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Design of laboratory setup for performance assessment of weed detection and herbicide application system

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Abstract
A laboratory setup was created, examined, and constructed to assess the effectiveness of a sensor-based weed detection and variable rate herbicide application system in weed recognition and precise herbicide application. The specific dimensions of lab setup were (112.0× 71.0× 71.5 cm3). The lab setup consisted of mechanical system and power transmission system which was integrated with image processing system for weed detection and smart spraying system for chemical application. The mechanical system of lab setup was modelled, analyzed and fabricated using Finite element Analysis (FEA). The mechanical system was geometrically modeled in Creo parametric 5. Chassis and base frame were the key structural mechanical component for support and accommodation of the other components. The designed components were tested for structural strength in Creo simulation 5.0 using Static FEM analysis and validated for the design consideration. Chassis and base frame were loaded with total of 0.8 kN and 1,2 kN normal load. The maximum von mises stress, and strain developed within the chassis and base frame were (44.12 MPa, & 8.89 MPa) and (2.200×10^{-4} & $3.973\times10^{-}5$) respectively. The stress and strain induced in chassis, and base frame were within the safe limit of material. Therefore, base frame and chassis frame design were accepted for the design limits and laboratory setup was fabricated. All the other components procured were mounted to lab setup. The computer aided design using creo-parametric software was found suitable to reduce the time required for repetitive design calculation, fabrication, and assembling work during the actual entire fabrication process.

Keywords: FEM, CAD, Creo software, lab setup, sensor based weed detection, herbicide application, strain, von mises stress

1. Introduction

Weeds are undesirable plants that grow in agricultural fields and compete with crops for water, nutrients, and light. They reduce crop yields and quality, and if left uncontrolled, they can cause significant economic losses (Ekwealor *et al.* (2019) [5]. Chemical weeding is a valuable tool in modern agriculture for controlling weeds efficiently and effectively. It offers several advantages over traditional mechanical weeding, including faster and more precise weed control (Gerhards *et al.* (2022) [7]. While there are some drawbacks to chemical weeding, such as overreliance on herbicides can lead to the development of herbicide-resistant weeds, reducing the effectiveness of chemical weeding. Additionally, its potential dangerous environmental impacts such as contamination of soil and water resources. One solution to this is Site-specific weed management (SSWM), which is a weed control approach that involves the use of precision technology to apply herbicides only where needed (Lopez F. (2011)) [12]. This approach is based on the principle that weeds are not uniformly distributed in a field and that selective weed control can be achieved by targeting weed hotspots while minimizing herbicide use in areas with low weed pressure. The use of SSWM based precision technology apply herbicides only where needed and can help reduce overall herbicide use, leading to cost savings and reduced environmental impact (Hamouz *et al.* (2014) [8]. The design and development of such agricultural machines play a critical role in increasing the efficiency, profitability and productivity of the farming sector. However, the design process of these machines involves multiple challenges such as determining the optimal structure and size, predicting the stress and strain distribution under various loads, and ensuring their durability and reliability. In this context, the Finite Element Method (FEM) provides a valuable tool for the design and analysis of agricultural machines. FEM analysis is a numerical method that can be used to predict the behavior of complex systems, including the response of structures and materials to external loads, vibrations, and thermal conditions (Al-Furjan *et al*., 2011; Jeyaraj *et al*., 2009, Malkani *et al*., 2020) [1, 11, 13]. In agricultural machinery, FEM analysis can be used to simulate the behavior of different components, such as frames, suspension systems, and hydraulic systems (Chen *et al*., 2020) [4]. Also, for the stresses and strains in the frame of a tractor, the deformation of a plow blade, or the fatigue life of a harvester's cutting head. The method is based on dividing the machine into smaller, manageable components known as elements, which can be easily analyzed using mathematical algorithms. The results obtained from the analysis of individual elements are then combined to obtain a comprehensive understanding of the entire machine. This information can be used to make design changes that improve the performance and reliability of the machine. In a study by Zhou *et al*. (2021) [7], FEA was used to analyze and improve the structural design of a potato harvester. The researchers used the simulation results to identify areas of the harvester that were subjected to high stress and strain, and then modified the design to reduce these areas. The improved harvester showed improved reliability and reduced maintenance costs compared to the original design. The study by Vegad & Yadav, (2018) [16] on finite element analysis of three types of rotavator blades (C-shaped, Hatchet-shaped, and L-shaped) in Solidworks and ANSYS software. The simulation results indicated that the Hatchet-shaped blade had the maximum deformation, equivalent stress, principal stress, and shear stress, making it more susceptible to failure compared to the C-shaped blade. The above studies demonstrated the practical applications of FEA in the design of agricultural machinery, as it allows engineers to make informed decisions about the structural design of their machines based on the results of simulations. FEM analysis can play a vital role in optimizing the design of intelligent chemical weeding equipment to ensure accurate and efficient herbicide application. This paper introduces a finite element analysis approach for design of a laboratory setup that can be used to assess the effectiveness of a system for weed recognition and herbicide application on detected weeds.

2. Materials and Methods

The present study was undertaken for designing, analyzing and fabricating the laboratory setup for analyzing the performance of a system in weed detection and herbicide application based on Finite Element model (FEM) based approach. The system was built in the divisional workshop of the ICAR-Division, IARI's of Agricultural Engineering, where this study was carried out during 2018-2021. The FEM analysis process involves the modelling, meshing, analysis and optimization of the model. Modeling is the first step in FEM analysis is to create a computer model of the component or system that is to be analyzed. This involves defining the geometry, material properties, and boundary conditions. Meshing of the computer model is then divided model into small, discrete elements using a meshing algorithm. The size and shape of the elements can be adjusted to optimize the accuracy and speed of the analysis. Analysis using the FEM simulation software then solves a set of mathematical equations to determine the response of the system to the applied loads and boundary conditions. This can include stress and strain calculations, as well as dynamic simulations of vibration and thermal effects. The last one is optimization, once the analysis is complete, the results can be used to identify areas of the design that need improvement or modification. This can include optimizing the geometry, selecting better materials, or adjusting the boundary conditions to reduce stresses and improve performance.

