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Design and fabrication of sensor-based herbicide applicator using FEM

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Abstract
A hardware setup of sensor-based herbicide applicator of dimension (l.6 m× 0.55 m×1.1 m) was designed, analyzed and fabricated for site-specific weed management. The prototype consisted of chassis, load supporting structure, motor-gearbox, battery, pneumatic wheels, weed detection system and variable rate herbicide application system. Chassis and load supporting structure were the key components for the structural support and accommodation of the other components and were designed in Creo parametric5.0 using Finite element method (FEM). The designed structures were tested for structural strength in Creo simulation 5.0 using Static FEM analysis for validating the design consideration. Chassis and load supporting structure were loaded with a 1 kN and 0.60 kN normal load. Results revealed maximum von mises stress, deformation and strain developed within the chassis and load supporting structure were (5.09 MPa & 2.11678 MPa), (9.45×10^{-4} mm & 0.01426 mm) and (3.021×10^{-5} & 5.815×10^{-6}) respectively. The results of analysis revealed both the designs were within the safe limits of stress and strain, hence the designs values were selected and hardware was fabricated. All the other components procured were assembled and mounted to the chassis and load supporting structure and prototype was developed. 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, herbicide applicator, sensor-based weed detection, strain, von mises stress

1. Introduction
Increased in cost of agricultural inputs day by day added a clear preference of reducing the use of chemicals in agriculture to make agriculture more profitable and sustainable, and precision agriculture can be the promising alternative to reduce the chemical. The recent advancement in technology develops a need for precision agriculture which include right amount of input at right time and in right quantity to increase farm productivity by reducing farm losses due weed infestation and pest attack. Weeds grow in the fields and compete with main crop for nutrients water, light and space and thus reduce the crop yield (Ozluoymak, *et al*., 2019) [11]. The methods to control the weeds are generally classified into mechanical, chemical, thermal and biological. The mechanical measures are labor consuming which includes cutting or uprooting the weeds plants. Chemical measure of weed control includes use of herbicides at various stages of plant growth using sprayers. However, it applies large volume of solutions which is hazardous and cause environmental pollution caused by drift of these chemicals (Savci, 2012; Samir *et al*., 2020) [14, 13]. Therefore, it necessitates the need for an efficient method of controlling weeds without the risk of herbicide drift with minimal impact on non-target plants. Weed distribution particularly grass weeds in cereal crops are often ‘patchy’ rather than uniform or random (Tewari *et al*., 2014; Garibaldi *et al*., 2022) [16, 5]. Therefore, site specific based weed management (Patch spraying) may prove to be effective and could reduce the amount of herbicide applied. This practice results in no spraying where no or few weeds exist and chemical usage would be reduced and chemicals would be more effectively placed in the field. For weed control and management, the quantities of herbicide applied can be reduced by using a site-specific application approach. These practices would result in lower environmental pollution and increased profitability in the agricultural production sector. To guide site-specific herbicide application, a machine vision and image processing system, based on digital camera technology can be used to detect the presence and variability of weeds in the field and a

variable rate controller sprayer can apply herbicides over detected weeds by varying the valve opening and duration control (Tian *et al*., 1999) [17]. These site- specific technology based on digital image processing and variable herbicide applicator technology have potential to save 70-75% herbicide saving as compared to conventional chemical method (Yang *et al*. (2003) [19]; (Loghavi, & Mackvandi, (2008) [9]. Shirzadi *et al*., 2013 [21] developed and evaluated a real-time, trail- type, site-specific single inter-row herbicide application system based upon machine vision. The weeding control system consisted of an electronic circuit, an image acquisition, and processing system, a rotary encoder, spray nozzles, solenoid valves and other hardware. The target application outcome in 75% less herbicide consumption compared to the conventional application, with similar effectiveness in weed removal. The design and development of these sprayers using conventional design approach are time consuming and involves rework and refabrication. Finite element Model based analysis enables one to rapidly spot problem areas and it redesign the product without the costly rework and re-fabrication, thus saving time and money. FEM is a numerical based approach for solving physical problems using differential equations. It discretizes the domain region, formulates equations, and solved them, and finds the variables of interest (Velloso *et al*., 2018; Sagar *et al.*, 2017) [20, 12]. Many researchers suggested that the chassis need to be design by considering necessary assumptions of the gross weight of the vehicle and validate and improve their designs by using FEM in their investigation for the design and optimization of chassis for trailers, trucks, machinery, and for others agricultural implements (Hoefinghoff *et al*. 2011; Farhadi *et al*., 2013; De O. *et al*., 2014. Sagar *et al.*, 2017) [6, 4, 3, 12] developed a trolley type agrochemical sprayer was developed based upon FEM. The maximum stress and deformation observed on front wheel was 13.948MPa and 0.0000646 mm, while on trolley it was 6.370 MPa and 0.13576mm respectively. These limits were found to be safe for the design of sprayer. In this paper, development of sensor-based herbicide applicator using FEM is presented. The critical components providing structural strength such as chassis and load supporting structure were designed and analyzed using CREO software based on Finite element Method.

2. Materials and Methods

This study was conducted in Division of Agricultural Engineering, ICAR- IARI, New Delhi and the system was fabricated in the Divisional workshop. The setup is initially geometric modeled in Creo –parametric 5.0 and analyzed in Creo simulation 5.0. The prototype of sensor-based herbicide applicator consisted of hardware components (chassis, load supporting structure, microcontroller box and microprocessor box), Power source (Battery), Power transmission component (Gearbox and chain and sprocket), Pneumatic wheels, weed detection system and variable rate metering system (Fig 1). Different views of sensor-based weed detection and herbicide applicator system was in Fig (2). The overall prototype dimension (length ×width× height) was (l.6m× 0.55m×1.1m) respectively.

