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AUTOMATED SYSTEM BASED ON A DELTA ROBOT FOR OPERATIONS IN CONSTRAINED SPACE

Abstract: This article outlines the development of an automated delta robot system to improve manipulative tasks in confined workspaces by optimizing kinematics, control methods, and workspace positioning. The results may support future research and the creation of similar systems for automating production in limited environments.

Keywords: automated system, robot, constrained space, workspace, robotics, robot control, simulation, kinematics, 2D delta robot, Arduino, system, architecture, modeling, automatic control, robotic systems.

Introduction

Modern trends in robotics are aimed not only at large industrial systems but also at small-scale automation, for example in home or laboratory environments. This requires robotic systems capable of operating effectively in limited spaces: on a small footprint, within compact installations, or inside specialized containers or isolated setups. Under such conditions, it is critically important to ensure sufficient functionality of the robot with minimal dimensions, while maintaining accuracy, speed, and reliability.

Special attention in the automation of these processes has been given to parallel robotic systems, in particular delta robots. Leading global robotics companies such as ABB, Codian Robotics, Fanuc, and Omron actively employ delta robots in their automated systems to perform tasks of varying complexity, confirming the relevance and demand for such systems. At the same time, existing technical solutions often do not fully meet the specific requirements of individual production processes, creating a need for the development or modernization of suitable robotic systems. In particular, most industrial delta robots are not adapted for limited-space operations, as they are typically used on large production lines or at industrial facilities. This need underpins the relevance of developing an automated system based on a parallel delta robot, since the unique kinematic design of these systems makes it possible to create reliable, compact, and cost-effective solutions for operation in limited spaces.

Definition of the concept of “constrained space” and overall system requirements

The definition of “constrained space” is rather broad and not strictly defined. For some robotic systems, such as industrial drones a “constrained space” might be considered as an entire hangar or building. In contrast, when we take a look at micro-robots, which dimensions typically do not exceed one centimeter and which are used, for example, in invasive surgery, a “constrained space” may be measured in just a few millimeters.

Within the scope of this project, “confined space” refers to a small working area typical for a home workshop or a compact laboratory conditions. In other words, it is an environment where the robot must operate on a limited surface, such as a desk, a workbench, or any other structure with restricted area and volume. To function effectively under these conditions, the robotic system must meet the following requirements:

1. Compact design and optimal workspace area. The robot must occupy as little space as possible to fit, for example, on a desk or shelf. Its height is also constrained, it must be small enough to be comfortably and conveniently used in a room or workshop.
2. Safety and autonomy. In home or small-scale industrial environments, the robot often works alongside people or other equipment. Therefore, its movements must be precisely controlled, and its design must be safe for its surroundings.
3. Complexity of construction and production. The system should be assemblable in a home environment using only basic tools. To this end, widely available materials and technologies are preferred, specifically, the ability to 3D-print the main structural parts and frame elements.
4. Availability of components. Since the system is intended for home-built applications, using inexpensive, off-the-shelf components (e.g., joints, motors, servos) is an essential part of this project.
5. Positioning accuracy and repeatability. These are the key characteristics of any robot. The system must ensure minimal positional error along all axes to perform operations such as laser engraving or cutting. While industrial robots typically achieve positioning errors no greater than 0.1 mm, for our situation a tolerance of 0.5 mm is considered fully satisfactory.

2D delta robot

One of the best robotic designs for a limited space is the 2D delta robot. This is a simplified version of the traditional delta mechanism, designed to move only in the X and Y coordinates. Structurally, it is realized as a five-bar parallel-link jointed mechanism: two motors mounted on the base drive two active arms, which are connected through the passive arms to the end link called the end-effector (fig. 1). The main feature of this design is that the end effector always remains parallel to the base, regardless of its position within the robot’s workspace. This is ensured by an additional linkage that maintains the effector’s parallelism to the base.

This kinematic structure has two degrees of freedom (X, Y), which is sufficient for the end-effector to reach any point within the workspace. The inability to move along the Z-axis is offset by the simplicity and reliability of the design - fewer moving parts means fewer requirements for control and synchronization algorithms. Another advantage is that all drives are fixed to the robot’s stationary base, so the low moment of inertia of the arms allows for higher movement speed and greater accelerations.