2.1 Geometrical modelling

The laboratory setup for weed detection and herbicide application system consisted of mechanical system and power transmission system which was integrated with the systems of weed detection and herbicide application. The mechanical system comprised of base frame, chassis, microprocessor box, camera assembly, light emitting diode (L.E.D) assembly, and light protecting cover box. The mechanical system was mounted on main frame carriage of exiting soil bin. Image processing system for weed detection and spraying system for herbicide application were mounted to the mechanical system to complete the laboratory setup. The conceptual drawing of geometric model laboratory setup for weed detection and herbicide application system with different views were shown in Fig.1 and Fig.2. The different components were geometric modeled in Creo parametric 5 and assembled in it. Then statical analysis was carried out through Creo Simulation 5 purchased by Division of Agricultural engineering, IARI, New Delhi for base frame and chassis of mechanical system due to dependency of others components on them. Based on the analysis results a decision to modify or fabricate the components of laboratory setup were taken.

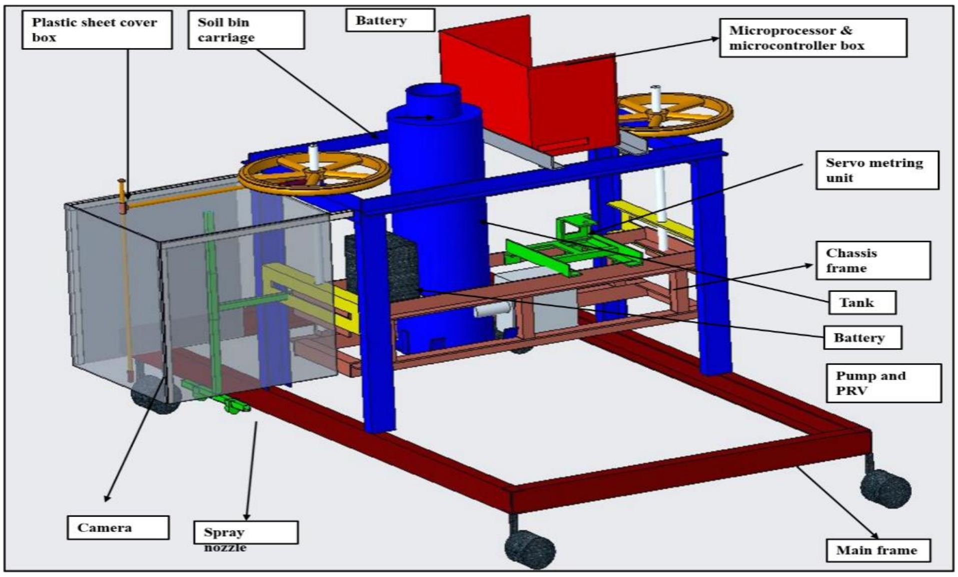

Fig 1: Conceptual drawing of laboratory setup for weed detection and herbicide application system

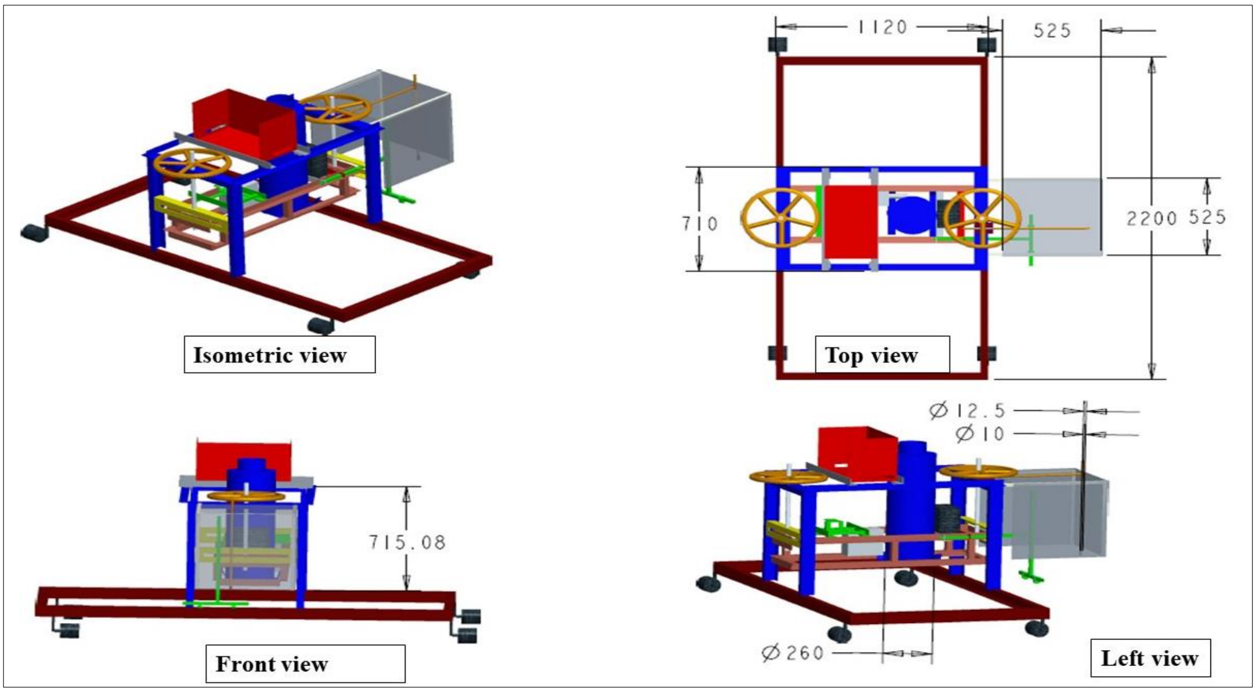

Fig 2: Different views of laboratory setup for weed detection and herbicide application system

2.1.1 Mechanical system

The mechanical system provides structural strength, stability and space for accommodation of image processing-based weed detection and herbicide application system.

