Design and Simulation of a CNC Machine for Controlled Seed Irradiation in Agricultural Research

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***Abstract*—Agriculture remains one of the most vital sectors for human survival, providing essential food resources and contributing significantly to the economy. Various technologies have been developed to enhance agricultural production, including seed irradiation. Research has demonstrated that irradiation can significantly improve seed quality and boost the productivity of seeds, particularly those affected by adverse storage conditions such as fluctuating temperature and humidity. However, traditional irradiation methods often relied on manual timers, resulting in inaccuracies and inconsistent seed treatments. This paper presents the development of an automated seed irradiation system using a Computer Numerically Controlled (CNC) machine. The proposed system ensures precise and controlled radiation exposure, offering greater accuracy and consistency in the irradiation process. By automating the procedure, this CNC-based machine enhances the effectiveness of seed treatment, ensuring optimal irradiation for improved seed quality and agricultural productivity.**

Keywords—CNC Machine, Seed Irradiation, Automated Irradiation, Precision Agriculture, Seed Quality Improvement

I. Introduction

Sudan is considered as one of the largest countries in Africa in terms of area and arable land [1], [2]. Agriculture is one of the most important resources in the world, which is the main source of livelihood in Sudan and more than 62% of the population is working in agriculture as of 1990. Agriculture is one of the main economic activities that contribute to the country's economy. The development of the agricultural sector contributes to the development of society and the fight against unemployment. Moreover, agricultural production represents a basic material for many industries [3].

One of the most critical factors influencing agricultural productivity is the quality of seeds. Seeds are not only essential inputs for agricultural production but also represent the most vital part of the plant. They serve as a primary source of food for millions of people worldwide [4]. Seed quality plays a pivotal role in ensuring successful harvests and increased production, which, in turn, significantly contributes to the economy [5]. One effective method for improving seed quality is irradiation, where seeds are exposed to a controlled laser beam for a specific duration. This process has been shown to enhance seed vigor, leading to better growth and higher yields.

The history of irradiation dates back to the 50th and 60th of the last century, when farmers around the world began to experiment with irradiation[6], [7]. Within the beginning of the spread of the benefits of this genetic plant mutation, some farmers started irradiating seeds and selling them, where irradiation is responsible for the current plant discovery such as some types of grapefruit. One of the most important advantages of irradiation is improving seed quality, reducing the effect of pests, improving productivity up to double, and yielding a high harvest, but the irradiation occurs manually, so it does not guarantee the irradiation of all seeds, and the required irradiation time is not accurate. Hence, this study utilizes a CNC machine to ensure the irradiation of all seeds and set the time required to irradiate the seed.

Computer Numerically Controlled (CNC) machine as a definition is any machine that is numerically controlled using a computer and that its movements are carried out by commands from the computer instead of manual control. CNC machining is a manufacturing process where a computer instructs machines using programming codes to manufacture a product, and the first CNC machine is credited to James Parsons in 1949. Before the first CNC was developed, some machines could be directed to make other tools it was called Numerical Controlled (NC) machine [8]. The first NC machines were made in 1940. Based on existing tools that were modified with motors that move the tool to follow points entered the system using data warehousing technology. These mechanisms were quickly augmented with analog and digital computers. This led to the creation of modern CNC machine tools that modernized manufacturing processes. Nowadays CNC machining is a popular manufacturing process with a wide range of industrial applications. Among the most important advantages of CNC are high speed, high accuracy and high efficiency, as well as reducing work time and increasing productivity [9].

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II. Literature Review

The independence of agricultural regions and the increase in production are crucial factors for economic growth, making seed quality a central focus. High-quality seeds directly contribute to higher agricultural yields. Seed irradiation, a process that has gained significant attention, offers numerous benefits by enhancing seed viability and boosting production. As a result, seed irradiation has become a key tool for farmers and agricultural investors, playing a pivotal role in improving crop productivity and supporting sustainable agricultural practices [10]. In previous years, numerous studies have been conducted on the irradiation of various types of seeds to assess the extent of their effects. Initially, irradiation was carried out manually or with simple machinery. One common method involved a moving conveyor line on which the seeds were placed, and a laser beam was projected from above. In the manual process, seeds were individually placed under the beam, and the exposure time was controlled using a timer. These basic methods were used to irradiate seeds and explore their potential benefits [11].

