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SOFTWARE DEVELOPMENT FOR SLM-3D PRINTER PROTOTYPE CONTROL SYSTEM USING KLIPPER FIRMWARE PROGRAM

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The paper presents the development of a simplified laboratory selective laser melting (SLM) unit aimed at cheapening the technology by replacing the complex powder feeding system with an open surface with software-controlled dosing and leveling mechanisms. The proposed design allows the use of typical 3D printing software with minimal modifications, facilitating integration and control. A technical implementation of the powder dispensing module is described, including stepper motors, an Arduino microcontroller, and a C# user interface. A layer formation algorithm is developed to ensure that mechanical damage to the part is prevented due to the special motion of the platform. The results of pilot experiments on the creation of a volumetric metal object using a 100 W fiber laser are presented.

Keywords: selective laser melting (SLM), 3D metal printing, additive technologies, laser control, 3D prototyping.

SLM-3D ПРИНТЕРІНІҢ ПРОТОТИПІН БАСҚАРУ ЖҮЙЕСІНЕ АРНАЛҒАН БАҒДАРЛАМАЛЫҚ ЖАСАҚТАМАНЫ KLIPPER FIRMWARE НЕГІЗІНДЕ ДАМЫТУ

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Бұл мақалада күрделі ұнтақ беру жүйесін бағдарламалық басқарылатын мөлшерлеу және тегістеу механизмдері бар ашық бетпен ауыстыру арқылы технологияны арзандатуға бағытталған зертханалық селективті лазерлік балқыту (SLM) қондырғысын жасау сипатталады. Ұсынылған құрылым типтік 3D басып шығару бағдарламалық жасақтамасын аз ғана өзгерістермен пайдалануға мүмкіндік береді, бұл интеграция мен басқаруды жеңілдетеді. Ұнтақ таратқыш модульдің техникалық іске асырылуы сипатталған, оған қадамдық қозғалтқыштар, Arduino микроконтроллері және C# тіліндегі пайдаланушы интерфейсі кіреді. Платформаның арнайы қозғалысына байланысты бөлшектің механикалық зақымдануын болдырмайтын қабат қалыптастыру алгоритмі жасалды.100 Вт қуатты талшықты лазерді пайдалану арқылы көлемді металл бұйымын жасау бойынша пилоттық тәжірибелер нәтижелері келтірілген.

Түйін сөздер: селективті лазерлік балқыту (SLM), 3D металл басып шығару, аддитивті технологиялар, лазерлік басқару, 3D прототиптеу.

РАЗРАБОТКА ПРОГРАММНОГО ОБЕСПЕЧЕНИЯ ДЛЯ СИСТЕМЫ УПРАВЛЕНИЯ ПРОТОТИПОМ SLM-3Д ПРИНТЕРА С ИСПОЛЬЗОВАНИЕМ ПРОГРАММЫ-ПРОШИВКИ KLIPPER

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В статье представлена разработка упрощённой лабораторной установки селективного лазерного плавления (SLM), направленной на удешевление технологии за счёт замены сложной системы подачи порошка на открытую поверхность с программно управляемыми механизмами дозирования и разравнивания. Предложенный конструктив позволяет использовать типовое программное обеспечение 3D-печати с минимальными модификациями, облегчая интеграцию и управление. Описана техническая реализация модуля распределения порошка, включающая шаговые двигатели, микроконтроллер Arduino и пользовательский интерфейс на C#. Разработан алгоритм формирования слоя, обеспечивающий предотвращение механических повреждений детали за счёт особого движения платформы. Представлены результаты пилотных экспериментов по созданию объёмного металлического объекта с использованием волоконного лазера мощностью 100 Вт.

Ключевые слова: selective laser melting (SLM), 3D-печать металлом, аддитивные технологии, лазерное управление;,3Д - прототипирование.

Introduction. Selective laser melting (SLM) is an additive technology based on layer-by-layer sintering of metal powder using high-power laser irradiation. The process is carried out in a controlled atmosphere (most commonly argon or nitrogen) to prevent oxidation of the melt.

