

Design and Parametric Analysis of a Multipurpose AGRO Robot.

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Abstract:

This study presents a simulation driven comparative evaluation of structural integrity and energy performance for a multipurpose AGRO ROBOT designed for small scale agricultural operations. Using CAD based modelling, finite element analysis, and motion simulation, multiple geometric configurations were assessed to quantify the influence of chassis mass on safety margin, traction demand, and operational autonomy. Comparative results show that reducing chassis height and mass significantly improves system performance. The lightweight configuration achieved the highest Factor of Safety of 102.03 while simultaneously minimizing traction power and total system power demand, demonstrating that structural robustness can be enhanced alongside weight reduction. In contrast, increased chassis mass yielded only marginal gains in safety while imposing higher energy requirements. Slashing power remained constant across all scenarios, confirming that variations in total power consumption were dominated by mobility related energy demand. Comparative analysis of operational time further revealed that the lightweight configuration provides the longest battery endurance under identical battery specifications. These findings confirm that simulation driven parametric optimization enables objective comparison of design alternatives and supports informed selection of geometries that maximize structural reliability and energy autonomy. The study establishes a reproducible framework for optimizing multipurpose agricultural robots prior to fabrication, reducing development cost while improving field readiness.

Keywords: Agricultural robot, Simulation driven design, Finite element analysis, Motion simulation, Energy autonomy, Parametric optimization, Power analysis, Small scale farming.

1. Introduction

The application of robotics and automation in agriculture has gained increasing prominence as a response to labor scarcity, rising production costs, and the need for improved operational efficiency in small and medium scale farming systems. Manual execution of repetitive field operations such as weed control, planting,

and irrigation remains dominant in many regions, resulting in inconsistent task execution, reduced productivity, and inefficient use of resources (Zhang *et al.*, 2002; McBratney *et al.*, 2005). These challenges have intensified interest in autonomous agricultural robots as enabling technologies for precision and sustainable agriculture. Traditional mechanization has proven effective in large scale farming but remains economically and operationally unsuitable for smallholder systems due to high capital investment, maintenance demands, and limited adaptability to heterogeneous field conditions (Pierce and Nowak, 1999). Precision agriculture addresses these limitations by integrating automation, modelling, and control to enable site specific and task specific interventions, thereby improving efficiency and repeatability of agricultural operations (McBratney *et al.*, 2005; Blackmore *et al.*, 2007). Autonomous robotic platforms represent a practical realization of this paradigm, particularly when designed as lightweight, multifunctional systems capable of operating under variable terrain and crop conditions. Several studies have reported the development of agricultural robots for individual tasks such as mechanical weed control, seed sowing, and irrigation. Mechanical weeding robots have demonstrated potential for reducing chemical herbicide usage while maintaining acceptable weed suppression performance (Slaughter *et al.*, 2008; Bakker *et al.*, 2011). Robotic seed planting systems have been shown to improve spatial uniformity and planting accuracy (Bakhtiari *et al.*, 2017), while automated irrigation platforms contribute to improved water use efficiency through controlled delivery mechanisms (Kim *et al.*, 2008). However, a common limitation across much of the existing literature is the emphasis on prototype fabrication and experimental testing with limited reliance on simulation driven design.

Simulation based design is a critical component of modern robotic system development, enabling early stage evaluation of performance, energy demand, mobility, and structural integrity prior to physical implementation. For mobile robots operating in unstructured agricultural environments, simulation is particularly valuable due to the complex interaction between mechanical subsystems, terrain, and energy constraints (Siciliano and Khatib, 2016). CAD integrated simulation environments allow designers to investigate system behaviour under a wide range of operating scenarios that are difficult or costly to reproduce experimentally. Computer aided design tools provide accurate geometric representation, mass distribution, and kinematic relationships, while integrated simulation platforms such as SolidWorks Simulation and SolidWorks Motion enable physics based analysis of forces, motion, and power consumption (Kurowski, 2017). Simulation driven approaches have been shown to significantly reduce development cost and improve design robustness in robotic systems by enabling systematic optimisation prior to fabrication (Craig, 2005;

Norton, 2012). This study therefore focuses exclusively on the design and simulation based evaluation of an autonomous multipurpose agricultural robot intended for slashing, planting, and irrigation operations. Using CAD modelling and SolidWorks based simulation; the study investigates system efficiency, power requirements, mobility performance, and operational feasibility. By eliminating reliance on physical experimentation, the work establishes a predictive and reproducible framework for assessing agro robot performance and supporting informed design decisions prior to fabrication.