In [12], a study of laser pre-sowing treatment of rice seeds by free fall transport method has been proposed. The laser treatment device consisted of a seed box, a semiconductor laser, a pulsed energy source, a transmission tube, and a window as shown in Fig. 1. As the seeds poured into the seed box pass through a tube through the port, two exposure windows are placed on either side of the tube. The box contains a control valve at the beginning that is used to control the amount of seeds that are sent to the tube in a unit of time. The result was improved seed germination. The height of the plant and the number of leaves, buds and ears increased, and the maturity of the rice became higher.

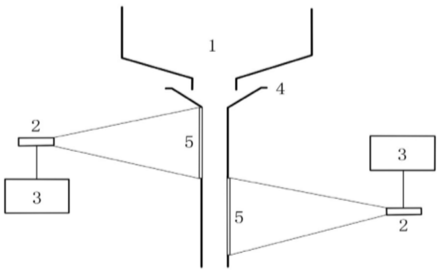

Fig. 1. Schematic diagram of laser treatment device [12].

In a separate study conducted in 2018 at the College of Agriculture and the Laser Laboratory at the Laser Institute for Postgraduate Studies, University of Baghdad [13], seeds were exposed to He-Ne red, green, and blue lasers. The lasers were set up in a specialized configuration, with each laser placed on its own bed within the open section of an optical ruler to operate continuously in normal mode for an indefinite period. The lasers were mounted on metal holders, and the front terminal edge of each was coated with silicon to improve the precision of the contact point. This design ensured that the laser beam remained stable and consistent, as shown in Fig. 2. The results indicated that the laser treatment had a significant impact on the height of the corn plants compared to untreated seeds. Among the lasers tested, the blue laser radiation produced the most notable increase in plant height. Furthermore, the study found that the interaction between the laser and corn seeds influenced the carotenoid content in the seedlings' leaves, suggesting that laser treatment positively affected the growth and development of maize plants.

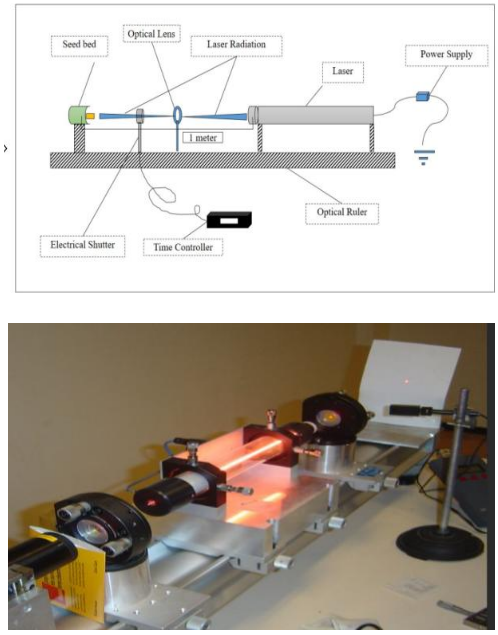

Fig. 2. Set structure for the laser irradiation on maize seeds [13].

Another study conducted at Krakow University [14] explored the effects of coherent laser irradiation on the germination and fungal contamination of soybean seeds. The seeds were found to have fungi on their surface, which significantly reduced the germination rate. Seed-borne diseases are a major obstacle to soybean production, with over 7 million tons of soybeans reported lost worldwide due to such diseases. The irradiation took place at the Department of Environmental Biotechnology and Ecology at the University of Science and Technology in Krakow. The soybean seed samples were exposed to two types of lasers: a helium-neon laser and an argon laser. The irradiation process was controlled by a stand-alone device with programmable drivers that allowed precise control over the operating times. The results showed that laser photo-stimulation significantly improved seed germination, and laser treatment increased both the germination capacity and the weight of the seedlings.