2.1 Design of hardware components

The design of hardware components was important for accommodation of other components and structural stability of prototype model. The prototype consisted of two frames 1) - chassis, 2)- Load supporting structure. Size of chassis and load supporting structure were kept 0.35 m×0.850 m and 0.90 m×0.45 m respectively (Fig 3). The others components were mounted to the chassis and load supporting structure. The chassis was provided with enough space to accommodate power transmission components (motor and gearbox) and tank of variable sprayer components, while microprocessor box, power source, and other components of weed detection and variable rate spraying components were mounted on load supporting structure. Table 1 list detail specification of chassis and load supporting structure of prototype. The chassis and load supporting structure were geometric modelled in crop parametric 5 and Static Finite Element Method (FEM) based force analysis was done by creating meshed structure and imparting boundary conditions.

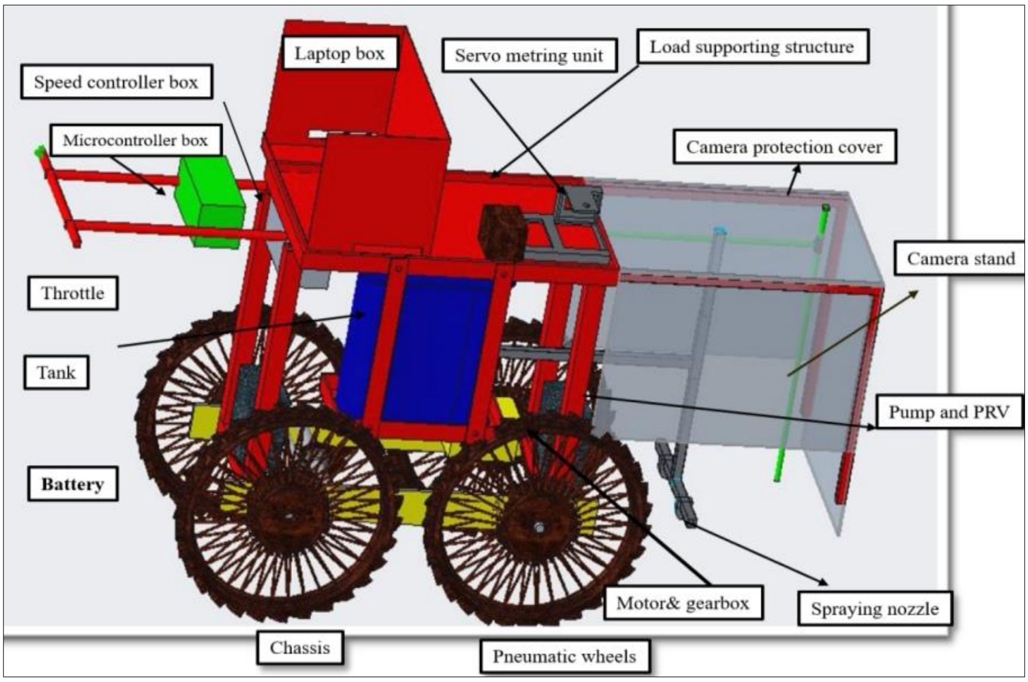

Fig 1: Computer aided design of sensor-based weed detection and herbicide applicator

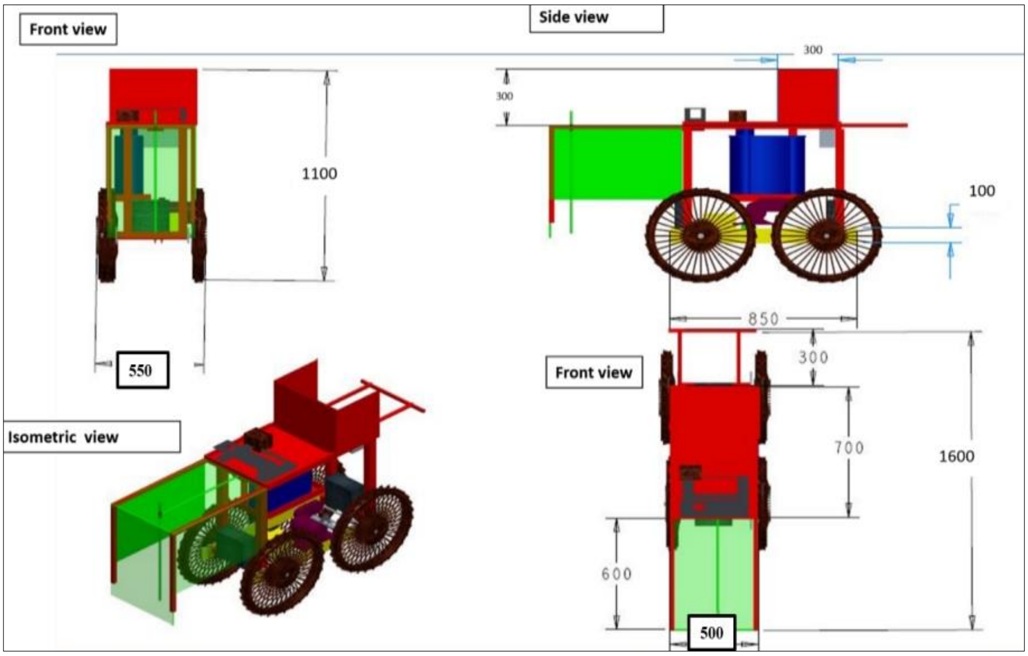

Fig 2: Different views of sensor-based weed detection and herbicide applicator system

