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DESIGN AND DEVELOPMENT OF NEXT-GENERATION CNC ROBOTIC MACHINE INTEGRATED WITH LASER TECHNOLOGY FOR SMART MANUFACTURING.

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Abstract

The rapid evolution of manufacturing technologies has driven the need for more efficient, precise, and adaptive systems. This paper presents the design and development of a next-generation Computer Numerical Control (CNC) robotic machine integrated with laser technology for smart manufacturing. By combining the advanced capabilities of CNC robotics with the precision of laser systems, this work aims to enhance manufacturing flexibility, accuracy, and automation in a wide range of industries. The proposed system leverages state-of-the-art robotic arms, high-power laser tools, and intelligent control systems to enable multi-material processing, rapid prototyping, and complex part production. This integration fosters improved precision, faster cycle times, and the ability to execute both traditional and laser-specific machining tasks with high efficiency. Furthermore, the system is designed with a focus on energy efficiency, safety, and adaptability, incorporating real-time data analytics and predictive maintenance capabilities aligned with Industry 4.0 standards. Despite challenges in integration complexity and cost, the presented CNC robotic machine integrated with laser technology holds significant promise in transforming manufacturing practices, offering the potential for smarter, more agile production environments. The paper concludes by discussing future trends, including the role of artificial intelligence and machine learning in optimizing CNC-laser systems, positioning this innovation as a key driver of next-generation manufacturing.

INTRODUCTION

In recent years, the manufacturing industry has witnessed a significant transformation driven by advancements in automation, robotics, and digital technologies. As industries increasingly demand higher levels of precision, flexibility, and efficiency, traditional manufacturing systems have struggled to meet these evolving needs. The advent of smart manufacturing, a paradigm characterized by the seamless integration of advanced technologies such as robotics, Artificial Intelligence (AI), the Internet of Things (IoT), and additive manufacturing, has opened new possibilities for optimizing production processes. At the heart of this transformation are Computer Numerical Control (CNC) systems, which have long been a cornerstone of precision manufacturing. A computer numerical control (CNC) machine is an NC machine with the added feature of an onboard computer [1]. The onboard computer is often referred to as the machine control unit or MCU. Control units for NC machines are usually hardwired, which means that all machine functions are controlled by the physical electronic elements that are built into the controller. The onboard computer, on the other hand, is "soft" wired, which means the machine functions are encoded into the computer at the time of manufacture, and they will not be erased when the CNC machine is turned off Computer memory that holds such information is known as ROM or read-only memory. The MCU usually has an alphanumeric keyboard for direct or manual data input (MDI) of part programs. Such programs are stored in RAM or the random-access memory portion of the computer. They can be played back, edited, and processed by the 10 control. All programs residing in RAM, however, are lost when the CNC machine is turned off. These programs can be saved on auxiliary storage devices such as punched tape, magnetic tape, or magnetic disk [2]. Newer MCU units have graphics screens that can display not only the CNC program but the cutter paths generated and any errors in the program. The components found in many CNC systems are shown in Figure 1.

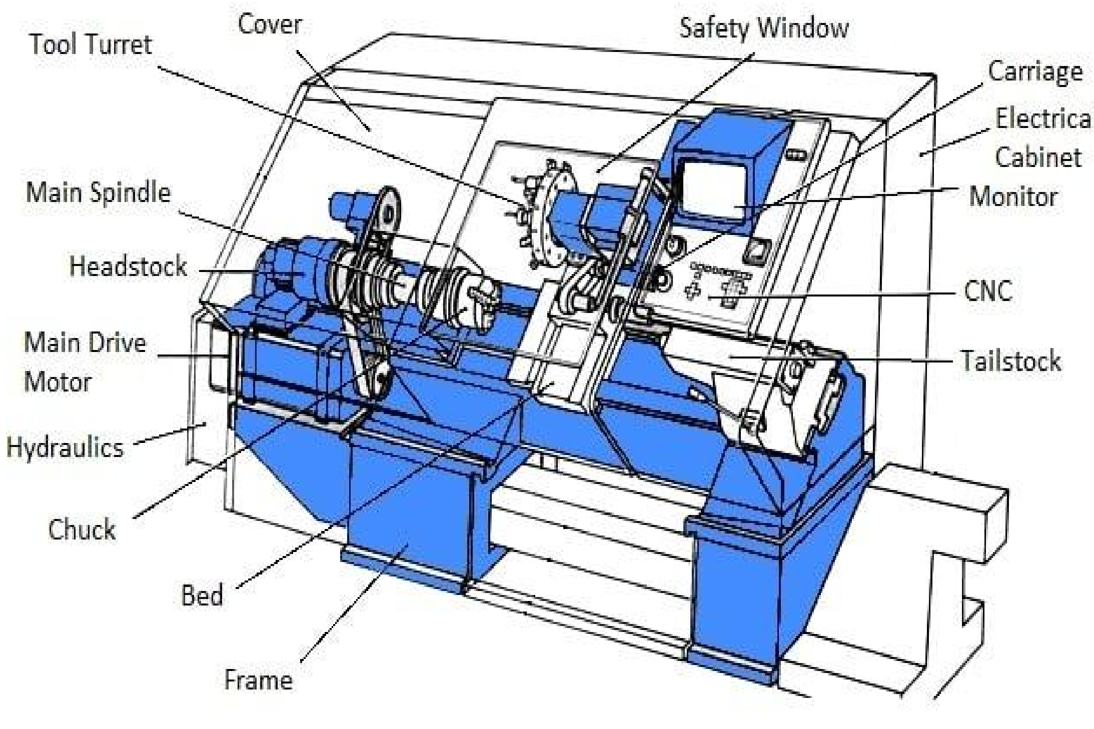

Figure 1: Components of modern CNC systems [3]

A laser cutting device has a cavity designed to provide a controlled environment while the laser beam is used to cut metals to reduce or eliminate heat energy and changes brought about by oxygen is termed as mechanical characteristics of the metal. A separate configuration is set up to provide gas to the controlled environment with the cavity, as well as a means for consuming gas and cutting out debris from the cavity is also described. A moving tool is used to provide the flow of a shielding gas and also provide an alternative means for dispersing laser beam before it produces any damage to the work piece [4]. The improvement gives a laser cutter to cutting sheet material that has been bent into a roll. The cutting means contains a laser, and then again a collimator, mounted in a settled edge for conveying a static laser shaft that is focused onto the sheet material as it disregards a tubular roller. The cutting sample is controlled by an assistant head which mounts reflecting and focusing means and is flexible longitudinally parallel to the material support suggests for moving the inside motivation behind the column longitudinally of the material reinforce infers in synchronism with improvement of the material under the control of bi-directional material nourishment infers. In a favored alteration, an optical sensor is mounted on the helper head for seeing stamps on the sheet material, the yield of the optical sensor being sent to a control PC which has a yield mode and a cut mode [5]. The yield technique for the PC is specialists to prompt the associate head and the bi-directional sustenance infers in synchronism while the laser is murdered, so that the optical sensor inspects the shape or sample on the sheet material. The delayed consequences of the yield are taken care of in the PC to construct, in the PC memory, a fancied cutting route composed to the shape or illustration on the sheet material and the cut system for the PC is specialists to enact the helper head and the bi-directional nourishment suggests in synchronism while the laser is ordered, to cut the looked for instance in the sheet material along the needed cutting way. Laser cutting machine was developed to cut the metal and other material also, the first production laser cutting machine was used to drill holes in diamond dies in 1965 [6].This machine was made by western electric engineering research center. The British pioneered in laser-assisted oxygen jet cutting for metals in 1967. In the early 1970s this technology was put into production to cut titanium for aerospace application at the same time CO2 laser was adapted to cut the non-metals like textiles and lather because at that time CO2 laser was not powerful enough to overcome the thermal conductivity of metals. For cutting the metal work piece the sufficient intensity of laser beam needs to fall on the surface of work piece. For sufficient intensity of beam we use coherent laser source which are free from other source of disturbance. Presently highly developed laser cutting machine are mostly used in industrial area, where they are used for mass production. The laser cutting machine is more accurate and precise rather than mechanical cutting and plasma cutting. Earlier CO2 laser were quite expensive and very few industries could afford them [7].