In [15], the protective effect of He-Ne laser on winter wheat from UV damage by analyzing protein changes in leaves has been investigated at Shanxi University. Ultraviolet radiation can affect the gene expression of plants in growth, and wheat, as a type of economic crop, is also affected by ultraviolet radiation. It was reported that He-Ne lasers can mitigate cell damage caused by ultraviolet radiation in plants. To obtain the pro-wheat changes attenuated by He-Ne laser irradiation the protein expression of winter wheat leaves was studied. The seeds to be irradiated were selected, washed and sterilized. The seeds were grown on cotton soaked with water. Once the seedlings began to germinate a complementary ultraviolet light was provided. Lamps were hung on top, and a semiconductor laser was directly irradiated with wheat seeds for two minutes every day. At 12 days after the treatment, wheat leaves were collected for analysis. It has been shown that laser treatment can significantly reduce the damage caused by ultraviolet radiation in winter wheat.

A study conducted at the University of Life Sciences in 2010, as referenced in [16], explored the estimation of the laser bio-stimulation dose. This study introduced a method for quantitatively determining the laser irradiation dose delivered to the surface of seeds and also discussed the most common geometries for laser irradiation. Specifically, it considered two scenarios: one where the seeds move at a constant speed, and the other where the seeds fall freely under the influence of gravity onto the illuminated area. The laser bio-stimulation technique used in the study is illustrated in Fig. 3. The key physical phenomenon involves the seeds' ability to absorb and store light energy, which is then converted into chemical energy that is later used for growth. The purpose of this work was to propose a method for calculating the dose of laser irradiation received by the seeds. In the most applied methods, seeds are moved over an area illuminated by a diverging laser beam. In some setups, the seeds travel at a constant velocity, while in others, they fall freely under gravitational acceleration. The constant velocity can be controlled by adjusting the angle of the trough. In both cases, the seeds traverse the irradiated area, and the differential energy density (DE) absorbed by the seeds over a time interval (DT) can be calculated using the following formula.

DE= Q(X) DT

The study concluded that when a fixed seed velocity geometry is chosen for laser bio stimulation, the irradiation dose can be easily administered. When the seeds fall freely with the acceleration of gravity, the exact irradiation dose cannot be represented.

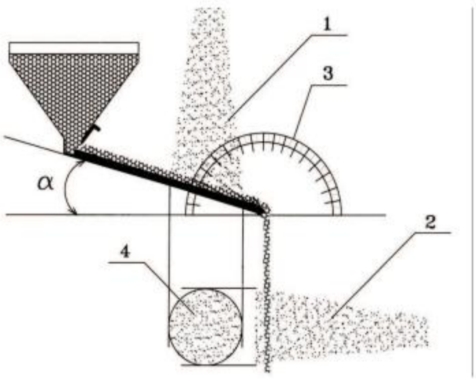

Fig. 3. Geometries for laser seed processing “1-Divergent laser beam geometry is used when a constant seed speed is chosen.2-Divergent laser beam geometry is used when seeds freely fall down with acceleration characteristic for the gravity.3-angle gauge.4-Illuminated area where seeds are bio stimulated by a laser beam” [16].

In [17], a study conducted at the University Kebangsaan Malaysia compared the effects of two laser devices on the biophysical properties of *Zea mays L.* seeds, focusing on their photo-biodegradation techniques. Maize (*Zea mays L.*) is a key crop, and the quality of its seeds directly influences seedling emergence and crop establishment. Seed viability, which is crucial for uniform and rapid seedling emergence, is a key physiological quality. The study was carried out in a hot and dry climate with an annual temperature averaging 34°C. In the experiment, the seeds were irradiated using a He-Ne laser, with the laser beams directed from the side and distributed evenly under the seeds. The exposure time was controlled using a timer. The results showed that laser treatment significantly improved seed emergence, with both the average emergence time and activity index values markedly increased.