The development of digital technologies has made it possible to create additive facilities for printing complex parts made of plastic and metals [1]. One of the most precise methods is Selective Laser Melting (SLM), which is widely used in scientific and experimental developments [2]. The main disadvantage of SLM is its high cost associated with the use of complex powder feeding mechanics [3]. To reduce its cost, an alternative approach is proposed: formation of a powder layer on an open surface without feed cylinders. This simplifies the design, reduces the price and increases reliability (Figure 1).

The proposed design approach ensures compatibility with typical firmware and software used for 3D printing metal powder models. This simplifies system customization and reduces the requirements for control electronics development. At the same time, the introduction of additional mechanisms for powder distribution and alignment has led to the emergence of new moving elements, the functionality of which is not supported by standard firmware. This requires the development or modification of control algorithms taking into account the kinematics of auxiliary units.

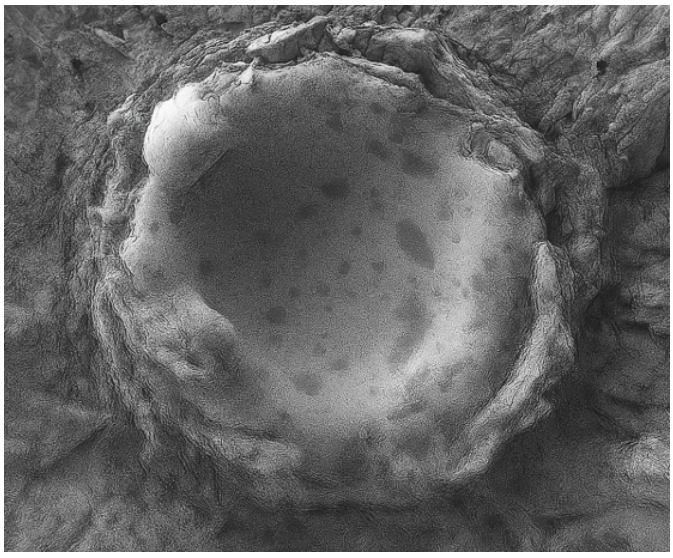


Fig.1 - Microphotograph of a crater formed by a laser pulse on the surface of iron powder

The physical and logical similarity of extrusion and laser melting processes makes it possible to use existing firmware, modifying it through macros, redistribution of G-code commands, and reconfiguration to replace the extruder with a laser module [4,5].

One of the design and technological difficulties of realization of the process of selective laser melting is the necessity of coordinated movement of the working platform during powder feeding and alignment. In the process of powder distribution, the platform with the printing area must be lowered to a predetermined value corresponding to the layer thickness. However, in order to perform the powder leveling operation, the platform must be temporarily returned to the initial position.

This operation is due to the physics of the melting process: when exposed to laser radiation, a crater is formed with a depression in the molten zone and elevation at the edges, reaching a height of 0.1 to 0.5 mm, depending on the shape and size of the powder (Figure 2).

The rigid walls of the powder distribution mechanism can collide with protruding fragments of the formed part, leading to the risk of mechanical damage to the product and premature failure of the distribution device [6,7].

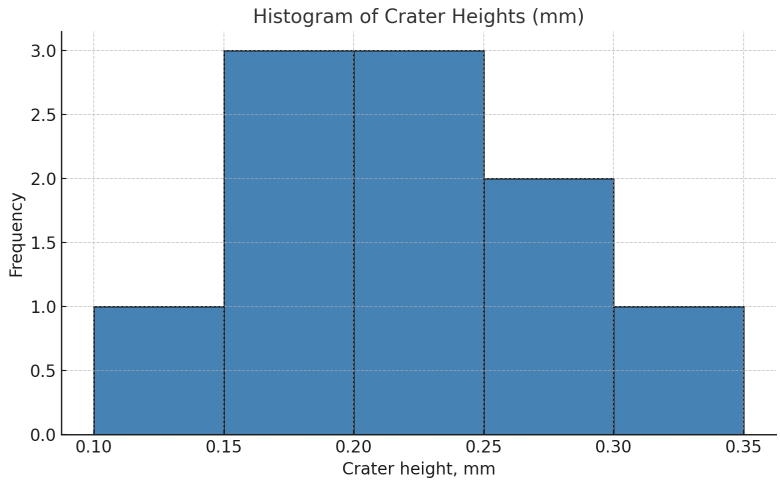


Fig.2 - Histogram of crater heights formed during laser melting

Experimental data shows a typical distribution of crater elevations, confirming the need to compensate for mechanical collisions by adjusting the platform position.