2.1.1.1 Base frame and Chassis

The experimental test setup consisted of two frames i.e., base frame and chassis. Chassis and base frame were of 0.986 m× 0.155 m×0.215 m and, 0.90 m×0.45×0.760 m respectively. Size of existing main frame 1.1 m×0.7 m. The chassis was attached to the base frame while base frame was attached to the existing main frame of soil bin carriage system. The soil bin carriage consisted of rope and pulley system through solid angle iron arms on both sides of the soil bin from the bottom side to propel the system which is powered by motor (Fig 3). Two steering wheels screws were also mounted on the two extreme sides of the base frame for height adjustment. Table 1 list detail specification of chassis and base frame of prototype. The chassis and base frame were geometric modelled in crop parametric 5 and Static Finite Element Method (FEM) based force analysis was carried out by creating meshing and providing boundary conditions. Table 2 enlist Physical and mechanical properties of steel selected for chassis and base frame.

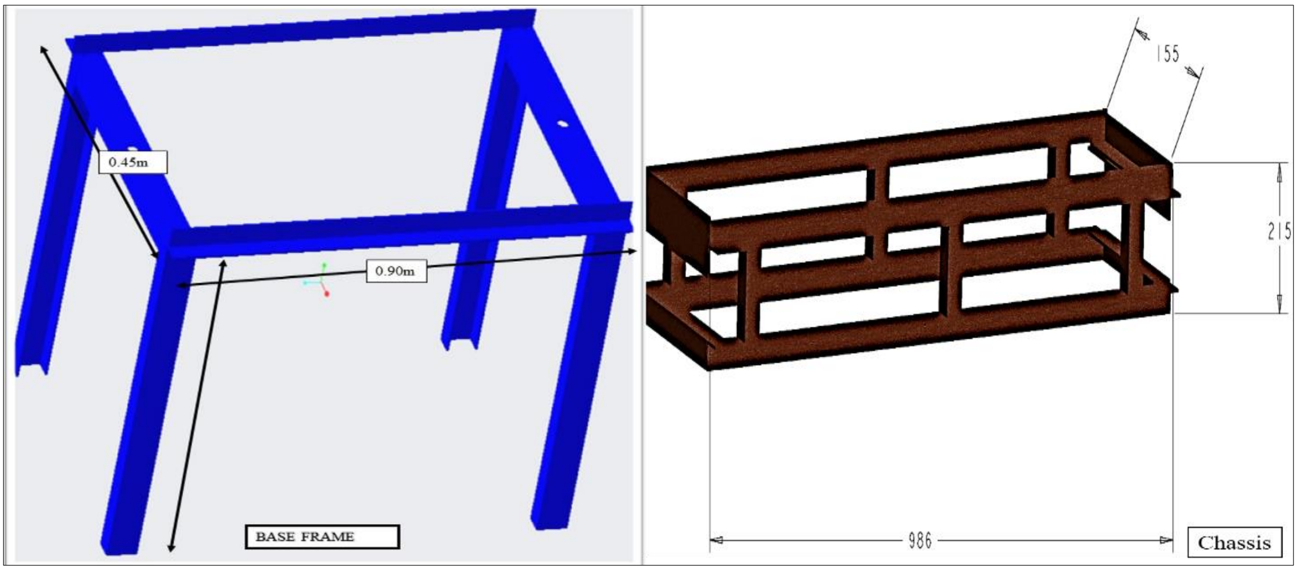

Fig 3: Computer aided design of mainframe and base frame of laboratory setup for weed detection and herbicide application system

Table 1: Detail specification of Chassis and Base Frame of prototype

Components	Component name	Cross section(mm)
Chassis	MS hollow frame	45 mm x 45 mm x 3.2 mm
Base frame	MS, U section Angle iron	75 mm x 40 mm x 4.8 mm 40 mm x 40 mm x 5 mm

Table 2: Physical and mechanical properties of steel selected for mainframe and base frame

Specification	Values
Yield strength	250 MPa
Density	7827Kgm^{-3}
Poisson's ratio	0.27
Young modulus	199.948Gpa

2.1.1.2 Microprocessor box

A microprocessor box of dimensions (48.7 cm×23.2 cm×13.8 cm) was fabricated with MS sheet to accommodate various types of laptops for image processing. It was provided with slots to allow webcam wires to connect easily. The box strength was sufficient for load carrying capacity of laptop and its accessories. It was mounted on the top of base frame with the help of angle iron bars.

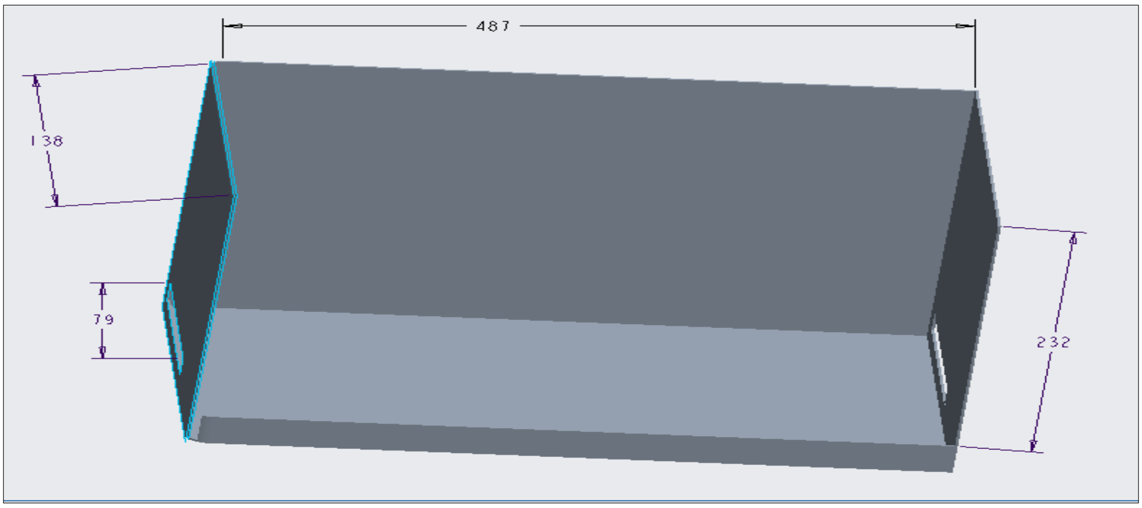

Fig 4: Computer aided design of microprocessor box of laboratory setup for weed detection and herbicide application system

2.1.1.3 Camera assembly

A camera assembly for lateral and vertical adjustment of webcam for image acquisition was modelled and fabricated using MS material (Figure 5 (left)). The camera assembly consisted of vertical hollow shaft and horizontal hollow shaft of dimensions (diameter× length) 25 mm, 800 mm & 25 mm, 600 mm respectively and was mounted to the base frame.