The effect of laser irradiation on the growth of Dracocephalum moldavica L. was studied in[18] using LED lasers that emitted monochromatic blue and red light. The results showed that laser treatment enhanced seed germination, accelerated plant growth, and increased root development and chlorophyll content. As medicinal plants used for their immunogenic, anti-inflammatory, and anti-viral properties, improving their growth through environmentally friendly methods is crucial. Traditional methods, such as excessive fertilizer use, can harm soil structure and contribute to pollution. In this study, the irradiation of seeds with monochromatic light was found to significantly improve germination rates and plant survival, with the LED laser enhancing seed viability by activating the photochromic system.

In a study presented in [19], the effects of different doses (100, 300, and 500 mJ) of low-power He–Ne laser (632.8 nm) irradiation on seed germination, thermodynamic properties, enzyme activities, and changes in seed metabolites were investigated. The results showed that He–Ne laser irradiation enhanced the activities of amylase (Amy), protease (Pro), and glucosidase (Gluco), leading to significant improvements in seed thermodynamics and germination traits. Laser treatment resulted in a rapid increase in free fatty acids (FFA), free amino acids (FAA), chlorophyll (Chl), carotenoids (Car), total soluble sugars (TSS), and reducing sugars (RS) in the seeds, while seed oil content and total soluble proteins (TSP) decreased. Positive correlations were observed between the enhanced seed energy levels, germination rates, and enzyme activities with higher levels of FAA, FFA, Chl, TSS, and RS. Conversely, a negative correlation was found between TSP and oil content. In conclusion, treatment with 100 and 300 mJ He–Ne laser irradiation proved more effective in improving seed germination potential, likely due to increased enzyme activity and the accelerated breakdown of seed reserves into simpler metabolites necessary for growth.

The increase in agricultural crop production, especially cotton, was studied in [20]. where each form of physical and chemical effects was investigated, and the relationship between seed yield, development and production with the laser irradiation dose was investigated by irradiating thin fiber seeds using a red laser beam. The result was positive and led to an increase in the crop. The study contains a table summarizing the results.

In [21] the effect of lighting and laser radiation on the germination of caper seeds has been investigated considering the difficulties of caper seed germination. The aim of this study was to analyze the response of caper seed germination to exposure to light. It was analyzed using positive wavelengths (white, red, blue, and red + blue) and He-Ne laser. It was found that irradiating caper seeds using He-Ne laser improved the germination rate. The effect of laser irradiation on seed germination, vegetative characteristics, and mitotic division in *Atropa belladonna*, both in the laboratory (using tissue cultures) and in the field has been investigated in [22]. The seeds of *Atropa belladonna* were irradiated with helium-neon (He–Ne) laser rays. The results showed a significant improvement in seed germination percentage and plant height following laser treatment. The effect of helium-neon (He-Ne) laser light irradiation on the growth, yield and essential oils of anise and cumin plants was studied in [23]. The results were an increase in anise size, plant height and number of branches per plant.

The objective of this research is to design a CNC machine that precisely controls the timing and process of exposing plant seeds to laser rays. Seeds stored for long periods often suffer from stress due to poor storage conditions, including fluctuations in temperature and humidity. These stresses can negatively affect seed viability, plant growth, and crop yield. Currently, the process of exposing seeds to laser rays is done manually, which introduces variability and makes it difficult to ensure consistent exposure. As a result, not all seeds are treated effectively, leading to suboptimal germination and poor crop productivity. The goal is to automate this process to improve accuracy, consistency, and seed quality, ultimately enhancing plant growth and yield.

III. METHODOLOGY

The CNC machine operates in a 7 × 10 matrix grid. The machine's movement is controlled by motors that receive signals from the CNC shield. The process begins by moving the machine to the first position in the matrix.

