DECENTRALIZED MULTI-AGENT SYSTEMS

Heterogeneous Fleet Coordination for Precision Agriculture

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CURRENT AGRICULTURAL CHALLENGES DEMAND INTELLIGENT AUTOMATION

GLOBAL FOOD DEMAND CRISIS

Global food demand is projected to increase by **50% by 2050**, while agricultural resources become increasingly constrained. Climate change, water scarcity, and labor shortages threaten food security worldwide.

TRADITIONAL METHODS INSUFFICIENT

Traditional farming methods cannot meet these challenges efficiently. Smart Farming technologies, particularly Multi-Agent Systems, offer a path forward by enabling autonomous, coordinated operations that optimize resource use while reducing environmental impact.

EXISTING MAS LIMITATIONS

Existing MAS solutions face critical limitations: **centralized control** creates single points of failure, **homogeneous fleets** lack operational flexibility, and **static coordination strategies** cannot adapt to dynamic agricultural environments.

RESEARCH QUESTION AND OBJECTIVES

> *How can a decentralized multi-agent system effectively coordinate a heterogeneous fleet of agricultural robots for integrated pest management while remaining scalable and robust?*

KEY OBJECTIVES

OBJECTIVE 01

Design a decentralized coordination architecture that eliminates single points of failure

OBJECTIVE 02

Implement heterogeneous fleet support for ground scouts and aerial workers with distinct capabilities

OBJECTIVE 03

Develop adaptive resource management that accounts for agent energy and payload constraints

OBJECTIVE 04

Validate the system through comprehensive testing and simulation

LITERATURE REVIEW REVEALS CRITICAL GAPS IN CURRENT APPROACHES

CENTRALIZED CONTROL DOMINATES

Din et al. (2022) achieved **84% coverage efficiency** using centralized DDQN, but introduced vulnerability to controller failures and communication bottlenecks. *[A deep reinforcement learning-based multi-agent area coverage control for smart agriculture]*

HOMOGENEOUS FLEETS LIMIT FLEXIBILITY

Most research assumes identical agents, missing opportunities for task specialization and complementary capabilities. Current systems cannot leverage the distinct advantages of ground-based inspection and aerial application.

INSUFFICIENT REAL-WORLD VALIDATION

Skobelev et al. (2019) proposed visionary **Agriculture 5.0** concepts with ontology-driven knowledge bases, but practical implementations remain limited. *[Smart Farming – Open Multi-agent Platform and Eco-System]*

EMERGING OPPORTUNITIES

Pérez-Pons et al. (2021) demonstrated deep Q-learning for agricultural decision-making, showing promise for integrating AI with MAS. *[Deep Q-Learning and Preference Based Multi-Agent System for Sustainable Agricultural Market]*

> These gaps motivated our focus on **decentralization**, **heterogeneity**, and **practical implementation**.

CONTRACT NET PROTOCOL ENABLES DECENTRALIZED TASK ALLOCATION

The contract net protocol provides a proven framework for distributed decision-making without central control.

FOUR-PHASE COORDINATION

1. **Task Announcement**
   Scout agents detecting infestations broadcast spray tasks with location and density parameters
2. **Bidding**
   Worker agents evaluate tasks and submit bids based on distance, energy level, and available pesticide
3. **Task Awarding**
   Scout agents select the worker with the lowest bid value (closest, highest energy)
4. **Task Execution**
   Winning workers navigate to locations, apply pesticide, and update resource levels

BID CALCULATION

bidValue = distance + (100 - energyLevel)

Lower bid values indicate better suitability for task allocation

SYSTEM ARCHITECTURE SUPPORTS TWO SPECIALIZED AGENT TYPES

SCOUT AGENTS

Ground Robots

EQUIPMENT

High-resolution cameras and multispectral sensors for detailed crop inspection

PRIMARY FUNCTION

Detect pest infestations and announce spray tasks to the fleet

PROTOCOL ROLE

Act as task managers in the contract net protocol

PERFORMANCE

Lower speed but higher inspection accuracy compared to aerial agents

WORKER AGENTS

Aerial Drones

EQUIPMENT

Precision sprayers for targeted pesticide application

PRIMARY FUNCTION

Bid on announced tasks based on proximity and resource availability

OPERATIONAL ADVANTAGE

Higher speed and coverage area but limited payload capacity

RESOURCE MANAGEMENT

Energy-constrained operations require strategic task selection

This **heterogeneous design** enables task specialization and operational efficiency