The integration of CNC technology with robotic systems and laser tools marks a significant evolution in manufacturing capabilities. CNC robotics, which combine automated control with robotic manipulation, allow for greater versatility and automation in handling complex, multi-material tasks. By incorporating laser technology into CNC robotic machines, manufacturers gain the ability to perform highly precise machining operations, such as cutting, engraving, and welding, with superior speed and accuracy [8]. This combination of CNC robotics and lasers offers the promise of a new era in manufacturing—one that is more adaptive, efficient, and capable of producing intricate and customized products. The concept of laser-integrated CNC robotic systems has gained traction in industries where precision and flexibility are paramount, including aerospace, automotive, medical device manufacturing, and electronics. Laser technology, known for its ability to deliver high-power, focused energy, enables the machining of materials with minimal thermal impact, making it suitable for both delicate and robust applications. The integration of these technologies into a single unified system creates an ecosystem that enhances not only production speed but also the complexity of tasks that can be achieved. Furthermore, as the manufacturing world moves towards the principles of Industry 4.0, which emphasizes smart, connected, and automated systems, the need for next-generation solutions like CNC robotic machines integrated with laser technology becomes more pressing [9].

This paper explores the design, development, and implementation of a next-generation CNC robotic machine integrated with laser technology for smart manufacturing. The primary goal of this research is to demonstrate how this innovative system can address the growing demand for high-precision, low-cost, and highly flexible manufacturing solutions. By combining the power of CNC systems, robotics, and lasers, this work aims to create a versatile and adaptive manufacturing environment capable of performing traditional machining tasks as well as advanced laser-based operations. The paper outlines the technological advancements involved, the challenges faced during system integration, and the potential impact on industries looking to embrace the future of smart manufacturing. Through the design of this system, the paper highlights key features such as energy efficiency, safety, and predictive maintenance, all of which are aligned with the evolving standards of Industry 4.0. Ultimately, this research presents the integration of CNC robotics with laser technology not just as a technological innovation, but as a critical step toward the realization of more intelligent, adaptable, and sustainable manufacturing environments. As we continue to explore the potential of artificial intelligence, machine learning, and real-time data analytics in optimizing these systems, it is clear that such developments will play a pivotal role in shaping the future of modern manufacturing.

2- Research Objective:

The primary objective of this research is to design and develop a next-generation CNC robotic machine that integrates laser technology for advanced smart manufacturing applications. This paper aims to achieve the following specific objectives:

1. **Design a CNC Robotic System Integrated with Laser Technology**: Develop a detailed conceptual and mechanical design for a CNC robotic machine that seamlessly incorporates laser-based tools for high-precision machining processes [10]. The design will focus on flexibility, stability, and the capability to perform both traditional CNC tasks and advanced laser operations.

2. **Enhance Precision and Speed in Manufacturing**: Investigate how the integration of laser technology can improve the precision, surface quality, and processing speed of the CNC system, specifically in complex machining operations such as cutting, engraving, and welding.

3. **Develop Intelligent Control Systems**: Design and implement an intelligent control system that integrates both robotic and laser components, enabling adaptive behavior and real-time process optimization. This includes the incorporation of IOT connectivity for smart manufacturing and data-driven decision-making [11].

4. **Optimize for Multi-material Processing**: Explore the potential of the integrated CNC robotic system to handle a diverse range of materials, including metals, plastics, and composites, ensuring high versatility in industrial applications.

5. **Improve Manufacturing Efficiency and Sustainability**: Investigate methods to optimize energy consumption, reduce waste, and improve overall system efficiency through the integration of laser technology, automation, and intelligent control features.

6. **Evaluate the System's Impact on Industry 4.0**: Analyze how the proposed system aligns with the principles of Industry 4.0, particularly in terms of automation, predictive maintenance, and data analytics [12]. This will include exploring the integration of machine learning algorithms for predictive maintenance and real-time process monitoring.

7. **Identify Challenges and Future Directions**: Identify potential challenges related to system integration, cost, and material limitations, while proposing solutions and future research directions for overcoming these barriers and advancing the technology [13].

By addressing these objectives, this research aims to contribute to the development of more efficient, flexible, and precise manufacturing systems that can be adapted to the evolving needs of industries in the age of smart manufacturing and digital transformation.

3- Methodology:

This section outlines the systematic approach taken for the design, development, and integration of a next-generation CNC robotic machine with laser technology aimed at enhancing smart manufacturing capabilities. The methodology consists of multiple stages, including conceptual design, integration of laser technology, development of control systems, and evaluation through experimental testing. The process aims to achieve high precision, efficiency, and adaptability in automated manufacturing environments.

3.1- Conceptual Design and Feasibility Analysis:

The initial stage of the project involved a comprehensive feasibility analysis to determine the potential benefits of integrating laser technology with robotic CNC machines. The following steps were undertaken:

3.1.1- Market Research and Requirement Analysis:

An extensive review of existing CNC systems and laser technologies was conducted to identify gaps and opportunities for innovation [14]. Interviews with industry experts and manufacturers were used to gather insights into the specific needs of the market, particularly for industries requiring high precision and adaptability, such as aerospace, automotive, and electronics.

3.1.2- Design Criteria Definition:

The primary design criteria for the integrated CNC robotic machine were established, focusing on performance parameters such as:

- Precision and repeatability of movements.
- Compatibility of laser technology with various materials.
- Energy efficiency and cost-effectiveness.
- Integration with Industry 4.0 standards (e.g., real-time monitoring, adaptive control systems).

3.1.3- Preliminary Design Proposals:

Various configurations for integrating robotic arms with laser modules and CNC control systems were drafted. These proposals considered different robotic architectures (e.g., articulated arms, SCARA robots) and laser types (e.g., CO_2, fiber lasers). The designs were evaluated for scalability, ease of integration, and potential for future upgrades [15].

3.2- Mechanical Design and Simulation:

Once the conceptual design was established, the mechanical and structural design of the CNC robotic machine was developed:

3.2.1- 3D Modeling and CAD Design:

The system was modeled using Computer-Aided Design (CAD) software to develop detailed 3D models of the robotic arm, CNC machine components, and laser integration. The model included considerations for kinematic constraints, payload capacities, and tool attachment points.

