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2D SprayPath: um gerador paramétrico de varreduras planares em G-code aplicado à instrumentação científica

2D SprayPath: a parametric generator of planar scans in G-code applied to scientific instrumentation

2D SprayPath: un generador paramétrico de barridos planares en G-code aplicado a la instrumentación científica

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Resumo: A automação de laboratórios desempenha um papel importante na melhoria da reprodutibilidade experimental, na redução de erros humanos e no aumento da eficiência dos processos. Este trabalho apresenta o desenvolvimento e validação do 2D SprayPath, um software open source projetado para gerar trajetórias parametrizadas para sistemas de deposição por *spray coating*. Desenvolvido em Python, o software oferece uma interface gráfica intuitiva que permite definir parâmetros de deposição, visualizar trajetórias do bico de aspersão e gerar automaticamente arquivos G-code para controle de movimento. A validação foi realizada utilizando um *spray coater* de baixo custo adaptado de uma impressora 3D Creality Ender-3 PRO equipada com aerógrafo. Os testes experimentais com diferentes padrões em zigue-zague mostraram excelente concordância entre os parâmetros programados e medidos, com erros relativos inferiores a 1%. Os resultados demonstram a precisão, confiabilidade e reprodutibilidade das trajetórias geradas.
Palavras-chave: Software. Spray coating. Automação experimental. Trajetórias parametrizadas. Reprodutibilidade.

Abstract: Laboratory automation plays an important role in improving experimental reproducibility, reducing human errors, and increasing process efficiency. This work presents the development and validation of 2D SprayPath, an open-source software designed to generate parameterized trajectories for spray coating deposition systems. Developed in Python, the software provides a user-friendly graphical interface that enables the definition of deposition parameters, visualization of nozzle paths, and automatic generation of G-code files for motion control. Validation was performed using a low-cost spray coater adapted from a Creality Ender-3 PRO 3D printer equipped with an airbrush. Experimental tests employing different zig-zag deposition patterns showed excellent agreement between programmed and measured geometrical parameters, with relative errors below 1%. The results demonstrate the accuracy, reliability, and reproducibility of the generated trajectories. Furthermore, the software can be adapted to other laboratory applications involving controlled planar motion, contributing to accessible automation and scientific reproducibility.
Keywords: Software. Spray coating. Experimental automation. Parametrized trajectories. Reproducibility.

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Resumen: La automatización de laboratorios desempeña un papel importante en la mejora de la reproducibilidad experimental, la reducción de errores humanos y el aumento de la eficiencia de los procesos. Este trabajo presenta el desarrollo y validación de 2D SprayPath, un software de código abierto diseñado para generar trayectorias parametrizadas para sistemas de deposición por *spray coating*. Desarrollado en Python, el software ofrece una interfaz gráfica intuitiva que permite definir parámetros de deposición, visualizar las trayectorias de la boquilla y generar automáticamente archivos G-code para el control de movimiento. La validación se realizó utilizando un *spray coater* de bajo costo adaptado de una impresora 3D Creality Ender-3 PRO equipada con aerógrafo. Los ensayos experimentales con diferentes patrones en zigzag mostraron una excelente concordancia entre los parámetros programados y medidos, con errores relativos inferiores al 1%. Los resultados demuestran la precisión, fiabilidad y reproducibilidad de las trayectorias generadas.
Palabras-clave: Software. Spray coating. Automatización experimental. Trayectorias parametrizadas. Reproducibilidad.

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Preliminary considerations

The increasing complexity of scientific, technological, and organizational activities has driven the search for solutions capable of enhancing efficiency, reducing task execution time, and minimizing operational errors and delivery costs (Almusharraf, 2025). In this context, process automation has become an important approach, being applied across different fields with the aim of optimizing workflows and supporting decision-making (Almusharraf, 2025).

Automation can be defined as the integrated use of control systems, instrumentation, and information technologies to monitor, operate, and optimize processes in an efficient and predictable manner, aiming at greater reliability, reproducibility, and quality of results (Jämsä-Jounela, 2007).

Thus, automation in scientific laboratories has been adopted as an effective strategy to enhance experimental reproducibility, improve operational efficiency, reduce human errors, and optimize the use of time and resources, directly contributing to the quality and reliability of results (Holland; Davies, 2020; Jessop-Fabre; Sonnenschein, 2019; Kitney et al., 2019). Among these benefits, reproducibility stands out as a fundamental aspect, which can be defined as the property of an experiment whereby independent researchers, based on shared documentation, can conduct a new experiment whose interpretation of the results leads to the same scientific conclusions as the original study (Gundersen, 2021).

Despite the clear benefits of automation in scientific laboratories, its implementation still faces significant challenges, as commercial equipment and software are often expensive to maintain, requiring financial and technical investments that are beyond the reach of most academic institutions (Holland; Davies, 2020; Kempner; Felder, 2002; Storrs, 2013; Wrigley et al., 2014). In addition, the short duration of research contracts and the temporary nature of many projects hinder the development and integration of long-term automated solutions (Holland; Davies, 2020; Van der Weijden et al., 2016).

The complexity involved in developing customized systems, combined with the need for multidisciplinary coordination and continuous maintenance, may limit the widespread adoption of automation in routine experimental protocols (Abramo; D'Angelo, 2014; Holland; Davies, 2020; Kreiman; Maunsell, 2011). These challenges highlight the need for more accessible, flexible, and adaptable approaches capable of supporting the execution of experiments with greater efficiency, reproducibility, and reliability, without relying on substantial investments or established industrial infrastructures (Holland; Davies, 2020; Marx et al., 2013; Ochs et al., 2017).

In Materials Science, more specifically in thin film deposition, the cost of acquiring equipment and software for certain processes is high and requires technical expertise that may be limiting. These factors reflect the aforementioned complexity and motivate the present work, which proposes an open-source software for controlling a deposition system based on the spray coating technique, using low-cost resources and capable of meeting experimental demands.

Materials deposition techniques in Materials Science

In the context of Materials Science, with the aim of enhancing the reproducibility of scientific methodologies, various deposition methods have been proposed and employed in the literature, encompassing different physical principles and levels of experimental control, in order to meet the diverse demands of material fabrication and characterization (Toma et al., 2024).

Thin film deposition techniques exhibit a wide diversity and can be classified according to the physicochemical mechanisms involved and the nature of the precursor used (Puri; Shukla, 2022; Toma et al., 2024). In this context, vapor-phase physical deposition (PVD), vapor-phase chemical deposition (CVD), solution-based chemical methods, and emerging liquid-based and printing techniques stand out (Toma et al., 2024).

The PVD group includes thermal evaporation, sputtering, and molecular beam epitaxy (MBE), and these techniques are mainly employed due to the high purity of the films and nanometer-scale structural control. CVD techniques and their variants—LPCVD (Low Pressure Chemical Vapor Deposition), PECVD (Plasma Enhanced Chemical Vapor Deposition), and MOCVD (Metal Organic Chemical Vapor Deposition) are based on chemical reactions of gaseous precursors and are essential for obtaining conformal and highly uniform films in electronic and optoelectronic applications (Toma et al., 2024).

There are also solution-based chemical methods, such as chemical bath deposition (CBD), which stand out due to their low cost and experimental simplicity, enabling deposition over large areas. More recently, emerging liquid-phase deposition techniques, such as spray coating, have gained attention for combining low cost, scalability, and compatibility with flexible substrates, thereby expanding the set of available strategies for thin film fabrication (Toma et al., 2024).

