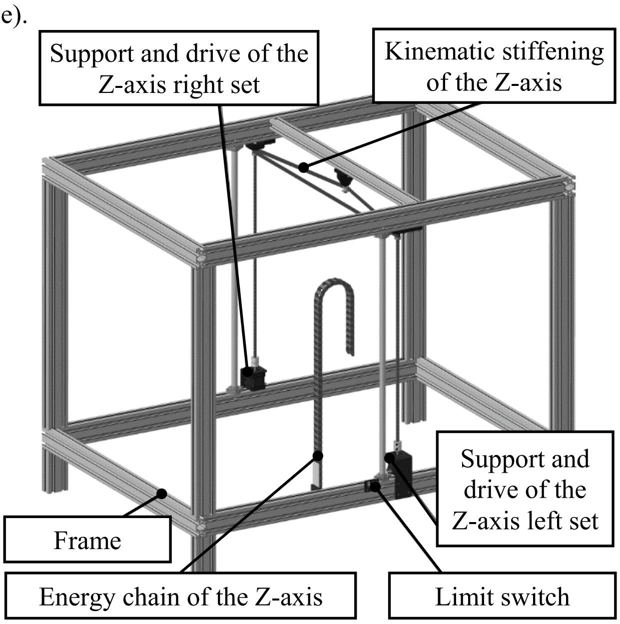

Fig.7. Representation of the technical solution of the Z-axis module [1]

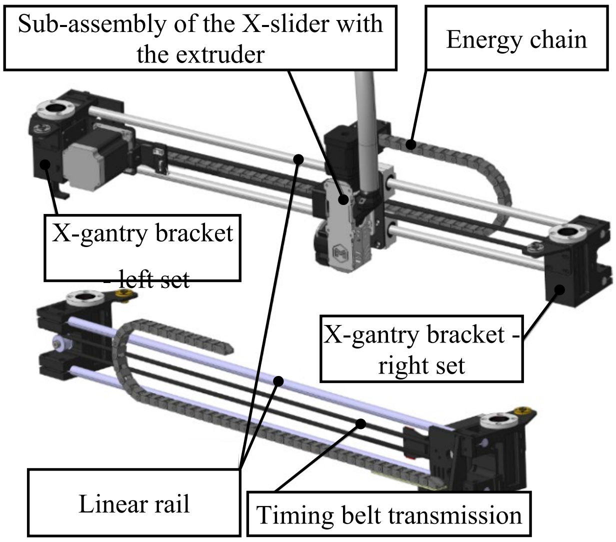

Fig.8. Representation of the components of the X-axis module with the extruder [1]

Peripheral Equipment Module: The peripheral equipment of the machine includes the reservoir assembly and the sheet metal protective cover assembly. The reservoir is manufactured through the 3D printing process using PETG material. In addition to the protective cover of the machine, it was necessary to adequately shield the electrical cabinet, display, and other control components. The protection for the electrical cabinet is made of plywood, while the display case is 3D printed using PETG material. The presentation of the peripheral equipment module can be seen in Figure 6.

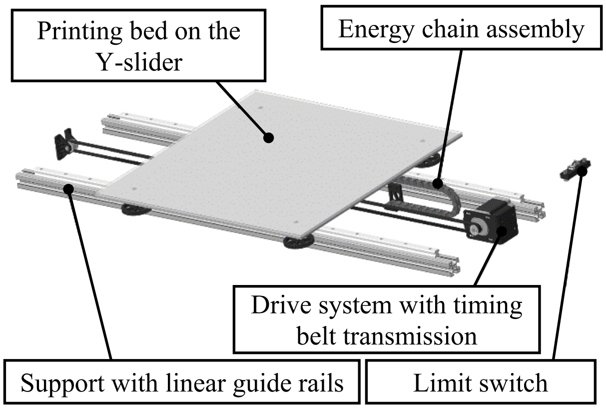

Fig.9. Representation of the technical solution of the Y-axis module with the printing bed [1]

The control module represents an automatic control system that will be further detailed in Chapter 3.

3. 3D PRINTER CONTROL

According to the already defined subsystems and requirements, the designed automatic control system is divided into two basic units:

1. Electronics.
2. Firmware.

3.1. Electronics

The task of **the control unit** is to implement the desired behavior specified by the program to the executive components (stepper motors and heaters). In other words, it is responsible for ensuring synchronized, proper communication and control between the drive systems of the X, Y, Z axes, and the extruder axis, automatic regulation of the printing bed heaters and temperature measurement devices, automatic control of the molten material application system, and so on. The hardware components of the control unit are:

- Programmable microcontroller **Arduino Mega 2560** where firmware is stored for recognizing, reading, and controlling processes during object manufacturing.
- Intermediate controller **Ramps 1.4** - provides simplified communication and signal distribution between **Arduino Mega 2560** and other control components and executive components.
- **Switching work MOSFET circuits** - represent a form of control protection, acting as intermediaries in the regulation of the temperature of the printing bed and extruder.
- **Switching work relay circuit** - represents a form of control protection along with the MOSFET circuit, acting as intermediaries in the regulation of the temperature of the 220V printing bed.
- **12V DC power supply** - powers the Arduino controller and other components with the specified operating voltage.
- **24V DC power supply** - provides power to the extruder heater, NEMA23 stepper motor driver, power supply for the switching work relay circuit, and switching work MOSFET circuits.
- **Microstep Driver DM556** - controls NEMA23 stepper motors, which act as the drive for the X and Y axes.

