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Development of a Low-Cost, Arduino-Based CNC Laser Cutting and Engraving Device for Laboratory Teaching/Learning and Engineering Purposes

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Abstract: The article presents the design and implementation of a low-cost, easy-to-implement, Arduino-based computer-numerical-controlled (CNC) laser cutting and engraving device. By means of a CNC shield and appropriate drivers, as well as the G-code Reference Block Library firmware, the Arduino-Uno board can control the motion of the motors and the laser head of the CNC device, enabling the laser (which emits at 450 nm, providing an optical output of about 5.5 W) to perform cutting and engraving processes. The device is lightweight and compact in size (thus, portable and easy to place and store) and made up of open-source, easily available (even recycled) equipment at a cost of about 190 €. Despite its simplicity and low cost, the device can adapt to lab and medium-demand engineering environments and can operate on a wide variety of materials. The described device can also serve as a learning and teaching tool through which students have the opportunity to encounter a diverse range of engineering topics and skills and fully exploit the attractiveness and effectiveness of project-based and discovery learning.

Keywords: CNC, laser cutting, laser engraving, Arduino, G-code

1. Introduction

The article presents the design and implementation of a low-cost, easy-to-build, Arduino-based computer-numerical-controlled (CNC) laser cutting and engraving device. The device has an Arduino-Uno board that, by means of a CNC shield and three motor drivers, controls three stepper motors that, in turn, control the motion of a laser head. This head can automatically move across the X–Y plane and manually move along the vertical (Z) direction to perform cutting and engraving processes on the material placed on the X–Y plane.

In general terms, a CNC laser cutting/engraving device operates as follows: First, the computer-aided-design/computer-aided-manufacturing (CAD/CAM) software reads the design and converts it into the so-called G-code command. Then, a specific software—in most cases, the open-source G-code Reference Block Library (GRBL) firmware—converts the G-code commands into motion control instructions for the motors and the laser head, which performs the cutting or engraving process.

The presented work is an extension of the work described by Akritidis et al. [1], and its objectives (as well as its main contribution) were:

1) The implementation of a CNC device that could meet the requirements of a lab as well as a low-scale/medium-performance engineering and/or lab environment. The device should be lightweight and compact in size (thus, portable and easy to place and store) as well as flexible regarding possible improvements and/or extensions.
2) The construction of the device by means of easily available (even recycled) materials and modules at the lowest possible cost, affordable even by a small lab. This was considered particularly important since CNC machines are usually expensive, so despite their didactic value, they are not affordable for training labs.
3) The use of the device as a teaching/learning tool that, through either its operation or its rebuilding and by fully exploiting the attractiveness and effectiveness of project-based and

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discovery learning, would give the involved students the opportunity to encounter a diverse range of engineering topics and, thus, to considerably enhance their knowledge and engineering skills.

The rest of the article is organized as follows: Section 2 presents a literature review mainly regarding low-cost, Arduino-based CNC devices. Section 3 provides a description of the individual modules as well as of the integrated CNC device and its implementation procedure. In Section 4, a discussion is made regarding the proposed device, and finally, Section 5 concludes the article.

2. Literature Review

Since their first use, the CNC laser machines and their industrial applications have been rapidly expanded. Besides this and owing to the high cost of CNC equipment, several attempts have been made (particularly in the last 10–15 years) to build low-cost CNC laser cutting/engraving devices suitable for academic and training labs. For example, in the work of Linggarjati and Hedwig [2], a low-cost, three-axis CNC device with manually interchangeable heads is presented while in the work of Kumar et al. [3], a portable CNC laser cutting and engraving machine is described, controlled by an Arduino-Nano board and including a stepper motor and a laser-diode module. In Koprda et al. [4], the possibility of developing a low-cost Arduino-based CNC laser engraving machine is investigated in detail, and a fabricated prototype is presented that uses, among others, an Arduino-Uno board (together with a GRBL shield), two stepper motors, and a 2 W diode laser that emits at the wavelength of 405 mm (blue). The cost of the proposed device was estimated to be about 236 €. Nasir Khan et al. [5], in turn, propose an Arduino-Uno-based CNC machine employing a diode laser with the aim to show that the fabrication of such a device at a low cost is possible, while Divitarova and Bocevska [6] describe the design and implementation of an Arduino-Uno-based CNC diode laser engraving machine. Ahmed et al. [7] present the design of a CNC machine that uses an Arduino-Nano board and a diode laser for drawing and engraving processes, and Raikar et al. [8] describe a CNC Arduino-Uno-based laser-diode machine that can perform cutting and engraving operations on various materials. Durna et al. [9], on the other hand, describe the adjustment of a 3D printer for laser cutting and engraving processes, while Attar et al. [10] concentrate on the study and analysis of the control system of CNC machines. Yusuf et al. [11] attempt an evaluation of the performance of a CNC machine with the aim to optimize its operation. Finally, Peixoto and Monteiro [12] focus on the pedagogical value of CNC devices, and after noticing that the high cost of CNC equipment hinders its use for the support of teaching/learning activities, it highlights the need for implementing low-cost CNC devices that would be affordable by training Institutions with budget limitations.