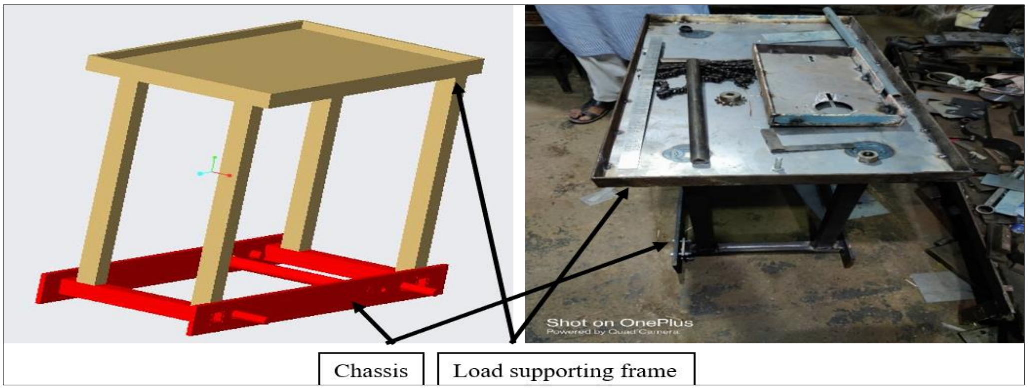

Fig 3: Computer aided design and actual fabricated system of chassis and load supporting structure

Table 1: Detail specification of chassis and Load supporting structure of prototype

Components	Component name	Cross section(mm)
Chassis	MS hollow frame	40×40×2
	MS Flat	100×10
Load supporting frame	MS hollow frame	40×40×2
	MS sheet	500×2

Table 2: Physical and mechanical properties of steel selected for chassis and Load supporting structure

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

2.2 Power source for sensor-based weed detection and herbicide applicator system

The prototype was provided with motor to propel the system which was powered with battery as power source (Fig. 4). Motor transferred the power to drive wheels with power transmission system. A motor ((MY 1016Z- 024V, 480RPM 450 W) was selected based on total load to propel at various speed. Two batteries (12v, 25Ah each) were provided based on total motor power requirement at various operating condition. Table 3 list details specification about power source used.

Table 3: Specifications of Battery for sensor-based weed detection and herbicide applicator system

Model No.	Type	Capacity	Size	Probable Life
260240	Lead- Acid Rechargeable battery	12 V-7 AH	150×65×95 mm	5 years

Fig 4: Motor and pneumatic wheels for sensor- based herbicide applicator

2.3 Power transmission components of sensor- based herbicide applicator

The power was supplied through motor to drive wheels via. transmission system. Transmission system consisted of gearbox and chain and sprocket. The maximum rotational speed of motor was (480 rpm) which was reduced using suitable gear box of gear reduction (1:10). The speed was further reduced by the chain sprocket system gear ration (1.8:1) from the gearbox to the wheel shaft. Speed controller was also provided to get various range of speed. Gear box and chain and sprockets were mounted on chassis.

2.4 Pneumatic wheels for sensor- based herbicide applicator

Pneumatic tires with rim, transfers the normal load of the system from chassis to the ground using axle and develops traction force at soil-tire interface. Four pneumatic wheels were selected for front and rear wheels (Fig. 4). Rear wheels were provided with separately fabricated rims of MS steel for generating the traction, while the front wheel tires were provided with spokes type rim. The pneumatic wheels were selected based on load to be carried, power requirement and local availability of tires. The detailed specifications of the mounted tire are given in Table 4.

Table 4: Specifications of selected pneumatic tire for sensor-based weed detection and herbicide applicator system

SI No.	Rim Dia.(mm)	Section width (mm)	Section Height (mm)	Overall Dia. (mm)
1	426	52	35	480

2.5 Storage Tank of sensor- based herbicide applicator

Storage tank of 20-liter capacity and made of PVC material was provided based on the storage tank capacity and number of fillings required per acre. The tank of moderate capacity, non-corrosive and the maximum number of fillings required 5-7 times per acre and was mounted in between space of chassis and load supporting frame

2.6 Microprocessor and microcontroller box of sensor-based herbicide applicator

A microprocessor box of dimensions (40cm×20cm×20cm) and 0.5mm thickness was fabricated with MS sheet to accommodate various types of laptops and microcontroller. 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.

2.7 Camera assembly of sensor-based weed detection and herbicide applicator system

A camera assembly consisted of vertical hollow shaft and horizontal hollow shaft was fabricated from MS pipe to attach the webcam at front side (Fig.5). The dimensions (Diameter× length) of shafts were (25mm, 800mm & 25mm, 600 mm) respectively.

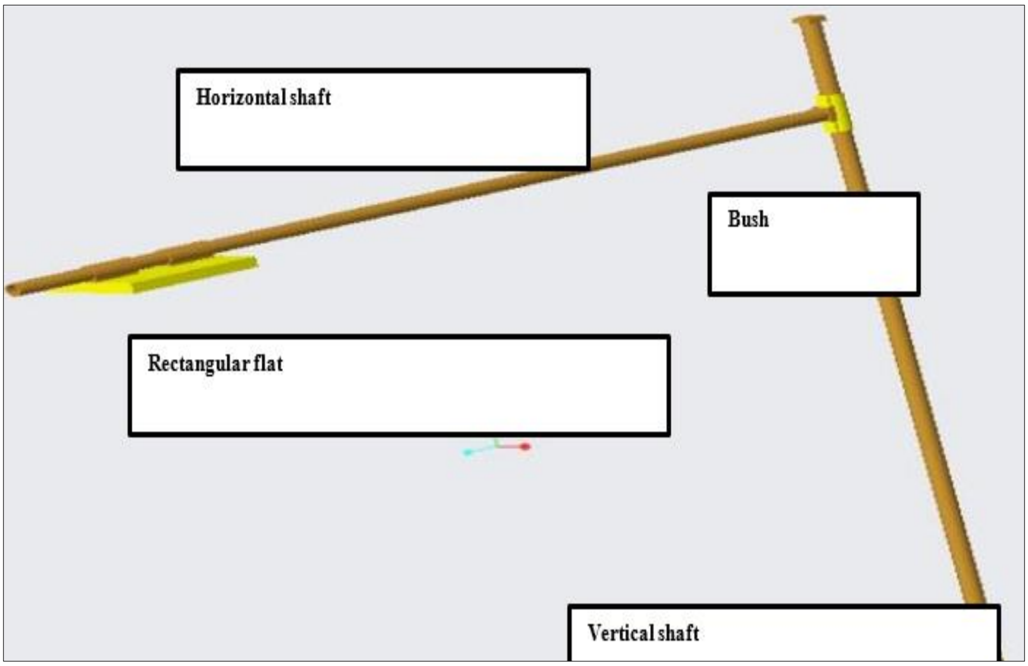

Fig 5: Camera assembly for prototype

2.8 Light protecting box of sensor-based weed detection and herbicide applicator system

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

2.9 Roller pitch chain for power transmission in prototype

A roller pitch chain of 12.5 mm pitch of length 450mm was selected based on power transmission from gear box shaft to driving wheel. The gearbox sprockets and axle connected sprockets teeth were 20 and 36 teeth and desired speed for system was in between 1.5-3 kmh^{-1}.

