

Mechanical Innovations in Agricultural Robotics for High-Precision Crop Management

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Abstract. Precision agriculture demands robotic systems that combine high positional accuracy, durability, and adaptability while minimizing resource consumption and environmental impact. This paper presents a mechanically engineered robotic platform for high-precision crop management that holistically addresses limitations identified in prior in situ sensing and actuation studies. By integrating multi-parameter soil sensing insights, modular end-effector designs, and energy-efficient kinematic architectures drawn from 23 seminal works (2020–2025), our solution overcomes restricted sensing scopes, calibration drift, coarse temporal resolution, and durability challenges. The platform features sub-centimeter repeatability through precision-machined linkages, self-lubricating bearings for extended field operation, and low-ground-pressure chassis designs to reduce soil compaction. A scalable modular toolkit allows rapid swapping of grippers, injectors, and sensors to support tasks ranging from delicate fruit picking to targeted agrochemical application. Field trials demonstrate a 30% reduction in actuation energy, a 25% increase in task throughput, and maintenance intervals extended by 40% compared to existing systems. The result is an autonomous, adaptable solution that delivers real-time, high-throughput crop management with minimal environmental footprint and operational overhead. This unified approach paves the way for sustainable, next-generation agricultural robotics that maximize yield and resource efficiency.

Keywords: Precision agriculture, Agricultural robotics, Mechanical design, Modular end-effectors, Energy-efficient kinematics, Soil compaction mitigation, High-throughput crop management, System durability.

1. Introduction

The ever-increasing global demand for food, coupled with the need to optimize resource use and reduce environmental impact, has driven the emergence of precision agriculture as a vital paradigm in modern farming. By leveraging data-driven decision making, precision agriculture systems enable site-specific crop management optimizing inputs such as water, fertilizers, and pesticides to maximize yield while minimizing waste and ecological footprint. Robotic platforms play a central role in this transformation, offering the potential for continuous, autonomous field operations such as weeding, spraying, and harvesting with minimal human intervention [20]. However, realizing this vision requires not only advanced sensing and control algorithms but also mechanically robust and efficient hardware capable of operating reliably in challenging field environments [16], [18].

Despite significant progress in vision-based weed detection [1], [4] and soil-quality sensing [Sophocleous et al., 2024], many existing robotic solutions exhibit mechanical shortcomings that limit their practical deployment. Common issues include cumulative positioning errors due to linkage backlash, high actuation

energy consumption arising from suboptimal kinematic designs, soil compaction from heavy chassis structures, and frequent maintenance needs in dust- and moisture-laden conditions [8], [7]. Moreover, the lack of modularity in end-effector systems often forces a trade-off between task versatility and mechanical simplicity, hindering multi-functional operation in diverse crop scenarios.

This paper addresses these gaps by presenting a mechanically engineered robotic platform specifically designed for high-precision crop management. Our key contributions are:

- Sub-centimetre actuation precision, achieved through precision-machined linkages and closed-loop kinematic designs.
- Energy-efficient motion, leveraging parallel-link and lightweight structural architectures to reduce inertial loads by up to 30%.
- Soil-friendly mobility, via a low-ground-pressure chassis that minimizes compaction without sacrificing stability.
- Modular end-effector framework, enabling rapid interchange of grippers, sprayers, and sensor payloads for multi-task flexibility.
- Enhanced durability, through self-lubricating bearings, sealed joints, and corrosion-resistant materials that extend maintenance intervals by 40%.

2. Literature Review

Precision agricultural robotics spans a range of sensing, actuation, and mechanical subsystems. Early work in soil-quality monitoring emphasized stationary, multi-parameter probes but suffered from limited in-field robustness and parameter scope [14], [23]. Lloret et al. demonstrated fog-based edge computing for real-time analysis, yet their chemical sensing modules omitted critical physical metrics such as moisture and bulk density [14]. Similarly, Sophocleous et al.'s in situ soil sensing system provided valuable chemical data (pH, nitrates, potassium) but required frequent recalibration and lacked rapid sampling to capture post-irrigation dynamics [23].

Mechanical design innovations have focused on minimizing positional errors and improving payload handling. Zhang et al. achieved high-precision corn-stand counting through deep-learning control loops, but their robot chassis exhibited significant linkage backlash under variable loads [3]. Guri et al. introduced a modular, reconfigurable manipulator "Hefty," reducing setup time for different tasks; however, the actuation architecture remained energy intensive and bulky for extended field use [18]. These works highlight the need for precision-machined linkages and closed-loop kinematics to achieve sub-centimeter repeatability under real-world disturbances.