As practical implementations of similar systems in industrial settings demonstrate, even with just two motors it is possible to achieve a highly efficient robotic system. All of these factors make this design the optimal choice for operation in confined spaces. The unique design of the 2D delta robot enables a technique that significantly enhances efficiency in confined spaces. Most robotic systems traditionally operate in a horizontal plane. For a delta robot, this means its moving platform typically travels above a table or conveyor, performing manipulations along the X, Y, and Z axes. However, in very tight spaces, a horizontal workspace is not always optimal: it requires table surface area and clearance height for movement. Shifting the workspace into a vertical orientation — i.e., mounting the delta robot on a wall or vertical frame, can save substantial space. In this configuration, the robot occupies only the vertical footprint, leaving the horizontal surface free for other uses.

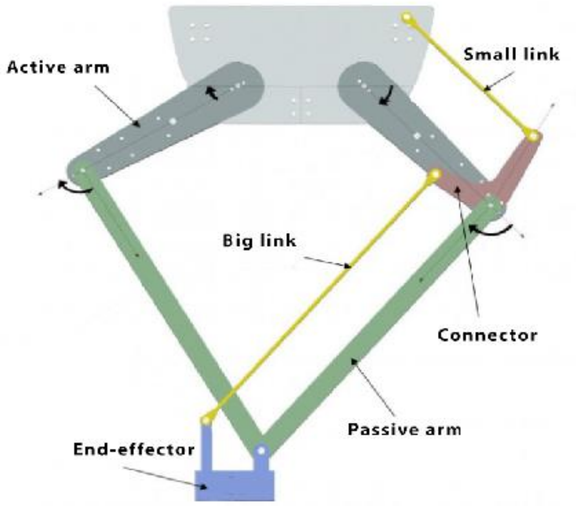

Figure 1. Kinematic schema of the 2D delta robot

To enhance clarity, a small-scale experiment was conducted using two drawing robots: a conventional Cartesian robot and a 2D vertical manipulator. The workspace, identical for both systems, is shown in green. First, we'll determine how many Cartesian robots can fit on a standard workbench measuring 70 cm in width and 110 cm in length (fig. 2).

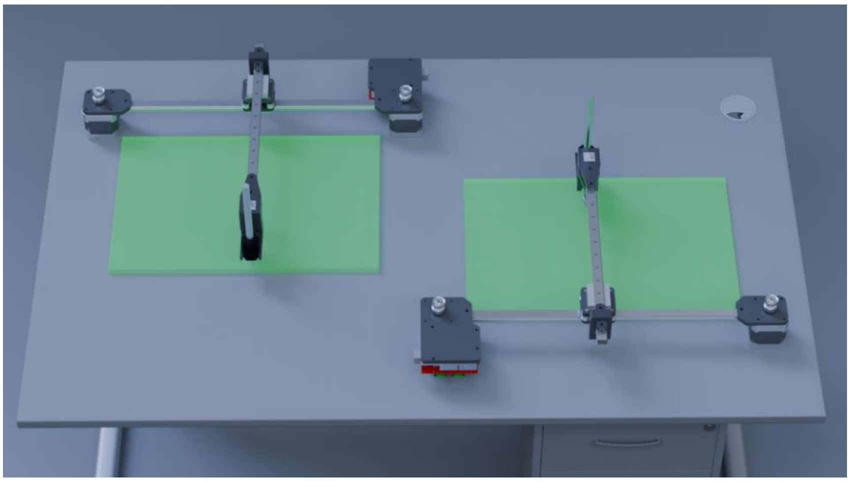

Figure 2. Visualization of two CNC plotters on a workbench

As can be seen on the fig. 2, it is possible to comfortably fit two Cartesian drawing robots on the workbench, which should be more than enough for most household tasks. However, if it is intended to set up a small-scale production, we first need to increase our

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production capacity. In this case, robots' workspace can be transferred into a vertical plane, since for tasks such as drawing or laser engraving it makes no significant difference which plane these operations are performed in (fig. 3)