2.1.1.4 Led assembly for illumination control

A led assembly for attaching different led bulbs to maintained desired illumination was constructed. It consisted of a led frame of MS sheet (250 mm ×200 mm ×5 mm), vertical and horizontal square pipe of length 0.6 m and cross-section (25 mm×25 mm) (Figure 5 (right)). The assembly was connected at the front side to the base frame and was enclosed inside the light protection box.

2.1.1.5 Light protection box

A plastic sheet cover box of dimension (70×60×70 cm^3) was fabricated with angle iron (25 mm×25 mm) and plastic PVC sheet of thickness 0.5 mm. This was provided to obstruct the external light. It was fixed to base frame of test setup from the front side.

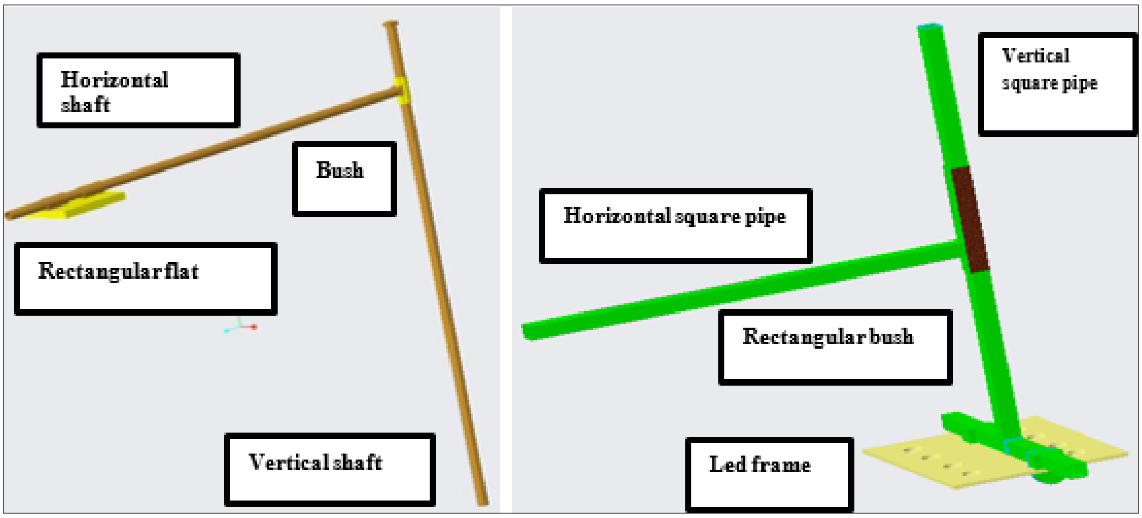

Fig 5: Camera assembly (left) and led assembly (right) for laboratory setup

2.1.2 Weed detection system of laboratory setup

The weed detection system comprised of webcam-based image sensor and microprocessor for real time weed detection. Image based webcam sensor (HD 1080 logitechc 615) resolution was selected for the real time image acquisition of weeds and mounted on camera assembly. The digital computer used for processing the images was ASUS Vivo book ultra 14 core i5 laptop due to its fast-processing speed and kept on microprocessor box. The laptop was installed with MATLAB software and pre developed code was inserted in it for image processing and weed recognition. The MATLAB code process the image capture in real time and supplies the output in terms of variable rate green index to the variable rate herbicide applicator unit.

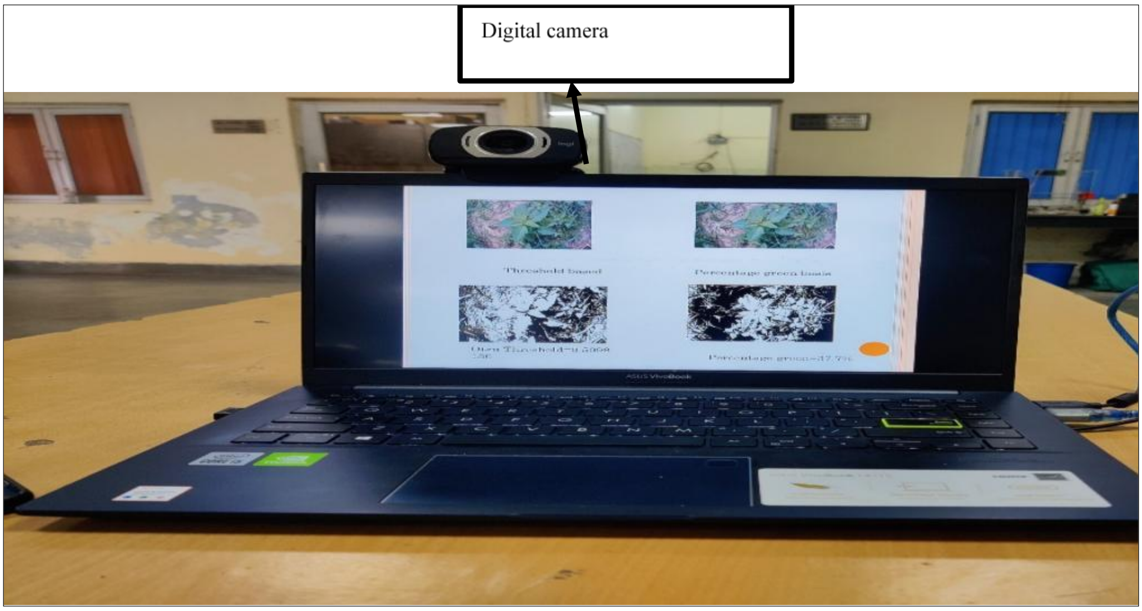

Fig 6: Weed detection system of image sensor- based weed detection and herbicide applicator system