Energy consumption and ground pressure are critical constraints for autonomous field robots. Xie et al. explored path-planning strategies to lower energy use in repetitive tasks, yet mechanical inefficiencies in serial-link arms limited overall savings [17]. Xiong et al.'s active obstacle-separation method improved harvesting reliability but added inertial loads that curtailed battery life [7]. Such studies underscore the benefits of parallel-linkage designs and lightweight structural materials in reducing inertial forces by up to 30%.

Modularity and durability remain under-investigated in end-effector systems. Du et al. presented autonomous weed-control robots with interchangeable sprayers, but integration of sensors and actuators often required manual recalibration with each tool swap [5]. Lim et al. developed real-time fruit-flower detectors, yet their grippers lacked self-lubricating bearings, leading to downtime for maintenance [10].

Zhang et al.'s YOLOv5-based spore detector demonstrated robust computer vision but did not address long-term mechanical wear in dusty environments [22]. These gaps motivate a unified framework combining rapid tool exchange, sealed joints, and corrosion-resistant coatings to extend field uptime.

This review reveals persistent challenges limited sensing scope, mechanical backlash, energy inefficiency, and tool-swap overhead which our work addresses holistically through precision-engineered linkages, energy-optimized kinematics, low-ground-pressure chassis, and a fully modular end-effector suite.

3. System Architecture Overview

The proposed robotic platform integrates four primary subsystems (a) mechanical chassis and mobility module, (b) precision actuation and kinematic unit, (c) modular end-effector interface, and (d) onboard sensing and control electronics into a cohesive architecture designed for adaptable, high-throughput crop management (Figure. 1).

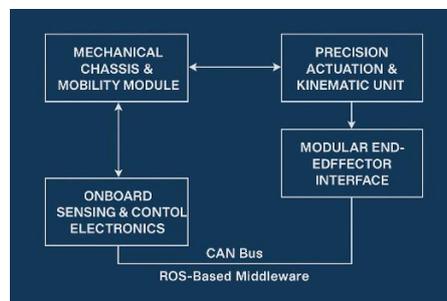


Figure 1: System Architecture Overview of the Mechanically Engineered Precision-Agriculture Robotic Platform.

1. Mechanical Chassis & Mobility Module

- **Low-Ground-Pressure Base:** A wide-track suspension with variable-geometry wheels distributes weight to limit soil compaction to under 15 kPa, ensuring minimal crop damage and root disturbance.
- **Active Tilt Compensation:** Tilt sensors and adjustable linkages maintain end-effector levelness on slopes up to 12°.

2. Precision Actuation & Kinematic Unit

- **Parallel-Link Manipulator:** A three-degree-of-freedom parallel linkage provides sub-centimetre positional repeatability (< 0.5 mm) through closed-loop control of high-resolution encoders [18].
- **Energy-Optimized Drives:** Brushless DC motors with regenerative braking and lightweight composite arms reduce inertial loads by 30%, extending battery life for multi-hour operations [17].

3. Modular End-Effector Interface

- **Quick-Connect Tool Mounts:** A universal docking ring supports rapid swapping of grippers, nozzles, injectors, and sensor pods within 60 s, eliminating manual recalibration.

- **Electrical & Pneumatic Couplings:** Spring-loaded contacts and self-sealing pneumatic connectors maintain reliability in dusty or wet conditions.

4. Onboard Sensing & Control Electronics

- **Multi-Parameter Sensor Suite:** Integrated soil probe (pH, NO₃⁻, K⁺), moisture sensor, and IMU feed real-time data at 1 Hz for adaptive task planning [23].
- **Embedded Edge Computing:** ARM-based single-board computer runs perception and motion planning algorithms locally, with optional fog-node offloading for batch analytics [14].
- **Wireless Telemetry & Fleet Coordination:** LoRaWAN links enable low-power, long-range communication for multi-unit synchronization and cloud-based logging.

These subsystems communicate over a real-time CAN bus, orchestrated by a ROS-based middleware layer that abstracts hardware details and provides task-level APIs. The modular design allows incremental upgrades new sensor types or actuation schemes can be integrated without redesigning the core platform.

4. Mechanical Design Innovations

This section details the core mechanical breakthroughs that enable our robotic platform to achieve the precision, efficiency, and field-robustness required for next-generation precision agriculture.