1. **Seed Detection and Laser Activation**:
A sensor detects the presence of a seed at the current matrix position (1 × 1). When a seed is detected, the system sends a signal to stop the motors, and the laser is activated. The laser irradiates the seed for 5 seconds to improve its viability.
2. **Movement to Next Position**:
After the irradiation is complete, the machine returns to its G-code instructions and moves to the next position in the matrix.
3. **Repeating the Process**:
The sensor checks for the presence of a seed at each subsequent position. If a seed is present, the laser is activated for the same duration (5 seconds). The machine continues to move row by row across the matrix, treating each seed as it is detected.
4. **End of Matrix**:
Once the machine has processed all positions in the matrix, the End Stop is triggered, sending a command to signal the completion of the treatment cycle. The machine then returns to its starting position, completing the process.

IV. DESIGN AND CAD MODELLING

SolidWorks is a powerful computer-aided design (CAD) software widely used in mechanical engineering and industrial design [24]. Developed by Dassault Systems, it is one of the most popular programs for creating detailed and complex designs of products and mechanical parts. SolidWorks offers a comprehensive set of features, including parametric design, simulation, and analysis tools, which facilitate the engineering design process. These features enable designers to create accurate models, test them virtually, and optimize designs before physical production. By reducing errors and improving design efficiency, SolidWorks helps ensure high-quality products [25].

In our project, the model was designed using SolidWorks to develop a detailed digital representation of the CNC machine, including precise dimensions and assembly requirements. This digital model serves as the foundation for the physical construction of the machine. The development and fabrication of the CNC machine involve several processes and parameters, with the design of the model being a key step. The design process began by establishing the machine's dimensions (working volume) as a primary design parameter. To achieve 2D motion, the movement of the machine in the X and Y axes is synchronized. This mechanism utilizes two stepper motors: one for the X-axis movement and one for the Y-axis. The Y-axis movement is controlled by a single motor connected to lead screws, which in turn move the laser in the vertical direction. The lead screws are driven by the motor, enabling precise control of the laser's horizontal position.

The initial conceptual design was visualized using SketchUp software, providing a basic 3D model of the machine for further refinement as shown in Fig. 4. The carriage designed to content the helium laser and move in X direction as shown, it consists of two cylindrical holes so the linear bearing fit in, the brass nut which attached on the lead screw will fix to the carriage, so when the motor rotate the carriage move in horizontal movement parallel to the screw and slides. The helium laser attached in-front of carriage perpendicular or vertical to the screw and rods.

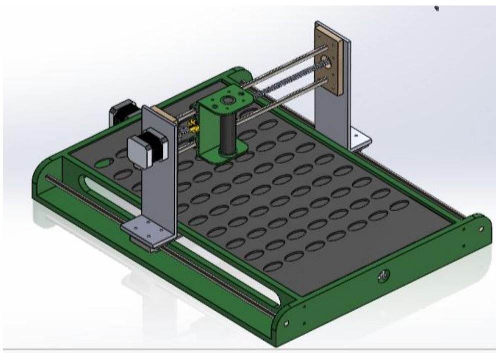

Fig. 4. Conceptual Design

Fig. 5. shows the rendered CAD model of the mechanism of lateral movement. It consists of lead screw, nut, two slides, four linear bearing and helium laser arranged as detailed. The rotary motion from the motor on the X-axis is converted into linear motion using a brass nut. This linear motion is then transferred to the helium-neon laser, which is the primary component of the machine. To facilitate horizontal movement, the laser is mounted on a carriage. However, mounting the laser on only one side of the carriage could create an imbalance, leading to potential machine failure. To address this, the carriage is supported by two rods, ensuring proper stability and balance.