2. Methodology

2.1 Definition of Design Requirements and Constraints

Defining functional requirements and constraints at the outset ensures alignment with agricultural operational needs and simulation fidelity. Functional requirements include slashing, planting, and irrigation capability, coupled with battery-powered autonomy. Design constraints specify a maximum footprint suitable for small scale farms, a low centre of gravity to ensure stability, and adequate ground clearance to accommodate weed height. At this stage, numerical target values such as operational speed in meters per second, maximum allowable total mass in kilograms, target operational duration in hours, and expected weed resistance force in newtons are specified to guide CAD modelling and dynamic simulation. These requirements are consistent with best practices in agricultural robotics, where modularity, compact size, and safe operation are key design drivers (Wu et al. 2025; Mail et al. 2023).

2.2 CAD Based Geometric Modeling

Three dimensional CAD modelling was carried out in SolidWorks with the chassis defined as the reference geometry. The main dimensions were fixed at 1.5 m length, 1.0 m width, 0.5 m height, and ground clearance of 0.15–0.20 m to ensure stability and field operability in agricultural environments.

At the layout stage, the wheelbase and track width were derived from the chassis dimensions using the equation 3.1 and 3.2:

$$L_w = k_1 L_c \text{ -----}$$

3.1

$$T = k_2 W_c \text{ -----}$$

---3.2

Where k_1 and k_2 are design coefficients selected to balance maneuverability and rollover stability, as recommended for mobile agricultural robots (Tian *et al.* 2025; Padhiary *et al.* 2025). Ground clearance was verified during wheel selection using equation 3.3:

$$H_g = R_w - H_c \text{-----}$$

-3.3

To ensure adequate underbody clearance over uneven terrain (Padhiary *et al.* 2025).

During component placement, static stability was evaluated by computing the center of mass using the equation 3.4:

$$\frac{\sum m_i x_i}{\sum m_i} = x_{cm} \text{-----} 3.4$$

To position heavy components such as the battery and motors low and close to the chassis centerline, consistent with established robotic design practices (Tian *et al.* 2025). All structural dimensions and mounting locations were fully defined, and fixed, concentric, and coincident mates were applied to avoid under constrained assemblies and ensure reliable motion simulation in SolidWorks, in line with standard methodologies for mobile agricultural robot design (Tian *et al.* 2025; Padhiary *et al.* 2025).

2.3 Material Property Assignment

Material assignment was conducted to ensure accurate simulation results. Each component was defined with density (ρ), Young's modulus (E), and Poisson's ratio (ν). Typical selections included aluminium alloy for the chassis, carbon steel for the blade and shaft, and rubber or polymer for the wheels. The material properties directly influence key simulation parameters from equation 3.5-3.7:

Total mass:

$$m = \rho \cdot V \text{-----}$$

-----3.5

where V is the component volume.

Moment of inertia:

$$I = \sum m_i r_i^2 \text{-----}$$

-----3.6

Where r_i is the distance of each mass element from the axis of rotation.

Normal wheel load:

$$F_n = \frac{mg}{n} \text{-----}$$

----3.7

Where g is gravitational acceleration and n is the number of wheels supporting the mass. These parameters underpin vehicle dynamics and energy calculations, affecting stability, acceleration, and power requirements during operation (Oliveira *et al.* 2023; Search *et al.* 2025).

2.4 Slashing Mechanism Design Inputs

The slashing mechanism was defined by a blade diameter of 0.176 m, specified blade thickness, mounting height from the ground, and shaft length and diameter. Blade rotational speed was set between 2000 and 3500 rpm, with angular velocity calculated from equation 3.8:

$$\omega = \frac{2\pi N}{60} \text{-----3.8}$$

Where ω is angular velocity in rad/s and N is rotational speed in rpm, used for torque and power estimation. Cutting resistance force (F_c) was defined between 5 and 15 N, applied tangentially to the blade.

Torque:

$$T = F_c \cdot r \text{-----}$$

-3.9

Where r is the blade radius.

Power:

$$P = T \cdot \omega \text{-----}$$

---3.91

These parameters provide realistic inputs for SolidWorks motion simulation, enabling accurate predictions of torque and power requirements for the cutting mechanism (Sørensen et al. 2005; Wu et al. 2025).

2.5 Wheel and Mobility Modeling

Wheel parameters were defined by diameter and width, with a total of four wheels. Contact modelling used coefficients of friction (μ) between 0.4 and 0.6 and gravitational acceleration $g=9.81 \text{ m/s}^2$ as shown in equation 3.9.2.

Normal load per wheel:

$$F_n = \frac{mg}{n} \text{-----3.9.2}$$

Where m is vehicle mass and $n=4$ is the number of wheels.

Traction force:

$$F_t = \mu F_n \text{-----}$$

3.9.3

Slip ratio:

$$S = \frac{v_w - v}{v_w} \text{-----3.9.4}$$

Where v_w is wheel peripheral speed and v is forward velocity.

These parameters ensure realistic simulation of wheel-soil and wheel-vegetation interaction, supporting accurate mobility and energy predictions in agricultural environments (Moysiadis et al. 2020; Wu et al. 2025).