Thus, the literature highlights the coexistence of traditional and emerging deposition methods, reflecting the wide range of approaches available to meet different requirements in terms of control, cost, application, and reproducibility in Materials Science (Toma et al., 2024).

Among the deposition techniques presented, those based on liquid-phase processes that involve the controlled movement of an emitting or injecting nozzle over the substrate are those that can most directly benefit from programs for the automatic generation of planar motion patterns (Quero, 2023).

In this context, spray coating stands out, along with emerging solution-assisted printing and deposition techniques such as inkjet printing, in which film uniformity, homogeneity, and process reproducibility strongly depend on the trajectory, speed, and overlap of nozzle passes. These characteristics make such techniques particularly suitable for the implementation of automation strategies based on x–y plane scanning, often performed in zig-zag patterns, especially in low-cost experimental setups or laboratory-developed systems, where commercial solutions are not always available (Toma et al., 2024).

Spray Coating

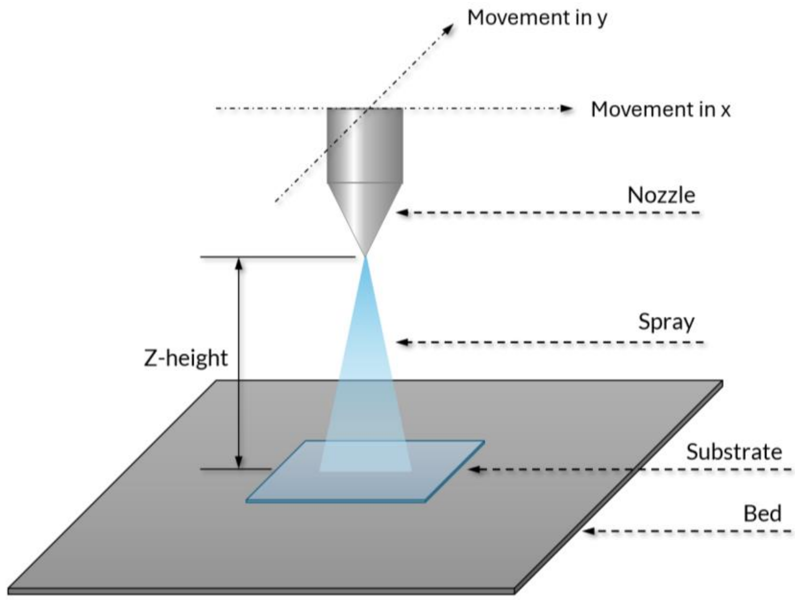
As previously mentioned, among the deposition techniques presented, those based on liquid-phase processes, such as spray coating, have stood out due to their experimental simplicity and their potential for automation and reproducibility.

Spray coating consists of the atomization of a precursor solution or liquid suspension through an emitting nozzle, which sprays the material onto the substrate for film formation after solvent evaporation and subsequent reactions (Kanakannavar et al., 2024).

The uniformity, homogeneity of the coating, and reproducibility of this process depend directly on the control of the nozzle trajectory, scanning speed, nozzle–substrate distance, pass overlap, and bed heating (deposition platform), making this technique particularly suitable for the implementation of automation strategies based on x–y plane motion, often organized in zig-zag patterns. In particular, in low-cost experimental setups or laboratory-developed systems, automated control of these parameters becomes essential for obtaining films with reproducible properties (Hanft et al., 2015).

Figure 1 illustrates the schematic of a spray coater device, highlighting its main components as well as the operational parameters that must be controlled for the proper execution of the deposition process.

Figure 1: Schematic of the spray coater operation with its main components.



Source: Authors' construction based on information from Ashgriz (2011) e Sunitha & Vasudev (2022). Image date: 2026.

The Figure 1 shows the main components of the spray coating process: the nozzle, which is responsible for the atomization of the liquid; the spray plume, which contains the atomized material to be deposited; the substrate, which serves as the support onto which the material is deposited; and the bed, which supports the substrate and the bed, which supports the substrate and provides temperature control during operation. In addition, the Figure 1 also illustrates the vertical (z-axis) positioning parameters, as well as the planar motion parameters in the x–y plane.

Although there are still several obstacles related to the automation of scientific laboratories (Holland; Davies, 2020), different research groups have sought to overcome these limitations through the development of low-cost equipment, which enables the automation of experimental processes and increases reproducibility in the production of scientific objects of interest (Blaskievicz; Soares; Mascaro, 2021; Falsetti et al., 2021; Naveca et al., 2017; Sanson et al., 2014).

In this context, the Heterogeneous Photocatalysis Laboratory of the Federal Institute of Education, Science and Technology of São Paulo (IFSP) – Itapetininga Campus proposed the development of a low-cost spray coater with the aim of ensuring material deposition with a high degree of reproducibility. This automation proposal involves both hardware development, through the adaptation of a 3D printer for the atomization of liquid suspensions of interest, and control software for defining the trajectories to be followed by the adapted nozzle.

The physical equipment was developed by adapting a Creality Ender-3 PRO 3D printer, with a maximum speed of 100 mm/s. The original filament extruder nozzle was replaced by a Wimpel 1003 dual-action airbrush (0.35 mm, adjustable cup), mounted on a support printed in ABS (acrylonitrile butadiene styrene) filament and connected to an air pump. This configuration ensures that the spraying point remains at a previously defined reference position, allowing its precise control through software.

The developed spray coater is primarily intended for the deposition of catalytic materials synthesized in the laboratory, aiming at the production of sensors, thin films with catalytic properties, among other applications. However, this system can be easily adapted to other applications that require the controlled atomization of liquid suspensions in a well-defined zig-zag pattern, as well as the assurance of homogeneous coverage of a flat surface.

The control of this deposition is typically carried out through a project-specific design, and G-code encoding is commonly used, as it is the machine language responsible for controlling the motion of deposition systems (Latif et al., 2021). However, the learning curve associated with understanding and using G-code can represent a significant obstacle, in addition to constituting a complex process that requires a considerable amount of learning time.

Therefore, the proposed system includes the development of software with a simple graphical interface for modeling the surface and the desired spray coater path, in which the user only inputs the parameters required for deposition and for generating the relevant G-code files

(Latif et al., 2021). This work focuses on the modeling and delivery of the software as an open-source tool aimed at generating G-code from parameterized motion patterns in the x–y plane.

Thus, the objective of this work was to present the challenges associated with the development and validation of the 2D SprayPath software, aiming at its application as a generator of parameterized trajectories for spray coating processes. The system is intended to automate laboratory processes, contributing to the reproducibility of the objects of interest produced with a low-cost spray coater, characterized by simplicity in both modeling and operation.

Methodology

The 2D SprayPath software was developed in Python due to it being free, open-source, and cross-platform, as well as providing numerous libraries that facilitate system development and maintenance ("Welcome to Python.org", 2025). For this purpose, the Tkinter library ("tkinter — Python interface to Tcl/Tk", *[S.d.]*) was used for developing the graphical user interface, Matplotlib ("Matplotlib — Visualization with Python", *[S.d.]*) for generating plots to visualize the path defined for the sprayer, and JSON (JavaScript Object Notation) ("json — JSON encoder and decoder", *[S.d.]*) for metadata handling. In addition, the auto-py-to-exe tool ("auto-py-to-exe", *[S.d.]*) was used to generate an executable, enabling the software to run on Windows systems in a "plug and play" mode, i.e., without the need to install dependencies.