3.2.2- Hardware Components:

This proposal outlines the planned construction of a two-axis Computer Numeric Control (CNC) and laser engraving machine, for the purpose of rendering two dimensional vector graphics by using Ink scape [16]. The CNC machine and control software will take vector image input in the form of Scalable Vector Graphics (SVG) files, and render the image onto a medium. The medium will be a flat surface, such as conventional paper, white board, or light reactive surface Styrofoam. The machine should meet the goals of balancing high precision and speed, use-limited resources and as many recycled parts as possible. Stepper motors or servo motors are used for precise motion. The working requirement of a router is larger which means requirement of longer ball screws. A good alternative can be to use belt for X and Y axes as they are cheap and requires less maintenance [17]. A microcontroller reads the program file, interprets it and later sends it to the machine. Arduino Nano is best suited to be used as a microcontroller since it is open source, cheap and readily available in the market. A Shield is inserted to the Arduino Nano to connect the stepper drivers, limit switches and Emergency stop. Limit switches restrict the machine movement beyond the safe limit and an emergency stop is used to stop the machine in case of emergency [18].

3.2.2.1- Stepper Motor:

A stepper motor is a brushless, synchronous electric motor that converts digital pulses into mechanical shaft rotations. Each rotation of a stepper motor is divided into a set number of steps, sometimes as many as 200 steps [19]. The stepper motor must be sent a separate pulse for each step. The stepper motor can only receive one pulse and take one step at a time and each step must be the same length and shown in figure 2. Since each pulse results in the motor rotating a precise angle, typically 1.8 degrees, you can precisely control the position of the stepper motor without any feedback mechanism.

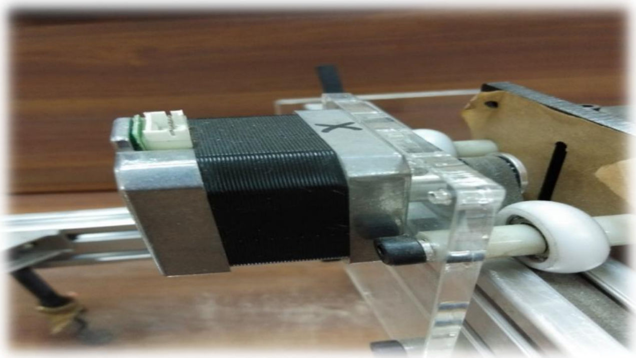

Figure 2: Stepper motor [20]

As the digital pulses from the controller increase in frequency, the stepping movement converts into a continuous rotation with the velocity of the rotation directly proportional to the frequency of the control pulses. Stepper motors are widely used because of their low cost, high reliability, and high torque at low speeds. Their rugged construction enables you to use stepper motors in a wide environmental range. The coils of stepper motor are shown in figure 3.

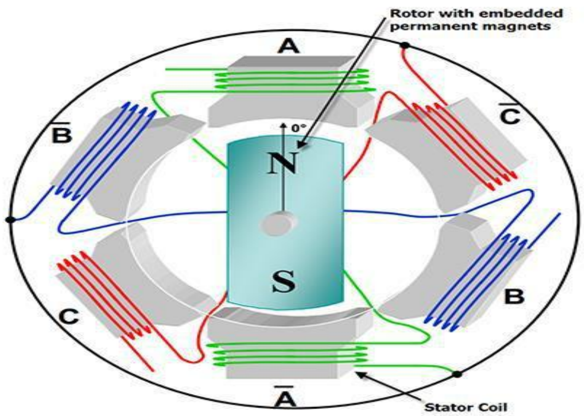

Figure 3: Coils of a stepper motor [21].

There are three kinds of step motors: permanent magnet, hybrid, and variable reluctance. Hybrid step motors offer the most versatility and combine the best characteristics of variable reluctance and permanent magnet stepper motors. Hybrid stepper motors are constructed with multi-toothed stator poles and a permanent magnet rotor [22]. A standard hybrid stepper motor has 200 rotor teeth and rotates 1.8 degrees per step. Hybrid stepper motors provide high static and dynamic torque and they run at very high step rates. Applications for hybrid stepper motors include computer disk drives and cd players. Hybrid stepper motors are also widely used in industrial and scientific applications [23]. Hybrid step motors are used in robotics, motion control, automated wire cutting, and even in high-speed fluid dispensers.

3.2.2.2: Laser Diode:

A Laser Diode is a semiconductor device similar to a light-emitting diode (LED). It uses p-n junction to emit coherent light in which all the waves are at the same frequency and phase. This coherent light is produced by the laser diode using a process termed as “Light Amplification by Stimulated Emission of Radiation”, which is abbreviated as LASER [24]. And since a p-n junction is used to produce laser light, this device is named as a laser diode. Figure 4 shows the laser diode driver circuit. Laser diodes require complex drive circuitries that involve feedback loops by measuring output optical power, temperature, voltage and input current. But for controlling a laser diode used in applications where high accuracy is not required a simple laser diode driver circuit can be constructed using LM317 voltage regulator IC [25].

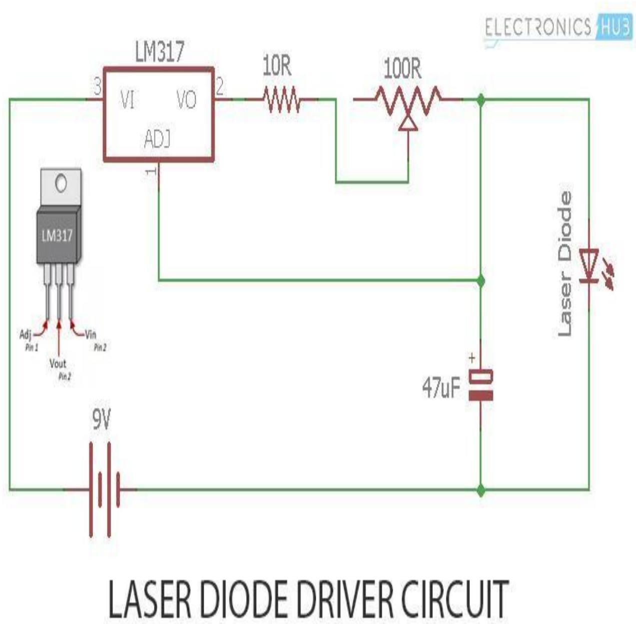

Figure 4: Laser driver circuit [26]

3.2.2.3- Sensors:

To ensure precise operation, **sensors** and a **vision system** are integrated into the system. **Machine vision cameras** are used for locating features on the workpiece, ensuring that the laser is aligned with the intended cutting path. These cameras provide real-time feedback to the control system, enabling automatic adjustments during the machining process. **Proximity and pressure sensors** are used to detect the position of the robotic arm, workpieces, and tools, ensuring the laser is properly aligned with the target material [27]. **Temperature sensors** are also incorporated to monitor the laser and workpiece temperatures, preventing overheating and ensuring consistent performance.

3.2.2.4- Power Supply:

The system's power supply and distribution are managed through a Power Distribution Unit (PDU), ensuring stable power to the robotic arm, laser system, and control components. A Uninterruptible Power Supply (UPS) is included to provide backup power in case of interruptions or power failures, ensuring continuous operation. Industrial Ethernet enables high-speed communication between the CNC controller, robotic arm, laser system, and sensors [28]. This ensures real-time data transfer for synchronization of all components. Furthermore, IoT integration allows the system to connect to cloud platforms for real-time monitoring, predictive maintenance, and data analytics, which are key features of smart manufacturing.

Safety is a critical concern, especially when integrating lasers and robotic systems. Laser safety curtains and barriers are installed around the operational area to prevent accidental exposure to the laser beam. The system also includes emergency stop buttons that can immediately shut down the machine in case of an emergency. Additionally, safety sensors are incorporated to detect human presence in the work area, automatically stopping the robot and laser to prevent injury. These components work together to create a highly efficient and precise CNC robotic machine with integrated laser technology, capable of performing complex manufacturing tasks in smart, automated environments [29]. The combination of robotics, lasers, sensors, and advanced control systems makes this project a significant step forward in the evolution of smart manufacturing.