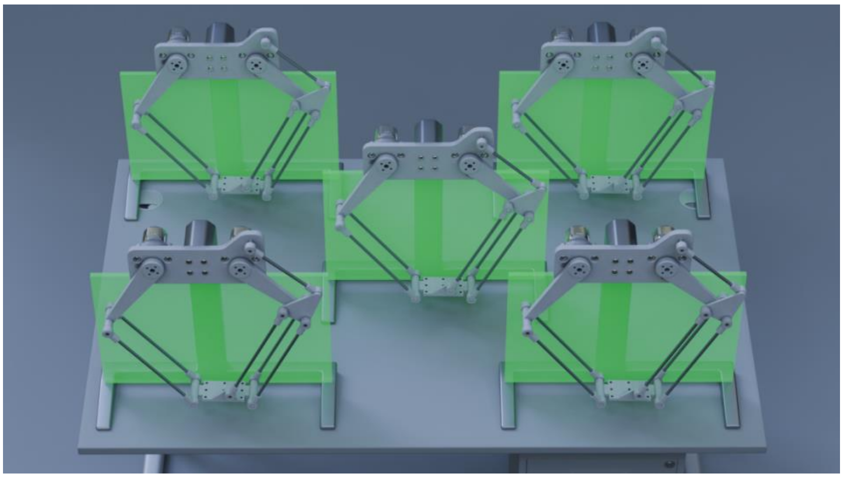

Figure 3. Visualization of five 2D delta robots on the workbench

As shown on fig. 3, five 2D delta robots can be easily placed within the same area as on the previous visualization. It is worth noting that the delta robots have the same workspace as the Cartesian robot (fig. 2), but it is oriented differently in space, which, as a result, significantly boosts production capacity, thanks to a greater number of robots and improved optimization of the available space.

So, based on the experiment's results, vertical workspace proves especially advantageous when horizontal space is limited but height is available. For example, a wall-mounted robot could execute drawing tasks on a vertical canvas or sort lightweight items placed in specialized wall-mounted slots. Another application might be a compact automated warehouse, where storage bins are stacked vertically—here, a parallel robot, fixed to the upper wall, could transfer objects between these bins. In this way, shifting the robot's workspace into the vertical plane enhances utilization of the available volume and can be useful in many practical scenarios.

Block diagram and component wiring schematic

A structural block diagram of the system was created to provide a clearer understanding of its functional components (Fig. 4). At its center there is a controller module, which is the "brain" of the system: it receives target carriage coordinates from the programming unit and feedback from position sensors, then generates the drive control pulses. The programming unit is a personal computer, it's responsible for a trajectory planning: it takes X–Y coordinates of the end effector as an input, computes the required rotation angles for the two drives, and manages the end-effector payload. Data exchange between this unit and the controller occurs via the communication module (typically one of the interfaces supported by the controller), ensuring reliable, deterministic transmission. The power supply unit maintains the stable voltages needed by three subsystems: the controller, the motion-control module (drivers), and the payload attached to the end effector (e.g., a laser engraver, electromagnet, or other tool). The driver module serves as the connection between the controller and the drive units. The drive units move the delta robot's kinematic structure, which consists of active arms joined by hinges to passive arms that then drive the end effector. To monitor each drive's position and prevent collisions, a position-sensor module is added. Sensor data goes back to the controller, where correction algorithms adjust movements for enhanced accuracy. Finally, the payload module performs the application-specific function: gripping, engraving, or another process under commands from the controller.