An overview of works related to the development of low-cost CNC laser cutting/engraving devices is shown in Table 1.

What becomes evident from the literature review is that the use of Arduino equipment is crucial for enabling easy and low-cost development of CNC laser cutting and engraving devices. There are several reasons for that: Arduino boards are low-cost, open-source, flexible and extendable, easy to program and use, and have very low power consumption. Through proper top-up equipment (the so-called Arduino shields), an Arduino board can interact with a wide range of external devices (such as sensors, motors, and communication modules) and exchange information over the Internet. Built up with an 8-bit or a 32-bit Atmel microcontroller, Arduino can be easily programmed and reprogrammed by using variants of the C or C++ language in the Arduino Integrated Development Environment (IDE) [13]. Nowadays, Arduino boards are at the heart of numerous systems and applications ranging from home automation (e.g., [14]) and weather and environmental monitoring (e.g., [15]) to mining and energy (e.g., [16, 17]). A detailed literature review regarding Arduino boards and fields of applications, as well as a presentation of the steps and the research questions related to prototyping with Arduino, is included in Kondaveeti et al. [18].

Table 1
An overview of works related to the implementation of low-cost CNC laser cutting equipment

Reference	Control module	Laser type (λ, P)	Motor type	Dimensions (cm)	Cost (€)	Material
[2]	PC (with Linux)	CO_2 (n/a, 40 W)	Servo (×1), Stepper (x2)	80 × 70 × 120	n/a	Paper
[3]	Arduino-Nano	Diode (450 nm, 0.5 W)	Stepper (×1)	n/a	n/a	n/a
[4]	Arduino-Uno	Diode (405 nm, 2 W)	Stepper (×2)	21 × 29 × n/a	236	Stainless steel
[5]	Arduino-Uno	Diode (450 nm, 0.5 W)	n/a	n/a	n/a	n/a
[6]	Arduino-Uno	Diode (n/a, 1.5 W)	Stepper (×2)	n/a	n/a	Wood
[7]	Arduino-Nano	Diode (450 nm, 5 W)	Stepper (×1)	n/a	n/a	Wood, linoleum
[8]	Arduino-Uno	Diode (n/a, n/a)	Stepper (×2)	n/a	n/a	Wood, MDF, cardboard, acrylic
[11]	Rasberry PI	n/a	Servo (×2), Stepper (×1)	n/a	n/a	n/a

Note: n/a: not available. λ, P: wavelength, power of emission.

Compared to the abovementioned CNC systems, the main merits and contributions of the presented work are the following:

1) The development of a CNC device that, besides its low cost (about 190 €), owing to the use of easily available (even recycled) materials, is also portable and quite easy to place and store due to its compact size and small weight. The cost of the proposed device is about 20% lower than that of Koprda et al. [4] (considered as a successful attempt to build a low-cost CNC device) though it uses a more powerful laser and three (instead of two) stepper motors to improve effectiveness.
2) The exclusive use of stepper motors to increase the motion's resolution and efficiency (by also employing the micro-stepping capability).
3) The ability (as proved by tests) to work on a variety of materials such as wood (various forms), acrylic, leather, paper, aluminum, and steel. Based on the information provided by the respective references, this may not be the case for most of the devices mentioned in Table 1.
4) The demonstration of the fact that CNC laser cutting/engraving prototypes can be built in modest student training labs even in the framework of few-month student projects.
5) The demonstration of the fact that participation in this kind of projects offers the involved students the opportunity to employ a wide range of topics and skills (regarding electrical, electronic, mechanical, and general engineering) and fully exploit the potential of project-based and discovery learning.