2.1.3 Variable rate spraying system of laboratory setup

The variable rate spraying system was mounted to the mechanical system on chassis and base frame to provide different volume of spray on the basis of variable rate output obtained of weed detection system. The variable rate herbicide application system consisted of servo motor operated metering unit, microcontroller (ATMEGA-2560), pump and pressure relief valve, pipe and hoses, nozzle, buck converter and serial port communication. Servo motor operated metering unit consisted of 40kgcm servo motor ((Robocraze, CYS-S8218), three- way valve (18 mm throat diameter), and pipes attached to the nozzles. These components were mounted on a Mild steal frame of dimension (30 cm×30 cm×15 cm) to the top of chassis and power was supplied through battery (Fig. 7). The output of weed detection system were in form of green index and it sent the signals to the Arduino. The Arduino sent the signals in terms of pulse to the servo motor for a particular rotation. The flow control valve attached to the servo motor opens at a pre-calibrated opening and the desired flow rate were applied to the weeds for a specific duration.

Fig 7: Variable rate servo motor operated spraying system

2.1.4 Power transmission system for the laboratory setup

The laboratory setup was provided with the three -phase motor (5 hp, 1430 rpm) as a power source to propel the laboratory system (Fig. 4). It was provided with a Delta VFD-M (3.7 kW, 460 V 3 phase) speed controller for regulating speed within a limit. Motor speed was reduced using the controller and gear box of reduction (30:1). The power transmission system was attached to the mainframe using rope and pulley arrangement for propelling the lab setup.

2.2 Boundary conditions for chassis and base frame of laboratory setup

Chassis and base frame were the critical components for supporting the other structures of lab setup. Therefore, further analysis was carried out for these two components. Boundary condition such as constraining and loading were applied to chassis and base frame. The boundary conditions for chassis and load supporting structure were shown in Fig. (8). Geometry was kept fixed for portion retaining the rest structure and forces were applied at the point of contact of loads. The chassis was kept fixed with constraints from 2 portions at end region points as shown by blue color arrow and loaded top portion highlighted with arrow in orange color. Maximum load to be supported by chassis was 80kg (800 N). The base frame was fixed from 4 sides (contact area=40×40 mm^2) on main frame and loaded from the top and chassis connected region side with external load of (L2=200N and L3=1000N).

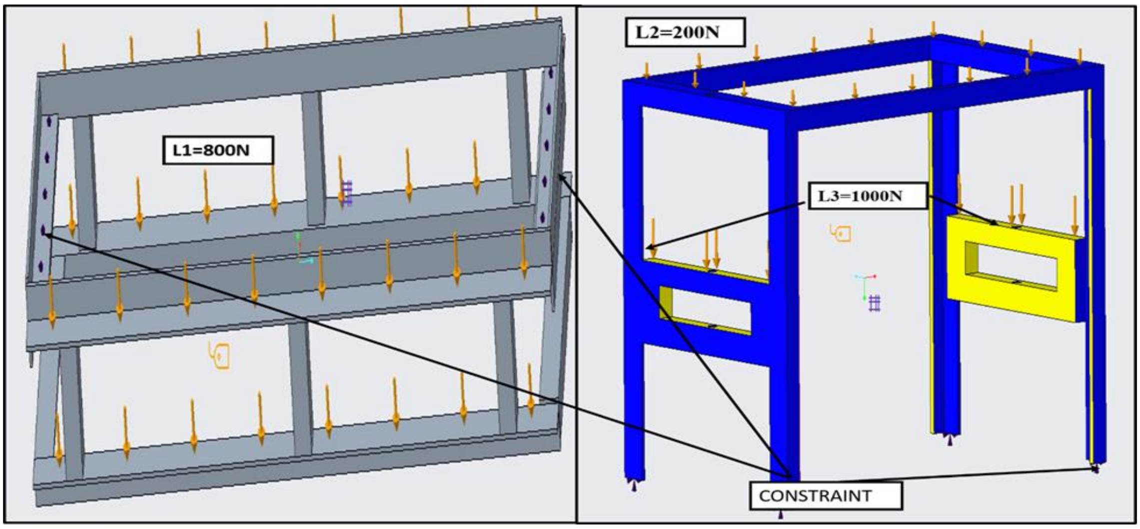

Fig 8: Boundary conditions of chassis, and base frame laboratory setup for weed detection and herbicide application system

2.3 Meshing of structures

After geometric modelling and boundary condition, mesh structure for chassis and base frame were created. Meshing is the discretization process in which chassis and base frame were divided into numbers of small elements (Anusha *et al*., 2013) [2]. Mesh structure for base frame and chassis were created with element size 10mm (Fig 9). Table 5 list out the details of mesh structure of chassis and base frame.