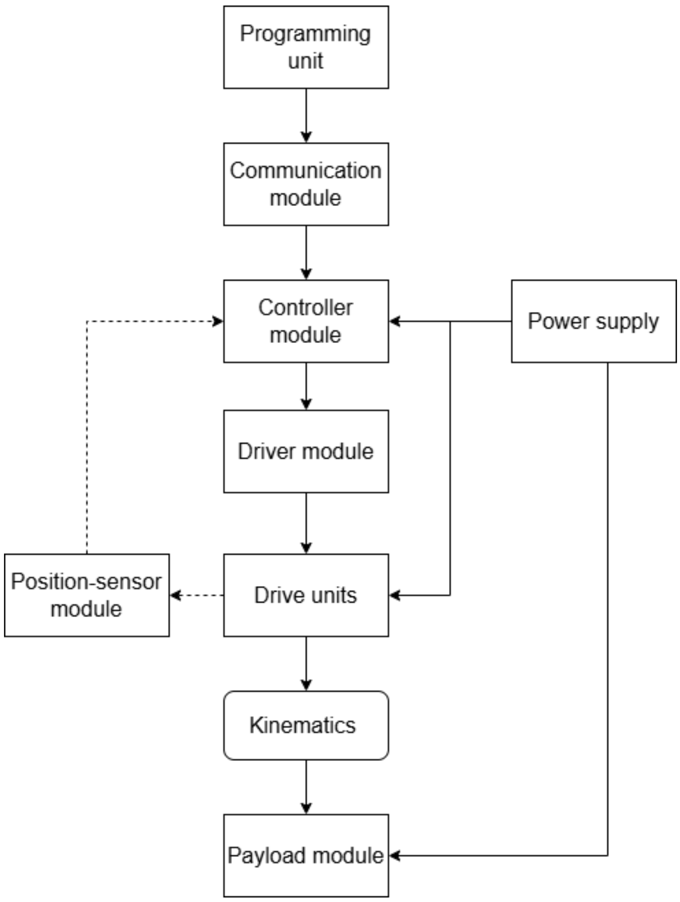

Figure 4. Block diagram of the system

The next required step is to create component wiring schematic. The core element of the system is the Arduino Nano board: it drives the stepper motors, reads sensor data and receives commands from the PC via a dedicated interface. Two ULN2003 driver modules are connected to the Arduino's digital outputs; each motor is controlled by four pins on the board. The Arduino's control lines feed into the corresponding inputs of each driver, and the ULN2003 outputs connect to the stepper motors via 5-wire ribbon cables. This type of connection provides independent control of each motor. Two limit switches are wired to digital pins D11 and D12; they enable the delta robot's homing procedure and protect against exceeding the motors' allowable rotation range. Power is supplied from an external adapter to

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the system's power line. Separate lines distribute power to the ULN2003 drivers. The Arduino Nano is also connected to the same power line, allowing a single power supply to serve the entire system. (fig. 5).