IMPLEMENTATION USES MODERN WEB TECHNOLOGIES FOR ACCESSIBILITY

TECHNOLOGY STACK

BACKEND

Node.js with tRPC for type-safe API procedures

DATABASE

MySQL for persistent storage of agents, tasks, and simulations

FRONTEND

React with real-time field visualization

TESTING

Vitest for comprehensive unit and integration testing

DATABASE SCHEMA

AGENTS TABLE

Stores type, position, energy, payload capacity

TASKS TABLE

Tracks status lifecycle (pending → assigned → completed)

SIMULATIONRUNS TABLE

Records metrics (completion rate, resource efficiency)

TASKBIDS TABLE

Maintains bidding history for analysis

WEB-BASED INTERFACE

- Real-time visualization of the agricultural field
- Agent positions and task status tracking
- Performance metrics dashboard

COMPREHENSIVE TESTING VALIDATES SYSTEM CORRECTNESS

Test Coverage: 11 Tests, 100% Pass Rate

TEST CATEGORY	TESTS	STATUS
Agent Management	4	✓ All Passed
Simulation Management	3	✓ All Passed
Contract Net Protocol	4	✓ All Passed

KEY TEST RESULTS

Agent Creation and Deletion

The system successfully creates both scout and worker agents with appropriate default parameters and can delete agents without affecting other system components.

Simulation Creation

Simulations are created with the specified number of tasks, which are randomly distributed across the agricultural field.

Task Allocation

The contract net protocol successfully allocates tasks to the most suitable worker agent based on proximity and energy level.

Robustness

When no agents are available to bid on a task, the system gracefully handles the situation by returning a "No bids received" message.

SYSTEM DEMONSTRATES EFFECTIVE COORDINATION AND RESOURCE EFFICIENCY

TASK COMPLETION

All announced tasks are successfully allocated and completed through the contract net protocol. The system processes one task per simulation step, enabling controlled evaluation.

ENERGY EFFICIENCY

Energy consumption calculated as **energyCost = distance × 0.5** provides realistic resource tracking. Agents only bid when energy level exceeds 20%, preventing resource depletion.

PESTICIDE EFFICIENCY

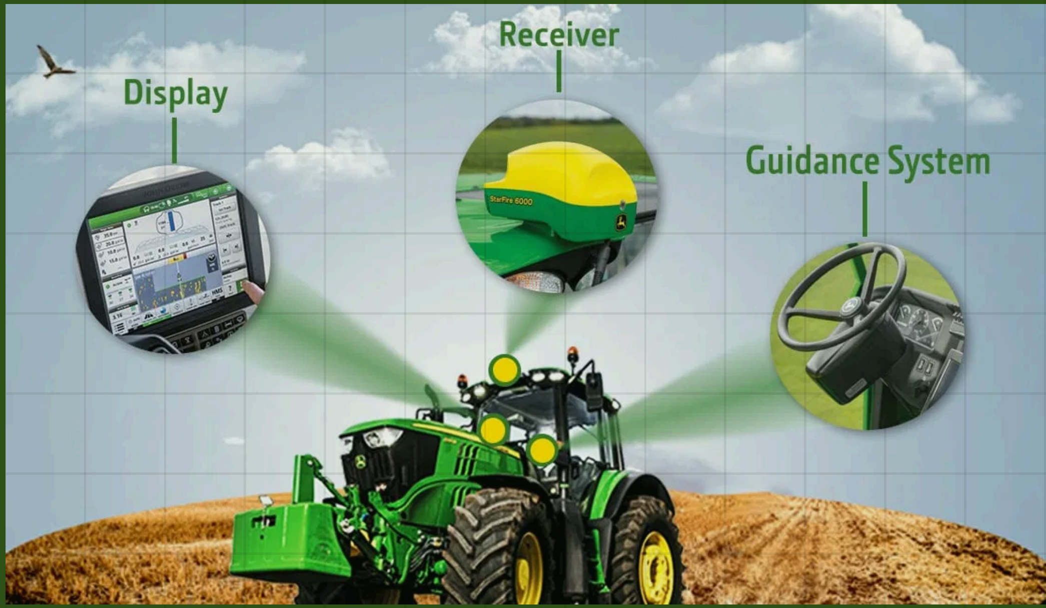
Pesticide usage proportional to infestation density ensures appropriate resource allocation based on severity. `pesticideUsed = density × 10 ml`