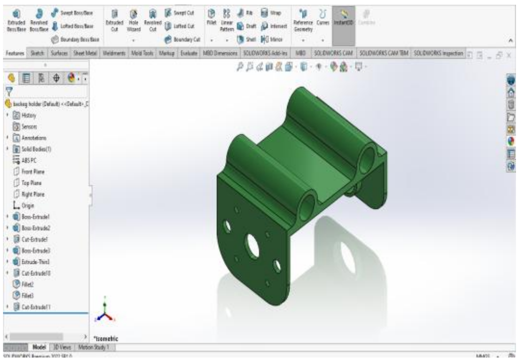

Fig. 5. Conceptual Design

The carriage moves horizontally along two cylindrical rods equipped with linear ball bearings, which reduce friction and ensure smooth motion. These rods are securely fixed to the carriage, allowing precise movement along the X-axis as depicted in Fig. 6. A lead screw is integrated into a pulley system, with one side driven by the motor and the other supported by a guide pulley. This system ensures controlled movement of the lead screw, enabling accurate positioning of the laser.

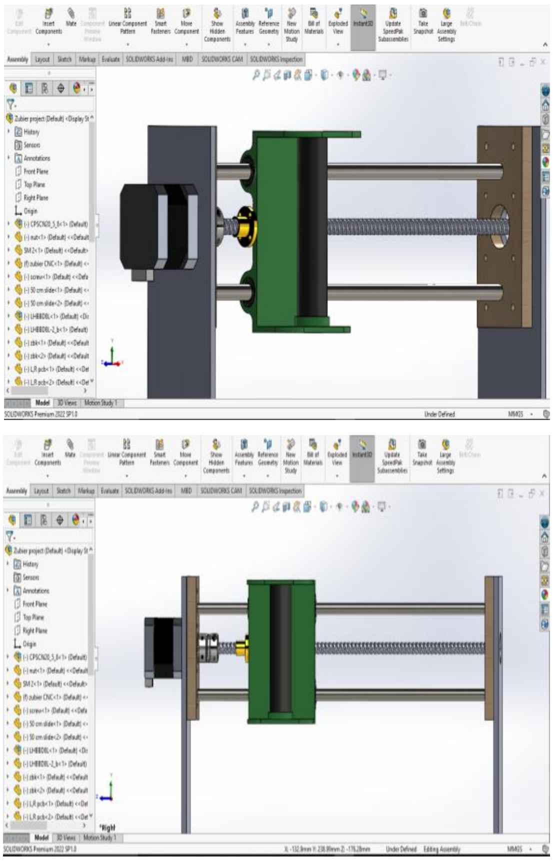

Fig. 6. X- Axis Movement Design

The carriage is securely attached to the lead screw, so that the rotation of the screw directly causes the carriage to move. When the motor rotates counterclockwise, the carriage moves from right to left. Conversely, when the motor rotates clockwise, the carriage moves from left to right. The design of the horizontal movement mechanism starts with the carriage, which is carefully engineered to maintain balance. This ensures that the combined weight of the carriage and the helium-neon laser is evenly distributed across both supporting rods. By achieving this balance, the system operates smoothly, minimizing the risk of instability or uneven wear, and ensuring precise motion along the X-axis. Fig. 7. Presents the designed CAD model of the Y axis movement mechanism. It consists of a lead screw, two roller slides, a linear ball bearing, and a brass nut attached to the screw.

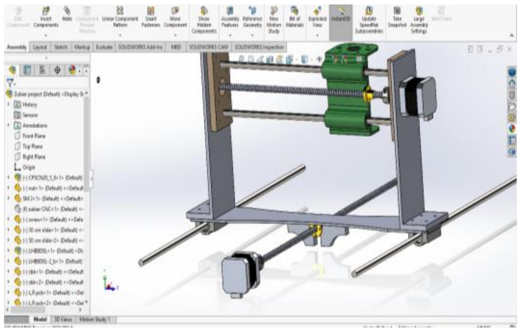

Fig. 7. Y- Axis Movement Design

V. CIRCUIT AND BLOCK DIAGRAMS

Numerical simulations were carried out in Ansys (15.0) based on FEA.