For the validation of the integrated system with pre-defined motions generated by the software and executed from the generated G-code, tests were carried out using the low-cost system developed by the group, a modified Creality Ender-3 V2 Pro 3D printer equipped with an airbrush, configured to function as a spray coater for the deposition of catalytic materials onto substrates. To visualize the deposition patterns, the experiments were performed on standard printing paper (75 g/m²) containing a grid with 1 cm subdivisions, which allowed visual assessment of the uniformity and geometry of the obtained patterns, as well as comparison with the experimental results.

The patterns were deposited using a suspension prepared as described by Falsetti et al. (2025), consisting of 18 mg of catalyst, 1.8 mg of carbon black, 0.9 mL of isopropyl alcohol, and 1.8 mL of water, without the addition of ionomer. The catalyst used was copper oxide

(CuO), obtained according to the methodology described by Nogueira et al. (2016) and Almeida et al. (2024).

In a typical synthesis, 1 mL of glacial acetic acid was added to 250 mL of an aqueous copper acetate solution (0.024 mol·L^{-1}). The mixture was heated to 90 °C under constant stirring. Subsequently, 50 mL of a potassium hydroxide (KOH) solution (0.4 mol·L^{-1}) was added to the previously heated solution, and the system was kept under heating and stirring for an additional 3 minutes after the addition. After this step, the resulting dispersion was left to stand for decantation. The supernatant was then removed, and the obtained precipitate was dried at 60 °C.

The depositions were scanned using an L365 printer with an image resolution of 20400 × 28079 pixels. The images were imported and scaled relative to the reference grid in the ImageJ software (Schneider; Rasband; Eliceiri, 2012), using a reference measurement of (10 ± 0.5) mm. The reported measurements were obtained from the average of 20 experiments performed with the software in each dimension of interest.

The relative error described in Equation (01) was used:

$$Relative\ Error\ (\%) = \frac{|Measured\ value - Nominal\ value|}{Nominal\ value} \cdot 100\% \qquad (02)$$

Where "Measured value" refers to the value obtained using the ImageJ software, and "Nominal value" refers to the value defined as the parameter.

Data analysis and results

The usual workflow for the atomization of liquid suspensions onto surfaces follows a standard procedure, in which the designer specifies the deposition of the material of interest using the 2D SprayPath software, and the hardware then executes the process in an automated manner, following the instructions generated by the software. The user must use a storage device to save the instructions in the form of G-code and load it into the printer. Figure 2 presents the process flowchart.

Figure 2 (a) shows the icon of the developed 2D SprayPath software. The 3D printer (Figure 2 (b)) is equipped with a clamp manufactured by 3D printing using ABS filament to accommodate the airbrush, which replaces the original filament-based print head, as shown in Figure 2 (c). This adaptation enables the system to function as a spray coater. The airbrush is a

Revista brasileira de iniciação científica
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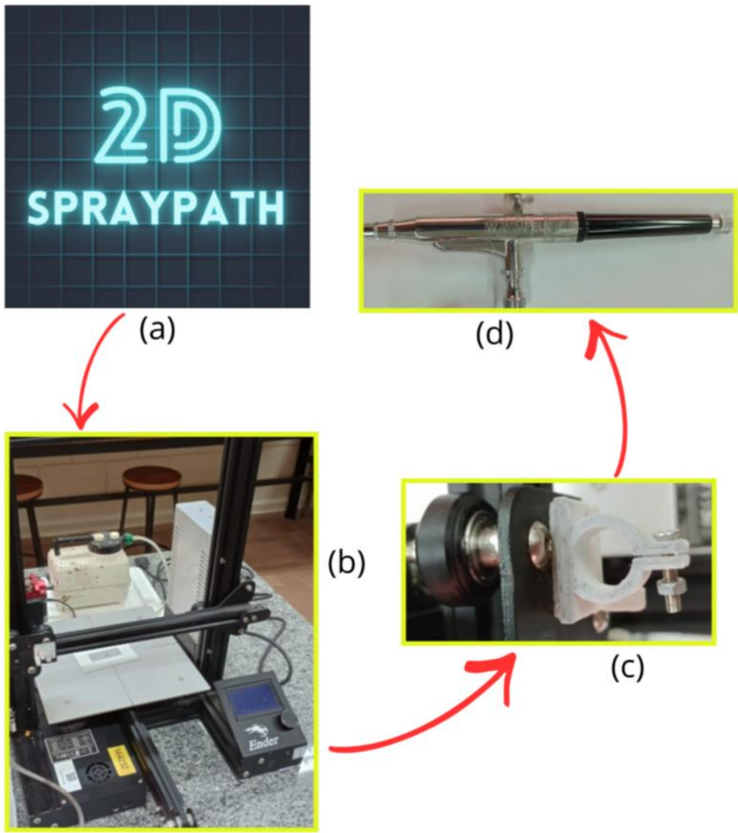
simple model (Figure 2 (d)) and is fixed to the clamp developed for the 3D printer and connected to a pump (Figure 2 (b)).

Figure 2: Schematic of the automation system using the 2D SprayPath software, which transfers data to a modified 3D printer equipped with a conventional airbrush for the atomization of liquid suspensions onto the target surface. (a) 2D SprayPath software icon; (b) Ender 3 3D printer; (c) clamp for airbrush support; (d) airbrush.



Source: Authors' construction (2026).

The 2D SprayPath software was designed to have a simple and flexible interface, with its main screen essentially divided horizontally into three main sections (Figure 3). Its description also follows parameters commonly found in the international literature written in English.

Revista brasileira de iniciação científica
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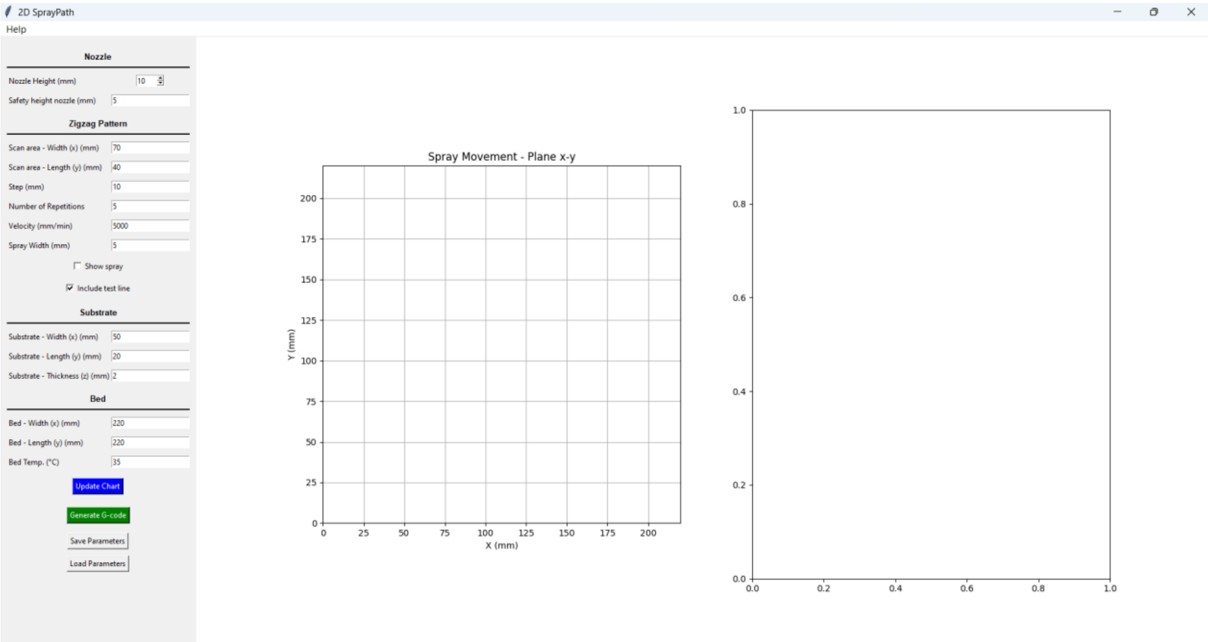
The left-hand section consists of a list of parameters to be configured for the execution of liquid suspension atomization. The central and right sections display two different plots: the central plot shows the deposition path, which at this stage is represented only by a zig-zag model (x–y plane), while the right plot illustrates how the spray nozzle moves away from the 3D printer bed.