2.10 Drive shaft for power transmission of motor

A shaft diameter 25.4 mm, length 450mm for transmitting power from axle sprocket to ground was selected to supply the power from motor-gearbox to ground.

2.11 Weed detection system of sensor- based herbicide applicator

The weed detection system comprised of sensor and microprocessor for real time weed detection. Image based webcam sensor (HD 1080 logitech C615) with 640×480 resolution was selected for the image acquisition of weeds due to its lower image processing time with selected digital computer. The digital computer used for processing the images was ASUS Vivo book ultra 14 (core i5 10 gen-(Ram 8Gb+32GB Optane /512 GB SSD) laptop due to its fast-processing speed. 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.

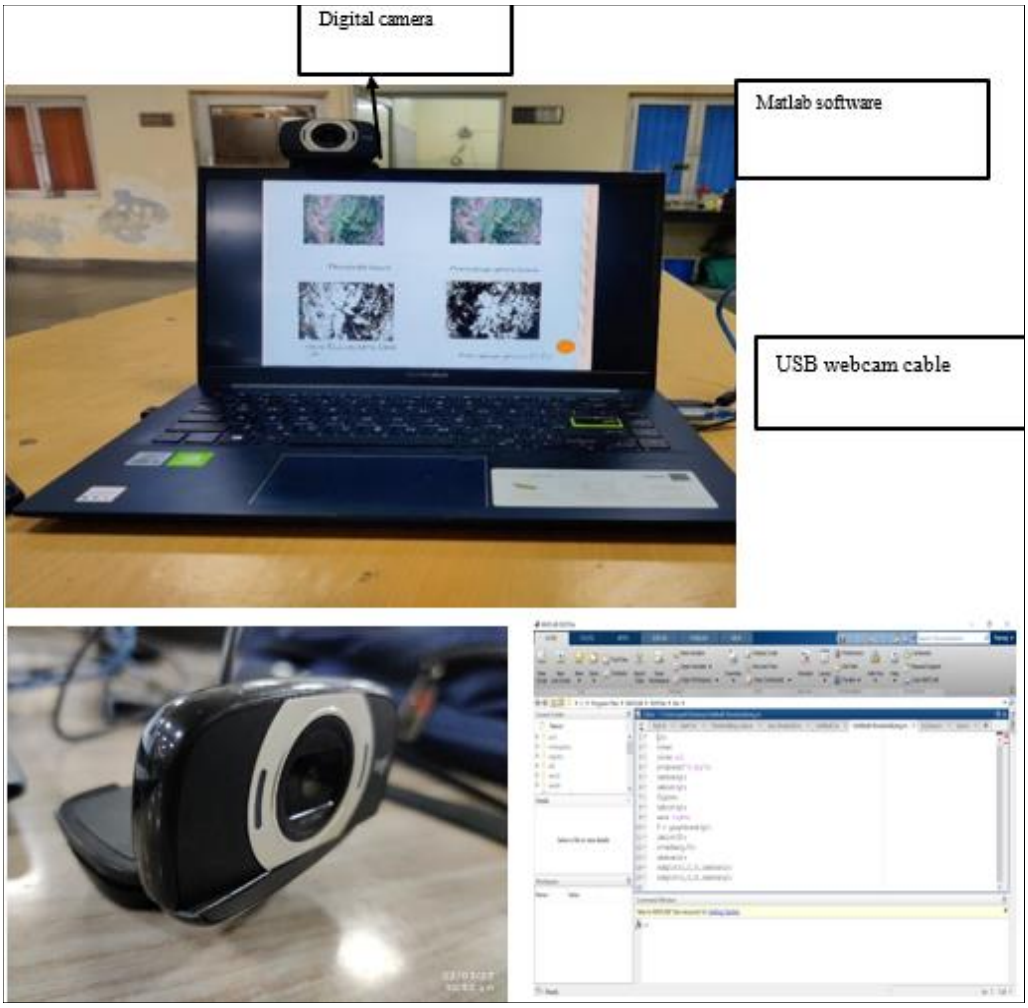

Fig 6: Weed detection system of image sensor- based weed detection and herbicide applicator system

2.12 Variable rate metering system of sensor- based herbicide applicator

The purpose of variable rate spraying was 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 (30cm×30cm×15cm) to the top of load supporting structure 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.