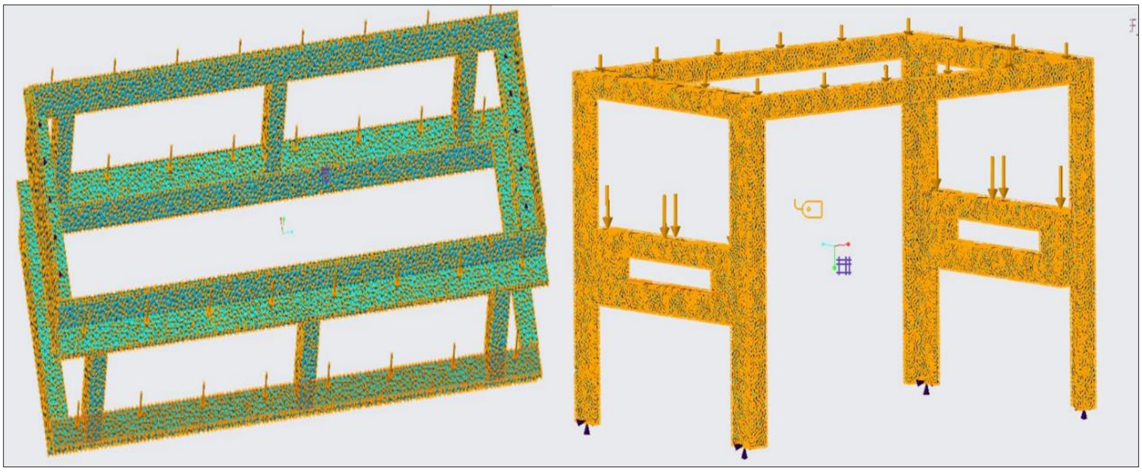

Fig 9: Mesh structure of chassis and base frame with cross section of mesh structure

Table 5: Meshing details of chassis and base frame of lab setup

S. No.	Name	Quantity in number (Chassis)	Quantity in number (Base frame)
1	Element size	10 mm	10 mm
2	No. of nodes produced	36558	80542
3	No. of elements produced	10161	28433

2.4 Simulation Analysis
After imposing the boundary condition and creation of mesh structure, static analysis was carried out for chassis and base frame. It was started by assigning the materials to the components. The important simulation analysis factors such as Von-Misses stress, deformation and strain in components were determined in Creo simulation 5.0.

2.4.1 Von –Misses stress
Von Mises stress is a measure of the stress in a material that is subjected to three-dimensional loading. It represents the equivalent stress in the material, taking into consideration all three principal stresses. For a component to not yield, the developed stress in component should not cross the ultimate strength of material. Steel material is used for designing chassis and base frame of lab setup which are constructed of ductile material. The Von-Misses theory can be applied in ductile materials. Von-Mises's stress is calculated by using the equation (1) (Bramanti, *et al.*, 2017).

$$\text{Von} - \text{Mises stress}(\sigma) = \sqrt{\left(\frac{(\sigma1-\sigma2)2+(\sigma2-\sigma3)2+(\sigma1-\sigma3)2}{2}\right)} \text{........ Eqn. 1}$$

In equation 1, $\sigma1$, $\sigma2$ and $\sigma3$ are the principal stresses connected with the three principal directions.

2.4.2 Deformation
It is the distortion in size and shape of material that occurs when the material is loaded (tensile, compressive etc.

2.4.3 Strain
It is the response of material to the applied stress. It is the ratio of change in length to the total length. Strain= $\frac{\delta L}{L}$.

3. Results and Discussion
The simulation results for chassis, and base frame were obtained in Creo simulation 5. These results are based on 3D modeling and numeric methods. Analysis were based on the given boundary conditions and are discussed as follows.

3.1 Analysis of chassis
3.1.1 Stress Analysis in Chassis
The maximum and minimum von mises stress developed were 44.12 MPa and 1.506×10^{-5} MPa respectively. Maximum stress was developed in the joint region of chassis (Farhadi *et al.*, 2012, Malkani *et al.*, 2020) [6, 13]. The maximum value of stress is smaller than the ultimate yield strength of steel which shows designed value is suitable for fabrication. Jakasania *et al.* (2016) [10] conducted a similar study and concluded that during design of model, working stresses should be less than the maximum or ultimate stress at which material failure occurs. The von mises stress developed in chassis were shown in Fig (10).

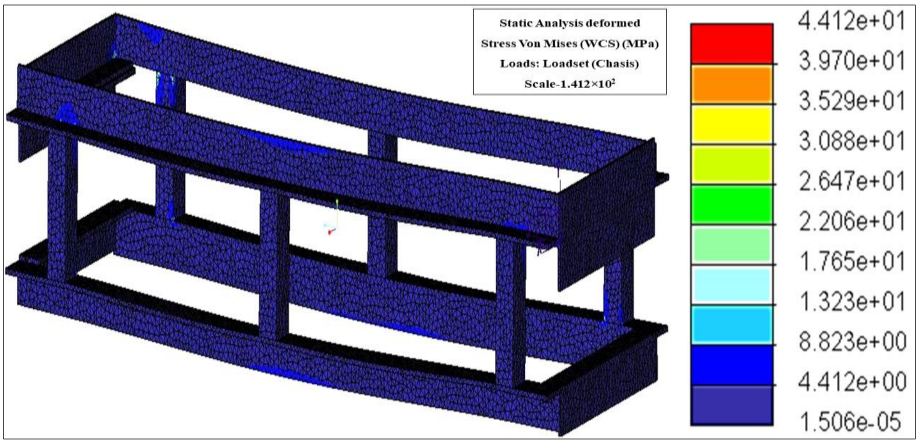

Fig 10: Von Misses Stress developed on Chassis after loading with external loads

3.1.2 Deformation analysis on Chassis
The maximum deformation 773.6×10^{-4} mm was at the center region Fig (11). It was because of higher bending moment developed at the center due to normal load (Holden, J. T, (1972)) [9].

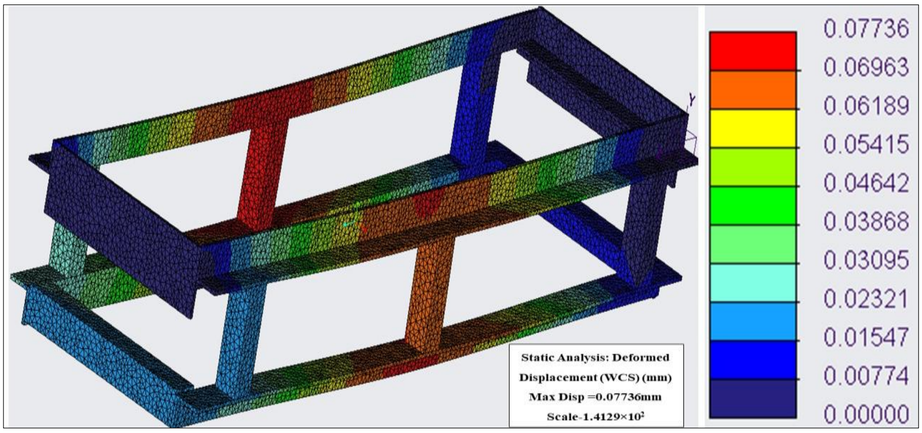

Fig 11: Deformation produced on chassis after loading with external loads

3.1.3 Strain Analysis on Chassis

The maximum strain induced in chassis was observed as 2.200×10^{-4} at the joint region as in Fig (12). It is due to the development of maximum stresses in these regions. The minimum value of strain observed was -3.531×10^{-6}.