3.3- Laser Technology Integration

The integration of laser technology into the CNC robotic system was a critical aspect of the design process. The methodology for laser integration included the following:

- **Laser Selection**: Based on the material types commonly used in the target industries (e.g., metals, plastics, composites), a suitable laser source was selected. Fiber lasers were chosen for their high efficiency, precision, and ability to cut through a wide range of materials with minimal heat-affected zones.

- **Laser Control Integration**: The laser control system was integrated with the CNC machine's control architecture. This involved developing a synchronized control mechanism that coordinates the motion of the robotic arm with laser activation. The laser power, focal length, and beam positioning were adjusted in real-time based on feedback from the machine's sensors and the CNC system [30].

- **Safety and Calibration**: Safety protocols were established, including the installation of laser safety barriers and sensors to monitor the system's operational conditions. The laser module was calibrated to ensure consistent beam alignment and power output, minimizing the risk of errors during machining operations.

3.4- Control System Development

A robust control system is essential for ensuring the synchronized operation of the CNC robotic machine and laser technology. The control system development process involved the following steps:

- **PLC and Motion Control**: A Programmable Logic Controller (PLC) was selected for managing the robot's motion, while a specialized motion control system was used to synchronize the robotic arm's movements with the laser operations. This was achieved through the use of a real-time communication bus, allowing for precise coordination between the laser system and the robotic arm.

- **Software Development**: Custom software was developed to interface with the CNC control system, allowing for the programming of laser operations alongside traditional machining tasks [31]. The software allows operators to input design files and modify machining parameters, such as laser intensity, cutting speed, and tool path generation, via a user-friendly interface.

- **Sensor Feedback and Adaptivity**: To further enhance the adaptability of the system, advanced sensors (e.g., vision systems, laser scanners) were integrated into the system. These sensors provide real-time feedback to adjust parameters dynamically during the manufacturing process, ensuring optimal results in terms of accuracy and surface quality. The flow diagram of this project are shown in figure 5.

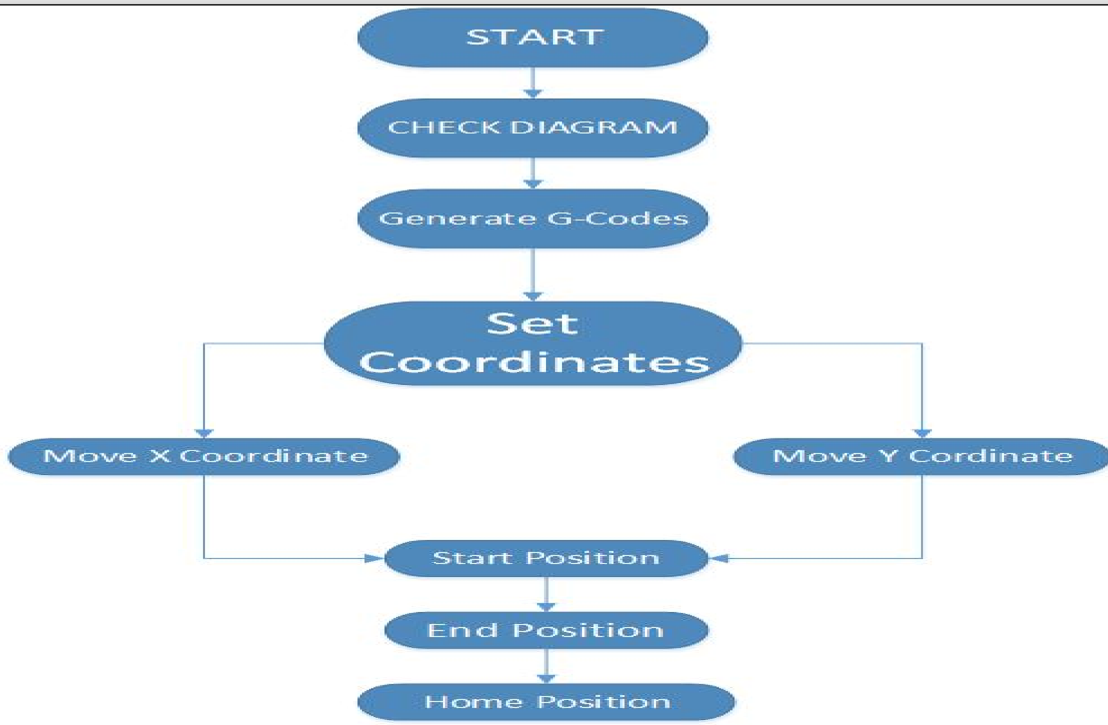

Figure 5: Flow Diagram [32].

This proposition diagrams is arranged for development of a two-axis Computer Numeric Control (CNC) machine, with the end goal of rendering two dimensional vector designs. The CNC machine and control programming will take vector picture contribution to the type of Scalable Vector Graphics (SVG) records, and render the picture onto a medium [33]. The medium will be a level surface, for example, traditional paper, white board, or light receptive surface. The machine will have the capacity to proceed onward for drawing laser. The machine ought to meet the objectives of adjusting high exactness and speed, utilize constrained assets and however many reused parts as would be prudent.

The image conversion software will take SVG image file on standard input and output Gcode on standard input [34]. The Arduino programming language has been chosen to write the software, due to ease of use, ubiquity, and integration as a scripting language in third party applications such as Inkscape and MC. Our algorithm for conversion will consist of several conversion stages, each stage providing a transformation towards G-code. The first step will be to de-sugar the SVG file. SVG is a complex format, allowing advanced constructs like embedded bitmap images, text and font effects, and stroke and fill styles. To make the rendering feasible, all the extraneous elements will be removed or simplified to basic paths. Some of these simplifications, such as text to path conversion of text or polygon to path conversion, may be performed as scripted actions inside the Inkscape editor. This step may consist of several independent reductions. Once the SVG file has been simplified, the resulting XML will be parsed into a data structure consisting of a set of paths. A series of object classes will be defined to provide a convenient storage medium for the variety of paths descriptions used (e.g. Bezier curves, simple Cartesian lines). Next, the paths will be ordered into a render priority queue. One simple algorithm would be to define a starting location for the write head, locate the path closest in distance to this location, and add it to the render queue. Calculate the location of the write head at the end of this path, and add the next nearest path from that location [35]. Repeat this process until there are no line segments. This greedy algorithm should provide good performance by limiting movement between paths. Drawing closely located elements would also provide an aesthetically pleasing rendering process, as the write head will not simply scan down the page, but instead render the drawing in a more varied way [36]. Finally, the priority queue will be used to generate the actual G-code paths. Each path will generate a pen down command and a sequence of movement instructions, followed by a pen up command a move instruction to the starting location of the next path. G-code supports a variety of control codes, and will be better understood once we have written a series of test G-code scripts. The completed G-code instruction file will be output on standard input [37]. Our work procedure had various steps including cutting, engraving and desiginig of patterns the wood chunks were cut to the required dimensions and had good enough round shaped hole for stepper motor mountain. We used belt and rollers to support our X and Y axis movement.

