RESEARCH AND IMPLEMENTATION OF A POLAR COORDINATE LASER ENGRAVING MACHINE

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ABSTRACT

This article presents a breakthrough in the field of laser engraving from the perspective of polar coordinates. Laser engraving has become a crucial tool in many industries, primarily constructed and operated based on Cartesian coordinates, determining the position of a point on a given plane using coordinates (x, y) or (x, y, z), which means the laser head moves on the plane horizontally, vertically, or up and down in a straight line. Therefore, when encountering designs with curved or circular shapes, the machining process faces issues such as rough and non-smooth product results, distinctive step-like patterns when the motor's rotation increases, and larger deviations. The outcome of this project is the result of research and the practical development of a device that operates with the laser head moving according to positions determined by polar coordinates and polar axes. With this device, curved and circular cuts have a smooth and aesthetically pleasing finish, reduced processing time, shortened non-productive running time of the executive mechanism, optimized operations, and increased machine longevity. The system has applied scientific and technical principles to the automation of production, enhancing productivity, and reducing human labor.

NGHIÊN CỨU VÀ THI CÔNG MÁY KHẮC LASER TỌA ĐỘ CỰC

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TỪ KHÓA

Điều khiển bền vững
Thuật toán cắt ngắn cân bằng
Hệ thống bậc cao
Giảm bậc mô hình
Góc tải máy phát đồng bộ

TÓM TẮT

Bài viết này trình bày một sự khám phá trong lĩnh vực khắc laser thông qua góc nhìn của tọa độ cực. Khắc laser đã trở thành một công cụ quan trọng trong nhiều ngành công nghiệp, nhưng chủ yếu được xây dựng và hoạt động dựa tọa độ Descartes, xác định vị trí của một điểm trên một mặt phẳng cho trước bằng một tọa độ (x, y) hoặc (x, y, z), tức là đầu laser di chuyển trên mặt phẳng theo chiều ngang, dọc hoặc lên xuống theo đường thẳng. Vì vậy khi gặp các thiết kế dạng cong, tròn thì quá trình gia công gặp các vấn đề như: kết quả sản phẩm không được trơn, mịn, có dạng bước bậc thang đặc biệt khi bước quay của động cơ tăng thì bề mặt càng thô, sai số lớn. Sản phẩm của đề tài là kết quả của quá trình nghiên cứu, triển khai xây dựng thực tế một thiết bị hoạt động với đầu laser di chuyển theo vị trí được xác định bởi gốc cực và trục cực. Với thiết bị này, các nét cắt dạng cong tròn có độ trơn mịn, thẩm mỹ cao, thời gian gia công nhanh, rút ngắn được quá trình chạy không công của cơ cấu chấp hành, tối ưu hoạt động và tăng tuổi thọ sử dụng máy móc. Hệ thống đã áp dụng khoa học kỹ thuật vào quá trình tự động hóa sản xuất, giúp tăng năng suất, giảm sức lao động của con người.

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1. Introduction

Laser technology, invented by Robert N. Hall in 1962, amplifies light using stimulated emission of radiation and is applied in various fields, including CD/DVD reading, printing, barcode scanning, DNA sequencing, and surgery. Laser engraving machines are versatile tools used for industrial cutting, jewelry design, and electronics fabrication, offering efficiency gains, cost savings, and environmental benefits [1].