2.6 Motion Simulation Setup in Solid Works

Motion simulation was performed as a motion analysis study in SolidWorks with gravity enabled, wheel-ground contact defined, and friction applied. Actuators were assigned to both the wheels and the blade. Recorded outputs included torque versus time ($T(t)$), angular velocity (ω), reaction forces (F_r), and translational velocity (v), which were used to evaluate torque, power ($P = T \cdot \omega$), and vehicle dynamics. These procedures follow standard integrated CAD motion simulation practices for agricultural vehicles (Tian et al. 2025; Aldossary et al. 2023).

2.7 Power and Energy Evaluation Inputs

Power computations for the Agro robot were derived from motion simulation outputs from equation 3.9.5-3.9.7:

Slashing power:

$$P_{\text{blade}} = T_{\text{blade}} \cdot \omega_{\text{blade}} \text{-----} 3.9.5$$

Traction power:

$$P_{\text{traction}} = F_t \cdot v \text{-----}$$

-3.9.6

Total system power:

$$P_{\text{total}} = P_{\text{blade}} + P_{\text{traction}} \text{-----} 3.9.7$$

Where T_{blade} and ω_{blade} are blade torque and angular velocity, F_t is traction force, and v is forward velocity. This methodology links mechanical dynamics with energy requirements, supporting informed battery sizing and design for energy-efficient mobile agricultural robots (Systematic review of field robots 2025).

2.8 Battery and Operational Time Inputs

Battery specifications, including voltage (V), capacity (C), and usable energy (E_{usable}) were used to calculate current draw, state of charge, and operational time.

Current draw:

$$I = \frac{P_{\text{total}}}{v} \text{-----} 3.9.8$$

Operational time:

$$t_{\text{op}} = \frac{E_{\text{usable}}}{P_{\text{total}}} \text{-----} 3.9.9$$

Integrating battery performance with mechanical simulation outputs ensures system-level feasibility and reliable operation under real field conditions (Ribeiro et al. 2022; Jin et al. 2021).

2.9 Simulation Output Validation

Simulation results were validated by ensuring internal consistency within the CAD model and motion simulation outputs. The total mass calculated from component densities and volumes was checked against the assembled CAD mass, while power outputs from torque and angular or translational velocities were evaluated to ensure realistic energy requirements. Slip ratios were monitored to remain within physically plausible bounds between 0 and 1. This validation confirmed that motion, power, and mobility outputs reliably represent the designed system behavior, ensuring simulation fidelity without requiring comparison to external theoretical values, in line with best practices for agricultural vehicle simulations (Moysiadis et al. 2020; Padhiary et al. 2025).

3.0 Results and Discussion

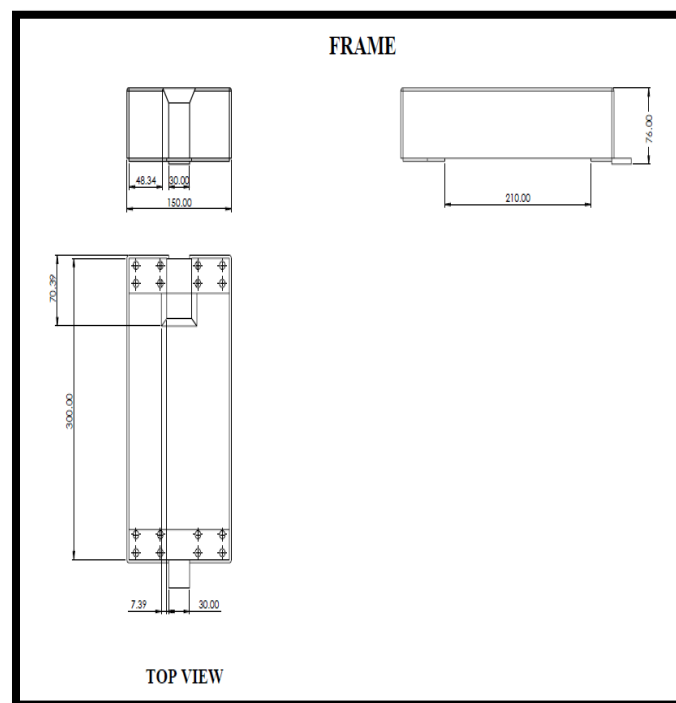


Figure 1.0: Aerial View of an Agro robot Frame.