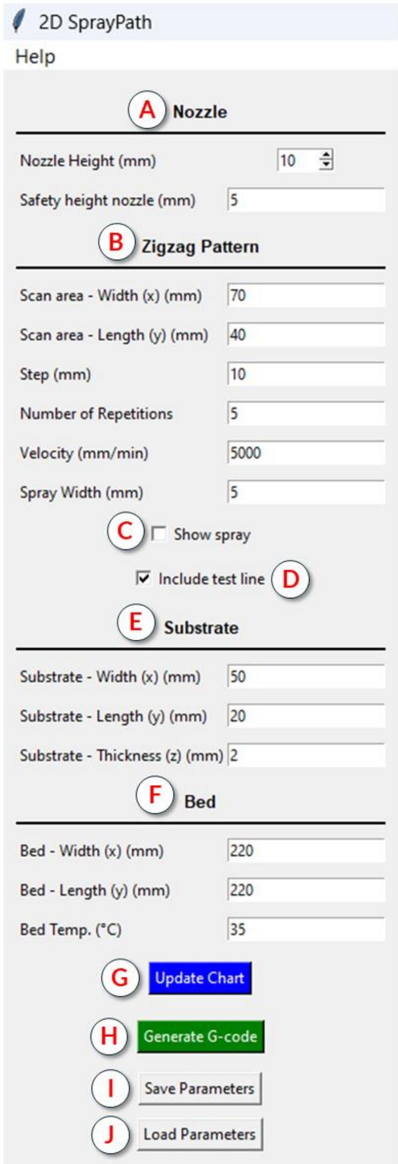
Figure 3: Main window of the 2D SprayPath software.



Source: Authors' construction (2026).

The configuration parameters in the first region of the software interface define the generation of the desired zig-zag patterns. Figure 4 highlights the available configuration options, which, due to the large number of parameters, were organized into groups of related settings: "Nozzle" (Figure 4 (a)), "Zig-zag Pattern" (Figure 4 (b)), "Substrate" (Figure 4 (e)), and "Bed" (Figure 4 (f)).

Figure 4: Left-side tab in which the parameters for generating zig-zag patterns can be defined, along with other functionalities. Each relevant section has been identified by a letter, which will be referenced throughout the text for purposes of description and explanation.



Source: Authors' construction (2026).

In the "Nozzle" group (Figure 4 (a)), it is possible to adjust the nozzle height relative to the "bed", which corresponds to the platform where the substrate is placed, via the "Nozzle Height (mm)" parameter. The "Safety Height Nozzle (mm)" parameter plays a fundamental role in process safety, as in certain equipment the spray nozzle may collide with the bed or the substrate, leading to undesirable incidents. Therefore, the definition of this parameter must consider the characteristics of the system being used, as well as the desired level of safety during the deposition process, serving as a graphical warning element for the user.

In the “Zig-zag Pattern” parameter group (Figure 4 (b)), it is possible to define the parameters related to the path that the nozzle will follow during the deposition process. The “Scan Area – Width (x) (mm)” and “Scan Area – Length (y) (mm)” parameters correspond, respectively, to the width and length of the scanning area over which the zig-zag pattern will be applied.

The “Step” parameter refers to the distance between two consecutive lines of the zig-zag pattern, while the “Number of Repetitions” parameter indicates the number of alternating passes that the pattern will perform over the scanning area. This alternation consists of changing the motion orientation at each pass, with one performed in the horizontal direction and the next in the vertical direction, resulting in the formation of a more homogeneous deposition mesh.

The “Velocity” parameter is associated with the nozzle movement speed and depends directly on the constructive characteristics of the system, in this case the travel speed of the Creality Ender-3 V2 Pro 3D. Thus, it is necessary to know the range of speeds at which the equipment operates most efficiently, avoiding instabilities or process failures. Finally, the “Spray Width (mm)” parameter refers to the effective width of the deposition jet, which should, in principle, be determined experimentally, as it depends on the rheological behavior of the solution used.

In addition, the software provides two checkboxes: “Show Spray” (Figure 4 (c)), intended for visualizing the spray width in the plots, and “Include Test Line” (Figure 4 (d)), which allows the inclusion of a test line positioned outside the substrate area. This test line enables the user to verify whether the spray flow and appearance are as expected, as well as to assist in the stabilization and normalization of the jet when the spraying system is activated.

In the “Substrate” parameter group (Figure 4 (e)), it is possible to define the dimensions of the substrate to be used in the process. The “Substrate – Width (x) (mm)”, “Substrate – Length (y) (mm)”, and “Substrate – Thickness (z) (mm)” parameters correspond, respectively, to the substrate dimensions along the x, y, and z axes. The software was designed to always center the substrate with respect to the size of the “bed”.

In the “Bed” parameter group (label “f” in Figure 4), it is possible to define the dimensions and operating temperature of the bed. The “Bed – Width (x) (mm)” and “Bed – Length (y) (mm)” parameters correspond, respectively, to the bed dimensions along the x and y axes. The “Bed Temp. (°C)” parameter defines the operating temperature of the bed during the deposition process.

Subsequently, the software provides four buttons: “Update Chart” (Figure 4 (g)), “Generate G-Code” (Figure 4 (h)), “Save Parameters” (Figure 4 (i)), and “Load Parameters” (Figure 4 (j)). The “Update Chart” button allows the graphs to be refreshed, including the visualization of the x–y plane of the bed and the corresponding side view in the x–z plane (Figure 5). Whenever any parameter is modified, this button must be pressed to update the plots.

The “Generate G-Code” button is responsible for generating the G-code corresponding to all the input parameters, opening a window for the user to select the directory where the file will be saved/exported. The “Save Parameters” button enables saving the parameters in JSON format, which can later be reloaded/imported into 2D SprayPath via the “Load Parameters” button.