To exclude this effect, a technical solution, the algorithm of powder layer formation is proposed, which consists of the following [8]:

1 - lowering the printing platform by two heights of the printing layer;

2 - powder distribution on the printing surface;

3 - raising the printing platform by one height of the printing layer;

4 - leveling the powder surface with an elastic scraper.

Realization of cyclic movement of the working platform within one layer allows to compensate these effects and ensure stable operation of the mechanism while maintaining the geometric accuracy of the product. As a result of the implementation of the above-mentioned technical solution, the complete operating cycle of the additive installation includes the following stages:

1) application of a uniform layer of metal powder on the working platform;

2) selective melting of the material by laser beam according to the trajectory specified in the 3D-model layer;

3) Parking of the laser module - closing of the

limit switch

4) Start of the powder layer formation algorithm and cycle repetition.

Materials and methods. Currently, pilot experiments are being conducted to control the process of selective laser melting [9].

Extensive work is to be done to determine the optimal parameters of laser melting of metal powder. In this regard, the control of the process of selective laser melting at the current stage is carried out in manual mode.

For experimental studies, a laboratory setup including a software and hardware module for distribution and leveling of metal powder and a laser system based on a 100 W fiber marker (Figure 3) has been developed [10].

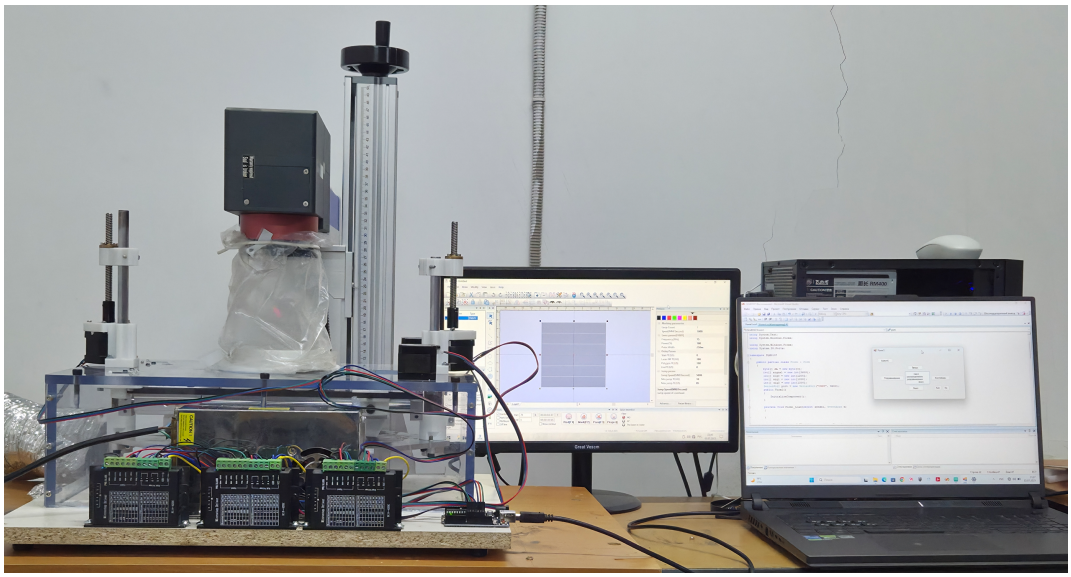


Fig.3 - Photograph of experimental additive installation of selective laser melting of metal powders

The software and hardware module of metal powder distribution and leveling is a sealed working chamber made of monolithic polycarbonate, inside of which there is a complex of mechanical and digital components that ensure the movement of the open platform, as well as the functioning of the systems of dosing and leveling of powder material.