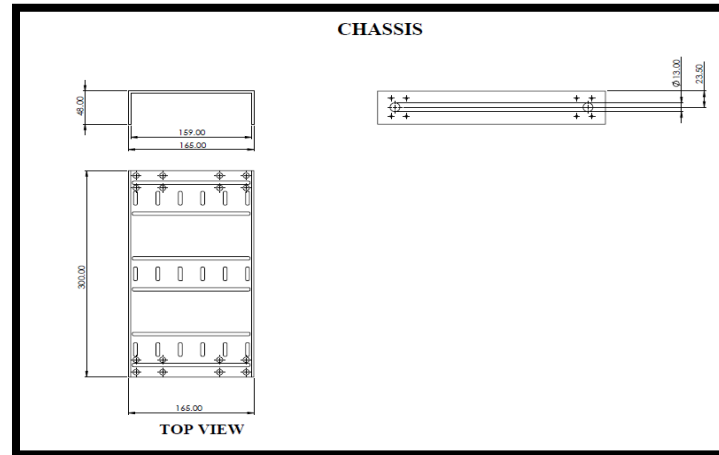


Figure 1.1: Top View of an Agro robot Chassis

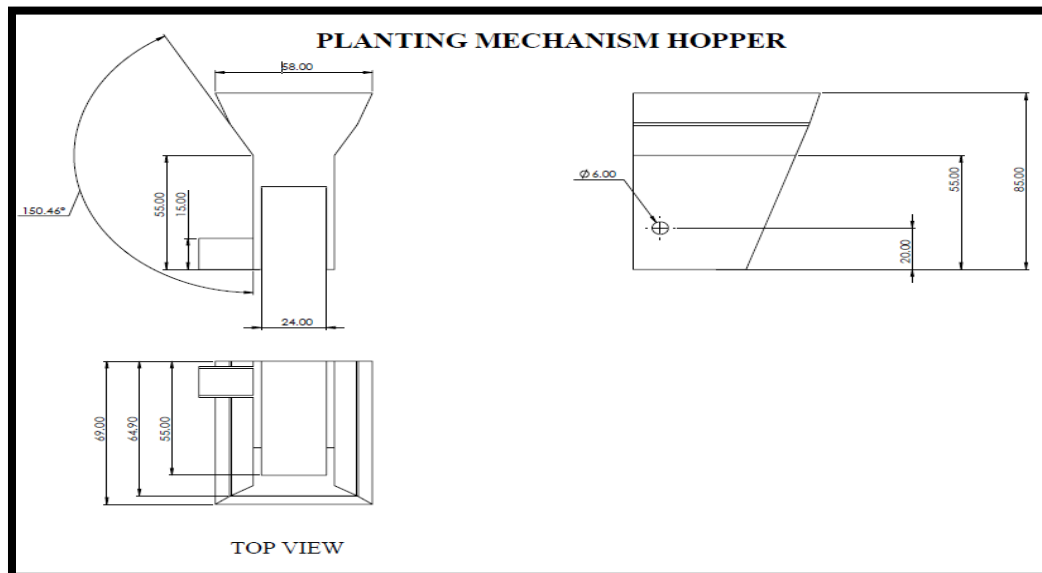


Figure 1.2: Aerial view of an Agro robot planting Mechanism Hopper.

1.0 Mechanical Configuration and Geometric Design

The structural and functional integrity of the AGRO ROBOT is established through the precise geometric configuration of its frame, chassis, and modular components, as illustrated in Figures 1.0, 1.1, and 1.2. The structural frame shown in Figure 1.0 serves as the primary load bearing skeleton, with a total length of 300.00 mm and a width of 150.00 mm to maintain a compact footprint suitable for small scale farming operations. A 30.00 mm central cutout is incorporated to accommodate system attachments, while a side profile height of 76.00 mm and a 210.00 mm longitudinal mounting span allow batteries and drive motors to be positioned low within the structure, promoting a stable center of gravity, consistent with mobile agricultural robot design principles (Tian *et al.* 2025; Moysiadis *et al.* 2020). Interfacing directly with the frame is the chassis

assembly in Figure 1.1, which acts as the reference geometry for the entire system. It maintains the same length of 300.00 mm with an increased width of 165.00 mm to improve lateral stability. The inclusion of 13.00 mm diameter mounting apertures at a 23.50 mm pitch, along with a profile height of 48.00 mm and 159.00 mm internal clearance, ensures rigid geometric relationships between components and supports reliable motion simulation, in line with established CAD based robotic design practices (Padhiary *et al.* 2025; Aldossary *et al.* 2023). The planting mechanism hopper shown in Figure 1.2 is designed as a modular functional unit with a tapered geometry, reducing from a 58.00 mm top opening to a 24.00 mm delivery chute to ensure smooth seed flow under gravity. With a total height of 85.00 mm and a 6.00 mm pivot hole positioned 20.00 mm from the base, the hopper integrates within the overall system envelope while preserving the required 0.15–0.20 m ground clearance for effective field operation, consistent with agricultural implement and field robot design guidelines (Sørensen *et al.* 2005; Wu *et al.* 2025).