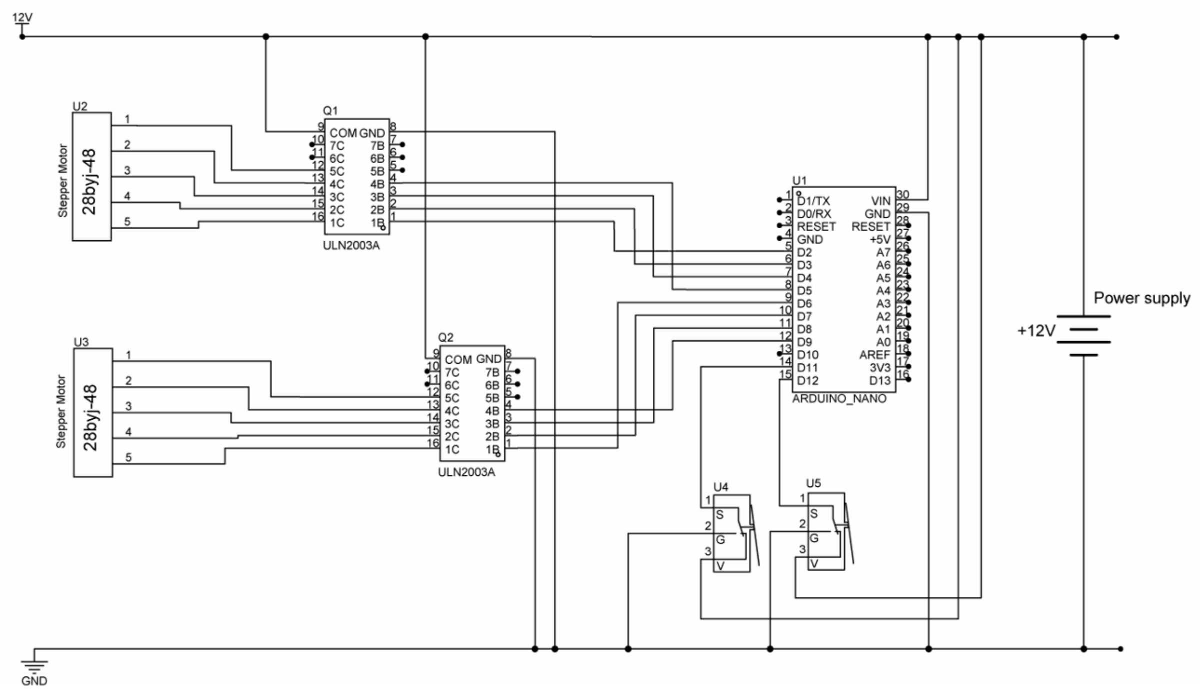

Figure 5. Component wiring schematic

3D Model of the Robot

In order to facilitate subsequent testing and simulation of the system, a 3D model of the delta robot must first be created. Its primary components are: planetary gearboxes, the main platform, active and passive arms, the end effector, connector, hinge assemblies and mounting frame. The 2D delta robot is built on a rigid base platform with mounting holes for the stepper motors. Each motor is coupled with a two-stage planetary gearbox, each one has an overall reduction ratio of 16:1, providing high torque in a compact package. Extending from each gearbox is a 100 mm-long active arm with a stiff cross-section, which connects via a custom connector to two passive arms. The passive arms consist of M4 steel rods, each fitted with an integrated sliding hinge mechanism. Each hinge is a three-element assembly (socket, sliding cylinder, and cap). The end effector is modeled as a robust block with mounting holes for the passive arms and additional fixtures for the parallel auxiliary links. Its geometry is adaptable to accommodate various payloads (e.g., laser head, engraver, gripper) (fig. 6).

To mount the robot, a dedicated support frame has been designed. The frame is constructed from 10 mm-diameter steel tubes, providing the necessary stiffness and strength. Custom 90° corner brackets clamp the tubes securely at each joint. To prevent tipping, two separate stabilizers are attached to the lower section of the frame, ensuring the entire assembly remains rigid and upright.

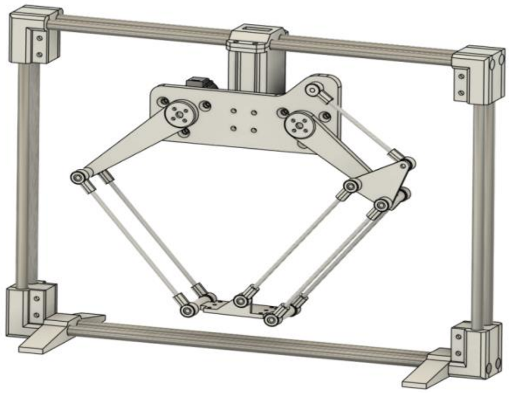

Figure 6. 2D delta robot mounted on the frame

All parts (except metal ones) have been specifically designed for 3D printing, allowing easy assembly of the robot while ensuring sufficient precision and versatility.

Testing and Simulation

To validate the design and control algorithms of the 2D delta robot, a dedicated simulation environment was constructed. The initial simulation confirmed correct joint operation, absence of collisions, stable end-effector orientation parallel to the ground, and error-free movement throughout the 3D workspace (Fig. 7).

As can be seen on the simulation frames, the delta robot executes its basic motions correctly and without errors. Starting from the lower-left corner and proceeding clockwise, the robot traces a square in the vertical plane. At each corner, it returns to the center of the workspace before moving on to the next vertex and then repeats the sequence. Once the square is complete, the robot returns to the center and then begins to follow a spiral path in the opposite direction. From this simulation, we can conclude that the delta robot handles both linear and nonlinear trajectories accurately, allowing us to move on to more complex scenarios.

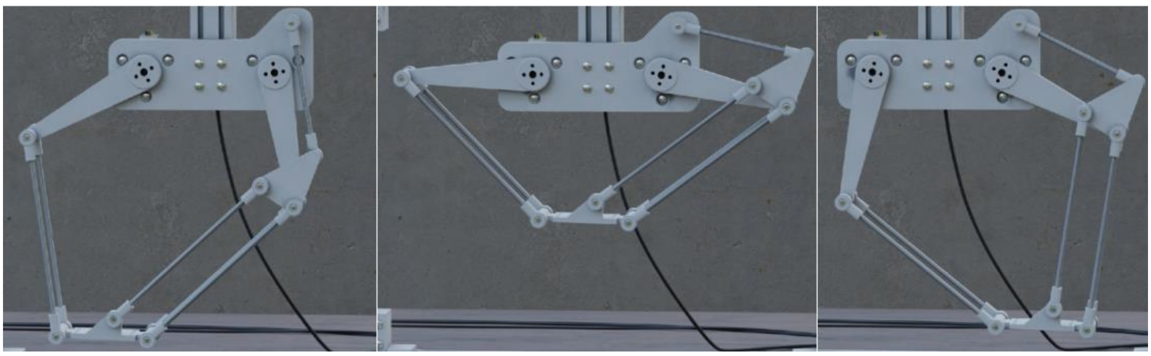

Figure 7. Frames from the robot motion simulation

The second simulation was performed to evaluate the robot's object manipulation capabilities. The primary goal of the "Pick and Place" simulation is to grasp an object and transfer it to another location in space (fig. 8).