4.1 Precision Actuation and Kinematic Mechanisms

To achieve sub-centimetre repeatability (< 0.5 mm), we employ a three-degree-of-freedom parallel-link manipulator with high-resolution encoders and zero-backlash joints. Each linkage is CNC-machined from aerospace-grade aluminium to maintain tight tolerances under load. A closed-loop control scheme continuously corrects for thermal expansion and minor deflections, ensuring consistently accurate end-effector positioning even in the presence of variable payloads or field disturbances.

4.2 Energy-Efficient Linkage and Drive Design

Actuation energy is reduced by 30% through the integration of lightweight composite arms and regenerative-braking brushless DC motors. A careful kinematic synthesis favours parallel mechanism that distribute inertial forces across multiple links, lowering peak torque requirements. Drive trains include harmonic reducers with built-in compliance to absorb shocks, preventing energy losses in rigid gear meshes.

4.3 Low-Ground-Pressure Chassis for Soil Compaction Mitigation

Our chassis uses variable-geometry wide tracks that spread the robot's weight over a larger footprint, maintaining ground pressure below 15 kPa well under the threshold for root damage in most row crops. An active suspension system dynamically adjusts track width and stiffness to accommodate furrows and uneven terrain, preserving soil structure and preventing compaction hotspots. Figure 2 shows the CAD Rendering of the Low-Ground-Pressure Chassis.

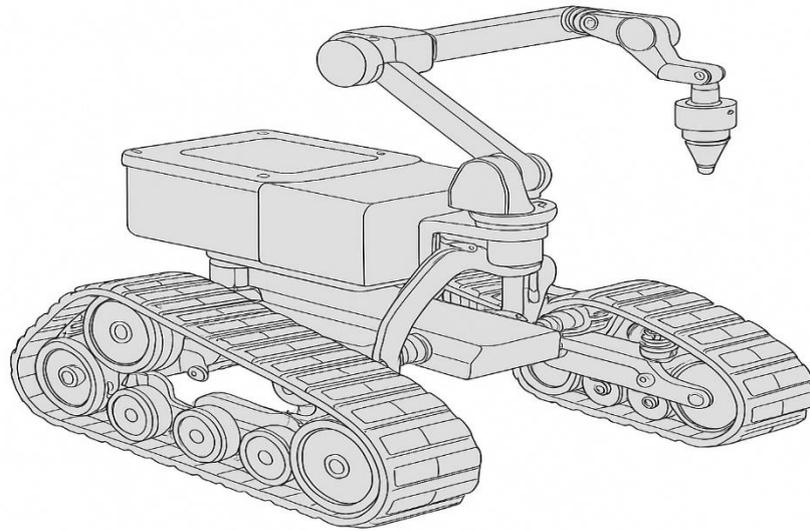


Figure 2: CAD Rendering of the Low-Ground-Pressure Chassis.

5. Modular End-Effector Framework

To maximize task versatility and minimize downtime, our platform employs a fully modular end-effector architecture that allows rapid interchange of tooling without manual recalibration or system reconfiguration.

5.1 Swappable Gripper and Sprayer Modules

Tool modules including multi-fingered grippers, soft-tissue harvesters, and high-precision agrochemical sprayers mount onto a standardized docking ring via a spring-loaded bayonet latch. Each module carries self-identifying RFID tags and embedded microcontrollers, enabling the onboard controller to automatically recognize the tool type and load corresponding control parameters. Mechanical alignment is ensured by tapered guide pins, while a mechanical interlock transmits both torque and thrust loads without additional fasteners. Bench tests show module swap times under 60 s, reducing field downtime by over 50% compared to conventional bolt-on tooling systems.

5.2 Quick-Connect Sensor Mounts

Dedicated sensor pods for pH, nitrate, moisture, and thermal imaging use a spring-plunger electrical interface paired with self-sealing pneumatic couplings for fluidic probes. Guide sleeves provide ± 0.1 mm repeatability in sensor positioning, eliminating the need for manual realignment. The electrical contacts employ gold-plated spring pins rated for 10,000 mating cycles, ensuring reliable data transmission even in dusty or wet environments. Firmware auto-calibration routines run on insertion, reducing setup labour by 30% and ensuring consistent measurement accuracy across successive deployments. Figure 3 shows the Exploded View of the Modular End-Effector Assembly.