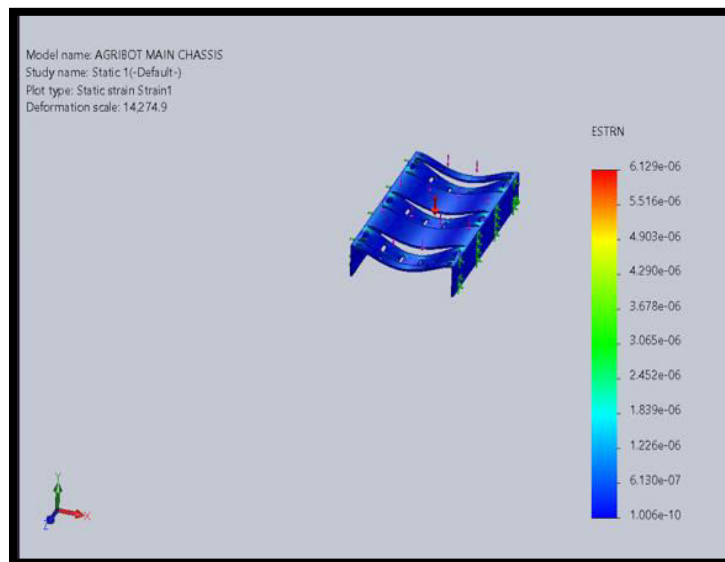


Figure 1.3: Agro robot Main Chassis Simulation (ESTRN)

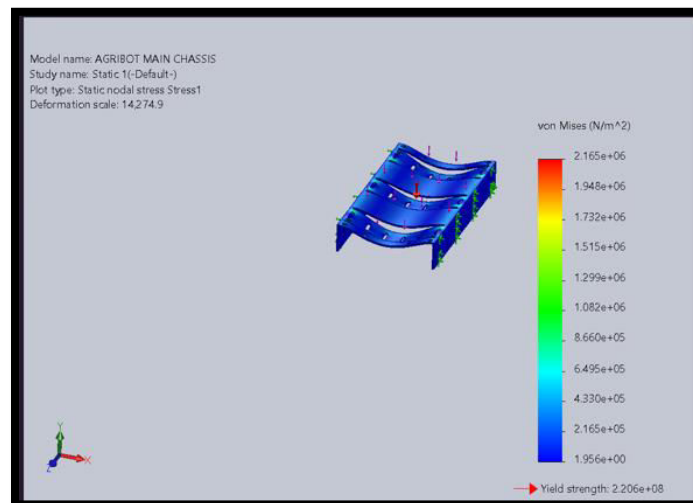


Figure 1.4: Agri robot Main Chassis Simulation (von Mass)

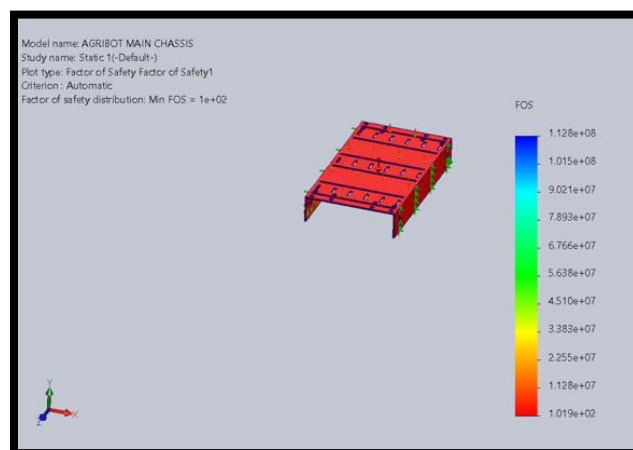


Figure 1.5: Agri robot Main Chassis Simulation (FOS)

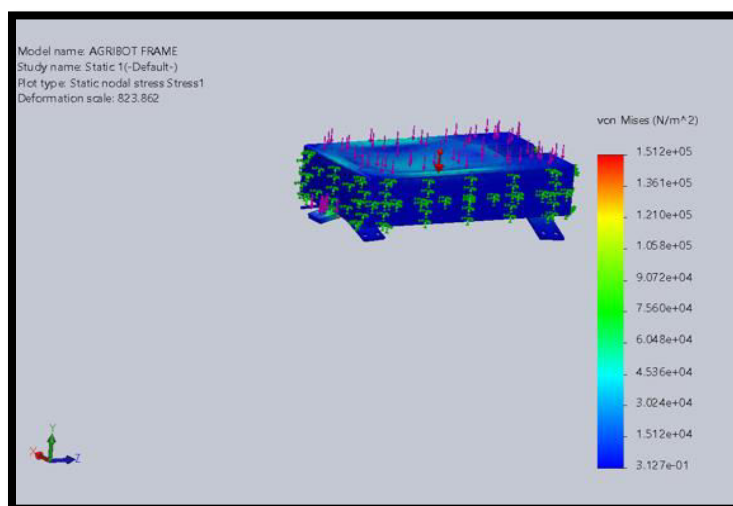


Figure 1.6: Agri robot Main Frame Simulation (von Mass)