Revista brasileira de iniciação científica
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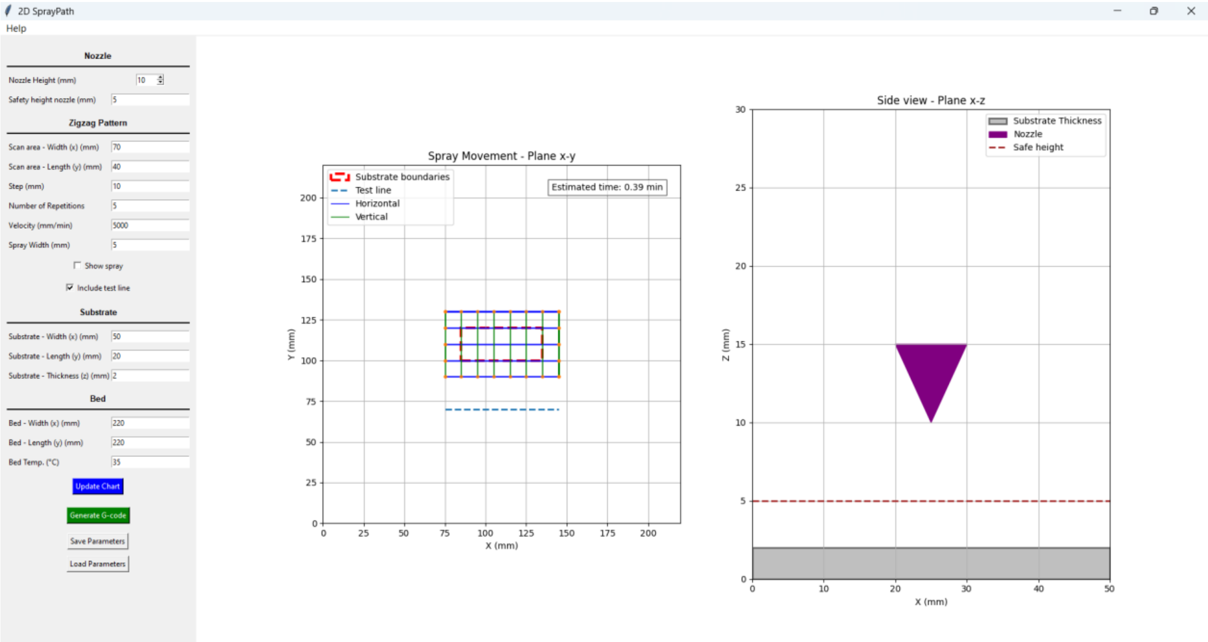
Figure 5: 2D SprayPath window after clicking the "Update Chart" button, which generates the "Spray Movement – x–y Plane" and "Side View – x–z" plots.



Source: Authors' construction (2026).

After defining all the desired parameters and pressing the "Update Chart" button, the following plots are displayed: "Spray Movement – x–y Plane", which corresponds to the top view of the bed (x–y plane), showing the generated zig-zag pattern, the scanning area, and the substrate area (Figure 6); and "Side View – x–z", which represents the lateral view, where parameters related to nozzle height, safety height, and substrate thickness can be visualized (Figure 6).

Revista brasileira de iniciação científica
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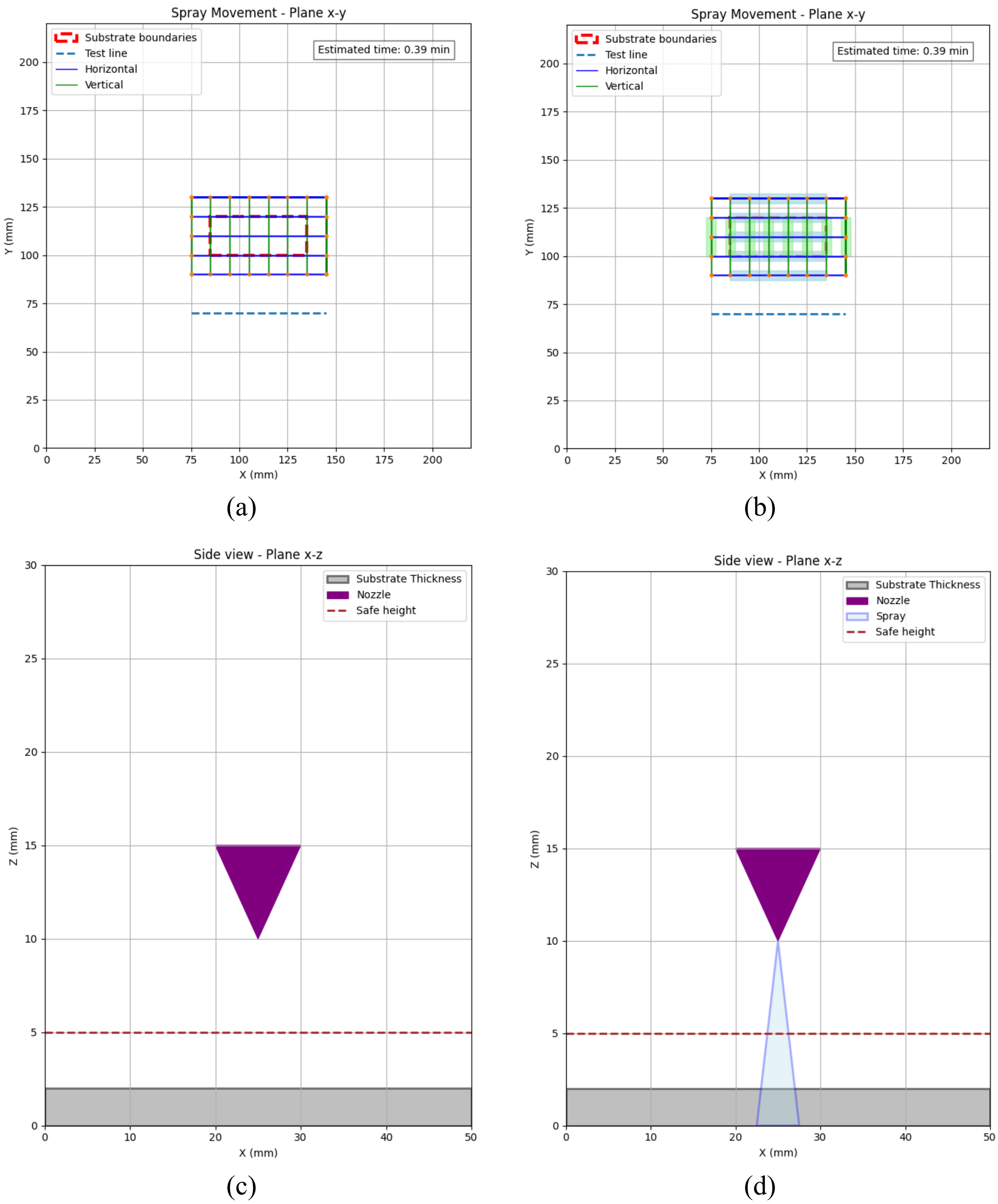
Figure 6: (a) Generated “Spray Movement – x–y Plane” plot. (b) “Spray Movement – x–y Plane” plot with the “Show Spray” checkbox enabled, allowing visualization of the spray width. (c) Generated “Side View – x–z” plot. (d) “Side View – x–z” plot with the “Show Spray” checkbox enabled, in which a visual simulation of the spray can be observed.



Source: Authors’ construction (2026).

The following present two zig-zag deposition patterns using the 2D SprayPath software and the spray coater system developed by the group. Table 1 and Source: Authors' construction (2026).

Table 2 compares the nominal (programmed) and experimentally measured values of the main deposition parameters, providing an assessment of the system's accuracy. Overall, the results show a strong agreement between setpoints and measured values, with very low relative errors across all parameters. The scan area dimensions exhibit deviations below 1%, indicating high precision in the spatial control of the motion system. The step size presents a slightly higher relative error (1.5%), which may be associated with mechanical tolerances and motion resolution limits. The spray width remains effectively unchanged, confirming stability in the deposition process. These results demonstrate the reliability and repeatability of the system in reproducing the intended deposition conditions.

Table 3 present the deposition parameters used to generate the zig-zag patterns in the 2D SprayPath software, corresponding to

Figure *7* and Figure ***9***, respectively, which were used to perform the depositions shown in Figure 8 and Figure ***10***, respectively. Table 2 and Table *4* compare the measured values of the selected main geometric parameters with the corresponding experimental values obtained, as well as the associated error for each deposition, also referring to Figure 8 and Figure ***10***, respectively.

Table 1 – Deposition parameters used to generate the plot in

Figure *7* and to perform the deposition in Figure 8.