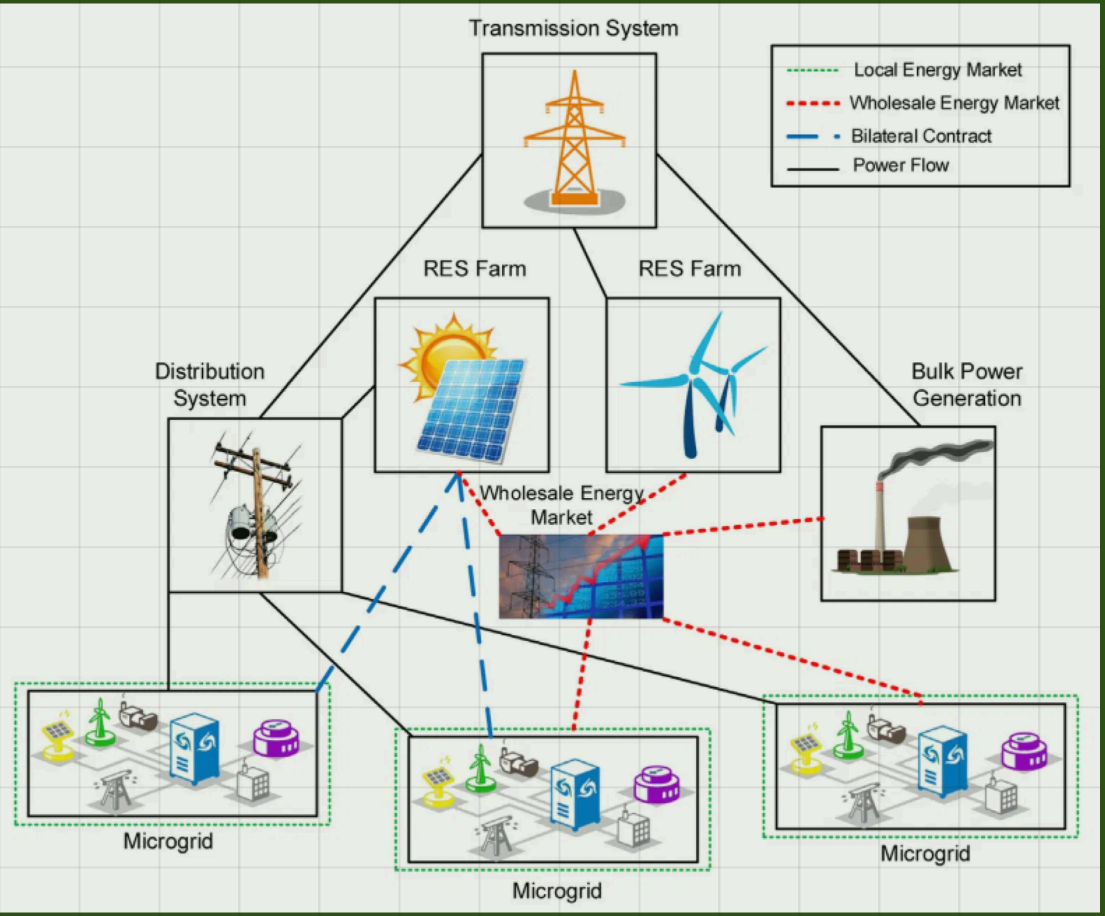
ADAPTIVE BEHAVIOR

Workers refuse to bid on tasks when resources are insufficient, demonstrating intelligent self-management and preventing system failures.

ROBUSTNESS

System continues to operate when individual agents are unavailable, with tasks remaining in pending state until suitable agents become available.