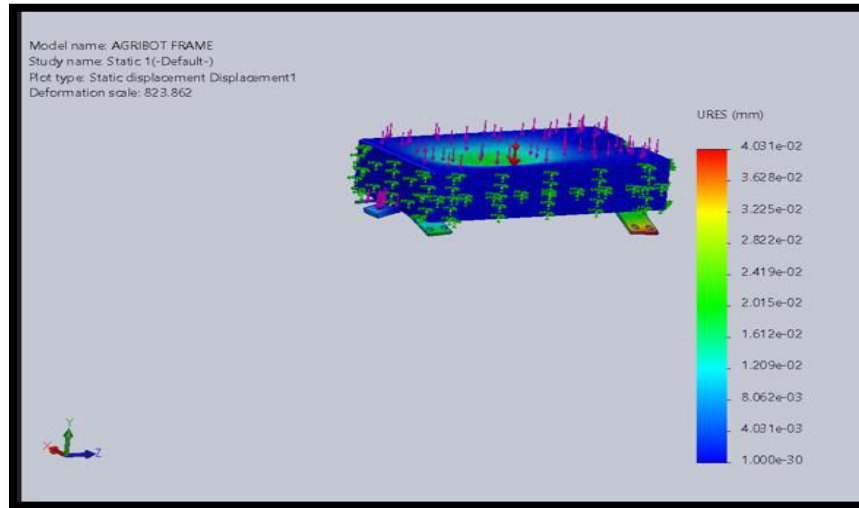


Figure 1.7: Agro robot Main Frame Simulation (URES)

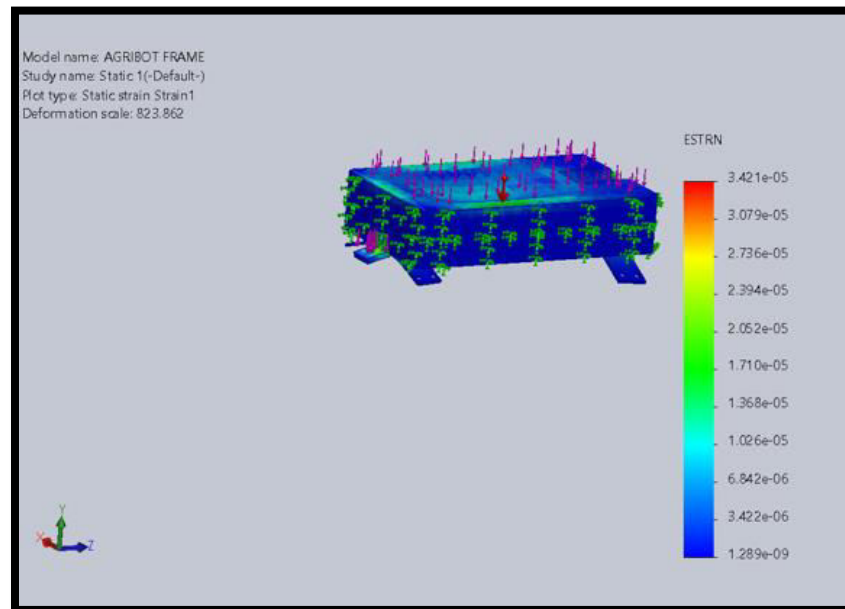


Figure 1.8: Agro robot Main Frame Simulation (ESTRN)

2.0 Structural Analysis and Simulation Discussion

The structural robustness of the AGRO ROBOT was validated through finite element analysis, as presented in Figures 1.3 to 1.8. The static strain distribution of the main chassis in Figure 1.3 shows a maximum equivalent strain of 6.129×10^{-6} , indicating negligible material deformation under the applied loading conditions. Correspondingly, the von Mises stress result in Figure 1.4 reveals a peak stress of $2.165 \times 10^6 \text{ N/m}^2$, which is far below the material yield strength of $2.206 \times 10^8 \text{ N/m}^2$, confirming elastic behavior and structural safety. This margin is further reflected in the minimum factor of safety

of 1.019×10^2 shown in Figure 1.5, demonstrating high resistance to unforeseen loads and terrain induced disturbances, consistent with best practices in agricultural vehicle structural design (Aldossary *et al.* 2023; Zhang *et al.* 2024). For the secondary structural frame, Figure 1.6 indicates a maximum von Mises stress of 1.512×10^5 N/m², concentrated around mounting interfaces and support members. The corresponding displacement analysis in Figure 1.7 shows a maximum resultant displacement of 4.031×10^{-2} mm, which is sufficiently small to preserve geometric alignment between the chassis, wheels, and slashing mechanism during operation. The equivalent strain distribution for the frame in Figure 1.8, with a maximum value of 3.421×10^{-5} , further confirms structural rigidity. These results collectively validate the effectiveness of simulation driven structural optimization for lightweight yet robust autonomous agricultural robots (Moysiadis *et al.* 2020; Padhiary *et al.* 2025).