NOZZLE	
Nozzle Height (mm)	10
Safety height nozzle (mm)	5
ZIGUE-ZAGUE PATTERN	
Scan Area - Width (x) (mm)	100
Scan Area - Length (x) (mm)	100

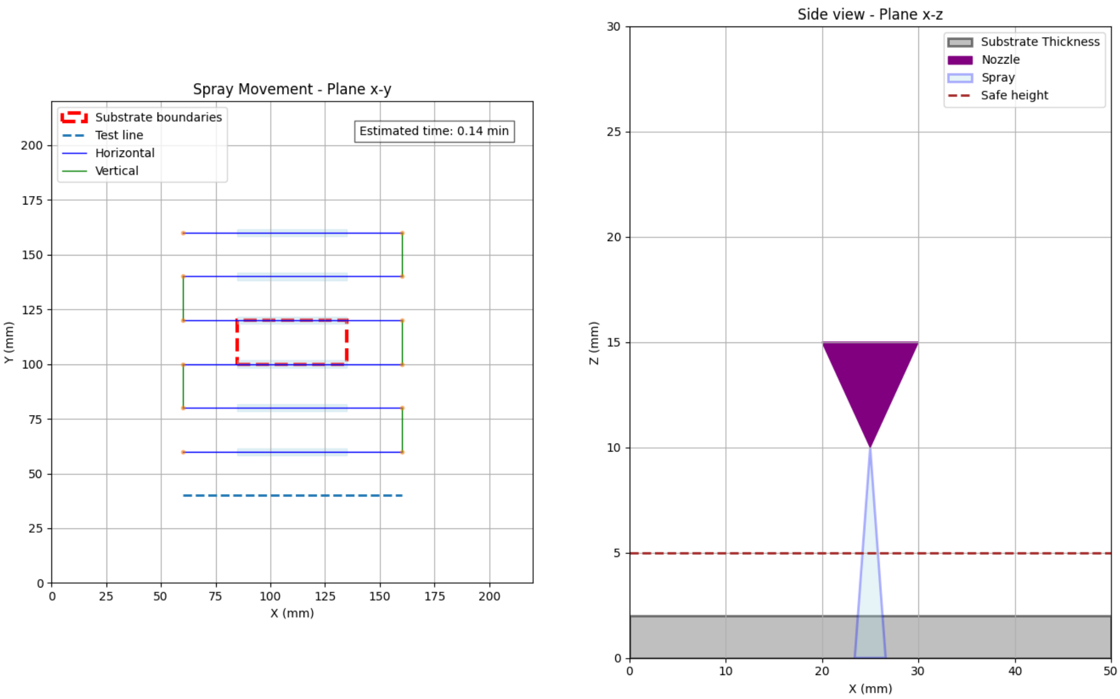
Step (mm)	20
Number of Repetitions	1
Velocity (mm/min)	5000
Spray Width (mm)	3.2
Show spray	True
Include test line	True
SUBSTRATE	
Substrate - Width (x) (mm)	50
Substrate - Length (x) (mm)	20
Substrate - Thickness (x) (mm)	2
BED	
Bed - With (x) (mm)	220
Bed - With (y) (mm)	220
Bed Temp. (°C)	30

Source: Authors' construction (2026).

Table 1 summarizes the deposition parameters employed both for the generation of the simulated nozzle trajectory shown in Figure 7 and for the experimental deposition presented in Figure 8. A zig-zag scanning pattern was defined over a 100 × 100 mm^2 area with a 20 mm step size, resulting in a uniform coverage strategy. The deposition was performed with a nozzle height of 10 mm and a travel speed of 5000 mm min^{-1}, while the spray width was set to 3.2 mm. The substrate dimensions (50 × 20 × 2 mm^3) and the heated bed temperature of 30 °C were selected to reproduce typical laboratory coating conditions. These parameters demonstrate the capability of the proposed software to generate and execute reproducible deposition trajectories under user-defined operating conditions.

Revista brasileira de iniciação científica
ISSN: 2359-232X

Figure 7: Generated deposition pattern (x–y plane) and side view (x–z plane) based on the data in Table 1.



Source: Authors’ construction (2026).

Figure 7 illustrates the deposition pattern generated within the software, showing both the x–y plane trajectory and the corresponding side view in the x–z plane based on the parameters defined in Table 1. The zig-zag scanning strategy is clearly visualized over the defined scan area, allowing verification of path continuity, spacing, and overall coverage before any physical deposition is performed. The side view provides additional insight into the nozzle motion relative to the substrate, including the maintained height and safety clearance. This virtual representation demonstrates the capability of the software to accurately design and preview spray-coating trajectories, supporting parameter validation prior to experimental execution.

Revista brasileira de iniciação científica
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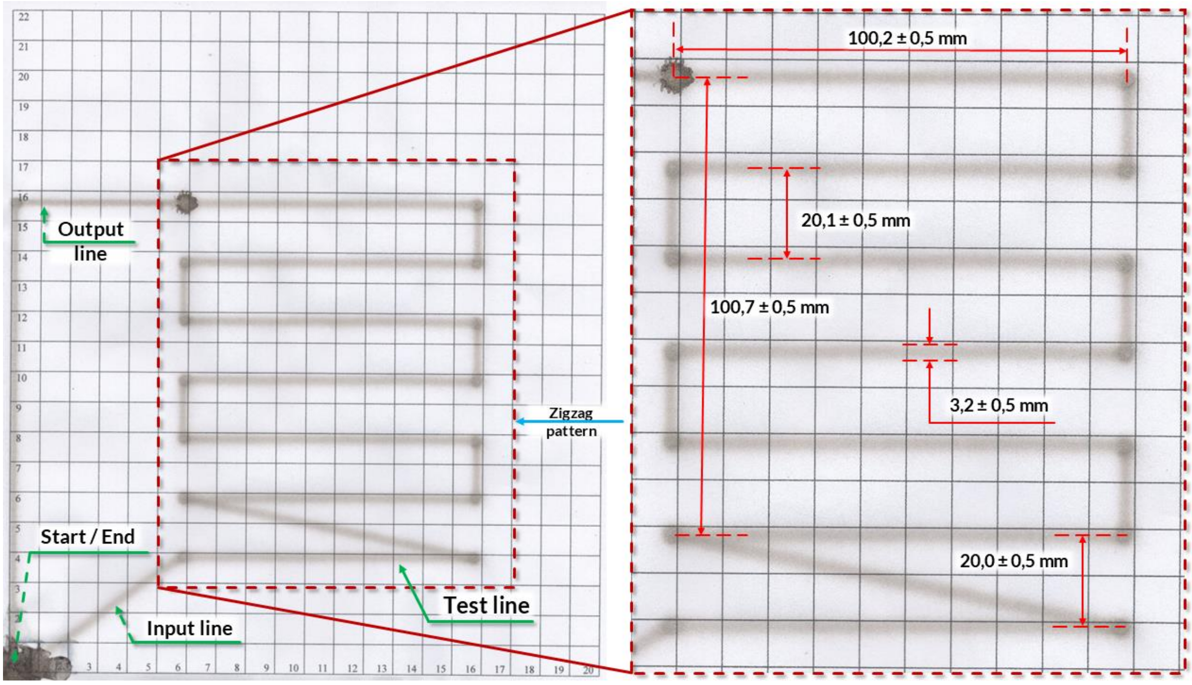
Figure 8: Deposition performed using the spray coater with the data from Table 1.

Figure **7** shows the previously generated deposition.



Source: Authors' construction (2026).

Figure 8 presents the actual deposition performed using the spray coater under the parameters defined in Table 1, corresponding to the trajectory previously generated and visualized in Figure 7. The deposited pattern follows the expected zig-zag scanning strategy, indicating good agreement between the planned path and the experimental result. The uniformity of the coated area suggests stable spray conditions and adequate control of the nozzle movement during the process.