The versatility of laser technology has led to its application and study across various fields, as evidenced by numerous scientific investigations. Notably: In a study focused on low-cost laser engraving [1], materials like plastics, acrylic, glass, wood, cardboard, and leather were employed for precision engraving. Laser beam thermal energy facilitated the engraving process, with CREO 2.0 software utilized for 3D modeling and simulation. The assembly of the machine employed Arduino and various controller boards, resulting in a satisfactory, cost-effective outcome. Crystal laser engraving's custom 3D art expression gained attention [2], introducing methods for mesh subdivision and simplification to enhance model density and maintain vertex distance. Filtering algorithms improved point cloud models, demonstrating practicality in practice. A mixed focusing technology was proposed for high-speed, precise laser engraving [3], combining pinhole and interference methods. The design realized focus speeds of 200Hz with 5μm precision and 500Hz with 20μm precision, essential for advancing the laser engraving industry. The transferability of laser-engraving processes was studied across different machines [4], exploring polymer samples like Polypropylene, Polymethyl methacrylate, and ABS-PC for automotive decorative applications. Sensor fusion, specifically camera and ultrasonic sensor fusion, was explored for CNC Engraving Machines [5], yielding a cost-effective 3D presentation method. Femtosecond laser engraving's precision, cleanliness, and versatility were highlighted [6], with parameter optimization studies performed on SiC, PEEK, and sapphire materials. Real-time monitoring and control of ultra-fast laser scribing processes using spectrometers was developed [7], enabling precise adjustments and algorithm-based control for optimal engraving quality. Fiber optic laser engraving's role in high-precision machining was investigated [8], with adjustable parameters leading to controlled roughness and surface structures on metallic and non-metallic materials. These studies collectively underscore the diverse applications and advancements in laser engraving technology, contributing to its growing importance across various industries.

The article discusses the exploration and development of a Polar Coordinate Laser Engraving Apparatus as a response to the limitations posed by Cartesian coordinates in laser technology. Traditional laser systems rely on Cartesian coordinates (x, y) or (x, y, z) to determine the position of a point on a plane, which leads to challenges when dealing with complex curved or circular designs, resulting in uneven surfaces.

The proposed apparatus, developed through research and practical implementation, operates based on polar coordinates and axes. It offers smoother and more aesthetically pleasing results for curved and circular designs, reduces processing times, minimizes unproductive movements, optimizes operations, and increases the machine's longevity. This integration of scientific and technical principles into automated production processes enhances productivity and reduces labor requirements. The main objective of this investigation is to create a specialized device for engraving curved designs using optical engraving techniques, focusing on electronic and laser technologies and coordinate system conversion. The resulting apparatus promises utility, ease of use, reduced labor, streamlined tasks, faster work, higher product quality, cost savings, and energy efficiency. Achieving these objectives involves establishing a mathematical foundation for the polar coordinate system, understanding system principles, selecting appropriate hardware and software, designing the machine's framework, and developing control algorithms.

The research focuses on a rotary optical engraving device with an 15 cm radius circular processing table. It utilizes computer-based software for control, allowing for the execution of cutting and engraving based on predefined templates, adjusted for material properties, laser head specifications, depth, complexity, and various parameters such as dimensions, speed, resolution, and step sizes.

This comprehensive research project covers multiple aspects, including laser technology's relevance in optical engraving, the Polar Coordinate system, programming languages, and the Arduino IDE. It also explores software for managing computer-aided laser engraving devices, examines hardware components like the Arduino Uno R3, A4988 stepper motor driver module, step motor, 0.5W laser head, and laser engraving head driver module. Ultimately, it results in the construction of a laser engraving machine driven by polar coordinates.

2. Materials and Methods

2.1. Software Tools

The Arduino programming language, based on Wiring, is introduced, highlighting the structure of an Arduino program with its setup() and loop() functions. The setup() function initializes variables and sets initial conditions, while the loop() function performs continuous tasks. The Arduino program is divided into structure, variables, constants, functions, and procedures.

The Arduino Integrated Development Environment (IDE) is introduced as a crucial software tool for uploading code to Arduino components. The primary programming steps are outlined, emphasizing file creation, code saving, control programming, error checking, and loading programs into the board. The IDE's essential functions include code verification, upload, file management, and serial data monitoring.

The various software components used for laser engraving, focus on Inkscape, UniversalGcodeSender, Engraver Master, and LaserGRBL. These tools collectively facilitate the creation, control, and execution of laser-engraved designs. The discussion covers their features, interfaces, and configuration settings.

2.2. Components

Arduino Uno R3 is a microcontroller board featuring the ATmega328 microcontroller. It offers 32KB of Flash memory for storing programmed instructions, 2KB of SRAM for storing variable values, and 1KB of EEPROM for non-volatile data storage.