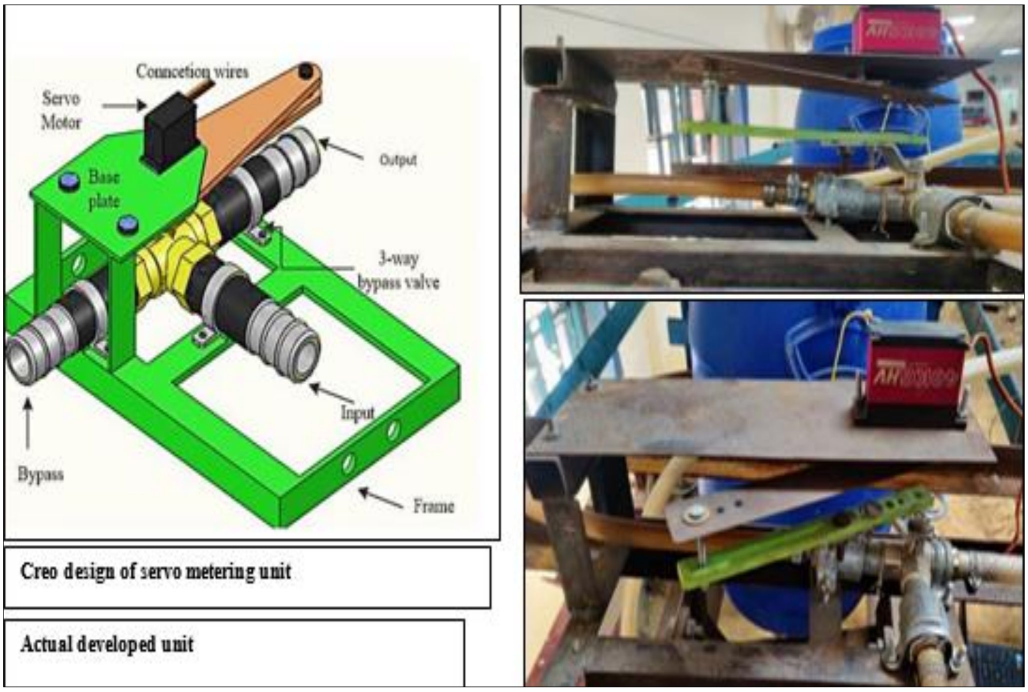

Fig 7: Creo design and developed servo operated metering unit

2.13- Meshing of structures

After geometric modelling of critical components (Chassis and load supporting structure), mesh structure was crested. Meshing is the discretization process in which chassis and load supporting structure was divided into numbers of small elements (Anusha *et al*., 2013) [1]. Mesh structure for chassis and load supporting structure was created with element size 5mm (Fig 8). Chassis was loaded with normal load (external weights) 1000 N kept on top of it, while on load supporting structure maximum amount of load to be supported were 600N.

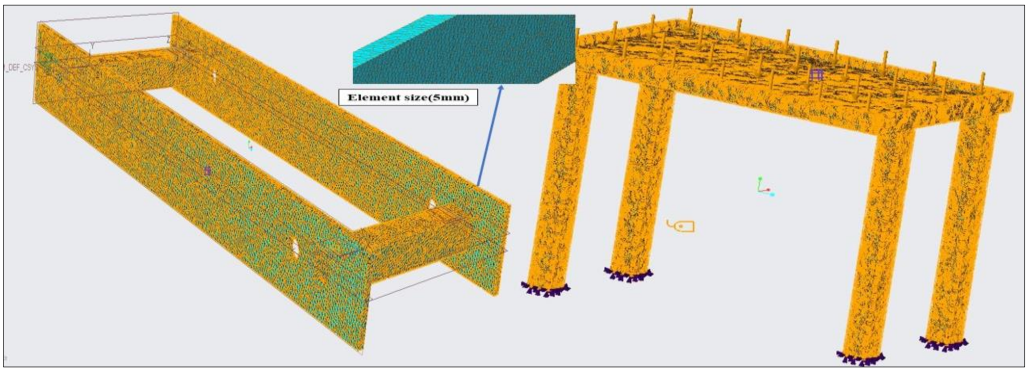

Fig 8: Mesh structure of chassis and load supporting structure with cross section of mesh structure

Table 5: Meshing details of chassis and load supporting structure

S. No.	Name	Quantity in number (Chassis)	Quantity in number (Load supporting structure)
1	Element size	5 mm	5 mm
2	No. of nodes produced	75826	162018
3	No. of elements produced	328355	714574

2.14 Boundary conditions and simulation Analysis

Boundary condition such as constraining and loading was applied on the entire model. 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 4 portions at the shaft connected region points as shown by blue color and loaded at four 4 contact surfaces (40×40 mm^2) highlighted with arrow in green color. Maximum load to be supported by chassis was 100kg (1000 N). The load supporting structure was fixed from 4 sides and loaded from the top with external load of (600N) for keeping the others items on it. The load is divided equally on contact points. The boundary conditions for chassis and load supporting structure were shown in Fig. (9). After imposing the boundary condition static analysis was conducted in native bond mode. 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 simulation5.0.

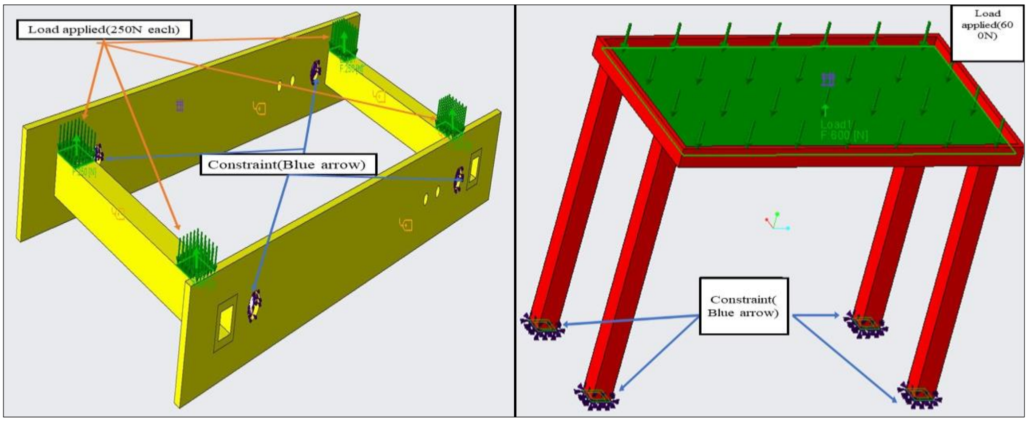

Fig 9: Boundary conditions in Chassis and Load supporting structure

2.14.1 Von –Misses stress

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 load supporting structure which are constructed of ductile material. The Von-Mises theory can be applied in ductile materials. Von-Mises's stress is calculated by using the equation (1).

$$Von - \text{Mises stress}(\sigma)\sqrt{\left(\frac{(\sigma 1-\sigma 2)2+(\sigma 2-\sigma 3)2+(\sigma 1-\sigma 3)2}{2}\right)} \quad (1)$$

In equation 1, $\sigma 1$, $\sigma 2$ and $\sigma 3$ are the principal stresses connected with the three principal directions.