3. Description of the Device

3.1. The modules of the CNC device

The modules included in the described system are listed in Table 2.

3.1.1. The Arduino-Uno module

Of the Arduino variants used, the most popular ones are the Arduino-Uno, Nano, and Mega. Among those, the Arduino-Uno board, based on the ATmega-328 processor, was chosen due to its flexibility and low cost.

The Arduino-Uno (R3) module (Table 3 [18] and Figure 1 [19]) is perhaps the most widely used Arduino board. The module has 14 digital input/output pins (numbered 0,. . . , 13), and six of them can operate as pulse-width-modulation (PWM) ports capable of simulating analog outputs. The board also has six analog input pins (named A0,. . . , A5) as well as additional pins for the power supply. The digital signals (at the digital outputs) have values of 0 or 5 V, while the analog ones (at the analog ports) obtain values between 0 and 5 V.

Table 2
The CNC device's modules

Module	Type/model/version	Quantity
Arduino-Uno	R3	1
CNC shield		1
Stepper-motor drivers	DRV8825	3
Stepper motors	Nema17	3
Laser head	NEJE N30820 diode laser (450 nm, 5.5 W)	1
Power supplies	12V (desktop-PC type)	2
Bakelite bench		1

Table 3
Technical characteristics of the Arduino-Uno module

Parameter	Value
Processor	ATmega-328
Frequency	16 MHz
Analog inputs/outputs	6
Digital inputs/outputs	14
Flash memory size	32 KB
ROM/RAM size	1 KB EEPROM/2 KB RAM
Voltage	5 V
Dimensions	69 × 54 mm

As mentioned above, to activate an Arduino-Uno board, one needs the IDE, available from the Arduino Team [20]. An advantage of an IDE is that it is compatible with all the existing variants of Arduino boards as well as the Windows, Linux, and MacOS operating systems. Programming the module is made possible by means of the Wiring language, which is a variation of C++. In this context, the user downloads the IDE to a PC that is connected to the Arduino board through a USB port. The user writes the program (the so-called "sketch") on the PC by means of the Wiring language and uploads the code to the Arduino microcontroller. Through the avr-g++ or Fritzing compiler, the microcontroller compiles and executes the code and interacts with the inputs and outputs of the Arduino board. The basic steps of Arduino programming are depicted in Figure 2.

In the proposed system, a CNC shield, together with three DRV8825 stepper-motor drivers, is connected on top of the Arduino-Uno board (Figure 3). The CNC shield enables the interaction of the Arduino board with the various modules of the CNC device, while the DRV8825 drivers convert the low-level transistor-transistor-logic (TTL) signals of Arduino into higher-power signals (precise electric pulses) to enable the motors to implement the desired motion.

3.1.2. The stepper motors

Compared to servomotors, stepper motors are best suited for applications that require low speeds (below 2000 rpm—revolutions per minute), low-to-moderate values of acceleration (such as the ones encountered in the described CNC device), as well as position accuracy. For this project, three stepper motors have been used (Figure 4), one for the X-axis and two for the Y-axis, which were selected with the aim to achieve the desired level of precision and control in the CNC device.

The stepper motors used in the project provided 200 revolution steps, which is 3600/200 = 1.80 per step. In the described device, each step was further divided into 256 micro-steps (the maximum possible number) to achieve a resolution of 1.80/256 = 0.0070. The holding torque of the motors was 0.75 nm.

3.1.3. The laser head

The diode laser used (Figure 5) emits at a wavelength of 450 nm (blue), providing an output power of 5.5 W (class 4) with

Figure 1
The Arduino-Uno module (top view)