The CNC Shield V3 is an expansion board for the Arduino Uno R3 designed to control mini CNC machines. It can control up to 4 stepper motor axes (X, Y, Z, and an optional fourth axis). It is compatible with GRBL, supports 2 end stops per axis, and includes features for controlling the spindle and coolant.

The A4988 driver is a compact stepper motor driver capable of various operating modes, current adjustment, and thermal shutdown protection. It supports full, 1/2, 1/4, 1/8, and 1/16 step modes, enabling the creation of CNC machines with different degrees of precision.

Stepper motors are electric motors that convert discrete electrical pulses into precise rotational or linear movements. They are widely used in automation applications, robotics, and precise positioning systems. Stepper motors have high positional accuracy due to their step-wise motion and are controlled using step pulses.

The Laser Diode 0.5W is a laser engraving and cutting module emitting light at a wavelength of 445nm. It operates at 12V and can be controlled using PWM/TTL signals. It can engrave various non-metal materials such as wood, plastic, and leather.

The EleksLase Laser Driver Module is used to control mini CNC machines and laser engravers. It supports control of X, Y axes, spindle, sensors, limit switches, and laser diodes. It offers various software compatibility options and interfaces through MircoUSB.

Overall, these components constitute a setup for creating laser engravers, allowing for precise control and manipulation of various materials and applications.

2.3. Technological Requirements

The system is designed with the following functional blocks:

- Pre-processing block (software on a computer): Processes images and generates a Gcode file containing commands for the Control Block.
- Control Block: Receives commands from the pre-processing block to control the Execution Block.
- Motion Block: Operates according to commands from the Control Block.
- Power Block: Supplies energy to the system.

The system will operate when supplied with a 12V power source. Subsequently, images are input into the software on the computer to configure the parameters and send commands to the control unit through a connecting cable. Depending on the design and obtained values, the motor will move to various machining positions within the corresponding range, simultaneously, the laser head will be activated or deactivated with the appropriate intensity.

2.4. Mathematical Foundation

The distinctiveness of polar coordinates permits the incorporation of an integer count of full rotations (360°) to the angle, maintaining the original orientation. Furthermore, a negative radius is interpreted as an equivalent positive distance measured in the reverse direction. As a result, a solitary point could be denoted by an endless array of polar coordinates ($r, \varphi \pm n\times360°$) or ($-r, \varphi \pm (2n + 1)180°$), where 'n' represents any integer. Additionally, the origin can be depicted as (0, φ) with an arbitrary angle φ.

In cases where a unique representation is required for all points, such as in Figure 1, it is necessary to restrict r to non-negative values ($r \geq 0$), and φ to the range $[0, 360°)$ or $(-180°, 180°]$ (in radians, $[0, 2\pi)$ or $(-\pi, \pi]$). A distinct reference angle for the pole must also be chosen, for example, $\varphi = 0$.

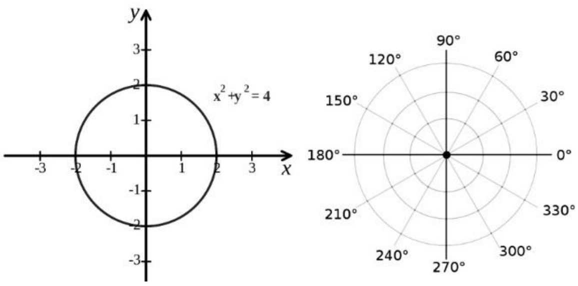

Figure 1. *A polar grid with labeled angles in degrees*

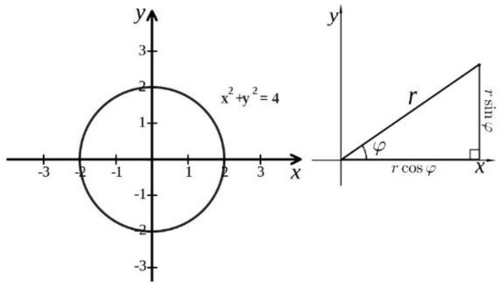

Figure 2. *Conversion between polar and Cartesian coordinate systems*

When using C# programming language on a computer, a software application can be developed to convert the position of a point from Cartesian coordinates *(x, y)* to polar coordinates *(r, φ)* as Figure 2, using the formula:

$$r^2 = x^2 + y^2 \quad (1)$$

$$tan\varphi = y/x \quad (2)$$

$$x = rcos\beta \quad (3)$$

$$y = rsin\varphi \quad (4)$$

The Cartesian coordinates x and y can be converted to polar coordinates r and φ, with $r \geq 0$ and φ within the range $(-\pi, \pi]$, using the common variant of the arctan function defined as:

$$\operatorname{atan2}(y,x)=\begin{cases}\arctan\left(\frac{y}{x}\right) & \text{if } x>0\\ \arctan\left(\frac{y}{x}\right)+\pi & \text{if } x<0 \text{ and } y\geq 0\\ \arctan\left(\frac{y}{x}\right)-\pi & \text{if } x<0 \text{ and } y<0\\ \frac{\pi}{2} & \text{if } x=0 \text{ and } y>0\\ -\frac{\pi}{2} & \text{if } x=0 \text{ and } y<0\\ \text{undefined} & \text{if } x=0 \text{ and } y=0.\end{cases} \quad (5)$$

The value of the angle φ above represents the principal value of the complex argument function arg applied to $x+iy$. An angle in the range $[0,\ 2\pi)$ can be obtained by adding 2π to its value in the case where it is negative.

3. Results and Discussion

3.1. Hardware Design

The basic mechanical framework for the Laser Engraving Machine consists of essential components: T-slot screws (M5), lead screws, GT3 timing belts. The laser head mount, rotating circular table, lead screw mount, machine frame axes, and other machine parts were designed by us, machined by the 3D printer, and CNC-milled from acrylic, as depicted in Figures 3, 4, 5, and 6.