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- **Microstep Driver A4988** - controls NEMA17 stepper motors, which act as the drive for the Z and extruder axes.
- **LCD display** - serves as a control panel for issuing commands for movement, heating, program loading, initiating 3D printing, etc. It includes a memory cards reader.
- **Limit switches (end stops) -** used to determine the home position of the extruder, from which absolute coordinates are specified in the X, Y, and Z-axis directions.
- **Thermistor 100k Beta 3950** - measures the current temperature. Together with the heater, it participates in the automatic temperature regulation systems of the printing bed and extruder.

The representation of the control unit is shown in Figure 10, where the specified hardware components and their connections can be clearly seen.

In addition to the shown 12V and 24V direct current supplies, the control unit also utilizes a voltage of 220V, not only as an alternating current source for generating direct current but also as a source of alternating current to power the printing bed heaters (220V, 750W).

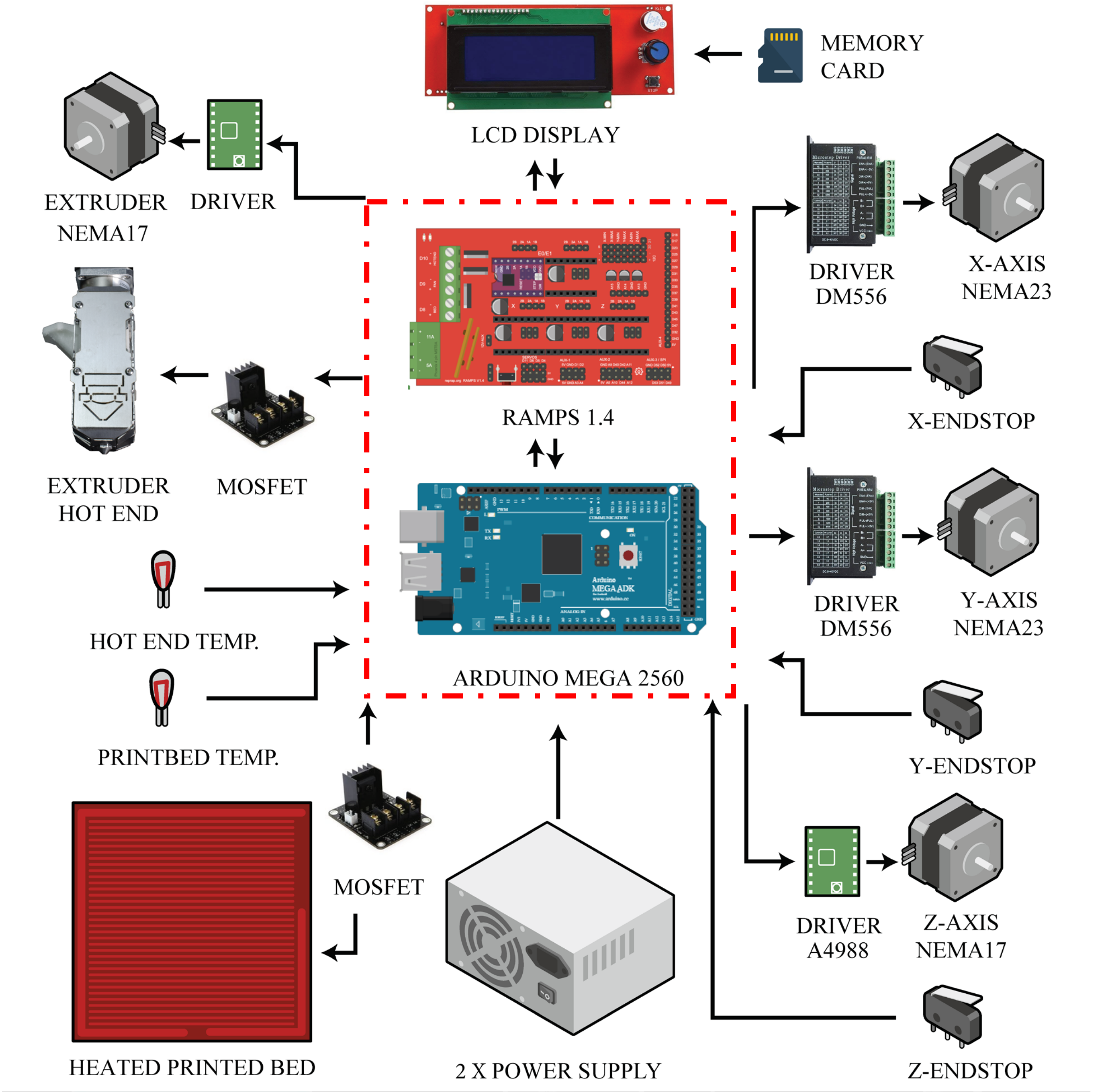

Fig.10. Representation of hardware components of the control unit

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3.2. Firmware

Every control board needs specialized code called firmware loaded on its microcontroller to make the electronics come to life. The firmware is responsible for interpreting the G-code commands sent to the electronics from the printer control application. How well the firmware does this will determine how well your 3D printer will print objects [6].