Table 2 – Comparison between the nominal values and the measured values.

PARAMETER	**NOMINAL VALUE (mm)**	**MEASURED VALUE (mm)**	**RELATIVE ERROR**

Revista brasileira de iniciação científica
ISSN: 2359-232X

Scan Area - Width (x) (mm)	100	100.2 ± 0.5	0.2%
Scan Area - Length (x) (mm)	100	100.7 ± 0.5	0.7%
Step (mm)	20	20.1 ± 0.5	1.5%
Spray Width (mm)	3.2	3.2 ± 0.5	0

Source: Authors' construction (2026).

Table 2 compares the nominal (programmed) and experimentally measured values of the main deposition parameters, providing an assessment of the system's accuracy. Overall, the results show a strong agreement between setpoints and measured values, with very low relative errors across all parameters. The scan area dimensions exhibit deviations below 1%, indicating high precision in the spatial control of the motion system. The step size presents a slightly higher relative error (1.5%), which may be associated with mechanical tolerances and motion resolution limits. The spray width remains effectively unchanged, confirming stability in the deposition process. These results demonstrate the reliability and repeatability of the system in reproducing the intended deposition conditions.

Table 3 – Deposition parameters used to generate the plot in Figure 9 and to perform the deposition in Figure 10.

NOZZLE	
Nozzle Height (mm)	10
Safety height nozzle (mm)	5
ZIGUE-ZAGUE PATTERN	
Scan Area - Width (x) (mm)	60
Scan Area - Length (x) (mm)	60
Step (mm)	10
Number of Repetitions	2
Velocity (mm/min)	2500
Spray Width (mm)	3.2
Show spray	True
Include test line	True
SUBSTRATE	
Substrate - Width (x) (mm)	50
Substrate - Length (x) (mm)	20
Substrate - Thickness (x) (mm)	2
BED	
Bed - With (x) (mm)	220

Bed - With (y) (mm)	220
Bed Temp. (°C)	30

Source: Authors' construction (2026).

Table 3 presents the deposition parameters used for both the generation of the trajectory in Figure 9 and the corresponding experimental deposition shown in Figure 10. Compared to the previous configuration, a reduced scan area (60 × 60 mm^2) and step size (10 mm) were employed, together with a lower scanning velocity (2500 mm min^{-1}) and two repetitions, resulting in a denser and more overlapped deposition pattern. The nozzle height and spray width were maintained at 10 mm and 3.2 mm, respectively, ensuring consistency in spray geometry. Additionally, the inclusion of a test line and visualization of the spray region allowed for better monitoring of the process behavior.

Figure 9: Generated deposition pattern (x–y plane) and side view (x–z plane) based on the data in Source: *Authors' construction (2026).*

Table 2 compares the nominal (programmed) and experimentally measured values of the main deposition parameters, providing an assessment of the system's accuracy. Overall, the results show a strong agreement between setpoints and measured values, with very low relative errors across all parameters. The scan area dimensions exhibit deviations below 1%, indicating high precision in the spatial control of the motion system. The step size presents a slightly higher relative error (1.5%), which may be associated with mechanical tolerances and motion resolution limits. The spray width remains effectively unchanged, confirming stability in the deposition process. These results demonstrate the reliability and repeatability of the system in reproducing the intended deposition conditions.

Rev. Bras. de Iniciação Científica (RBIC), IFSP Itapetininga, v.13, e026019, p. 1-28, 2026.

Revista brasileira de iniciação científica
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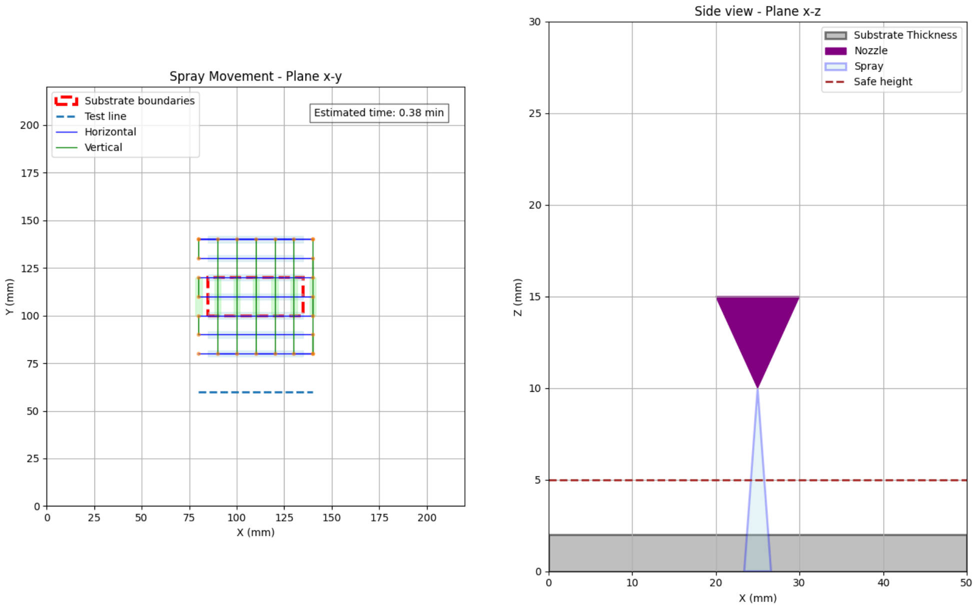
Table 3.



Source: Authors' construction (2026).

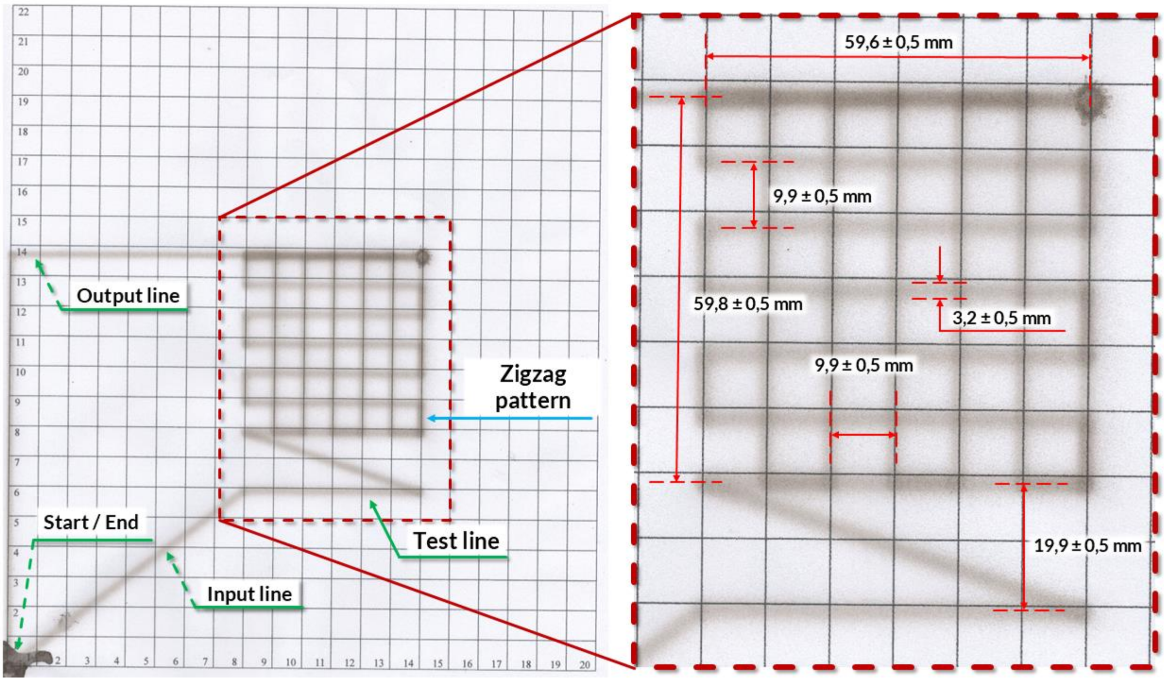
Figure 9 illustrates the deposition pattern generated within the software based on the parameters defined in Table 3, showing both the trajectory in the x–y plane and the corresponding side view in the x–z plane. The reduced scan area and smaller step size result in a denser zig-zag pattern, with increased path overlap compared to previous configurations.