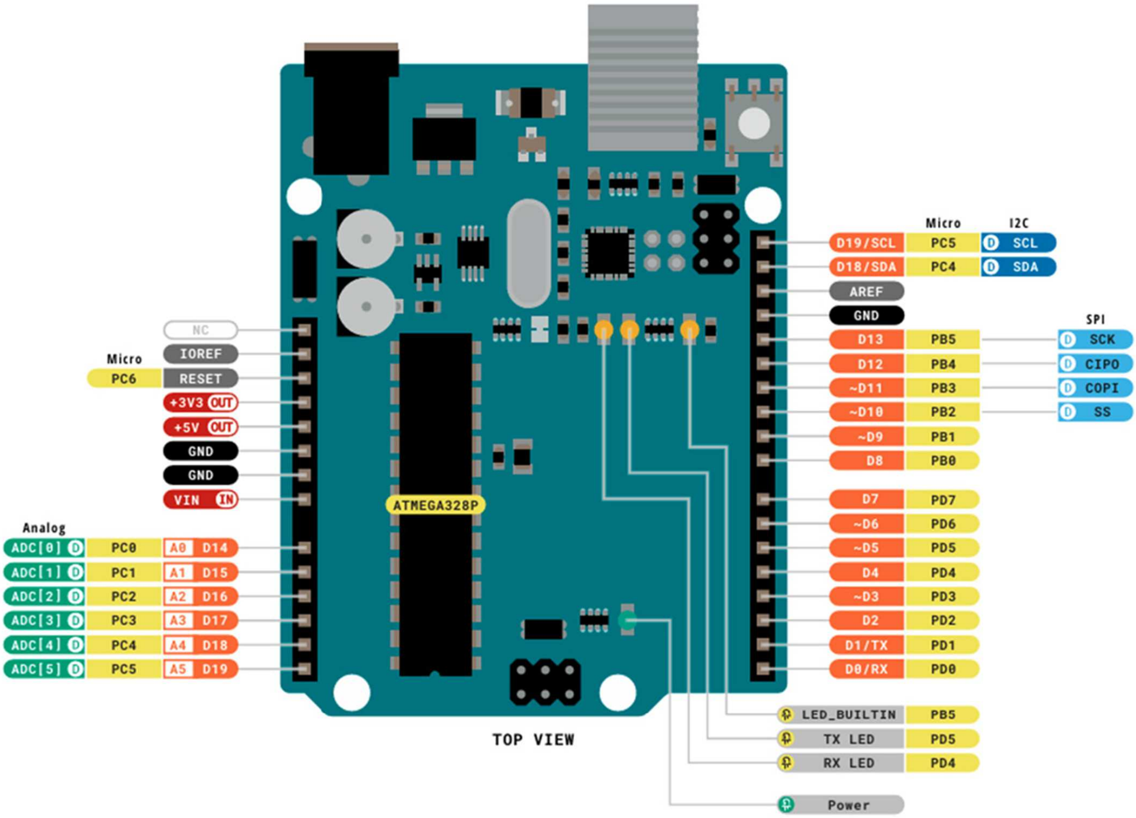


Figure 2
The basic steps of Arduino programming

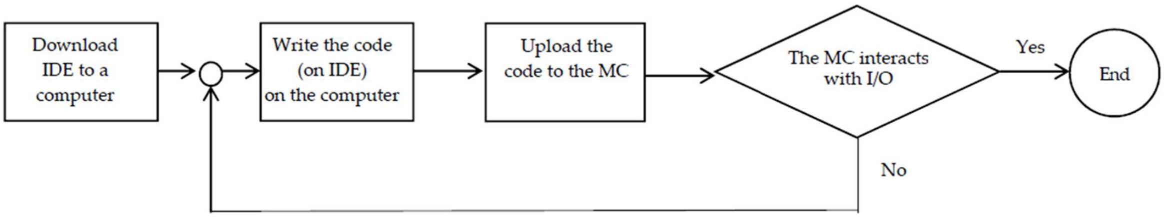


Figure 3
The CNC shield and the three DRV8825 stepper-motor drivers

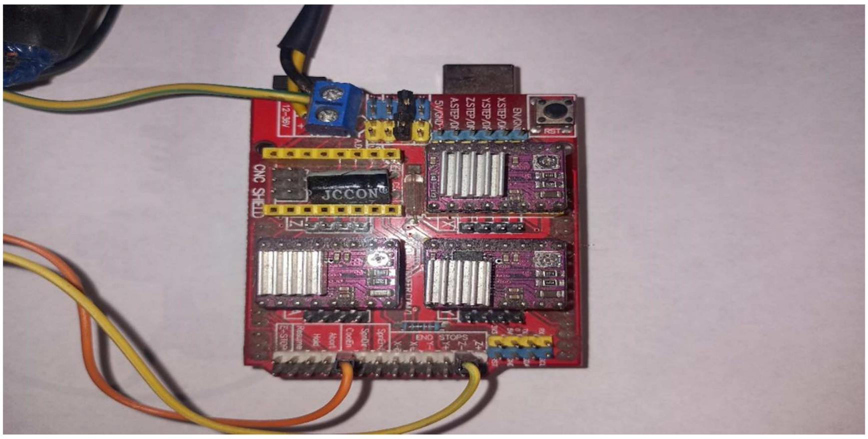
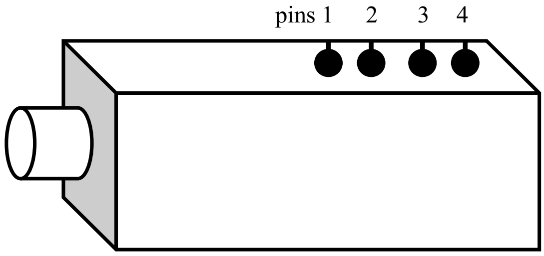