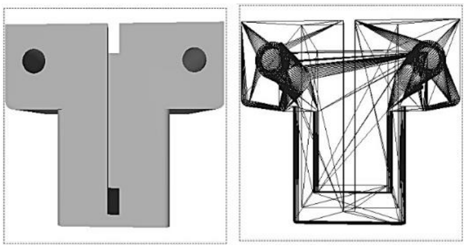

Figure 3. *Laser head mount*

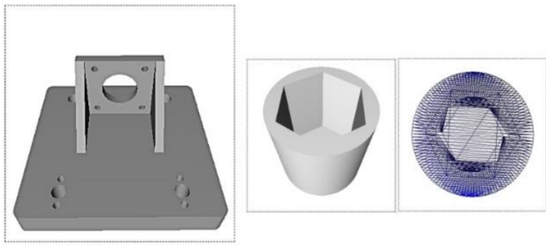

Figure 4. *Lead screw mount*

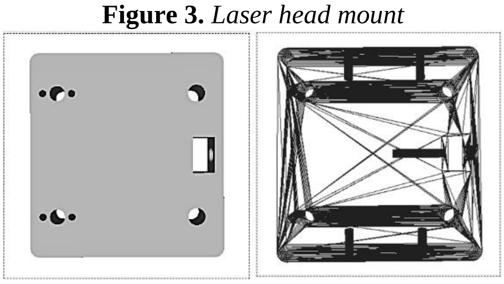

Figure 5. *Machine frame*

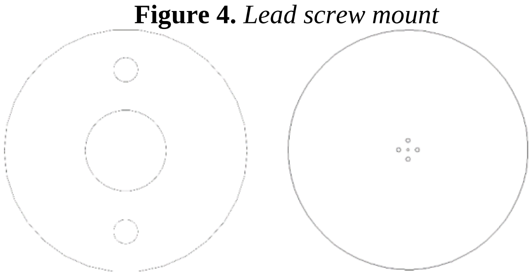

Figure 6. *Rotating table*

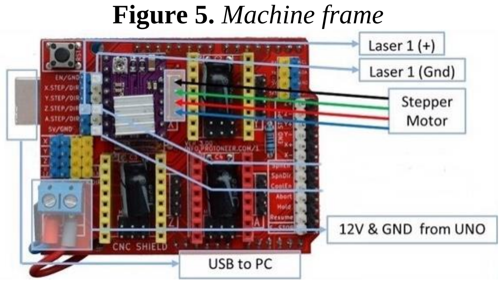

Figure 7. *Connection of Laser Driver to Arduino CNC Shield*

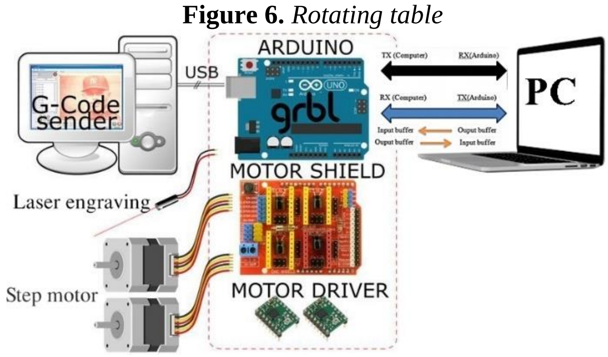

Figure 8. *Connections and communication between hardware devices*

Connect Arduino Uno R3 with CNC Shield V3, A4988 stepper motor driver module. The STEP and DIR pins of stepper X and stepper Y are respectively assigned to digital pins 2, 5, 3, and 6 of Arduino. Connect the laser driver to the Arduino CNC Shield as shown in Figure 7.

In the setup, designated pins are employed to manage different aspects of the machine. For effective stepper motor control, certain pins are responsible for transmitting pulses and indicating rotation direction. One pin facilitates motor activation, while additional pins monitor boundary conditions. Furthermore, a distinct pin is utilized to deliver PWM signals, allowing precise control of laser intensity in a laser engraving machine. In the CNC Shield, certain pins control stepper motors, and a terminal supplies DC power. The ENDSTOP connection manages limit switches, and a specific PWM pin (such as pin 11 with FW 0.9j) controls the SpnEn (formerly the Z-axis limit switch). Arduino's default USB port (Serial0) is utilized for communication, with the port driver assigning a COM port upon connection. This straightforward model parallels Serial communication through the Serial Monitor, where data exchanges between the board and computer via the designated COM port. All the connections are illustrated as shown in Figure 8.

3.2. Software Design

Initially, upon power supply, the values are initialized. After image processing is performed on the computer, the image is simplified and transformed into Gcode. Through software connected to the computer, the laser engraving machine receives signals input into the microcontroller, decodes the Gcode, and processes coordinates as numerical values for controlling the stepper motor and laser head.

Program initiation requires the declaration of libraries, including:

- *serial.h*: Configures UART serial communication between the computer and Arduino.
- *stepper.h*: Controls the stepper motor.
- *gcode.h*: Reads Gcode files to control the stepper motor and laser head.

At each point in time, the coordinate value changes according to the Gcode value. At coordinates where engraving is not required, the laser head will be turned off.

The program dynamically adjusts coordinate values based on Gcode input, activating laser engraving only when necessary. It leverages the GRBL library, an open-source solution known for efficient operation and compatibility with Arduino Classic boards. This library replaces the parallel-port-based communication commonly used in laser engraving machines. Implemented in C, the control library optimizes performance by fully utilizing the AVR chip's capabilities for accurate timing and multitasking operations.

The program structure for converting the position of a point from Cartesian coordinates (x, y) to polar coordinates (r, φ) using the C# programming language, based on the mathematical foundation, is described as follows:

- Namespace and Class Definition: The code begins by defining a namespace called PolarProcessor. Inside this namespace, a class named Polar is declared.

- Class Fields: Three private fields are declared in the Polar class:

+ mAngle: Represents the angle in degrees (polar coordinate).

+ mRadius: Represents the radius (distance from the origin) in polar coordinates.

+ z: A variable which doesn't seem to be used in the code.

- Class Constructor: A constructor is defined for the Polar class. The constructor initializes the mAngle and mRadius fields to 0 when an instance of the Polar class is created.

- Properties: Two properties are defined:

+ angle: Allows getting and setting the mAngle field, representing the angle in degrees.

+ radius: Allows getting the mRadius field, representing the radius (distance from the origin).

