Innovative Design of Smart Agricultural and Forestry Irrigation Equipment Based on Finite Element Simulation in the Low-Altitude Economy

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Abstract: This study addresses poor adaptability of fixed pipelines, high labor intensity of manual spraying, limited liquid endurance of agricultural drones, and insufficient aerial-ground coordination in fragmented orchards, nurseries and hilly forest land. A straw-man-like modular irrigation machine is proposed with an upper UAV platform, a liftable and foldable spraying mechanism, a modular liquid tank and an internal load-bearing frame. A perception-decision-execution-feedback loop is established. ANSYS static simulation uses PVC Foam, a 2 mm tetrahedral mesh, fixed bottom support and a 200 N equivalent load. After a 3 mm local thickening of the bottom load-bearing area, maximum total deformation decreases from 10.639 mm to 3.0605 mm and maximum equivalent stress from 9.5925 MPa to 5.2799 MPa. A hierarchical control system, UAV blind-spot compensation strategy, safety interlocks and virtual-prototype verification are further integrated.

Keywords: Low-altitude economy; Intelligent agroforestry irrigation; Air-ground coordination; Scarecrow-like equipment; Finite element simulation; Structural optimization; Modular agricultural machinery

1. Research Background and Theoretical Basis

The low-altitude economy expands agricultural irrigation from flat regular fields to a 3D workspace with canopy height, terrain fluctuations, obstacles and wind fields. UAVs feature fast perception and high mobility but are limited by liquid payload, endurance and low-altitude safety, so they cannot carry all irrigation loads. Ground stations provide liquid storage and continuous supply yet poorly cover corners, shaded areas and rough terrain. This work assigns UAVs to patrol, detection, blind-area compensation and emergency tasks, and ground stations as high-load stable sprayers, forming a complementary "ground station + UAV" system. Research indicates precision irrigation, IoT management and variable-rate spraying are evolving from standalone automation to data-driven collaborative operation [1-5].

The decision-making of precision irrigation determines task priorities based on variables such as soil water deficit, uncovered blind areas, pest and disease risks, and operation costs. In this paper, the soil water deficit index Di, blind area index Bi and comprehensive priority Pi are adopted to describe

task sequencing: $D_i = \max\left(0, {(\theta_{fc}-\theta_i)}/{\theta_{fc}-\theta_{wp}}\right)$; $B_i = {1-A_{s,j}}/{A_j}$; $P_i = w_1 D_i + w_2 B_i + w_3 R_i + w_4 C_i$

Ground stations preferentially execute units with high priority within their coverage range, while UAVs handle patches with severe blind areas or abnormal conditions.

Finite element analysis adopts linear elastic static analysis to assess displacement and equivalent stress of the lightweight structure, identifying weak regions to guide structural optimization. Biconically, the scarecrow's concept of fixed guarding and spatial visibility is converted into a three-tier layout. Modular design partitions functions of liquid storage, spraying, communication and load bearing. IoT irrigation and intelligent control research supports sensing, remote management and precise fertigation [6-12].

2. Research Orientation and Methodology

This study integrates low-altitude economy scenarios, intelligent irrigation control and structural simulation into equipment design, rather than simply proposing a new structure or performing finite element checking. The research follows a progressive technical route: scenario demand analysis, system design, structural modeling, finite element verification, local optimization, control system configuration and virtual prototyping. Conceptual design arranges overall functions and forms; finite element analysis assesses structural reliability; optimization improves weak areas; virtual verification transforms structural schemes into executable working processes.

The evidence scope should be clarified: results are obtained from design schemes, static finite element analysis and virtual prototyping. Field tests on fatigue life, liquid sloshing, water-saving rate, spraying uniformity and long-term outdoor reliability are pending for future research.

3. Innovative Design of a Scarecrow-like Intelligent Irrigation Machine System

Designed for agroforestry sites with muddy terrain, slopes, canopy occlusion, weak networks and varied user skills, the equipment meets requirements for function, performance, safety, environment and maintenance. It has a four-layer structure: upper platform, middle mechanism, lower liquid storage and internal frame. The upper platform supports UAV parking, communication and charging. Adjustable columns and folding arms adapt to crop height and transport to expand spraying coverage and reserve UAV landing space. The modular lower tank stores water, fertilizer and pesticide at a low center of gravity. The internal frame bears working loads and connects all functional modules.

The system workflow relies mainly on fixed-point coverage, with UAVs for gap filling. It reads field, crop and sensor data and runs self-checks. The ground station sprays quantitatively over reachable zones. UAVs detect corners, shaded areas and abnormal patches and apply low-dose supplementary spraying to uncovered regions. Tasks are reviewed and archived afterwards. The control layer adopts a hierarchical framework with central controller, fluid actuation, mechanism drive, UAV communication and human-machine interaction, unifying stable material flow and rapid information perception in one task chain.