2.14.2 Deformation

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

2.14.3 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 load supporting structure are presented below, based on the results, these components were optimized and assembled with the other components. These results are based on 3D modeling and numeric methods. FEM analysis saves time, money and energy consumption. Analysis based on the given boundary conditions is discussed as follows.

3.1 Analysis of chassis

3.1.1 Stress Analysis in Chassis

The maximum and minimum von mises stress developed was 5.09 MPa and 80×10^{-5} MPa respectively. Maximum stress was developed in a shaft axle connected region (Farhadi *et al.*, 2013, Malkani *et al*., 2020) [4, 10]. The maximum value of stress is smaller than the ultimate yield strength of steel which shows designed value is suitable for fabrication. The von mises stress developed in chassis were shown in Fig (10).

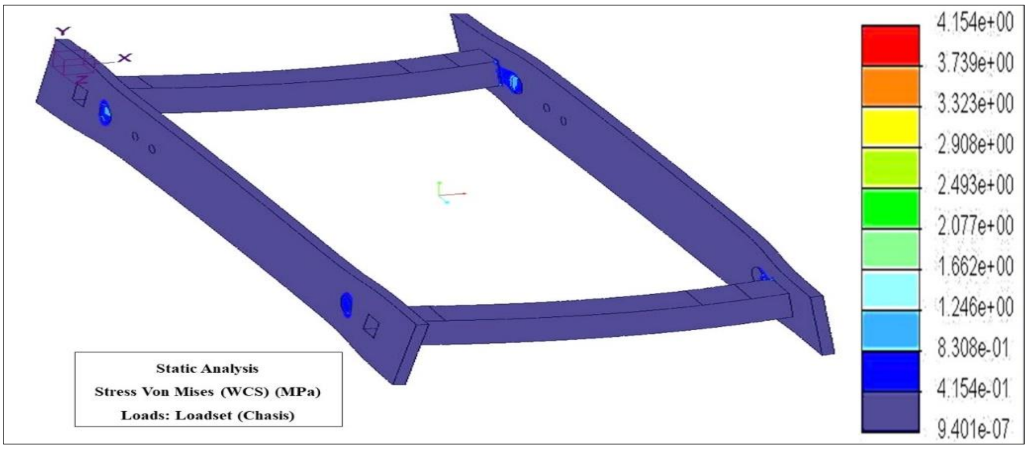

Fig 10: Von Misses Stress developed on Chassis after loading with external loads

3.1.2 Deformation analysis on Chassis

The maximum deformation occurs was 9.45×10^{-4} mm and it was at the center region as shown in Fig (11). It was because of high bending moment developed at the center due to normal load (Holden, J. T,. 1972) [7].

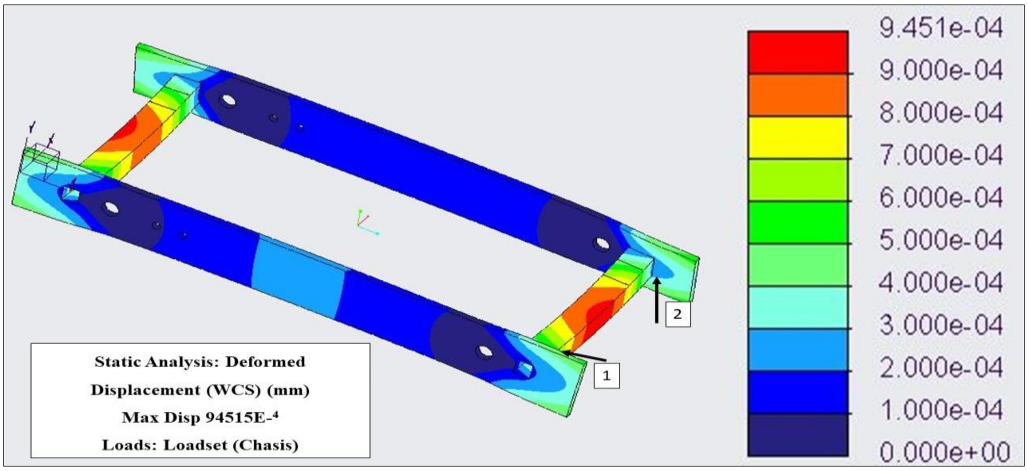

Fig 11: Deformation produced on chassis after loading with external loads

Displacement curve was drawn for edge length between point1 and point 2 as shown in Fig (11). It shows that the deformation was more at the center and minimum at the corner points where reaction force is provided by rest of the system (Fig 12).

Fig 12: Deformation produced on chassis after loading from point 1 to point 2

3.1.3 Strain Analysis on Chassis

The maximum strain induced was observed to be 3.021×10^{-5} at the point of contact of chassis with the shaft as in Fig (13). It is due to the development of maximum stresses in these regions.

The stresses and strain were more in shaft axle connected region 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. Similar type of results was obtained during the development of trolley type manually operated agrochemical sprayer (Sagar *et al.*, 2017) [17]. From the analysis result the chassis was good enough for the fabrication purpose.