- Method setFromCartesian: This method calculates the polar coordinates from Cartesian coordinates. It takes parameters (x, y, z) representing Cartesian coordinates and currentAngle representing the current angle in degrees. The method calculates the next desired angle using the

Math.Atan2(y, x) function to account for the quadrant of the point. It adjusts angles to be in the range [0, 360) degrees using the AbsAngle method. The method handles cases where the move crosses the 0-degree point to ensure the shortest rotation path. It calculates the polar radius using the Pythagorean theorem.

- Method AbsAngle: This method ensures that an angle is within the range [0, 360) degrees. If the angle is greater than 360, it calculates the modulo (%) to bring it within range. If the angle is negative, it also adjusts it to be within the range [0, 360) degrees.

- Method inRange: This method checks whether a given value testVal is within the range specified by low and high. It returns true if the value is within the range and false otherwise.

In summary, the Polar class encapsulates the logic for converting Cartesian coordinates to polar coordinates. It also includes methods to handle angle adjustments and range checks to ensure proper calculations

3.3. Building a polar-coordinate-operated laser engraving machine

The steps for controlling the polar-coordinate laser engraving machine are as follows:

- Connect the cable between Arduino Uno R3 and the computer.
- Design the image to be processed in Inkscape software.
- In Engraver Master software, export Gcode files for Cartesian coordinates x and y from the designed image.
- Convert the position of a point from Cartesian coordinates (x, y) to polar coordinates (r, φ).
- In LaserGRBL software, enter the command S1000 to start the laser machine. (Note that when connecting Arduino to the computer in LaserGRBL software, disconnect Engraver Master to avoid conflicts).

The result is a fully functional polar-coordinate laser engraving machine as shown in Figure 9.

Figure 9. *Polar-coordinate laser engraving machine*

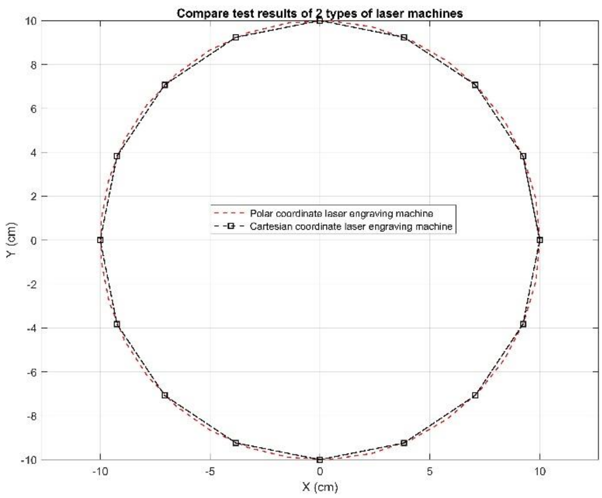

Figure 10. *Compare test results of 2 types of laser machines*

Evaluate and compare results: The installation of both types of laser engraving machines, namely the Cartesian coordinate laser engraving machine and the Polar coordinate laser engraving machine, with identical laser head power, step motors, and the common task of engraving a circular path with a 5 cm radius, was undertaken. To provide a clear visual representation of the process, the research team conducted simulations, calculations, and measurements using MATLAB, resulting in the machining outcomes shown in Figure 10.

- Figure 10 illustrates that the Polar coordinate laser engraving machine produces a smooth circular path, whereas the Cartesian coordinate laser engraving machine yields a polygonal representation (where the circular path is discretized into a series of straight-line segments). The cycle time of the two machines varies depending on the size and curvature of the details to be engraved, with the Cartesian coordinate laser engraving machine consistently requiring more time than the Polar coordinate laser engraving machine. In this scenario, the former is approximately 1.5 times slower. This disparity in results and processing time is due to the operational principles of the two machines.

- The Polar coordinate laser engraving machine operates by rotating the workpiece at various angles using the motor, while keeping the laser head stationary. Conversely, the Cartesian coordinate laser engraving machine maintains a fixed workpiece while moving the laser head incrementally along the X and Y (or Z) axes to approximate the circular path. The discrete movement of the latter machine causes the stepper motor to heat up rapidly, resulting in potential damage to the electromechanical system, reduced equipment lifespan, and lower machining quality. In contrast, the continuous and smooth movement along the motor's axis in the Polar coordinate system creates a smoother circular path, effectively avoiding physical wear and tear on the machinery.