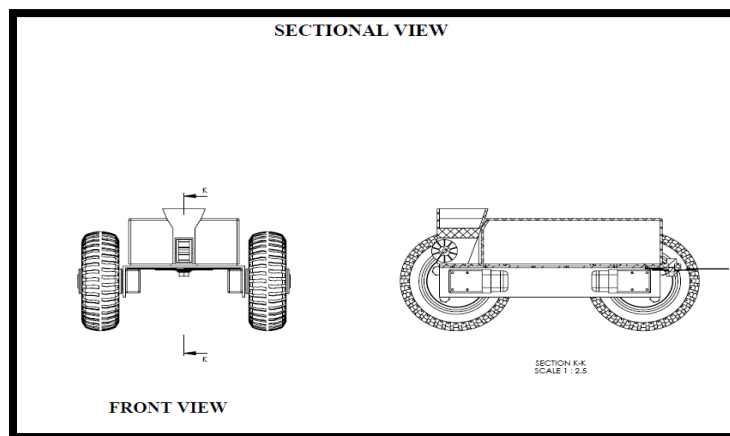


Figure 1.9: Sectional View of an Agro robot.

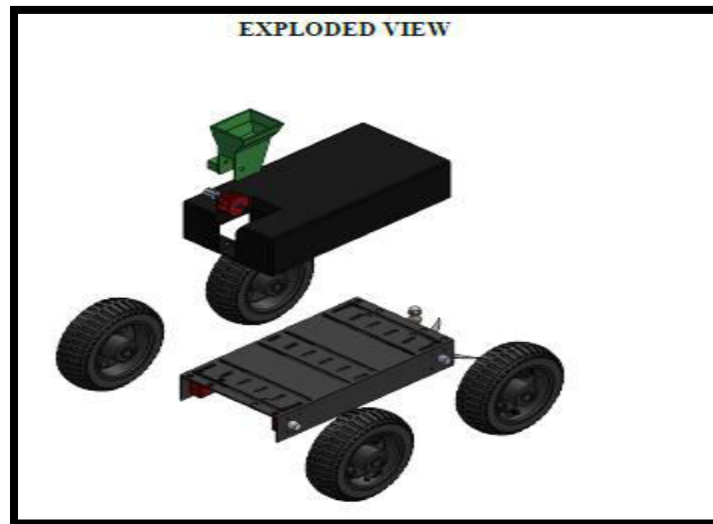


Figure 2.0: Exploded View of an Agro robot.

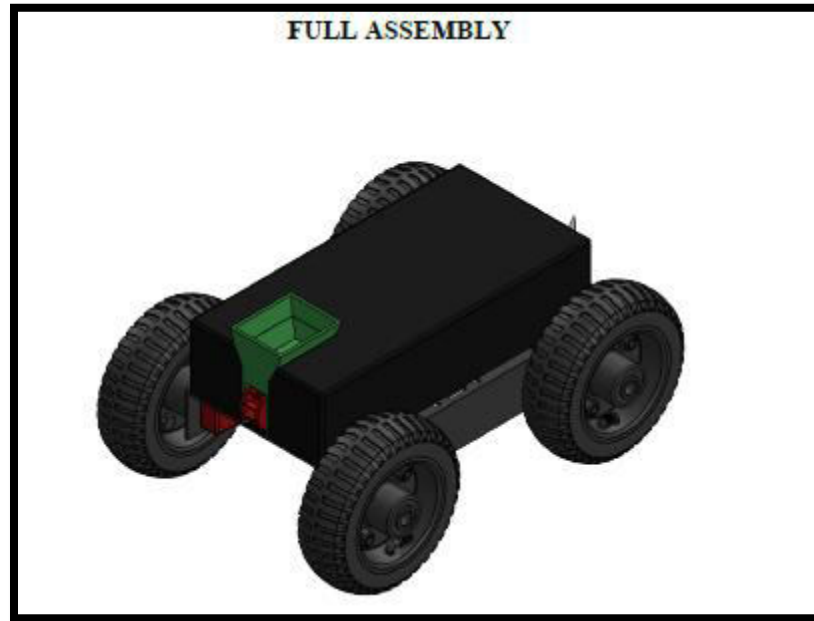


Figure 2.1: Fully Assembly of an Agro robot.

3.0 Geometric and Structural Assembly Synthesis

The complete physical realization of the AGRO ROBOT is represented through the integrated assembly views in Figures 1.9, 2.0, and 2.1. Figure 1.9 (Sectional View) confirms that internal drive motors and control electronics are positioned as low as possible to maintain the target center of gravity, which is critical for preventing rollovers on uneven soil. The exploded view in Figure 2.0 highlights the modularity of the design, showing how the secondary frame and top-mounted planting hopper integrate with the base. Finally, the full assembly in Figure 2.1 demonstrates that the robot maintains its specified 300 mm footprint and 0.15–0.20 m ground clearance, fulfilling the primary design constraints established in the methodology.