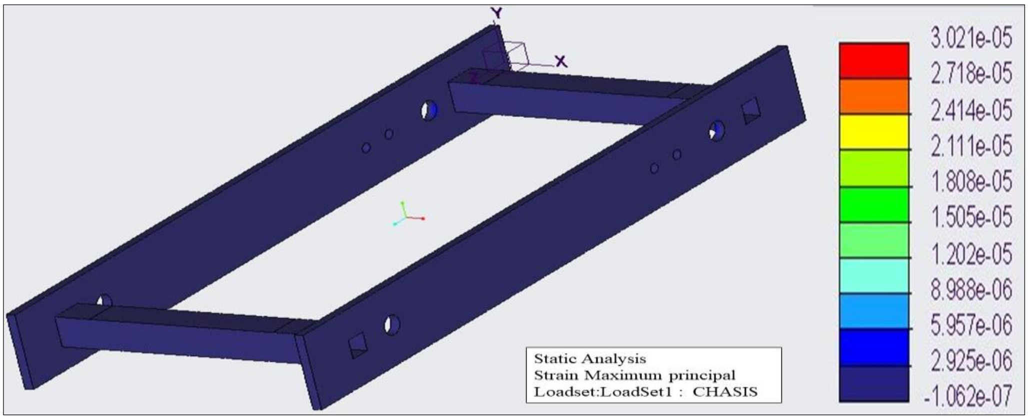

Fig 13: Strain developed on chassis after loading with external loads

3.2 Analysis of load supporting structure

Through the Static analysis, the maximum von mises stress occurs at the contact surface and top of MS sheet portion in load supporting structure. The maximum stress, deformation and strain were found to be 2.11678 MPa, 0.01426 mm and 5.815×10^{-6} as shown in Fig (14, 15 and 17) respectively. The maximum displacement occurs at the top center region of MS sheet.

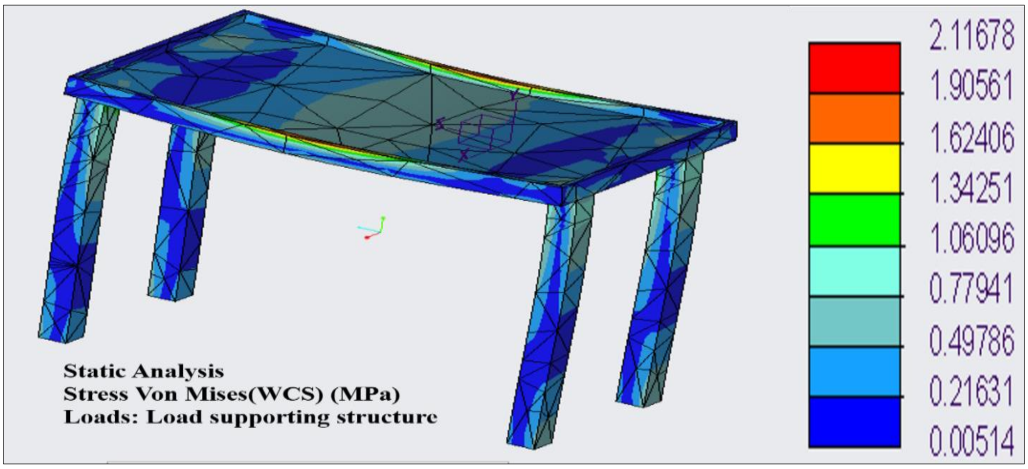

Fig 14: Von Misses Stress developed on load supporting structure after loading with external loads

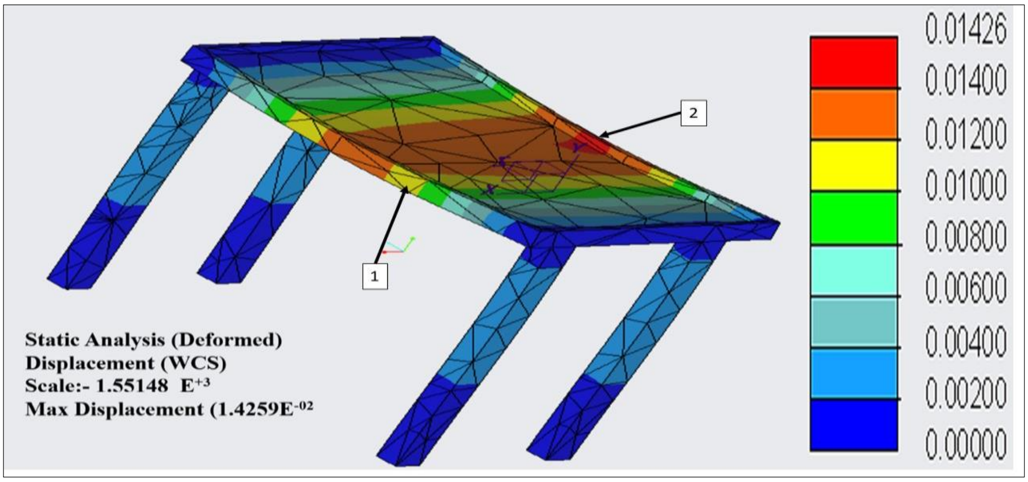

Fig 15: Displacement analysis on load supporting structure after loading with external loads

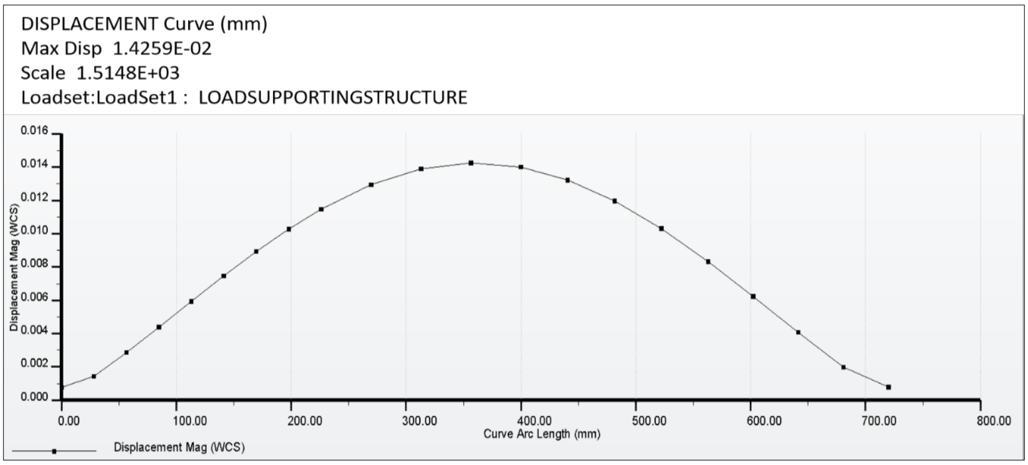

Fig 16: Deformation produced on load supporting structure after loading from point 1 to point 2