3.5- Prototyping and Testing

A prototype of the integrated CNC robotic machine was fabricated and subjected to a series of tests to validate the design and functionality:

- **Prototype Assembly**: The robotic arm, CNC controller, and laser module were assembled based on the finalized design. Integration testing was performed to ensure the components worked seamlessly together.

- **Performance Testing**: The prototype was subjected to various tests to evaluate its precision, speed, and repeatability. These tests included:

o **Laser Cutting Tests**: Precision cutting of various materials was performed to assess the accuracy of the laser system in conjunction with the robotic arm.

o **Movement and Calibration Tests**: The robotic arm's motion capabilities were tested, including its ability to execute complex paths and coordinate movements with laser activation.

o **Speed and Efficiency**: The system's processing time and energy efficiency were measured, focusing on improving throughput without sacrificing precision.

- **Quality Assurance**: A series of quality control measures were implemented to assess the consistency and reliability of the system. The laser's focal length, power consistency, and cut quality were continuously monitored during the testing phase.

4- Results and Simulation:

This section presents the results of the testing and simulation phases conducted during the development of the next-generation CNC robotic machine integrated with laser technology. The results include the performance of the system in terms of precision, efficiency, and adaptability, as well as the outcomes of simulation-based evaluations conducted prior to physical prototyping. Both aspects provided valuable insights into the effectiveness of the design and its potential for real-world manufacturing applications.

4.1- Simulation Results

Before assembling the physical prototype, various simulations were carried out to ensure that the design could meet the required specifications for precision, movement, and laser integration. The simulation phase primarily consisted of motion and structural simulations, along with laser system performance evaluations. We have used three softwares in our project i.e. GRBL Controller, Arduino and inkscape. These are used at different sections in our project to provide easy and efficient working. Although, all softwares are best but we have used each of them at different places where they could be easily used and were best.

Step # 1:

In the context of CNC machining or laser engraving, **G-code** is a set of instructions that the machine reads to carry out specific actions, like engraving. In this case, the process starts by creating a design (whether it's text or an image) in **Inkscape**, a popular vector graphics software [38]. Once the design is ready, the software is used to convert it into **G-code**, which is a machine-readable language that controls the engraving process. Figure 6 shows an example of this process.

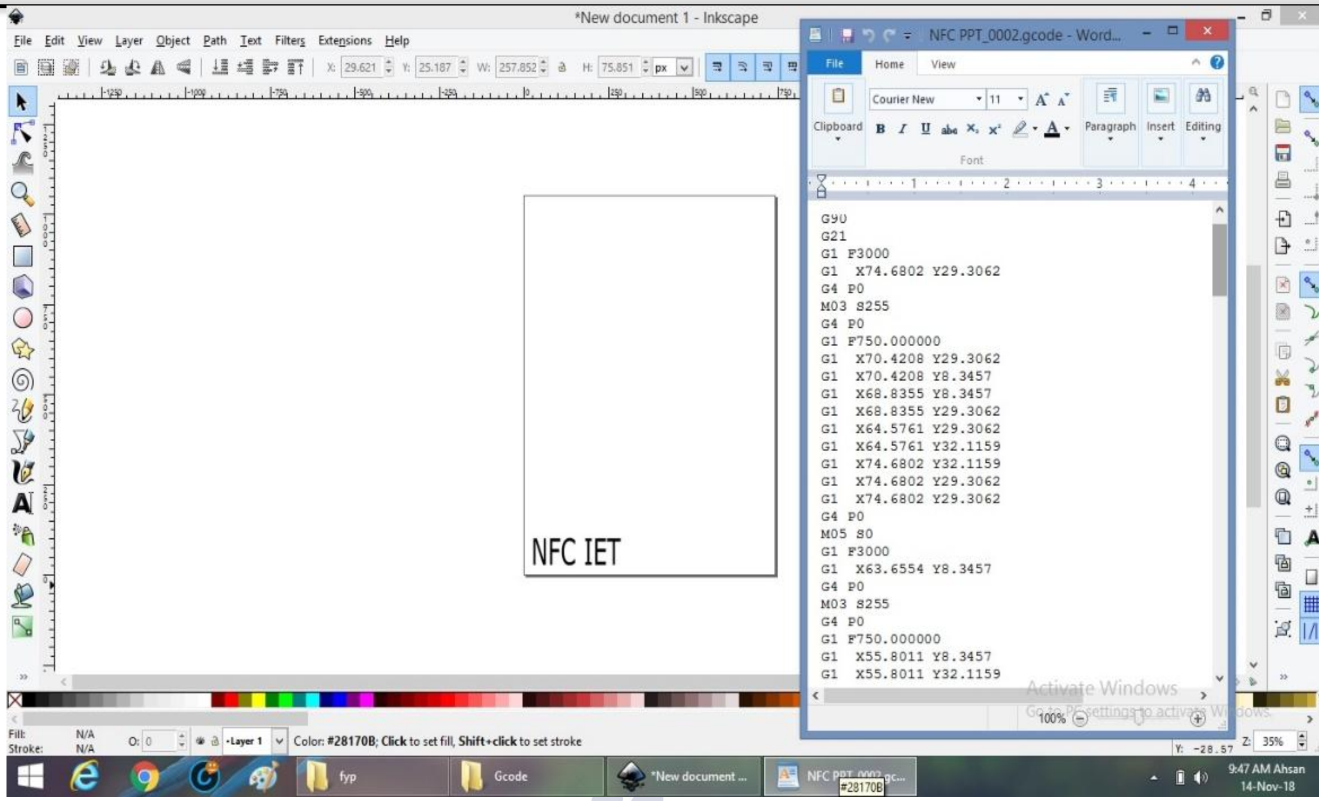

Figure 6: Creating Gcode of any text or image which is going to be engrave using Inkscape softwear.

Step # 2:

After the G-code is generated in Inkscape, the next step involves using a program called **Universal Gcode Sender (UGS)** to send these codes to the CNC machine or laser engraver. **Universal Gcode Sender** is a popular software tool used to communicate with CNC machines [39]. It reads the G-code and then directs the machine to follow the instructions for the engraving process. This tool acts as an intermediary between the design software (Inkscape) and the hardware (the CNC machine or laser engraver). **Figure 7** in your paper likely illustrates how UGS is used to transmit the G-code from Inkscape to the machine for execution.