Figure 10: Deposition performed using the spray coater with the data from Source: *Authors' construction (2026)*.

Table 2 compares the nominal (programmed) and experimentally measured values of the main deposition parameters, providing an assessment of the system's accuracy. Overall, the results show a strong agreement between setpoints and measured values, with very low relative errors across all parameters. The scan area dimensions exhibit deviations below 1%, indicating high precision in the spatial control of the motion system. The step size presents a slightly higher relative error (1.5%), which may be associated with mechanical tolerances and motion resolution limits. The spray width remains effectively unchanged, confirming stability in the deposition process. These results demonstrate the reliability and repeatability of the system in reproducing the intended deposition conditions.

Revista brasileira de iniciação científica
ISSN: 2359-232X

Table 3. Figure 9 shows the previously generated deposition.



Source: Authors' construction (2026).

Figure 10 presents the experimental deposition carried out using the spray coater according to the parameters defined in Table 3, corresponding to the trajectory previously generated in Figure 9. The resulting coating follows the expected denser zig-zag pattern, consistent with the reduced scan area and step size implemented in this configuration. A good agreement between the planned trajectory and the deposited pattern can be observed, indicating effective translation of the computational design into the physical system.

Table 4 – Comparison between nominal and measured values.

PARAMETER	NOMINAL VALUE (mm)	MEASURED VALUE (mm)	RELATIVE ERROR
Scan Area - Width (x) (mm)	60	59.6 ± 0,5	0.67%
Scan Area - Length (x) (mm)	60	59.8 ± 0,5	0.33%
Step (mm)	10	9.9 ± 0,5	1.0%

Revista brasileira de iniciação científica
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Spray Width (mm)	3.2	3.2 ± 0,5	0

Source: Authors' construction (2026).

Table 4 compares the nominal and experimentally measured values of the deposition parameters for the second configuration, providing an evaluation of system accuracy under a denser scanning setup. The results show good overall agreement between the programmed and measured values, with relative errors remaining below 1% for most spatial parameters. The scan area dimensions exhibit small deviations, indicating consistent control of the motion system even under reduced workspace conditions. The step size shows a marginal increase in relative error, likely associated with mechanical tolerances and discretization effects of the motion controller. The spray width remains unchanged, confirming the stability of the deposition process. Overall, these results demonstrate that the system maintains reliable dimensional accuracy across different parameter configurations.

It is worth noting that the test line was positioned at 20.0 ± 0.5 mm in the deposition shown in Figure 8 and at 19.9 ± 0.5 mm in the deposition of Figure 10 of the zig-zag pattern, values consistent with the source code, in which 20 mm was defined as the standard distance between the test line and the first zig-zag line.

The patterns generated by the 2D SprayPath software, when compared with the performed depositions and their measurements, show that the programmed instructions are consistent. The comparison between nominal and measured values (Table 2 e Table *4*) indicates that the highest relative error observed was 1.0% for the line spacing, while the remaining parameters, including scan area width and length and spray width, presented relative errors below 1.0%. These results show that the measurements are close to the planned values, reinforcing the software's fidelity in the construction of the patterns.

The small differences observed can be attributed to the mechanical limitations of the equipment (the adapted Ender-3 PRO 3D printer) and to the uncertainties associated with the measurement techniques used in the ImageJ software. In addition, the spray width must be determined experimentally, as it depends on several factors, such as the viscosity and composition of the suspension, fluid density, flow rate, nozzle geometry, and the operational parameters of the equipment.

Taken together, the data and images confirm that the software enables the construction of accurate and reproducible zig-zag patterns, while the small discrepancies reflect inherent characteristics of the equipment operation and the complexity of spray properties, without compromising the validity of the experimental process.

Conclusions

In this work, the 2D SprayPath software was developed and validated as a computational tool for generating parameterized trajectories in the x–y plane, with a focus on automating spray coating deposition processes. The results obtained demonstrate that 2D SprayPath is a robust, functional, and versatile software, capable of reliably generating zig-zag scanning patterns, while also enabling prior visualization of the trajectories and the main geometric and operational parameters involved in the deposition process. The experimental validation carried out using a low-cost spray coater, adapted from a 3D printer, highlighted the practical applicability of the tool and its direct contribution to improving the reproducibility and organization of experimental procedures.

The main objectives of this work were successfully achieved, namely the development of an open-source software for generating planar deposition trajectories and its experimental validation in a real spray coating system. The results confirm that the software is able to produce consistent G-code instructions that are effectively executed by the hardware, ensuring agreement between planned and deposited patterns.

The research question addressed in this study, whether a low-cost, open-source tool can generate reliable and reproducible deposition trajectories for spray coating systems, was positively answered. The comparison between nominal and measured parameters demonstrated low relative errors (below 1% in most cases), confirming the accuracy of the proposed approach.

Despite these positive results, some difficulties were encountered during the development and validation process. These include the mechanical limitations of the adapted 3D printer system, variations inherent to the spray process, and the dependency of spray width on experimental conditions such as fluid properties, nozzle geometry, and flow stability. In addition, measurement uncertainties associated with image processing using ImageJ also contributed to minor deviations in the results.

Finally, although 2D SprayPath was designed with a focus on spray coating techniques, its application is not limited exclusively to this process. Several laboratory activities involving controlled mechanical motion in the x–y plane can benefit from the software, such as thin film deposition processes, systematic substrate scanning, and automated positioning tasks. In this sense, the tool contributes to accessible laboratory automation and improved experimental reproducibility.

In order to contribute in a democratic, accessible, and collaborative way to the scientific community, the source code of 2D SprayPath is made fully open and available through a public GitHub repository (Falsetti, 2026), accessible at https://github.com/paulofalsetti/2D_SprayPath, allowing researchers, students, and developers to use, modify, and adapt the software to a wide range of applications, provided that proper citation of this work is maintained.

In conclusion, the 2D SprayPath software successfully meets its intended objectives, providing a low-cost, flexible, and open-source solution for trajectory generation in experimental systems, while maintaining accuracy and reproducibility under different deposition conditions.

Declaration on the use of artificial intelligence tools

Artificial intelligence tools were used in this work exclusively as auxiliary resources for (i) language revision and improvement of textual clarity, (ii) assistance in the translation from Portuguese into English of parts of the manuscript, (iii) optimization and debugging support in the development of the 2D SprayPath software code, and (iv) assistance in generating and refining suggestions for the naming of the software application. These tools were not used to generate scientific content, experimental results, or conclusions. All scientific decisions, methodological design, data analysis, and interpretation of results were independently performed by the authors, who assume full responsibility for the integrity, originality, and accuracy of the work, in accordance with the CNPq Policy on Integrity in Scientific Activity (Portaria CNPq nº 2.664/2026).

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