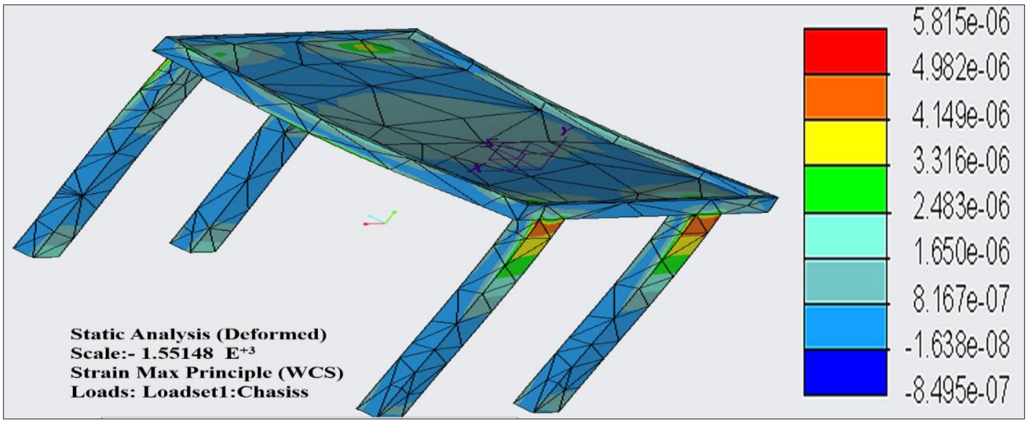

Fig 17: Strain analysis on load supporting structure after loading with external loads

Maximum stresses and strain develop in load supporting structure were within the bearable range of steel material. Malkani *et al*., 2020 [10] found similar results of stress and strain within the safe limit of ultimate yield strength of chassis frame for design of high clearance sprayer. Therefore, based on simulation analysis results load supporting structure can be fabricated with above dimension and material property.

3.3 Fabrication and assembly of test setup

Based on the results obtained chassis and load supporting structure was fabricated

The other components of sensor-based herbicide applicator were selected from the local market and some were fabricated. The actual fabricated model is shown in Fig [18]. Fabricated was done in the workshop of Division of Agricultural Engineering, ICAR-IARI, New Delhi. The chassis was fixed to load supporting structure through nut bolts and welding. The top of chassis was provided with motor, motor controller and gear box. The power was transmitted from motor -gearbox followed to the driver shaft through chain and sprocket to the tires. The tire took the load from chassis and propel the system. The load supporting structure attached to chassis at four corners supports all the other components such as weed detection at front side, servo metering unit and pump at top and spray tank at bottom side. The spray nozzle was provided just behind the webcam at front for rapid application of chemicals after the weed detection. The developed prototype applies chemicals only to weeds based on weed detection output at variable rate based on weed density.

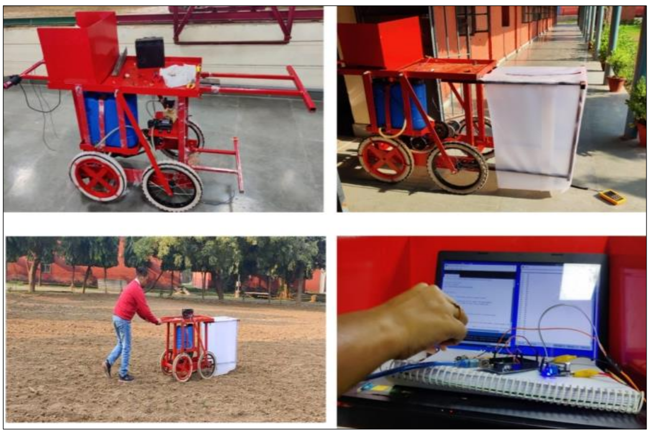

Fig 18: Developed prototype of sensor- based weed detection and herbicide applicator system

3.4 Cost economics

The cost of fabrication of the prototype was Rs. 45000.

3.5 Advantage and limitation of developed sensor-based herbicide applicator

The key advantages with the developed system were simplicity in design, light weight in handling of machine, reasonable initial cost as compared to other engines or tractor operated sprayer, high saves in number of labor and labor charges, 40-80% chemicals savings based on weed density, uniform maintenance of pressure of battery operated pump, lower maintenance cost and wide suitable for all wide row crops such as maize, Arhar, sugarcane etc. above 50 cm spacings during post emergence application of herbicides. The main limitation is non-suitability for very smaller row spaced crop.

4. Conclusion

Creo parametric 1 and Creo Simulation are very effective and powerful software for designing and analysis of the components. The maximum von mises stress, deformation and strain developed within the chassis were 5.09 MPa, 9.45×10^{-4} mm and 3.021×10^{-5} at respectively, while in load supporting structure the maximum stress, deformation and strain were found to be 2.11678 MPa, 0.01426 mm and 5.815×10^{-6}. The stress and strain induced in both chassis and load supporting structure were quite below the ultimate yield limits and falls within the safe limit. Therefore, the developed model for chassis and load supporting structure was accepted for fabrication. The overall dimension of sensor-based weed detection and herbicide application system were (l.6m× 0.55m×1.1m) and were simple and compact in design and had minimum fabrication cost. It will reduce the operational cost by savings the chemicals and is easy to operate, protect the environment by applying chemicals to only targeted plants. It can be concluded that the present project work becomes a ready reckoner for engineers for future developments in chemicals spraying machines using FEM. FEM based methods saved considerable time over hit and trial-based method of prototype development.

5. Acknowledgment

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6. Competing Interest

The authors have declared no competing interest exists.

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