Figure 4
A stepper motor

Figure 5
A schematic of the laser head and its pins (1: oC, 2: PWM, 3: GND, and 4: 12V)



an input power of 20 W. The laser has pins for the temperature (oC), the connection to the CNC shield (PWM), the grounding (GND), and the power supply (12V).

3.1.4. The power supplies

Two power supplies, of 12 V each, have been used: one for the Arduino and one for the laser head. Both power supplies were removed from recycled desktop PCs.

3.1.5. The GRBL firmware

As mentioned above, GRBL [21] is an open-source software that translates the G-code commands into motor movements. GRBL is compatible with a wide range of CNC machines and Arduino boards and can ensure precise and efficient control of a CNC device, which makes it ideal for applications such as laser cutting, engraving, and milling.

Through the IDE, the GRBL firmware (version 1.1) is installed on the Arduino board and enables it to read the G-code commands and, in turn, control the CNC device. The Laser-GRBL software, on the other hand, controls the laser head by translating the image to be cut or engraved into G-code commands.

3.2. The integrated CNC device

A schematic of the integrated CNC laser cutting device is depicted in Figure 6. The user provides the physical design, which, by means of the CAD/CAM software, is converted into G-code commands that are, in turn, translated into the appropriate motions of the motors and the laser heads through the GRBL software. The overall process is controlled by the Arduino-Uno board together with the CNC shield and the stepper-motor drivers that enable the stepper motors to implement the desired motions.

A photo of the CNC device is illustrated in Figure 7. The device has a surface of 40 × 30 cm^2 and a height of 23 cm that, together with the device's small weight, makes it portable and easy to place and store. The CNC device can automatically perform movement of the *X*-axis along the *Y*-axis (while keeping the cutting/engraving surface stationary), whereas the vertical (*Z*-axis) movement of the laser head is manual.

The materials on which the described CNC device can perform cutting and engraving processes are shown in Table 4. Several tests were performed, and some of the results are shown in Figure 8. Given that the laser was a class 4 one, protective glasses were used for the protection of the operator's eyes, and care was also taken for the protection of the operator's skin.

Figure 6
A schematic of the CNC laser cutting/engraving device

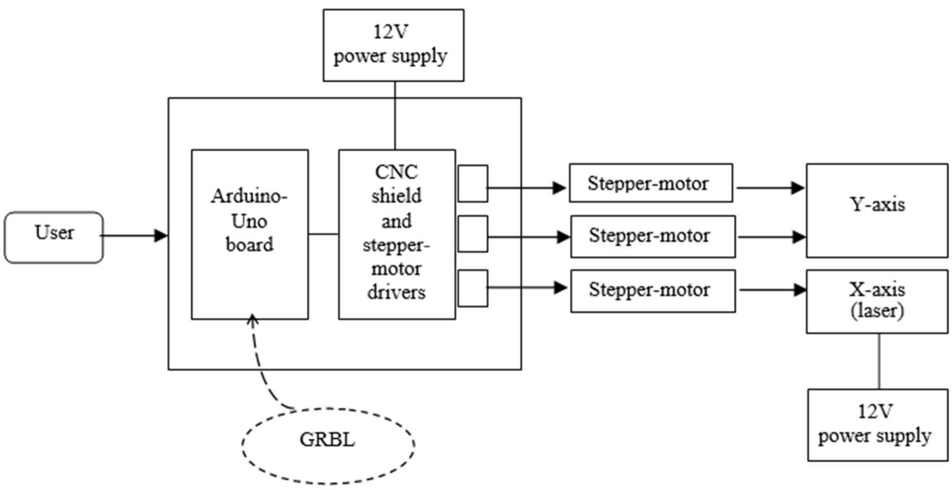


Figure 7
The CNC laser cutting/engraving device (photo)