The metal powder distribution system is realized in the form of a loading container, into which the powder material is loaded before the start of the experiment. In the lower part of the container there is a technological hole (slit) through which the powder enters the open surface. The spreader is moved by means of a linear actuator controlled by a stepper motor.

The system of powder layer leveling is made in the form of a scraper from heat-resistant flexible polyurethane. The use of flexible material is justified by the need to adapt to the microroughnesses arising on the surface of molten metal under the influence of laser radiation, which allows minimizing the mechanical impact on the formed structure.

The mechanism of movement of the open surface is realized in the form of a platform made of aluminum alloy, which provides effective thermal dissipation and promotes accelerated cooling of the welded layer.

The whole system is connected to the laser module by means of a hermetic flexible channel, which allows to carry out the processes of dosing, leveling and laser processing in a single closed volume, protected from external influence.

To control the stepper motors, a digital circuit based on the Arduino Uno microcontroller was developed [11]. Data exchange with the control

computer is carried out through the USB interface, through which the microcontroller receives control commands via UART protocol to perform specified technical operations.

Specialized software on the Arduino IDE platform was developed for programming the microcontroller [12]. The implemented firmware is designed to control the actuators of the laboratory unit of selective laser sintering (SLM), including modules of powder dosing, layer leveling and moving the working platform.

Interaction with the microcontroller is carried out via serial interface (UART) with the reception of control commands from an external control system, such as a personal computer or microcontroller.

```
Initialization: setup()

The setup() function configures the digital pins:

Pins 8–13 are configured as outputs and are used to control the
direction of rotation and to supply pulses to the stepper motors.

Serial port with baudrate = 9600 baud is initialized.

pinMode(8,OUTPUT); // Dispenser direction

pinMode(9,OUTPUT); // Dispenser step

pinMode(10,OUTPUT); // Leveler direction

pinMode(11,OUTPUT); // Leveler step

pinMode(12,OUTPUT); // Lifting mechanism step

pinMode(13,OUTPUT); // Lifting direction

Main loop: loop()

In the main loop() loop, the program waits for 3 bytes of data to arrive
via Serial. Depending on the first byte, different commands are
executed:

Command (byte data{[}0{]}) Description of action

111 (’ o’) Start powder dispenser –
Konteaner()

112 (’ p’) Start leveling mechanism –
Ravnina()

113 (’ q’) Raise platform – Upp()

114 (’ r’) Lower platform – Down()

115 (’ s’) Combined command: lower
platform, dispense powder, level – Down(); Konteaner(); Ravnina();

116 (’ t’) Partial powder feed forward –
KNS()

117 (’ u’) Partial powder feed backward –
KNL()

Actuator control functions
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Each function realizes a specific operation by controlling stepper
motors by supplying rectangular pulses to the corresponding pins
{[}13{]}.

Konteaner()

Powder feed:

Forward direction (pin 8 = HIGH).

Movement of 1700 steps (forward and backward).

Ravnina()

Leveling the layer:

Movement of the mechanism to the right (pin 10 = HIGH), then to the left
(pin 10 = LOW), 1700 steps each way.

Upp() / Down()

Raising or lowering the platform:

The direction is set at pin 13.

100 steps are taken at pin 12.

KNS() / KNL()

Partial powder feed to one side (forward or backward), 1000 steps.

DELAY(int SH) function
```

Table 1 - Powder layer formation cycle and corresponding UART commands

№	Process Stage	UART Command	Arduino Function	Description
1	Powder dispensing	111 (’o’)	Konteaner()	Feeds powder 1700 steps forward and backward
2	Surface leveling	112 (’p’)	Ravnina()	Moves scraper right and left (1700 steps)
3	Platform raising	113 (’q’)	Upp()	Raises platform by 100 steps
4	Platform lowering	114 (’r’)	Down()	Lowers platform by 100 steps
5	Full cycle	115 (’s’)	Down(); Konteaner(); Ravnina()	Executes full sequence for one layer

Represents a stub instead of a real delay - in this variant delay(0), which does not create a real waiting time. Apparently, it is intended to be modified to adjust the speed of stepper motors (it can be replaced by delayMicroseconds() for fine-tuning).