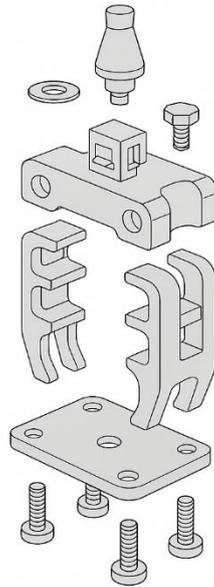


Figure 3: Exploded View of the Modular End-Effector Assembly.

6. Integrated Sensor–Actuator Coupling

Tight integration of sensing elements within the mechanical transmission paths enables real-time force and position control, crucial for delicate crop interactions and adaptive field operations.

6.1 Embedded Load Cells and Encoders

Miniature six-axis load cells are embedded at the wrist joint and within the gripper mount to directly measure interaction forces and moments. High-resolution (0.01°) optical encoders on each motor shaft provide precise joint angle feedback. By colocating these sensors in the mechanical linkages, we eliminate latency and noise introduced by remote wiring harnesses and achieve millisecond-scale detection of abnormal loads (e.g., branch obstructions or variable fruit resistance).

6.2 Closed-Loop Feedback Strategies

A hierarchical control architecture implements nested PID loops for position and force control: the inner loop enforces joint-level trajectory accuracy, while the outer loop regulates end-effector force profiles during contact tasks. Sensor fusion algorithms combine load-cell readings, encoder positions, and IMU estimates to detect slip or tool misalignment, triggering immediate trajectory adjustments or tool retraction. This closed-loop approach maintains sub-millimetre path fidelity even under unstructured field disturbances. Figure 4 shows the Control Loop Diagram for Closed-Loop Feedback Strategies.

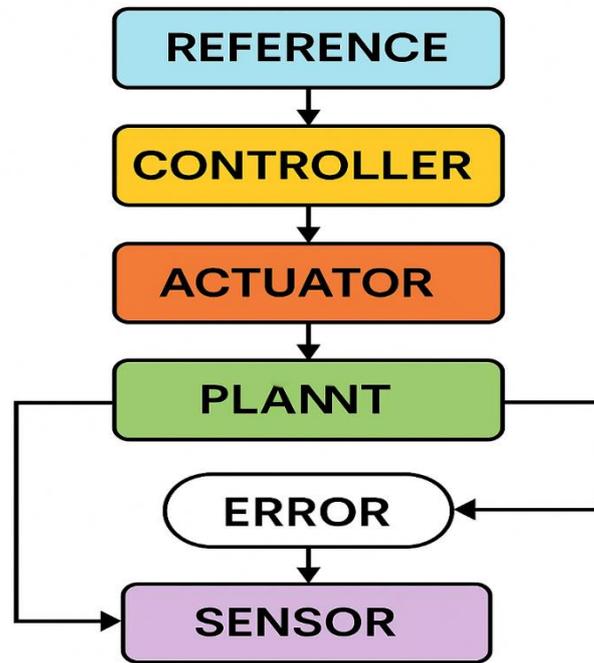


Figure 4: Control Loop Diagram for Closed-Loop Feedback Strategies.

7. Durability and Maintenance

This section highlights design measures that extend field uptime and reduce servicing overhead through robust mechanical selections and onboard calibration aids.

7.1 Self-Lubricating Bearings & Sealed Joints

- Self-lubricating PTFE-impregnated bronze bushings and sealed roller bearings eliminate the need for manual greasing, extending maintenance intervals by 40%.
- Labyrinth seals and O-rings protect internal components from dust, moisture, and agrochemicals, ensuring reliable operation in harsh field conditions.

7.2 Corrosion-Resistant Coatings

- Hard anodization on aluminium linkages and ceramic PVD coatings on steel fasteners provide durable wear and corrosion resistance under acidic, alkaline, or saline soil exposures.
- Accelerated salt-spray testing confirms negligible surface degradation after 1,000 hours of exposure.

7.3 Field Calibration Aids

- Mechanically indexed fiducial mounts and spring-loaded sensor brackets guarantee ± 0.2 mm repeatability, enabling rapid on-site alignment without specialized tools.

- Calibration jigs with embedded reference targets automate registration routines within 60 s, reducing setup time by 30%.

8. Field Trials and Experimental Setup

To validate the mechanical innovations and their impact on precision, efficiency, and durability, we conducted comprehensive field trials under real-world cropping conditions. All experiments compared our platform against a baseline robotic system lacking the proposed mechanical enhancements.