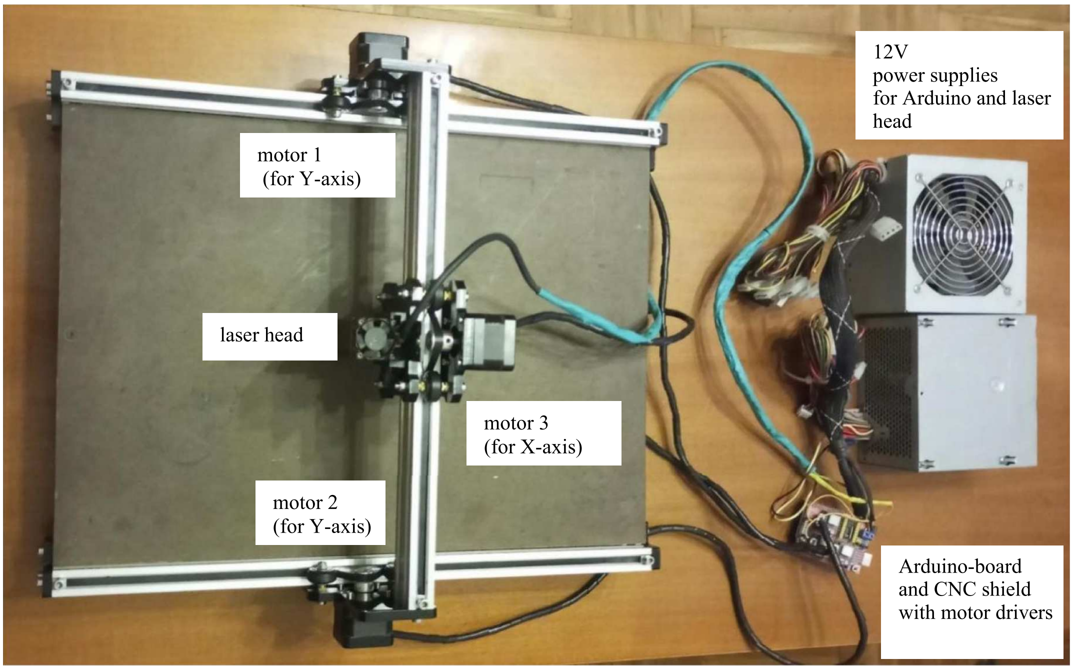


Table 4
Materials to be cut/engraved by the CNC device

Material	Process	Maximum depth	Cutting speed	Comments
Balsa wood	Cutting/engraving	8–12 mm		Rather easy cutting
Plywood	Cutting/engraving	3–8 mm	120 mm/min, 1 pass (depth: 3 mm) 80 mm/min, 1 pass (depth: 4 mm) 120 mm/min, 2 passes (depth: 5–8 mm)	Quality of cutting may vary depending on the plywood's coating
MDF	Cutting/engraving	3–4 mm	120 mm/min, 1 pass (depth: 3 mm)	Good ventilation is necessary
Solid wood	Cutting/engraving	3–6 mm		Outcome depends on wood's density
Acrylic (dark/black)	Cutting/engraving	3–5 mm	120 mm/min, 2 passes (depth: 3 mm) 120 mm/min, 4 passes (depth: 5 mm)	—
Leather	Cutting/engraving	1–2 mm		Care must be taken regarding gas emissions
Fabric or felt	Cutting/engraving	1–3 mm		Sharp cutting
Paper or cardboard	Cutting/engraving	up to 5 mm		Fast cutting
Anodized aluminum	Engraving	n/a		Colored coating is removed
Stainless steel	Engraving	n/a		Special cover or more powerful laser is necessary

Note: n/a: not available. Full (100%) power was used in all tests.