The developed program implements basic step-by-step control of actuators of the experimental unit

of selective laser sintering. Control commands are transmitted by a simple protocol through the serial interface UART, which provides compatibility and the possibility of integration with external control programs.

The control logic for powder dosing, platform movement, and leveling is summarized in Table 1.

To ensure the convenience of interaction with the software and hardware module of metal powder distribution and leveling, a specialized software in C# language was created. The program is a Windows Forms-application designed to control stepper motors driving the mechanisms of powder dosing, layer leveling and vertical positioning of the working platform as part of the SLM laboratory unit (see Figure 4).

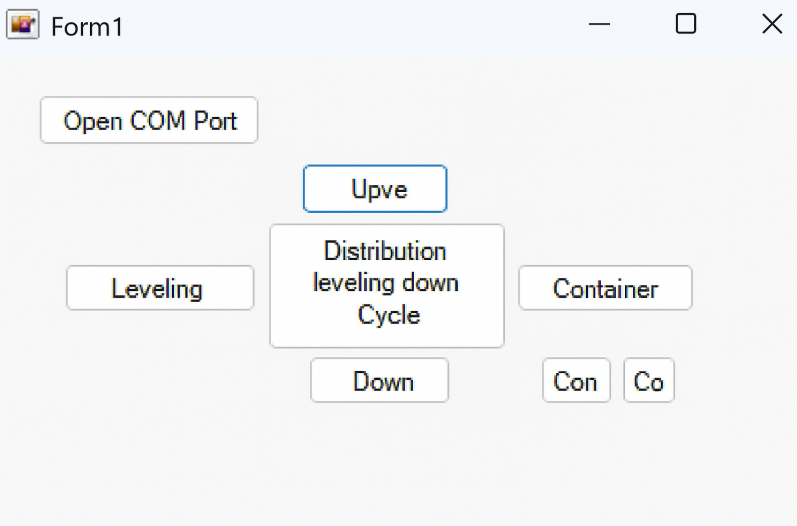


Fig.4 - Software interface for controlling software and hardware module for powder distribution and leveling

Interaction is carried out through a serial port (Serial, COM28), which sends control commands to a microcontroller (e.g., Arduino).

SerialPort port = new SerialPort("COM28", 9600); - the object of serial port at 9600 baud rate connected to Arduino is created.

byte[] AA = new byte[3]; - an array for transferring 3 bytes via control protocol (in fact, only the first byte is used).

Form1 contains several control buttons, each of which sends a command. Each button on the form corresponds to the Click event, which generates and sends a control command. The control logic is implemented by sending one byte in the AA[0] array and then "resetting" to 0 to complete the command:

Each command is sent in 2 steps:

AA[0] = < command code> → port.Write(AA, 0, 3);

AA[0] = 0 → port.Write(AA, 0, 3);

This provides a clear delineation of the command boundaries - first the activation signal is transmitted, then the zero command as a "completion flag" (or reset).

The program implements a simple and robust user interface for controlling the mechanics of the SLM machine in a laboratory environment. Through direct command control via UART, the operator can manually control the key steps: dispensing, leveling, platform raising/lowering, and test procedures.

Results and discussion. With the help of the developed experimental setup, pilot experiments on forming a 3D part by selective laser melting have been carried out.

Marking software was used to form the laser beam trajectory. The contour of a square with an

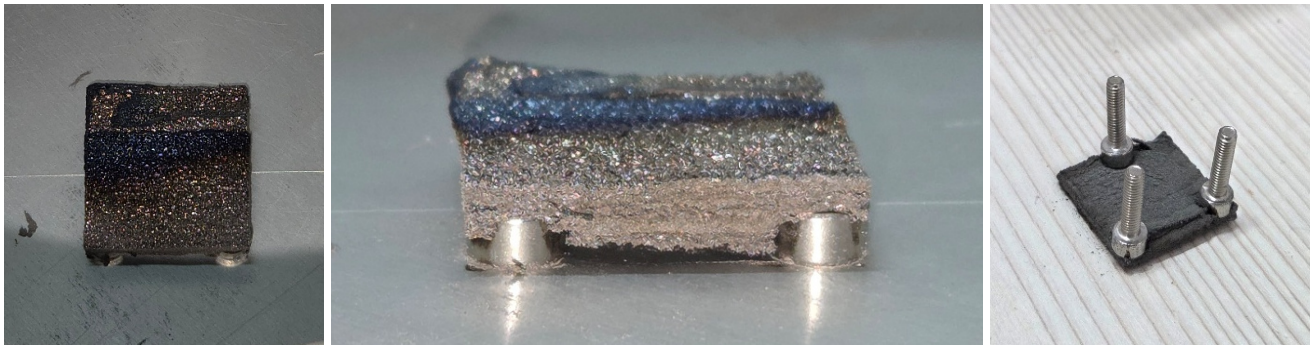
edge of 20 mm was used as a printing object (Table 2).