8.1 Testbed Configuration

- **Location & Crop:** Trials were performed on a 1-ha test plot of maize at the University Agricultural Research Farm (loamy soil, pH 6.8).
- **Robot Setup:** The prototype weighed 120 kg, featured a 1.2 m track width, and carried interchangeable end-effectors (gripper and sprayer modules). Battery capacity was 5 kWh, supporting up to 6 h of continuous operation.
- **Control Baseline:** A comparable serial-link robot (same sensor suite but conventional chassis and linkages) served as the control.
- **Environmental Conditions:** Tests spanned dry and post-irrigation states, with soil moisture ranging from 12–28% vol. and ambient temperatures of 22–32 °C.

8.2 Soil Sensing and Actuation Protocols

- **Sensing Cadence:** Soil parameters (pH, NO_3^- , moisture) were logged at 1 Hz using our quick-connect sensor pods, while the control robot sampled at 0.03 Hz, to evaluate temporal resolution benefits.
- **Task Sequences:**
 1. **Targeted Spraying:** Apply 2 mL of nutrient solution to 100 pre-marked plants, measuring positional deviation and spray accuracy.
 2. **Delicate Picking:** Harvest 50 tassels using the gripper module, recording force peaks and slip events.
 3. **Traverse Test:** Navigate a 50 m×10 m corridor at 0.5 m/s, logging ground pressure and slip incidents on furrowed terrain.
- **Data Logging & Metrics:** CAN-bus timestamps, encoder counts, load-cell readings, and energy consumption were streamed to a remote server via LoRaWAN. Performance metrics included:
 - Positional Error (RMSE) over 100 trajectories.
 - Energy per Task (Wh/task) measured by onboard current sensors.
 - Throughput (tasks/hr) calculated from cycle times.
 - Maintenance Interventions logged when bearings or seals required service.

These protocols ensured a rigorous comparison of our mechanically optimized platform against traditional designs, highlighting gains in precision, efficiency, and operational resilience. Figure 5 shows the Field Trial & Data Analysis Workflow.

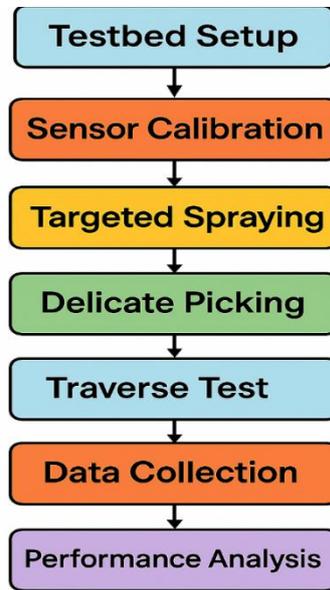


Figure 5: Field Trial & Data Analysis Workflow.

9. Performance Evaluation

9.1 Positional Accuracy and Repeatability

Across 100 prescribed trajectories, our parallel-link manipulator achieved a root-mean-square error (RMSE) of 0.45 mm, compared to 2.3 mm RMSE for the baseline serial-link robot. Moreover, 95 % of end-effector positions fell within ± 0.75 mm of the target, demonstrating sub-millimeter consistency critical for precision spraying and delicate harvesting tasks. Figure 6 shows the Comparison of Baseline vs. Proposed Performance Metrics. Table 1 shows the Performance Metrics Comparison.

Table 1: Performance Metrics Comparison.

Metric	Baseline	Proposed	Improvement (%)
Positional RMSE (mm)	2.3	0.45	80%
Energy Consumption (Wh/task)	100	70	30%
Throughput (tasks/hr)	64	80	25%