Figure 8
Works by means of the described CNC device: (a) on MDF and (b) on solid wood

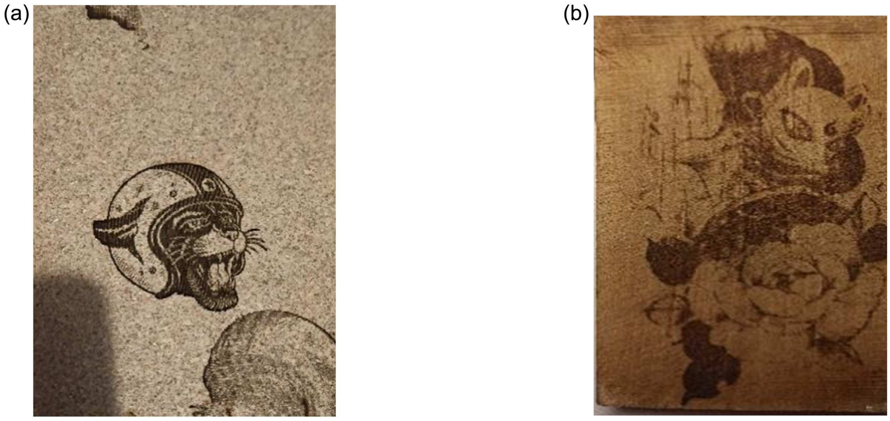


Table 5
The procedure of developing the CNC device

No	Step	Objective	Time needed
1	Conceptualization	To work on the project's main idea	1 week
2	Definition of the components needed	To encounter the procedure of market research and selection of the proper components for the development of the intended device	2 weeks
3	Setting up of the system's modules		
3.1	Setting up of the Arduino board and the CNC shield	To get familiar with the programming of an Arduino-Uno board (by means of the available SW tools) including interconnection with the CNC shield	3 weeks
3.2	Setting up of the stepper motors	To get familiar with the pros and cons of servo and stepper motors and the setting of the latter ones	2 weeks
3.3	Programming of the CNC device	To get familiar with the setting of a laser CNC device through the GRBL tool	3 weeks
4	Integration of the overall device	To encounter the procedure of combining individual modules to build an integrated device	2 weeks
5	Operation and testing	To encounter operation and testing of an integrated device including possible corrective actions	1 week

Electrical protection was provided through the lab's electrical installation.

The procedure for developing the CNC device is described in Table 5 and illustrated in Figure 9. The overall project took about 14 weeks to complete.

4. Discussion

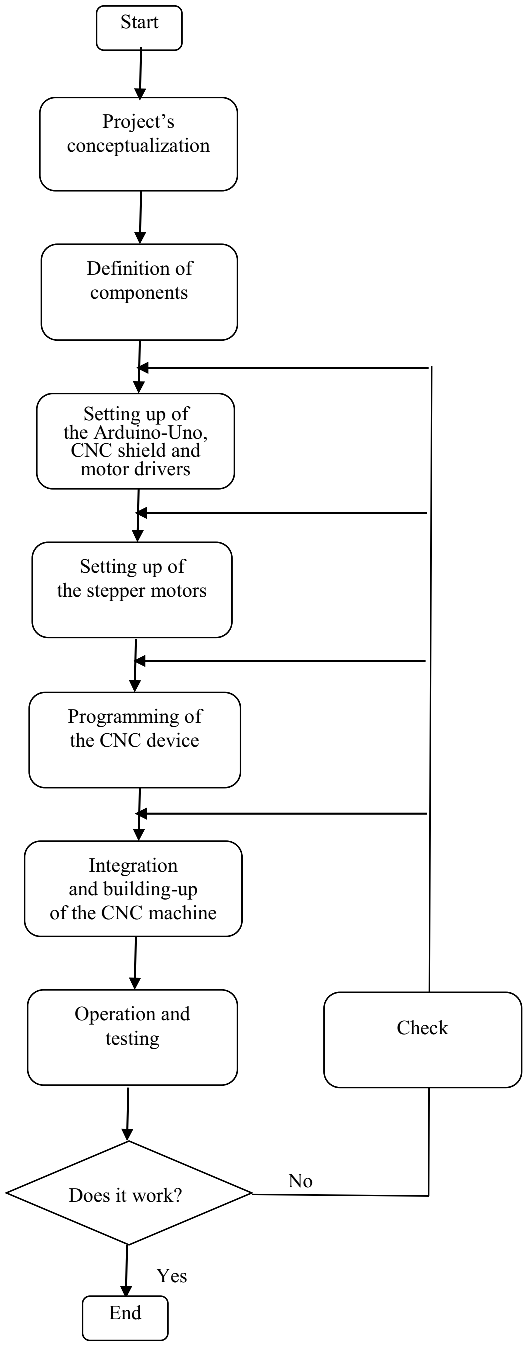
The implementation of the described CNC device took place during the spring semester of the 2022–23 academic year, at the Department of Electrical and Electronic Engineering Educators, School of Pedagogical and Technological Education (ASPETE), Athens, Greece. The graduates of that department have the option to be employed as teachers in technological high schools; hence, getting involved in projects such as the one described above prepares them for the transfer of a similar attitude to their future pupils and the incorporation of the STEM and active/discovery learning principles into their teaching practice.