REAL-TIME VISUALIZATION ENABLES MONITORING AND ANALYSIS

The web-based interface provides comprehensive visibility into system operations:

FIELD VIEW

- 2D visualization of the agricultural plot with grid overlay
- Agent positions marked with type-specific icons (🚁 for drones, 🤖 for scouts)
- Task locations color-coded by status (red=pending, yellow=assigned, green=completed)

METRICS DASHBOARD

- Real-time completion rate, energy efficiency, and pesticide efficiency
- Historical tracking of simulation performance over time
- Comparison of multiple simulation runs

CONTROL PANEL

- Create and manage agent fleet composition
- Configure simulation parameters (task count, distribution)
- Step-by-step execution for detailed observation

DECENTRALIZED APPROACH OFFERS KEY ADVANTAGES OVER CENTRALIZED SYSTEMS

ROBUSTNESS

No single point of failure. System continues operating even when individual agents fail or lose communication.

SCALABILITY

New agents can join the fleet dynamically without reconfiguring a central planner. System complexity grows linearly rather than exponentially.

SIMPLICITY

Contract net protocol is easier to implement and debug than complex deep learning models requiring extensive training data.

TRANSPARENCY

Bidding process provides clear rationale for task allocation decisions, enabling easier troubleshooting and optimization.

TRADE-OFFS

Centralized approaches may achieve better **global optimization**, but at the cost of robustness and flexibility. Future work could explore **hybrid architectures**.

RESEARCH CONTRIBUTIONS ADVANCE THE STATE OF THE ART

01 DECENTRALIZED COORDINATION

Demonstrated that effective task allocation can be achieved without central control, improving system robustness and scalability

02 HETEROGENEOUS FLEET SUPPORT

Successfully coordinated two different agent types with distinct capabilities, addressing a key gap in existing research

03 ADAPTIVE RESOURCE MANAGEMENT

Implemented bidding logic that accounts for dynamic agent state (energy, payload), ensuring sustainable operations

04 PRACTICAL IMPLEMENTATION

Developed a web-based prototype that makes MAS concepts tangible and accessible for evaluation and further development

05 COMPREHENSIVE VALIDATION

Achieved 100% test pass rate across 11 tests covering all major system components and coordination mechanisms

These contributions provide a **practical framework** for developing more robust, scalable, and adaptive agricultural automation systems

FUTURE RESEARCH DIRECTIONS BUILD ON THIS FOUNDATION

1 **SIM-TO-REAL TRANSFER**

Deploy the system on physical robots to validate performance in real agricultural environments with sensor noise and environmental variability

2 **MULTI-OBJECTIVE OPTIMIZATION**

Extend bidding to balance multiple objectives: minimize energy consumption, maximize coverage speed, and reduce pesticide usage

3 **LEARNING-ENHANCED COORDINATION**

Integrate reinforcement learning to optimize bid calculation parameters based on historical performance data

4 **DYNAMIC FLEET COMPOSITION**

Support agents joining and leaving the fleet during operation, handling battery swaps and maintenance cycles

5 **EXTENDED APPLICATION DOMAINS**

Apply the coordination framework to other agricultural tasks: irrigation, harvesting, and soil sampling

> *These directions aim to bridge the gap between* ***proof-of-concept*** *and* ***production-ready systems***

CONCLUSION: DECENTRALIZED MAS ENABLES ROBUST SMART FARMING

KEY ACHIEVEMENTS

Successfully designed and implemented a **decentralized multi-agent system** that coordinates heterogeneous agricultural robots for integrated pest management without central control. Achieved **100% test pass rate** across all system components.

RESEARCH IMPACT

Addressed critical gaps in existing literature by demonstrating that **robustness, scalability, and flexibility** can be achieved through decentralized coordination. Provided a practical framework for developing more resilient agricultural automation systems.

VISION FOR AGRICULTURE 5.0

This work contributes to the broader vision of **Agriculture 5.0**, where autonomous multi-agent systems work collaboratively to optimize resource use, reduce environmental impact, and enhance food security in the face of global challenges.

> *"The future of agriculture lies not in centralized control, but in the intelligent coordination of autonomous agents working together toward common goals."*

THANK YOU — QUESTIONS?