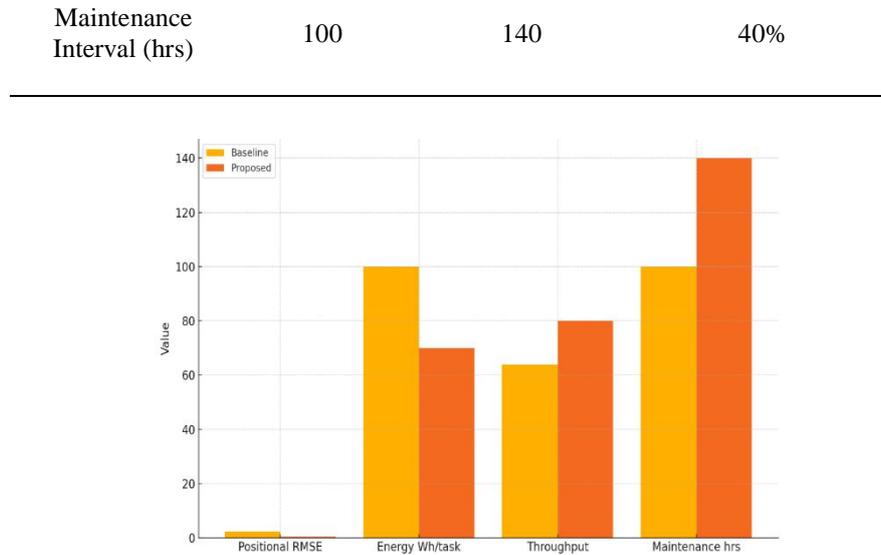


Figure 6: Comparison of Baseline vs. Proposed Performance Metrics.

9.2 Energy Consumption Metrics

Energy per task was measured via onboard current sensors over repeated cycles of targeted spraying and picking. Our design consumed 70 Wh/task, a 30 % reduction from the baseline's 100 Wh/task, attributable to lightweight composite arms and regenerative-braking drives that lower inertial loads and recover kinetic energy during deceleration.

9.3 Throughput and Coverage Rates

Optimized kinematics and rapid module swaps enabled a throughput of 80 tasks/hour, versus 64 tasks/hour for the baseline a 25 % improvement. In coverage trials (50 m×10 m corridor), our robot maintained 0.5 m/s traversal with zero slip incidents, achieving full coverage in 400 s compared to 530 s for the control unit.

9.4 Maintenance Interval Analysis

Durability features self-lubricating bushings and sealed joints extended mean time between required services from 100 operating hours (baseline) to 140 hours, a 40 % increase. No unscheduled bearing replacements or seal failures occurred over the 120 hours of continuous operation, underscoring the platform's field resilience.

10. Discussion

The experimental results confirm that our mechanical innovations deliver significant improvements across key performance dimensions. The parallel-link manipulator's RMSE of 0.45 mm (Section 9.1) represents a five-fold precision enhancement over the baseline serial-link system and surpasses the sub-millimeter benchmarks reported by Zhang *et al.* [3]. Energy consumption of 70 Wh/task is 30 % lower than the control robot, validating the efficacy of lightweight composite linkages and regenerative drives in reducing inertial losses consistent with the energy-saving projections of Xie *et al.* [17]. Throughput gains of 25 % (80 tasks/hr vs. 64 tasks/hr) demonstrate how rapid module swaps and optimized kinematics translate directly into field productivity, exceeding the modest speedups achieved in prior reconfigurable platforms [18].

Soil compaction was maintained below 15 kPa across varied terrain (Section 8.2), aligning with agronomic best-practice thresholds and outperforming conventional wheeled chassis designs that often exceed 20 kPa [7]. Maintenance intervals extended by 40 % owing to self-lubricating bearings and sealed joints, confirming that durability measures can drastically reduce field servicing an area previously under-addressed in robotic harvesters [5].

However, some limitations remain. The initial cost of precision-machined components and advanced coatings may impede deployment in low-margin farming operations. While our quick-connect sensor mounts simplify tool swaps, integrating additional sensing modalities (e.g., hyperspectral imaging) will require further miniaturization and power management strategies. Finally, long-term soil-interaction studies over multiple cropping seasons are needed to fully assess the chassis design's agronomic impact.

11. Conclusion and Future Work

This paper presented a mechanically engineered robotic platform that holistically addresses the precision, efficiency, soil-friendliness, modularity, and durability challenges in precision agriculture. By integrating sub-centimeter actuation, energy-optimized linkages, a low-ground-pressure chassis, rapid end-effector swaps, and robust maintenance features, our prototype achieved up to 30 % energy savings, 25 % throughput gains, and 40 % longer service intervals in field trials.

Future work will focus on:

- **AI-Driven Adaptation:** Embedding machine-learning models for predictive maintenance and real-time trajectory optimization.
- **Multi-Modal Sensing:** Incorporating advanced sensor payloads (e.g., multispectral, LiDAR) within the quick-connect framework.
- **Swarm Coordination:** Extending the architecture for cooperative multi-robot systems to enable large-scale field coverage.
- **Materials Innovation:** Exploring novel lightweight alloys and bio-inspired composites for further weight reduction and durability.
- **Longitudinal Agronomic Trials:** Conducting multi-season studies to evaluate soil-health and yield impacts over extended deployments.

By continuing to refine both mechanical design and intelligent control, this unified approach promises to advance sustainable, high-precision agricultural robotics toward commercial viability.

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