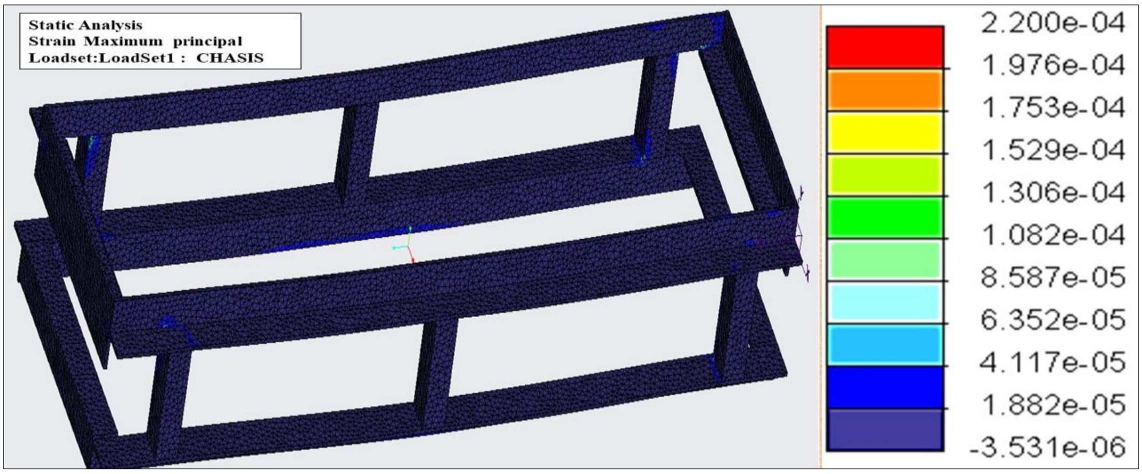

Fig 12: Strain developed on chassis after loading with external loads

3.2 Simulation Analysis of base frame

Through the Static analysis, the maximum von mises stress occurs at the contact surface and top of base frame. The maximum stress, deformation and strain were found to be 8.89 MPa, 0.00961 mm and 3.973×10^{-5} as shown in Fig (13, 14, and 15) respectively. The maximum displacement occurs at the top center region of MS sheet. Malkani *et al*., 2023 [14] reported similar results while designing the sensor-based herbicide applicator using FEM.

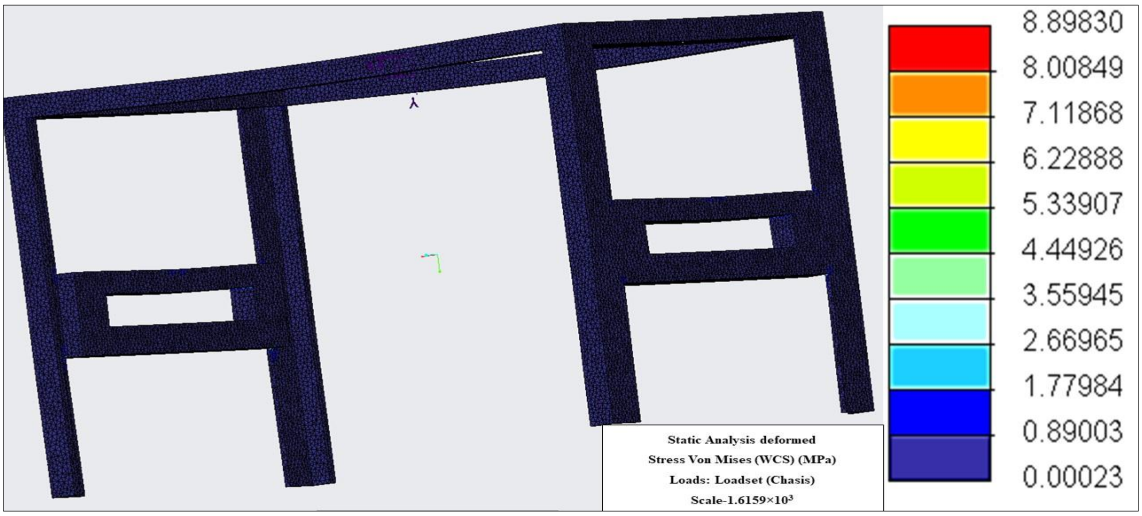

Fig 13: Von Misses Stress developed on base frame after loading with external loads