For the needs of this FGF 3D printer, standard **Marlin** firmware was used. Marlin is open source firmware originally designed for FDM 3D printers using the Arduino platform [6]. Today, it is used to control many 3D printers, especially those with the Arduino+RAMPS platform.

Although Marlin was developed and is predominantly used for FDM 3D printers, it has been successfully utilized and adapted here due to its similarity in control. It was necessary to adjust the following parameters:

- Travel limits after homing.
- Movement settings.
- Stepper motor movements.
- Temperatures of the printing bed and extruder.
- PID control for the closed-loop automatic control of printing bed and extruder temperatures.
- Type of LCD display used.

After loading the firmware, the control unit is ready to operate the 3D printer.

4. MANUFACTURING AND TESTING 3D PRINTER

The 3D printer has been successfully assembled (excluding the enclosure), and its appearance is shown in Figure 11. Printer calibration and preliminary testing have been conducted. The tests were performed using PLA plastic due to its ease of printing and familiarity with printing parameters.

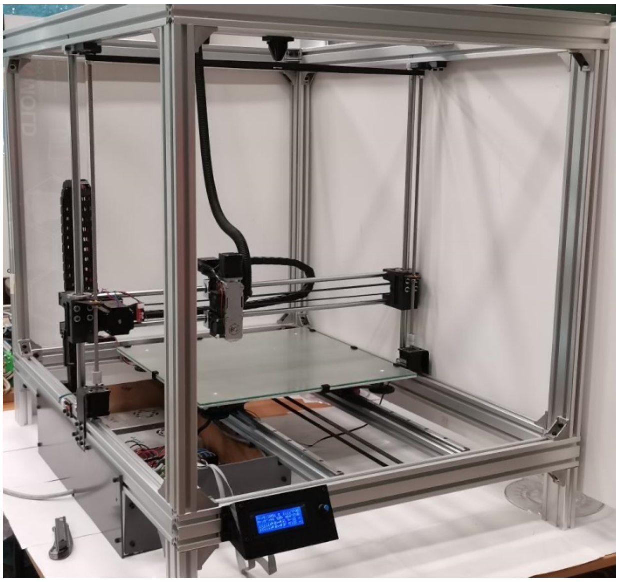

Fig.11. Appearance of the assembled 3D printer

To utilize the printer, it is necessary to generate paths, i.e., to prepare for printing. To generate the path for the printer’s extruder, we used a separate application called a slicer to take a solid 3D model and slice it into layers suitable for 3D printing. This process makes the code (G-code) that tells the 3D printer where to move the extruder, when to extrude plastic, and how much plastic to extrude [6].

For this printer, **Simplify3D** software was used, offering total customization and advanced control of your printing process. A completely new 3D printing process was created, where all necessary parameters were finely adjusted. In Figure 12, a 3D model of one of the test parts printed during the printer testing is shown. It involves 3D printing with the following printing parameters:

- material: PLA;
- layer thickness: 0.4mm;
- nozzle diameter: 0.8mm;
- wall thickness: 1.6mm.

Fig.12. Test part printed during the testing phase of the 3D printer

5. CONCLUSION

When designing the FGF 3D printer, technical and technological solutions of existing types of 3D printers were analyzed from the aspects of construction, kinematic structure, utilized technology, working volume dimensions, and, of course, cost.

The analysis concluded that there is no universal technical and technological solution for a printer with a larger working space, stable structural design, low cost, and the capability for quick adjustment of parameters, platform height, and starting. The 3D printer design prioritized the incorporation of technical solutions that, based on analysis, were considered the most suitable to fulfill the project's needs and requirements.

While manufacturing and testing the printer, a challenge emerged related to the misalignment of Z-axis stepper motor rotations when the machine was turned off. This directly affected the tilting of the X portal, leading to irregular geometry and shapes of printed parts. He mentioned problem was resolved by incorporating additional bracing for the Z-axis.

In addition, possible improvements to the 3D printer have been observed, namely:

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- Implementation of an additional extruder to expedite the production process on such a large working space;
- Development of a device for adding a certain percentage of additional colored granulate at specific intervals to create parts in multiple colors;
- Improvement of the granulate reservoir – assuming that the current granulate feeding solution may not function properly;
- System for automatic temperature regulation and airflow in the workspace.

Future work on this FGF 3D printer will focus on finding optimal print parameters for other types of plastics, especially those that cannot be purchased in filament form but are available in granulate form. This approach allows for testing the suitability of specific polymers for the 3D printing process.

Furthermore, there is an idea to design a system for producing granulates from PET packaging waste in the future, contributing to environmental protection.

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