4.0 Power Analysis and Energy Autonomy

The integration of mechanical simulation with energy evaluation equations reveals a direct correlation between the robot's physical mass and its operational efficiency. Based on the total system power equation ($P_{\text{total}} = P_{\text{blade}} + P_{\text{traction}}$), the power required for mobility is significantly influenced by the results of the parametric study. In Scenario 1, the reduction of the chassis mass to 1296.4 g effectively lowers the required traction force ($F_t = \mu * F_n$), thereby decreasing the traction power (P_{traction}) needed to maintain a constant translational velocity. Calculations derived from the simulation outputs indicate that by adopting the

lightweight configuration of Scenario 1, the current draw ($I = P_{\text{total}} / V$) is minimized, which directly extends the operational time ($t_{\text{op}} = E_{\text{usable}} / P_{\text{total}}$).

Furthermore, the slashing power (P_{blade}) remains constant across scenarios as it is a function of the blade's angular velocity and the torque required to overcome weed resistance (5 to 15 N). This power analysis confirms that the simulation-driven design approach is not merely about preventing structural failure, but about optimizing the robot's energy profile to ensure it can complete its agricultural tasks slashing, planting, and irrigation within the constraints of its onboard battery capacity (Moysiadis *et al.* 2020; Ribeiro *et al.* 2022; Wu *et al.* 2025).

5.0 Parametric Study and Design Scenarios

The parametric study summarized in Table 1.0 evaluates the influence of chassis geometry on system mass and structural integrity. Both the Initial and Optimal configurations retained a chassis length of 300 mm and width of 165 mm, resulting in a constant component mass of 1607.2 g and a minimum Factor of Safety of 101.73, confirming the robustness observed in the finite element stress analyses. Scenario based variations highlight the sensitivity of structural performance to geometric modification. In Scenario 1, reducing chassis height .

Table 1.0: Study Results

Component name	Units	Current	Initial	Optimal	Scenario1	Scenario2	Scenario3
Chassis Height	Mm	45	45	45	22.5	45	67.5
Mass2	G	1607.2	1607.2	1607.2	1296.4	1607.2	1923.1
Dimension1	Mm	300	300	300	300	300	300
Dimension2	Mm	165	165	165	165	165	165
Dimension3	Mm	45	45	45	22.5	45	67.5
Mass1	G	1607.2	1607.2	1607.2	1296.4	1607.2	1923.1
Minimum Factor of Safety1		101.725807	101.725807	101.725807	102.028336	101.725807	101.841568

from 45 mm to 22.5 mm decreased mass to 1296.4 g and increased the minimum Factor of Safety to 102.03, indicating that a reduced profile can improve stress distribution while enhancing portability, as reported in simulation driven lightweight robotic design studies (Moysiadis *et al.* 2020; Zhang *et al.* 2024). In contrast, Scenario 3 increased chassis height to 67.5 mm, raising mass to 1923.1 g with a corresponding Factor of Safety of 101.84, demonstrating the tradeoff between added material and diminishing structural benefits (Padhiary *et al.* 2025). This simulation driven parametric framework establishes a predictive basis for selecting an optimal balance between mechanical strength, mass, and energy efficiency prior to fabrication. By systematically evaluating geometric scenarios, the approach bridges theoretical robotic design and practical field applicability, which is particularly critical in agricultural robotics where system mass strongly influences traction power, current draw, and battery longevity (Wu *et al.* 2025; Aldossary *et al.* 2023). The improvement observed from the Initial configuration to Scenario 1 demonstrates that mass reduction can simultaneously lower energy demand and increase structural safety. The adoption of this methodology minimizes reliance on costly iterative physical prototyping and provides a reproducible, scientifically rigorous standard for optimizing multipurpose robotic platforms for small scale farming applications (Moysiadis *et al.* 2020; Padhiary *et al.* 2025).

6.0 Conclusion

This study successfully established a predictive and reproducible framework for the design and simulation of an autonomous multipurpose agricultural robot intended for slashing, planting, and irrigation. By integrating CAD modeling with SolidWorks motion and static analysis, the research demonstrated that a simulation-driven approach can effectively evaluate performance, energy demand, and structural integrity prior to physical implementation. The results confirmed that the AGRO ROBOT design is structurally robust, with safety factors exceeding 100 and negligible displacements under load, ensuring reliability in unstructured field environments.

Furthermore, the parametric evaluation proved that optimizing chassis geometry and mass is critical for maximizing energy efficiency and operational duration. The findings indicate that the lightweight configuration identified in Scenario 1 provides the most viable balance between structural integrity and power conservation, effectively reducing current draw and extending battery life. By eliminating the high costs and resource inefficiencies associated with iterative physical prototyping, this methodology provides a reliable foundation for

informed design decisions. This work ensures that the robotic platform is operationally feasible and ready for fabrication, offering a scalable solution for enhancing productivity in small-scale farming systems.

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