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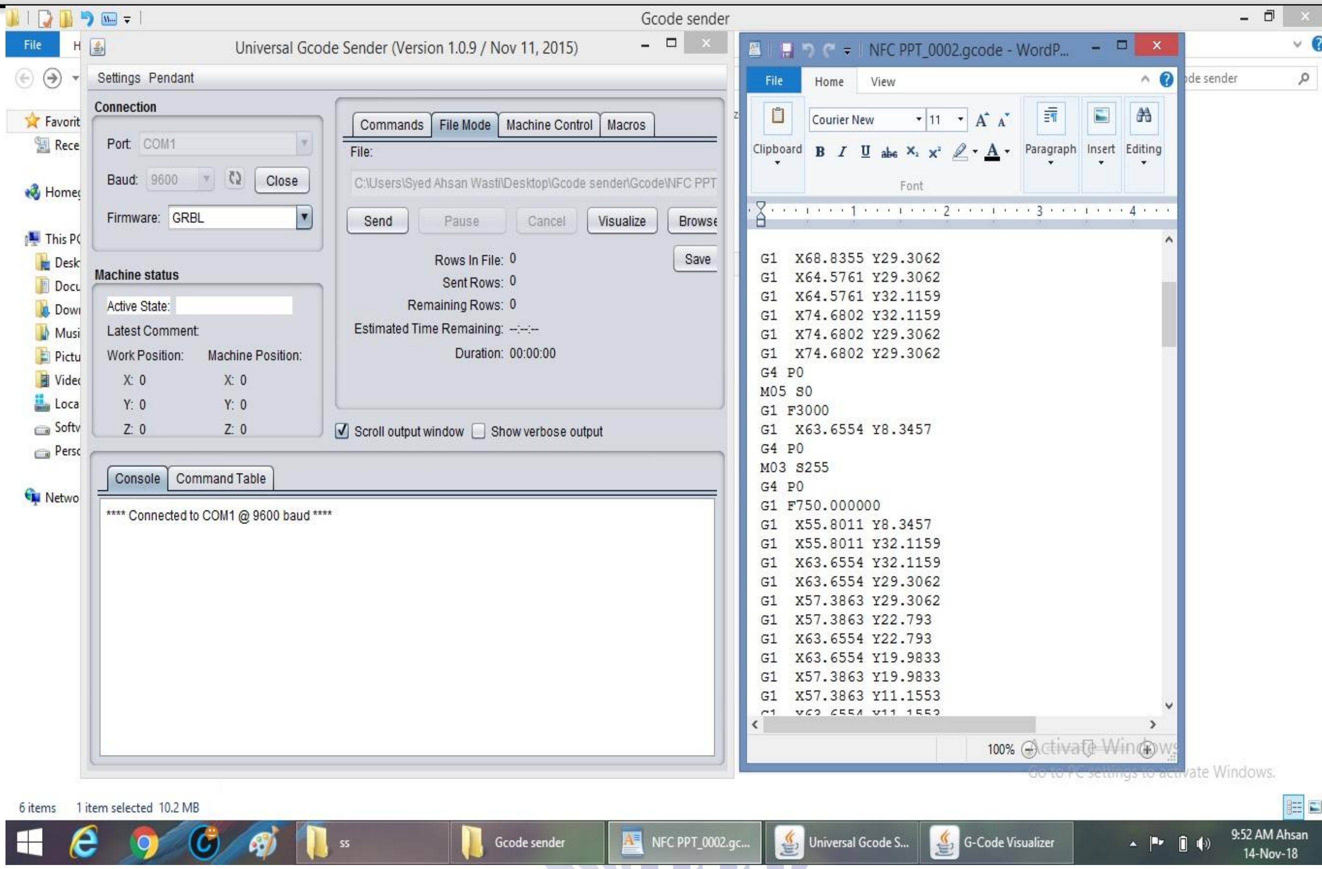

Figure 7: The codes which is created by inkscape is used by Universal G code Sender.

Step # 3:

Once the G-code is transferred using Universal Gcode Sender (UGS), the next step involves sending these codes to a simulated Arduino Nano in Proteus. Proteus is a simulation software used for designing and testing electronic circuits and systems before physically building them. In this case, the G-code is sent to a simulated version of an Arduino Nano, which is commonly used in CNC machines and other automation projects for controlling hardware [40]. By simulating the Arduino Nano in Proteus, you can test the functionality of the system and verify how the machine would respond to the G-code instructions in a virtual environment. This helps in detecting any errors or issues before actually implementing the hardware in real life. Figure 8 in your paper likely shows the simulation setup in Proteus, demonstrating how the G-code is sent to the Arduino Nano for testing purposes.

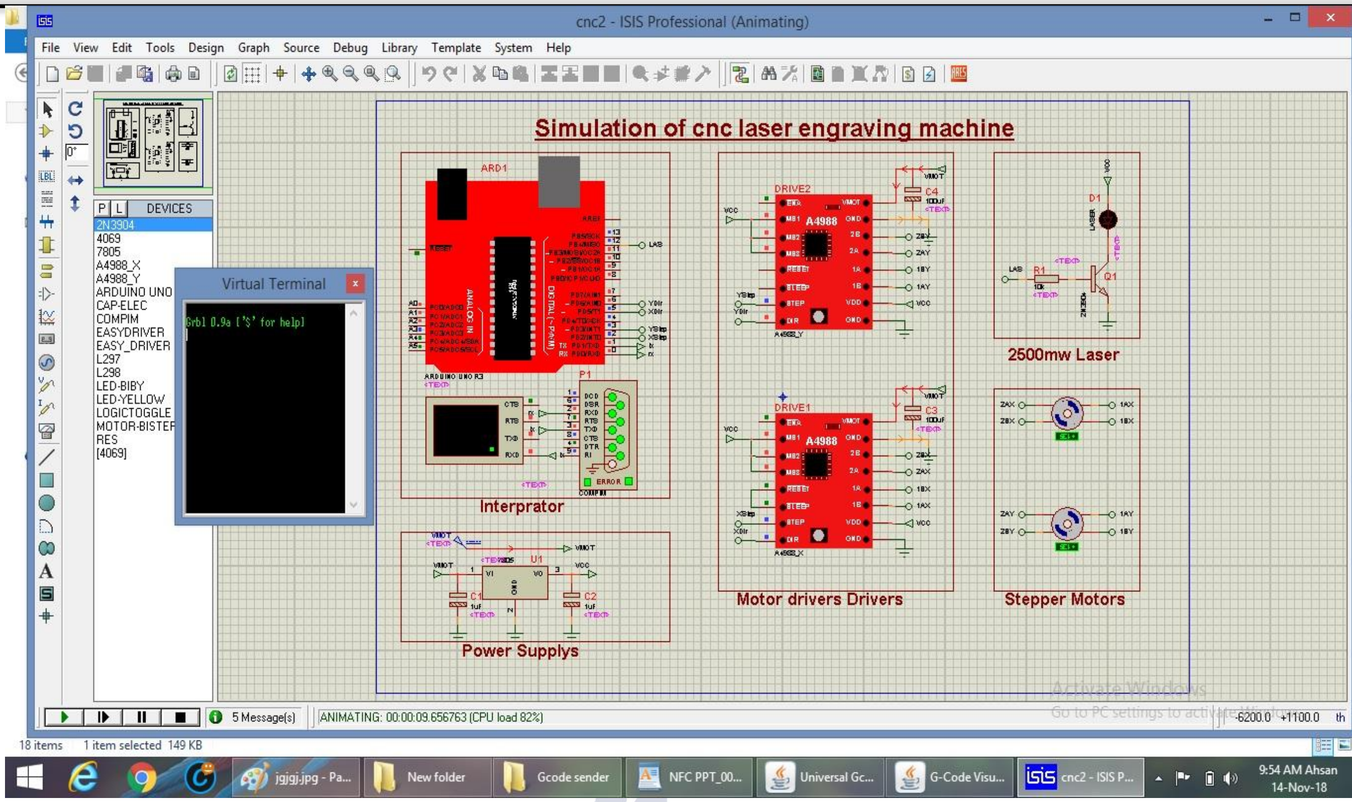

Figure 8: The codes are send to Simulated Arduino Nano in Proteus.

Step # 4:

The next step involves Universal Gcode Sender (UGS) generating real-time instructions (or G-code) and sending them to the Arduino Nano during the actual operation of the system. At runtime, UGS communicates with the CNC or laser machine by sending the G-code commands to the Arduino Nano, which acts as the controller for the machine [41]. The Arduino Nano receives these commands and processes them to control the movements of the CNC machine or laser engraver accordingly. This real-time communication is essential for performing tasks like engraving or cutting based on the design provided earlier. The system is in operation, and UGS continually sends new G-code commands to the Arduino Nano as the machine carries out each step of the process. Figure 9 in your paper likely illustrates this real-time interaction, showing how the Universal G code Sender dynamically generates and transmits instructions to the Arduino Nano during the machine's operation.