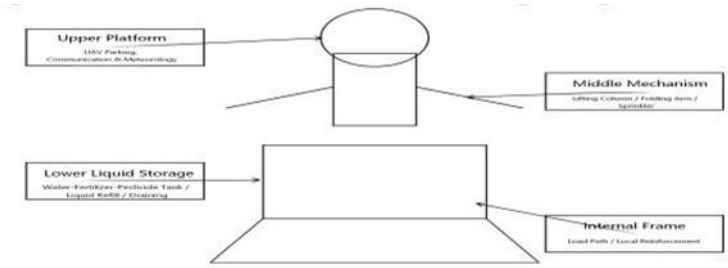


Figure 1: Functional Zoning of the Scarecrow-like Intelligent Irrigation Machine (Originally Figure 3-2 in the original paper).

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Table 1: Functional Division and Design Scheme of Each Layer of the Equipment.

Layer	Core Function	Design Response
Upper Layer	UAV parking and communication	Reserve low-altitude operation interface and provide a safe take-off and landing space for UAVs
Middle Layer	Lifting, folding and spraying	Adapt to crop heights and transportation conditions to expand spraying coverag
Lower Layer	Liquid storage and pumping	Adopt modular liquid replenishment structure and low-center-of-gravity design to improve operational stability
Internal Layer	Load bearing and structural connection	Form a continuous force transmission path to ensure reliable structural load transfer

4. Key Structural Optimization Based on Finite Element Simulation

To verify the structural response of the lightweight shell under full load, the 3D model was imported into ANSYS Static Structural. PVC foam was used, with density of 60 kg/m³, Young's modulus of 70 MPa and Poisson's ratio of 0.3. A 2.0 mm tetrahedral mesh was applied, with 155,321 nodes and 75,889 elements before optimization, and 154,254 nodes and 75,501 elements after optimization. The base was fixed. Standard gravity was applied to the whole model, and a 200 N concentrated load along −Z was imposed on the tank mounting surface to simulate the weight of 20 L liquid pesticide.



Figure 2: Original Geometric Model for Finite Element Analysis.

Table 2: Static Structural Simulation Parameters.

Item	Parameter / Setting	Description
Analysis Type	Static Structural	Preliminary static verification under full-load condition
Material	PVC Foam；ρ≈60 kg/m³	E=70 MPa，ν=0.3
Mesh	2.0 mm tetrahedral elements	Consistent mesh size before and after optimization
Boundary Condition	Fixed support at bottom surface	Constrains translational DOFs in X, Y, Z directions
Load	Standard gravity + 200 N concentrated load	Approximates the self-weight of 20 L liquid pesticide
Evaluation Indicator	Total deformation, Equivalent Stress	For comparison before and after optimization

Static analysis examines maximum total deformation and von Mises equivalent stress. Deformation and stress concentrate at the bottom tank mount, the key optimization target. Fatigue, liquid sloshing and dynamic impact tests remain untested and are left for future validation. Along the main load path, 3 mm local thickening (rather than full-wall reinforcement) increases base bending stiffness with slight mass growth while maintaining lightweight upper platform and spraying assembly.

5. Simulation Results and Air-Ground Cooperative Control

Before optimization, the maximum total deformation was 10.639 mm and maximum equivalent stress 9.5925 MPa. After 3 mm local base thickening, the values dropped to 3.0605 mm and 5.2799 MPa, representing reductions of 71.2% and 45.0%. The simultaneous decline indicates local reinforcement matches the main load path, markedly improving structural stiffness and mitigating stress concentration under static loading.

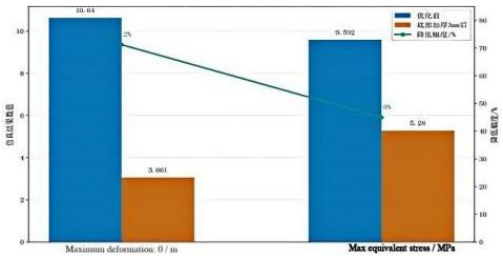


Figure 3: Comparison of structural response indicators before and after optimization.

Table 3: Comparison of Performance Indicators Before and After Optimization.