To ensures that all seeds in the matrix are irradiated accurately and for the correct duration, addressing the limitations of manual irradiation methods, we designed a CNC machine equipped with a helium-neon laser to ensure precise irradiation of seeds. The machine operates on a 10 × 7 matrix, with a total of 70 seed positions, guaranteeing that each seed receives the correct exposure time. The CNC machine was designed using SolidWorks and consists of both electronic and mechanical components:

1. CNC Shield V3 and Arduino:
    - The CNC Shield V3 is connected to the Arduino microcontroller, which receives the G-code and sends commands for the machine's operation.
    - Motor Drivers are connected to the CNC Shield V3, converting the G-code into electrical signals to control the stepper motors.
2. Motors and Movement:
    - NEMA 17 Stepper Motors are connected to the CNC Shield V3. These motors control the movement of the laser along the x and y axes, enabling precise positioning over the seed matrix.
    - End Stops:
    - End Stops are integrated into the CNC Shield V3 to detect the limits of the x and y axes, ensuring accurate movement and positioning of the machine.
3. Seed Detection and Laser Control:
    - A colour sensor is connected to the Arduino to detect the presence of wheat seeds at each position in the matrix.
    - When a seed is detected, the sensor signals the Arduino, which then activates the laser for a precise 5-second irradiation period to treat the seed.

Fig. 8 shows the circuit diagram and how the materials are connected to each other.

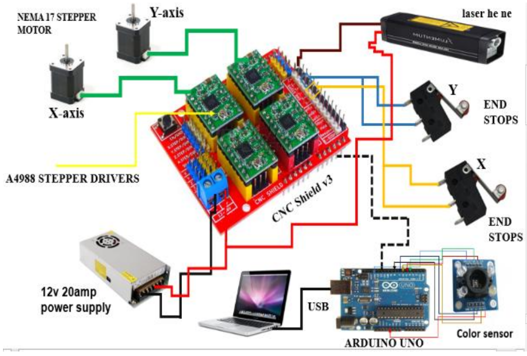

Fig. 8. Circuit diagram of a CNC machine

The block diagram of the proposed system is shown on Fig. 9.

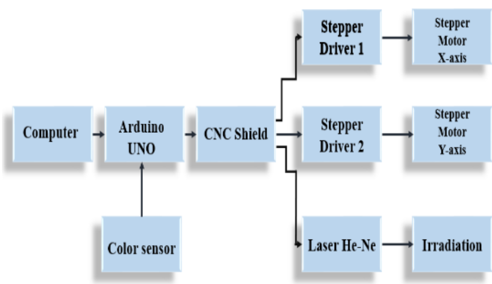

Fig. 9. Block diagram of a CNC machine

VI. Results and Discussions

As mentioned earlier, 12 modes were extracted in this analysis. The following tables list the obtained results for the two boundary conditions (free-free, and fixed-free) for each of the materials.

Proteus is a comprehensive electronic circuit design and simulation software that allows users to design, test, and analyze electronic circuits before physical implementation. It accurately simulates components such as microcontrollers and microprocessors, helping engineers identify and correct errors during the design stage. Notably, Proteus supports real-time simulation and includes advanced analysis tools, making it a valuable resource for education, training, and product development. It is compatible with various microcontrollers, including ARM, AVR, and PLC.

In the context of CNC machines, software plays a crucial role in facilitating communication between different components. The Arduino software serves as the programming platform for CNC machines. It allows users to specify movement parameters and calibrate the system, which are then uploaded to the controller. Additionally, the Arduino software acts as a bridge, enabling users to create models and designs using any CAD software, which are then translated into commands for the CNC machine, as shown in Fig. 10. The CNC machine operates on the principle of dividing the workspace into a 7 × 10 matrix, consisting of 7 columns and 10 rows. The stepper motors control the movement of the helium-neon laser along the x-axis and y-axis to irradiate the wheat seeds, to ensures that each wheat seed is irradiated for the correct duration, while optimizing the irradiation process by skipping empty positions.

1. X-Axis Movement: The laser moves along the x-axis to irradiate a seed for 5 seconds. If a wheat seed is detected at a specific position, the laser is activated. If no seed is present, the laser remains off, and the machine moves to the next position.
2. Y-Axis Movement: After completing one row, the machine moves to the next row along the y-axis. This process is repeated for all positions in the matrix.
3. Completion: Once the entire matrix is processed, the CNC machine returns to its starting position (zero point).