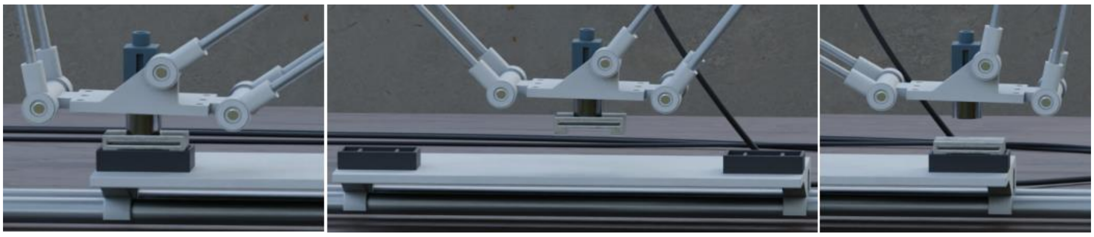

Figure 8. Frames from the Pick and Place” simulation

The simulation frames illustrate the delta robot performing the "pick-move-place" operation cycle. First, the end effector approaches Retract Point A (a predefined position where the robot’s moving platform moves into before performing the grasp). At Point A, the object is picked up using an electromagnetic module and carried to Retract Point B. The robot then descends to Point B, releases the object, and returns to Retract Point B. The sequence then repeats in reverse order as the robot moves the object back to its original position at Point A. Thus, we can conclude that the developed 2D delta robot is capable of precise object manipulation and can be applied in more practical scenarios such as sorting or assembly in production.

The third simulation demonstrated the application of a vertical workspace in a practical context. Moreover, the delta robot followed a predefined trajectory instead of performing point-to-point movements, as seen in earlier simulations (Fig. 9).

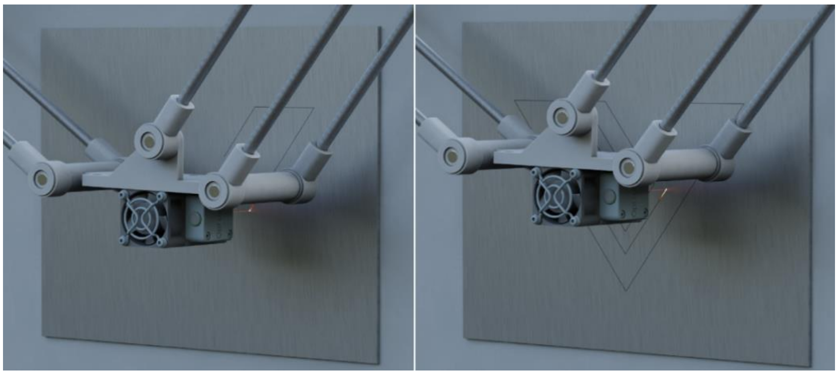

Figure 9. Frames from the laser engraving simulation

The simulation frames depict the 2D delta robot executing the engraving procedure. First, the robot moves to its start position just above the metal plate. Then it travels to the beginning of the engraving path, activates the laser and begins the engraving process. The laser module, mounted on the end effector, follows the predefined trajectory (in this case, the shape of an abstract logo) until the pattern is complete. The laser then switches off, and the end effector returns to its initial position. The result is an engraved pattern on the metal plate (fig. 10).

After analyzing the completed simulation, we can conclude that employing a vertical workspace is a justified solution in confined environments and can be used in practice for tasks such as engraving or drawing. Furthermore, it has been demonstrated that the developed delta robot is capable of high-precision manipulation and is well suited to these kinds of applications.

Figure 10. Result of the engraving simulation

Conclusions

This study provides a detailed account of the development process for an automated delta-robot system designed to operate in limited space. Following design, construction, testing, and simulations, demonstrates that the resulting system meets its requirements and can perform tasks effectively under spatial constraints. This performance is largely attributed to the careful kinematic design and the selection of appropriate technical components. Furthermore, the decision to shift the robot's workspace into the vertical plane is shown to be an efficient solution for applications such as engraving and drawing. The developed automated system is ready for physical prototyping and deployment in real-world scenarios.

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