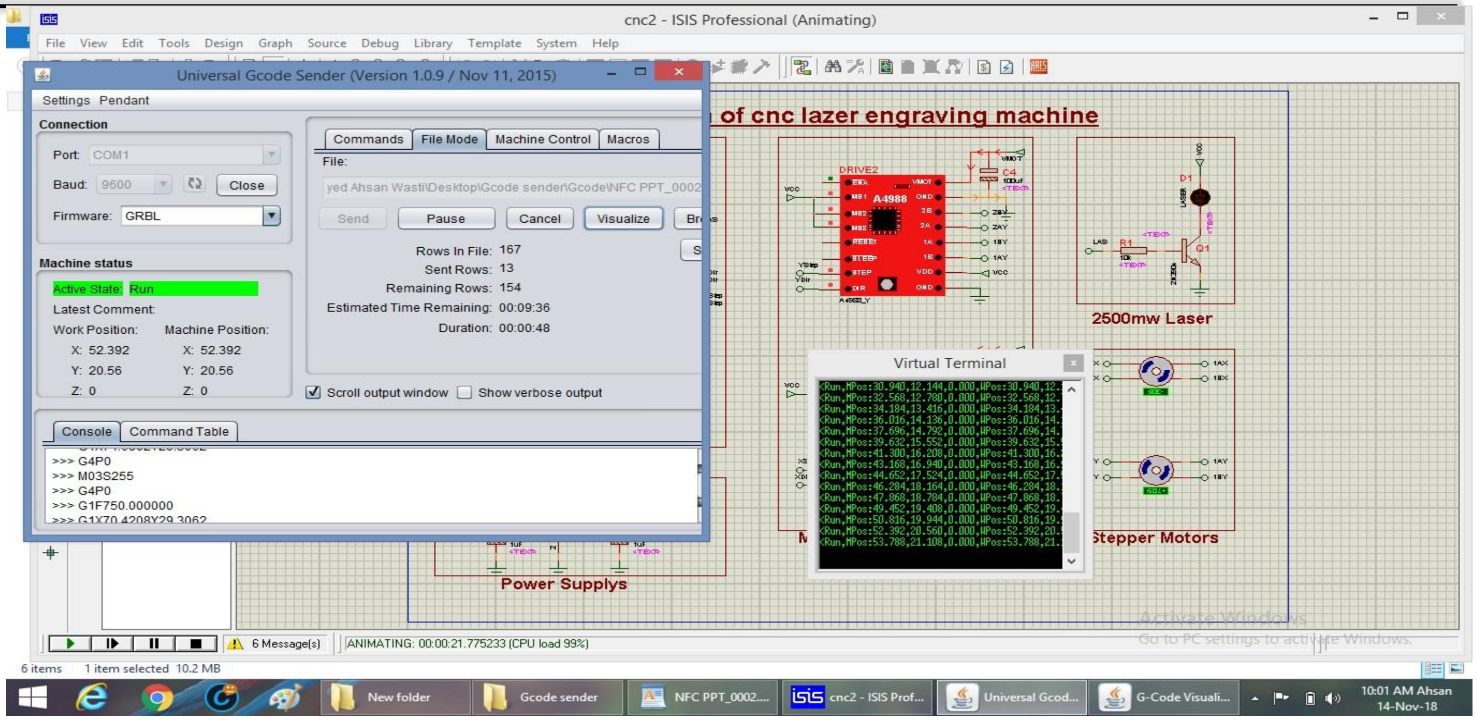

Figure 9: Run time codes are generated by Universal G code Sender to Arduino Nano.

Step # 5:

In the final step, based on the G-code received from the Universal Gcode Sender (UGS), the Arduino Nano activates the system's components—specifically the stepper motors and the laser. The G-code contains instructions that specify how the CNC machine or laser engraver should move (such as the path to follow, speed, and direction). The Arduino Nano processes these instructions and translates them into actions.

- **Stepper Motors**: The G-code commands tell the stepper motors to move the robotic arm or other moving parts of the machine in precise steps. Stepper motors are commonly used in CNC and laser systems because they offer precise control over positioning [42].

- **Laser**: The G-code also includes instructions for turning the laser on or off, adjusting its power, and controlling its movement to perform tasks like engraving or cutting. The Arduino controls the laser based on these instructions.

Figure 10 illustrates this final step, showing how the G-code triggers the Arduino Nano to activate the stepper motors and laser, thus executing the actual engraving or cutting task as specified in the design.

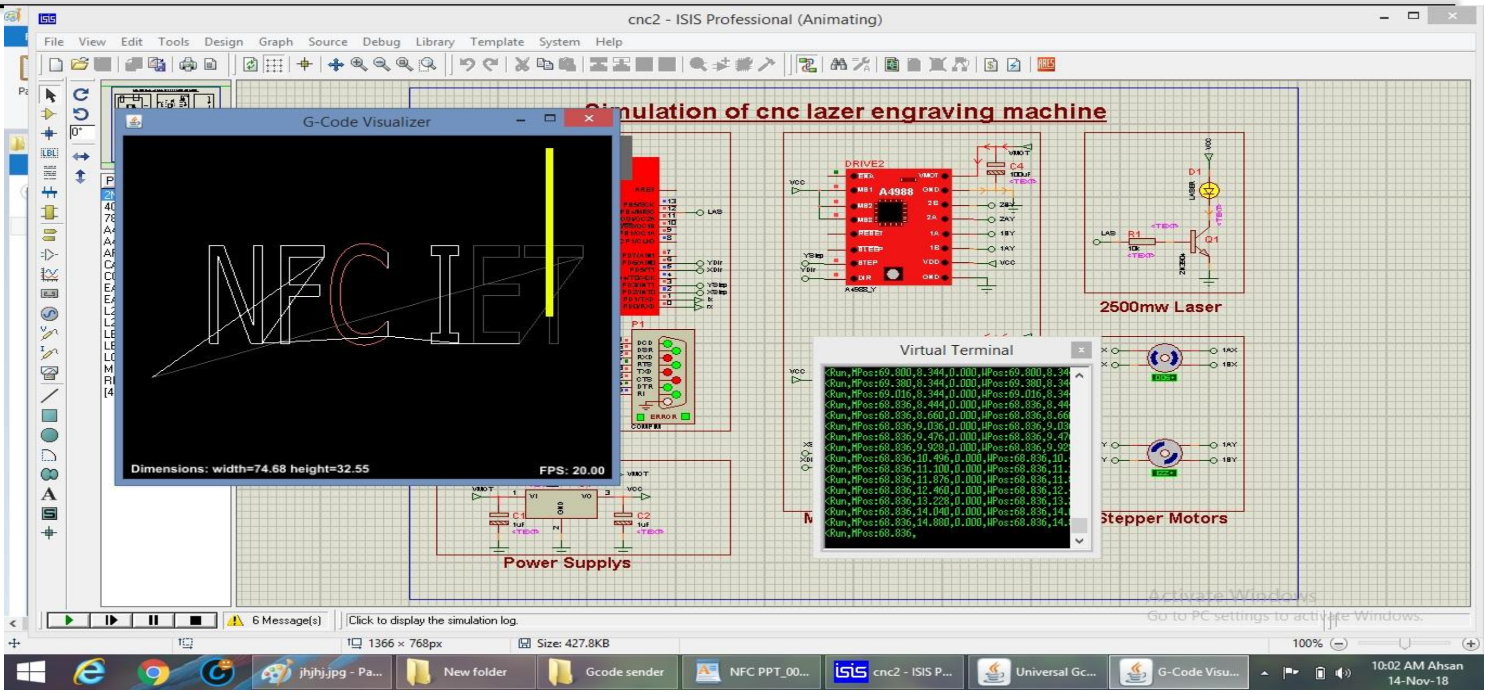

Figure 10: G codes Arduino turns on the stepper motors and LASER.