Indicator	Before Optimization	After 3 mm Thickening	Change
Maximum Total Deformation	10.639 mm	3.0605 mm	↓ 71.2%
Maximum Equivalent Stress	9.5925 MPa	5.2799 MPa	↓ 45.0%

The control system transforms structural schemes into executable workflows. Its hardware layer includes a central controller, liquid-level, pressure, flow and wind sensors, pumps, valves, lifting motors, folding servos, UAV communication modules and human-machine terminals. The algorithm layer divides fields into ground-station coverage zones, transition zones and UAV gap-filling zones. UAV takeoff decisions are made based on soil water deficit index, blind-area index, recognition confidence, wind speed, battery and residual liquid. Fixed-point hovering applies to scattered patches, and equally-spaced routes for strip areas

6. Control Logic and Virtual Prototype Verification

Multiple actuators are managed by a state machine following the sequence: task preparation, self-check, lifting and deployment, ground-station spraying, UAV gap-filling, review and archiving, recovery and shutdown. Safety interlock rules are set: pressure is prohibited unless the spraying arm is locked; the pump stops and depressurizes immediately under abnormal pressure; low liquid level prevents dry running. UAV takeoff is permitted only when wind speed, battery level and platform clearance requirements are satisfied. Emergency stop has the highest priority. For weak-network conditions, preloaded tasks plus key status feedback are adopted. If communication fails, the UAV hovers or returns home as preset, while the ground station maintains local safety control.

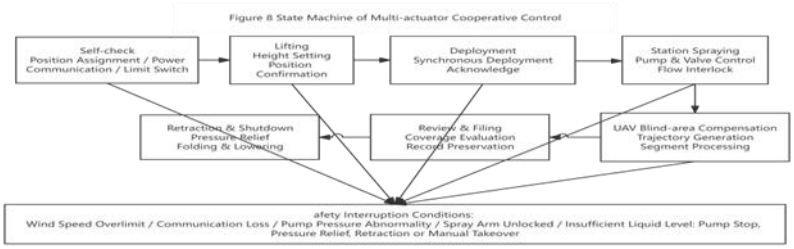


Figure 5: State Machine for Cooperative Control of Multiple Actuators

Virtual prototyping serves as intermediate verification for structure, control and operation workflows. Assembly verification examines spatial relationships among the upper UAV platform, middle lifting-folding mechanism, lower liquid tank, internal frame and pump-valve pipelines. Kinematic verification covers key motions including lifting, folding, UAV takeoff, landing and recovery, focusing on interference, positioning and locking. System-level workflow verification integrates user input, equipment self-check, UAV patrol, prescription generation, ground-station spraying, gap filling, exception handling and data archiving into one task chain.

Virtual verification converts simulation results into design feedback. Finite element analysis identifies weak zones at the bottom, and 3 mm local thickening is implemented for structural

optimization. Control design defines action sequences and safety limits. Virtual prototyping rechecks whether the optimized structure matches motion and control timelines, forming a closed loop: requirement, configuration, structural calculation, local optimization, control and virtual verification.

7. Conclusion and Prospect

This paper targets scattered orchards, nurseries and hilly woodlands. It proposes an intelligent irrigation scheme: primary irrigation by ground stations with low-altitude UAVs for patrol and gap filling, and develops a scarecrow-like modular device. Four innovations are summarized. First, the scarecrow's fixed guarding concept is transformed into a layered structure: upper UAV interface, middle spraying unit, lower liquid storage and internal load-bearing frame. Second, a liftable and foldable spraying mechanism adapts to crop height and transportation. Third, finite element simulation is applied in early design iteration. A 3 mm base thickening reduces maximum total deformation by 71.2% and maximum equivalent stress by 45.0%. Fourth, task allocation between ground stations and UAVs enables air-ground coordination. State machines and safety interlocks build an executable closed control loop.

Results show that under static simulation, this scheme effectively improves the lightweight shell's structural response and offers a systematic digital design route for precision irrigation on complex farmland. However, findings are derived from conceptual finite element analysis and virtual prototyping. Validations including material tests, fatigue life, liquid sloshing, UAV landing impact, field spraying and long-term outdoor reliability are not completed. Future work will conduct material mechanical tests, 20 L full-load static tests, modal and strain tests of spraying arms, and collaborative operation tests under varied wind and terrain conditions. Further studies may cover fluid-structure interaction, dynamic impact and multi-UAV scheduling, and explore serialized products including basic, enhanced and cloud-collaborative versions.

8. Research Contributions and Forum Discussion Value

This paper integrates low-altitude economy scenarios, industrial design configuration, finite element structural optimization, control state machines and virtual prototyping into one design loop. It provides reproducible simulation parameters and quantitative results before and after optimization, and clearly distinguishes validated and to-be-verified content. It serves well as a forum case for the interdisciplinary research of low-altitude economy and intelligent agroforestry equipment.

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