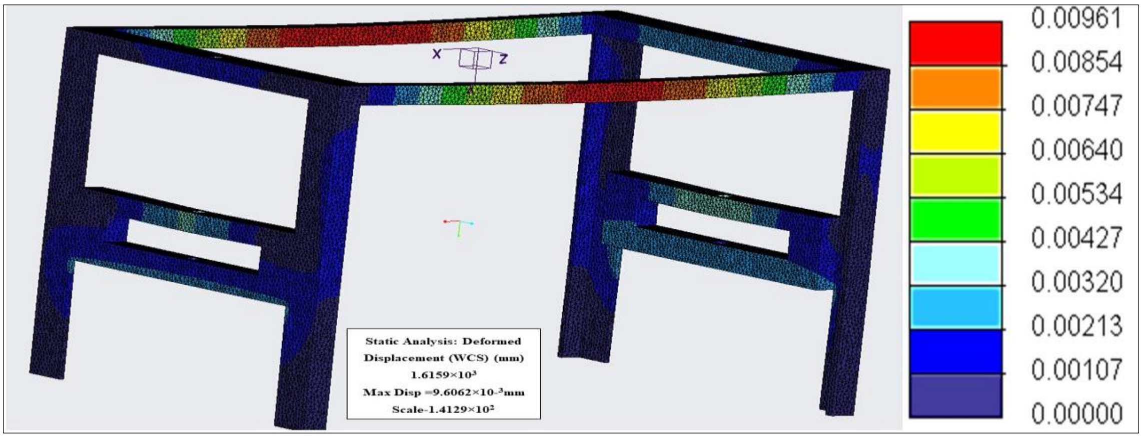

Fig 14: Displacement analysis on base frame after loading with external loads

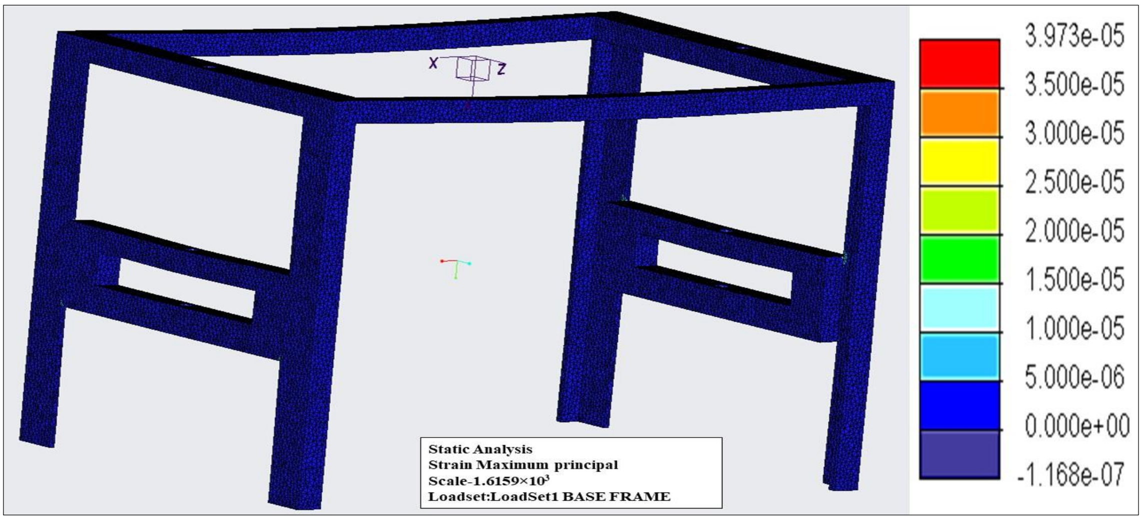

Fig 15: Strain analysis on base frame after loading with external loads

3.3 Optimization of base chassis and base frame

The stresses and strain in chassis were more in joint portion and deformation was maximum at the center of chassis. The stress and strain values were found to be significantly lower than the yielding strength of steel material. Therefore, chassis was considered safe and suitable for fabrication and no further improvement was required. Similar type of results was obtained during the development of trolley type manually operated agrochemical sprayer (Sagar *et al.*, 2017). From the analysis result the chassis was good enough for the fabrication purpose. While for base frame maximum stress and strain develop were within the bearable range of steel material. Therefore, it was safe for final fabrication purpose with no modification. Malkani *et al*., 2020 [13] found similar results of stress and strain within the safe limit of ultimate yield strength of chassis frame for design of high clearance sprayer.

3.4 Fabrication and assembly of test setup

Based on simulation analysis base frame and chassis were fabricated with the selected dimension and material property. The other components of laboratory setup for automatic weed detection and herbicide application system were selected from the local market and assembled for final prototype as shown in Fig [16]. Fabricated was done in the workshop of Division of Agricultural Engineering, ICAR-IARI, New Delhi. The chassis was fixed to base frame through nut bolts and welding. The top of chassis was provided with servo motor operated unit, battery and spray tank. The base frame transmits the load to the main frame and on top of it supports microprocessor box and, on the front, supports the camera assembly, light assembly and light protecting cove box. The spray nozzle was provided just behind the webcam at front for rapid application of chemicals after the weed detection. The existing main frame was connected to the power source through rope and pulley arrangement. The developed prototype detects the weeds and allows application of chemicals on weeds.

Fig 16: Developed prototype of sensor- based weed detection and herbicide applicator system

3.5 Advantage of developed sensor-based herbicide applicator

The key advantages of lab setup for weed detection and herbicide application system was its ability to test the performance of individual weed detection system and effectiveness in assessment of spraying accuracy over the weeds. Also, its simple design, and control allow it to use it for other purpose such as nozzle testing, weeding tool testing etc.

4. Conclusion

The study concluded that the Finite Element Analysis (FEA) in Creo parametric 5 and Creo Simulation 5 for design and analysis study are very effective and powerful for designing, testing and optimization of performance of mechanical components. The maximum von mises stress, deformation and strain developed within the chassis were 44.12 MPa, 773.6×10^{-4} mm and 2.200×10^{-4} respectively, while in base frame the maximum stress, deformation and strain were found to be 8.89 MPa, 0.00961 mm and 3.973×10^{-5}. The stress and strain induced in chassis, and base frame were quite within the safe limit. Therefore, the developed model design for chassis and base frame were accepted for fabrication. The overall dimension of laboratory setup for weed detection and herbicide application system was ($112.0 \times 71.0 \times 71.5$ cm^3) and were simple and compact in design. It allows easy testing of weed detection and spraying unit performance. FEM based methods saved considerable time over hit and trial-based method of prototype development. In can be concluded that the use of FEM in the design of agricultural machines provides a powerful tool for improving their efficiency, reliability, and safety. The method can help engineers to make informed decisions about the design and performance of these machines and to optimize their performance for specific applications.

5. Acknowledgment
The authors would like to thanks faculty members, workshop staff, juniors and friends of Division of Agricultural Engineering, IARI, New Delhi for necessary help.

6. Competing Interest
The authors have declared t no competing interest exists.

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