Our CNC machine is created in such a way which can draw or engrave in a canvas or a given flat surface. Our primarily tested canvas is 12 inch by 12 inch. It is set in a way on purpose so that the machine can travel and exceed 12 inch on both sides [43]. Hence our machine has the ability to travel 15 inch, therefore it has an edge to travel 1.5 inch extra in both sides. The figure 11 below illustrated frame of our machine.

Figure 11: Aluminium frame

The Acrylic sheet that is shown in figure 12 is the lower part or base part of our machine. The size of this sheet is 24X18 inch. The whole machine is held by this part. The frame stays on this part. We have installed a rail so that the X axis can move freely. The rails are made of aluminum. We have tried to make the movement along X axis and Y axis as smooth as possible [44]. Though our sheet is made of acrylic and a bit heavy, our prime concern has always been to make our motor movement precise and sheets to be strong. So that it can take any load and drill any object. This is in brief full picture of our machine.

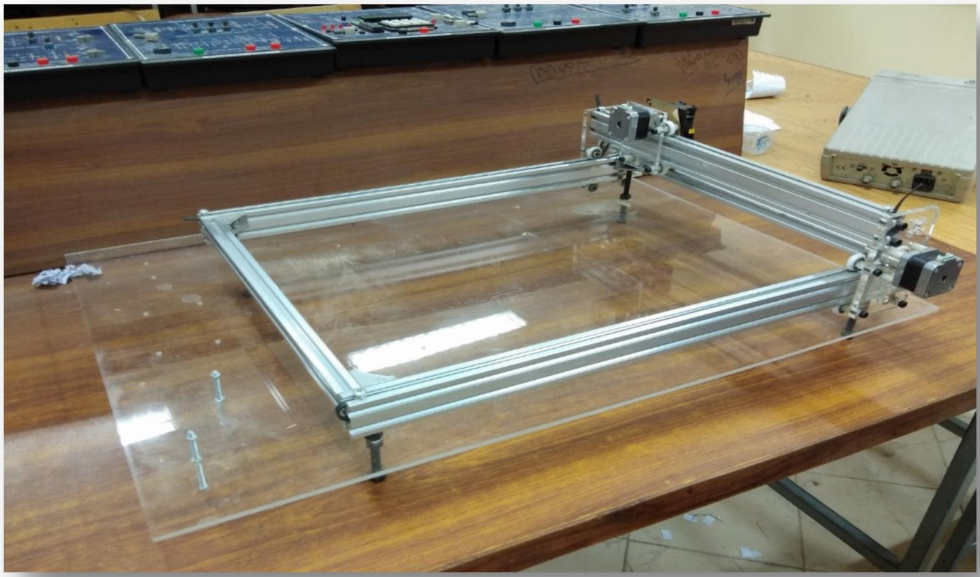

Figure 12: Acrylic Base.

5- Future Work:

While this research provides a foundation for the design and development of a CNC robotic machine integrated with laser technology, there remain several areas for further exploration and enhancement. The following future directions are identified for expanding the capabilities and applications of the proposed system:

1. **Advanced AI and Machine Learning Integration**: The integration of AI and machine learning algorithms could be further developed to enable real-time decision-making, adaptive machining, and self-optimization of the system. Future work could focus on developing machine learning models that predict material behavior, adjust laser parameters on the fly, and optimize robotic movements based on feedback from sensors and the manufacturing environment.

2. **Multi-Process Integration**: Further research could explore the combination of additional manufacturing processes, such as additive manufacturing (3D printing) or advanced material deposition techniques, within the same CNC robotic platform. This would enhance the versatility of the system, allowing for hybrid manufacturing processes that combine cutting, welding, engraving, and 3D printing in a single automated system.

3. **Enhanced Laser Technologies**: Future work could investigate the development and integration of next-generation laser technologies, such as ultra-fast lasers or high-power fiber lasers, which could expand the range of materials and applications the system can handle. Research into improving laser energy efficiency and the precision of laser beams will be crucial in achieving higher-quality manufacturing outcomes.

4. **Integration with Cloud-Based Systems and IoT**: To fully capitalize on the potential of smart manufacturing, integrating the CNC robotic system with cloud-based platforms for real-time data analytics, process monitoring, and predictive maintenance could be explored. Cloud-based IoT platforms can allow for remote control, diagnostics, and the sharing of operational data across networks of machines, facilitating optimized production across multiple sites.

5. **Collaborative Robots (Cobots) for Increased Flexibility**: Another area for future exploration is the use of collaborative robots, or "cobots," to work alongside human operators in a shared workspace.

Cobots, with their enhanced safety features and intuitive controls, can enable more flexible and interactive manufacturing environments, especially in smaller-scale and custom production scenarios.

6. **Improvement of Human-Machine Interface (HMI)**: The development of more user-friendly and intuitive HMIs, potentially utilizing augmented reality (AR) or virtual reality (VR), could simplify system operation and enhance the efficiency of programming and troubleshooting tasks. Future work could involve designing interfaces that allow operators to interact with the CNC robotic system in real-time, providing an immersive and intuitive environment for system management.

7. **Sustainability and Green Manufacturing**: Future research should also consider the environmental impact of the integrated CNC robotic machine and laser system. Exploring energy-efficient laser sources, sustainable materials, and reducing waste in the machining process can contribute to the growing trend of green manufacturing. Research into closed-loop systems for material recycling and waste minimization would align with sustainability goals.

8. **Industrial Deployment and Scalability**: Finally, testing the system in real-world industrial environments, with varying materials and production scales, is essential. Future work will involve assessing the scalability of the system in mass production, as well as addressing challenges related to cost, system reliability, and ease of integration with existing manufacturing infrastructures.

By pursuing these avenues, future research will not only refine the CNC robotic machine integrated with laser technology but also contribute to the broader adoption of smart manufacturing systems, paving the way for more efficient, adaptable, and sustainable production methods.

6- Conclusion:

This research presents the design and development of a next-generation CNC robotic machine integrated with laser technology for smart manufacturing. By combining CNC robotics with laser tools, the system enhances precision, speed, and flexibility in machining processes, enabling multi-material processing and rapid prototyping. The integration of intelligent control systems, real-time data analytics, and predictive maintenance positions the system at the forefront of Industry 4.0. Despite challenges in integration and cost, the proposed system offers significant improvements in manufacturing efficiency and adaptability. Future research focusing on AI-driven optimization, advanced laser technologies, and collaborative robotics will further enhance the system's capabilities. This work provides a foundation for the evolution of smart manufacturing systems, offering the potential to revolutionize industries like aerospace, automotive, and medical devices. Ultimately, the integrated CNC-laser system promises to contribute to the development of more efficient, sustainable, and agile production environments.

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