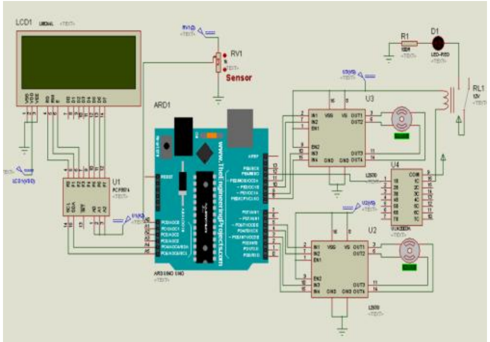

Fig. 10. Show circuit diagram

Fig. 11 illustrates the operation of the CNC machine where both the first row and first column are sensitive. When no wheat seed is present in a hole, the irradiation is paused, and the machine moves to the next hole.

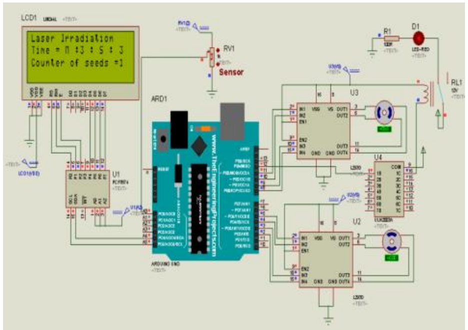

Fig. 11. Show circuit diagram

Fig. 12 depicts the operation of the CNC machine where the first row and the third sensitive column are responsible for detecting the presence of a wheat seed in the hole. Once detected, the irradiation is activated for a duration of five seconds, after which the machine moves to the next hole.

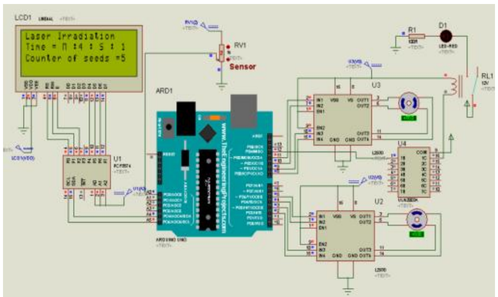

Fig. 12. Show circuit diagram

Fig. 14 illustrates the operation of the CNC machine. In this case, the sensor in the seventh row and tenth column detects the presence of a wheat seed in the hole. The irradiation is activated for a period of five seconds, and once the matrix, consisting of 7 rows and 10 columns, has been fully scanned, the machine returns to its starting point.

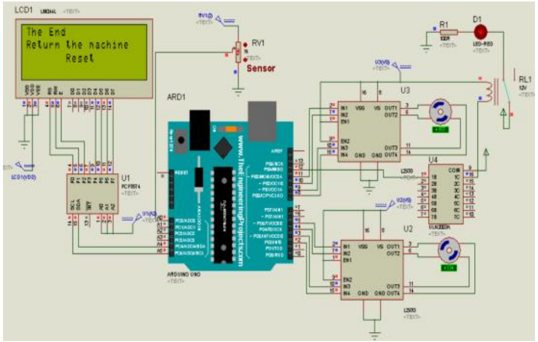

Fig. 13. Fig. 13. Show circuit diagram

VII. Conclusions

The outcome of this project is the successful development of a CNC machine designed to irradiate wheat seeds with a helium-neon laser. The machine improves seed irradiation accuracy and ensures precise timing for each seed, addressing the limitations of manual methods. The system uses a colour sensor to detect the presence of each seed in its position. Once detected, the sensor triggers the laser to irradiate the seed for a fixed duration of 5 seconds. After each irradiation, the stepper motors move the laser to the next position, and the process continues until all seeds in the matrix are treated. This machine has demonstrated the ability to precisely control irradiation time and guarantee complete seed coverage, resulting in a reliable and efficient irradiation process that improves seed treatment consistency.

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