4. Conclusion

In this comprehensive research project, we have introduced and developed a Polar Coordinate Laser Engraving Apparatus as a response to the limitations posed by traditional Cartesian coordinates in laser technology. By focusing on the principles of the polar coordinate system, we have created a specialized device for engraving curved designs using optical engraving techniques, integrating electronic and laser technologies.

The results of our research demonstrate the significant advantages of the Polar Coordinate Laser Engraving Apparatus over traditional Cartesian systems. We have successfully addressed the challenges associated with engraving curved and circular designs, resulting in smoother, more aesthetically pleasing outcomes. This innovation reduces processing times, minimizes unproductive movements, optimizes operations, and increases the machine's longevity. The integration of scientific and technical principles into automated production processes enhances productivity, reduces labor requirements, and results in cost savings and energy efficiency. The comparative results of our machine against traditional Cartesian systems highlight the superiority of the Polar Coordinate Laser Engraving Apparatus. It provides a smooth circular path, reducing machining time and minimizing wear and tear on the equipment. The Polar Coordinate system's continuous and smooth movement results in higher product quality and energy efficiency.

In conclusion, our research and the development of the Polar Coordinate Laser Engraving Apparatus represent a significant leap forward in laser engraving technology. This innovation promises utility, ease of use, reduced labor, streamlined tasks, faster work, higher product quality, cost savings, and energy efficiency. We believe that this technology will have a substantial impact on various industries and open up new possibilities for precision laser engraving applications.

REFERENCES

[1] M. S. Khalid, S. M. Jaleed, A. Zafar, S. A. Khan, H. Z. Ur Rehman, and Z. H. Khan, "Design and Experimental Verification of a Laser Engraving Machine," *2023 International Conference on Emerging Power Technologies (ICEPT)*, Topi, Pakistan, 2023, pp. 1-6.

[2] Z. Ma, Y. Wang, and Y. Li, "Processing of Three-Dimensional Models for the Crystal Laser Engraving," *2016 Nicograph International (NicoInt)*, Hanzhou, China, 2016, pp. 112-115.

[3] W. Zhan, J. Wang, J. Hu, and R. Li, "Research on high-speed precise mixed focusing technology in laser carving," *2017 IEEE 2nd Information Technology, Networking, Electronic and Automation Control Conference (ITNEC)*, Chengdu, China, 2017, pp. 748-751.

[4] A. Bouland, P. Durand, D. Farcage, M. Géléoc, P. Manscour, and J. -P. Renault, "Cleo®/Europe-EQEC 2019: A Study of Laser-Engraving Surfaces Portability on Polymer for the Automotive Industry," *2019 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics*

Conference (CLEO/Europe-EQEC), Munich, Germany, 2019, doi: 10.1109/CLEOE-EQEC.2019.8872685.

[5] M. J. Seikavandi, "Low-cost 3D scanning using ultrasonic and camera data fusion for CNC Engraving Laser-Based Machine," *2020 International Conference on Machine Vision and Image Processing (MVIP)*, Iran, 2020, pp. 1-4.

[6] D. Pallarés-Aldeiturriaga and X. Sedao, "Femtosecond Laser micromachining of Various Materials for Industrial Engraving Applications," *2021 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC)*, Munich, Germany, 2021, doi: 10.1109/CLEO/Europe-EQEC52157.2021.9542109.

[7] M. Ruutiainen, H. Roozbahani, M. Alizadeh, H. Handroos, and A. Salminen, "Real-Time Monitoring and Control of Ultra-Fast Laser Engraving Process Utilizing Spectrometer," *IEEE Access*, vol. 10, pp. 27113-27120, 2022.

[8] F. Corb, I. Stanasel, T. Buidos, R. Veres, and D. Flonta, "Study of Surface Quality Processed by Fiber Optic Laser Engraving of Steel According to Working Parameters," *2023 17th International Conference on Engineering of Modern Electric Systems (EMES)*, Oradea, Romania, 2023, pp. 1-4.