Through the described work, it was demonstrated that it is indeed feasible to build a portable CNC laser cutting/engraving prototype suitable for a training or a medium-demand engineering lab in just the framework of a three-month final-year project and at an estimated cost of less than 200 € (Table 6), which is considered affordable by most training labs and institutions.

The fabricated CNC device is flexible regarding changes and/or extensions. Possible improvements could be the following:

1) The incorporation of an additional motor in the Z-axis to enable the automatic control of the laser's vertical motion.
2) The incorporation of a stop-switch that could also be used for auto-homing the device.
3) The addition of a second laser head (a router one) to enable cutting and engraving of thicker items.

Figure 9
Flowchart of the development procedure



4) The placement of the device into an enclosure, preferably with a small fan, to protect the user from harmful gas and smoke emissions caused by the cutting/engraving process (in addition to the already compulsory use of protective glasses and skin coverage). Those protective measures, together with proper supervision, are considered necessary for the device to be used for student training purposes.

The development of the CNC device can be considered as a rich learning activity given that the involved students have the opportunity to employ a broad range of engineering knowledge topics and skills that, among others, include:

Table 6
Estimated cost of the CNC device

Module	Approximate cost (€)
Arduino-Uno, CNC shield, stepper-motor drivers	20
Stepper motors	30
Laser head	120
Power supplies	— (*)
Bakelite bench	20
TOTAL	190

Note: (*) Power supplies were removed from recycled desktops (if purchased, the additional cost would be 10 €).

1) Familiarity with laser basics and applications (with emphasis on industrial lasers).
2) Aptitude in microcontrollers and their programming with emphasis on the Arduino-Uno boards.
3) Aptitude in servomotors' and stepper motors' regulation and operation.
4) Familiarity with computer numerical control (CNC) devices.
5) Familiarity with the CAD/CAM software and the use of the G-code and the GRBL tool for the programming of CNC laser cutting/engraving devices.
6) Familiarity with power-supply units.
7) Acquisition of experience regarding the integration of individual modules into an operational device.
8) Familiarity with technical aspects of tests (e.g., general aspects such as repeatability or more specific parameters associated with the particular tests performed).
9) Acquisition of general skills such as time planning, communication, and cost-related considerations.

The fabrication of the CNC device involved all three components of the TPACK framework [22], particularly the Content Knowledge and the Technological Knowledge ones. Regarding Bloom's revised taxonomy [23], the development of the CNC laser cutting/engraving device involved all six layers including the upper "create" one since it regarded the production of a new device right from scratch.

As far as the technological readiness level of the developed device is concerned, it could be considered equal to 4 or 5 (validation in lab or in a relevant environment) [24].

Regarding possible future projects and prior to their assignment, the involved students' behavior may have been monitored through the Reflective Tutorial Dialogue System (ReTuDiS [25]) to infer their initial cognitive profile and possibly decide on a more personalized supervision and support.

5. Conclusion

Through the article, it was demonstrated that it is indeed feasible to build an affordable CNC laser cutting/engraving device that could be used either for medium-demand engineering or teaching/learning purposes. The evaluation of the educational outcomes in combination with the estimation of the required time and effort could help in the planning of similar projects that might be assigned either to individual students or teams of students with the aim to support their education while fully exploiting the potential of project-based and discovery learning.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

The data that support the findings of this study are available within the manuscript.

Author Contribution Statement

Georgios Akritidis: Software, Validation, Investigation, Data curation. **Leonidas Dritsas:** Conceptualization, Methodology, Supervision, Project administration. **Gerasimos Pagiatakis:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. **Andreas Papadakis:** Methodology, Investigation, Resources, Data curation, Writing – review & editing. **Ioannis Katsiris:** Investigation, Resources, Data curation, Writing – review & editing. **Nikolaos Voudoukis:** Investigation, Data curation, Writing – review & editing. **Dimitrios Karaoulanis:** Investigation, Data curation, Writing – review & editing. **Dimitris Uzunidis:** Investigation, Data curation, Writing – review & editing.

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