As a result of experimental studies, a parallelepiped with a base of 20x 20 mm and a height of 2 mm was synthesized (Figure 5).

Table 2 - Parameters of the pilot experiment

Parameter	Value
Laser type	100 W fiber laser
Object size	20 × 20 × 2 mm
Scanning speed	Not specified
Number of layers	Not specified
Layer thickness	Estimated ~0.1–0.2 mm

The figure below summarizes the main parameters of the SLM process used during the pilot test.



Top view ***Side view*** ***View of the part removed from the platform***

Fig.5 - Results of pilot experiments obtained at the additive unit of selective laser

Test prints confirmed the performance of the system: several layers were successfully fused.

Conclusion. The conducted research confirmed the feasibility of developing a low-cost laboratory setup for Selective Laser Melting (SLM) with an open powder delivery system and software-controlled leveling mechanisms. Integration of widely available firmware platforms, such as Klipper and Arduino, with custom hardware components ensures reliable powder feeding, surface leveling, and platform movement within a compact and sealed environment.

The proposed control algorithm, which involves cyclic movement of the platform, eliminates crater formation on the surface layer, thereby enhancing mechanical stability of the printed object and reducing wear of the equipment. The custom-developed C# software provides an intuitive user interface for manual operation and laboratory testing.

Pilot experiments using a 100 W fiber laser confirmed the system’s functionality and its potential for further optimization. Future developments will focus on automating the laser control process, refining melting parameters, and implementing a closed-loop control system with feedback.

The developed system can be effectively used in educational and research laboratories for training and experimenting with metal powder 3D printing

technologies. This is particularly relevant for countries aiming to strengthen technological independence and develop their own engineering infrastructure.

The novelty of the research lies in the adaptation of standard 3D printer control components to address the specific challenges of metal powder laser sintering. This approach significantly reduces equipment cost while maintaining essential functionality, thus expanding the practical applicability of additive manufacturing in resource-limited settings.

Further work will include the integration of a machine vision module for powder layer quality monitoring, implementation of an automatic platform calibration function, and extended interfacing with external modeling and control systems.

Prospects for Further Development. The current prototype of the SLM system has demonstrated the feasibility of using open powder distribution and leveling mechanisms combined with software-controlled automation. However, several directions for further improvement remain relevant for increasing system efficiency, precision, and integration into broader manufacturing workflows.

First, the integration of machine vision systems is considered a priority. Real-time image processing can be used to assess powder bed quality, detect defects, and ensure proper alignment of each layer before laser exposure. This feedback will enable a closed-loop control system that can automatically halt or adjust printing parameters when inconsistencies are detected.

Second, automated platform calibration would enhance system reproducibility and minimize human error. A software-controlled homing and alignment protocol using optical or inductive sensors could ensure proper Z-axis positioning before and during the build process.

Third, expansion of the user interface functionality is planned. The current interface enables manual control and basic operation. Future iterations may include automatic slicing integration, G-code preprocessing tools, and detailed process logging, enabling researchers to analyze build quality over time.

Additionally, extending the system to support multi-material capabilities or controlled atmosphere integration (e.g., argon or nitrogen chambers) may significantly broaden the applicability of the installation for more advanced metal alloys and sensitive materials.

Finally, collaboration with educational institutions will allow the SLM platform to be used in academic training programs, where students can gain hands-on experience with digital manufacturing, firmware development, and industrial automation.

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