Swarm Robotics for Sustainable Weed Management: Algorithm and Design

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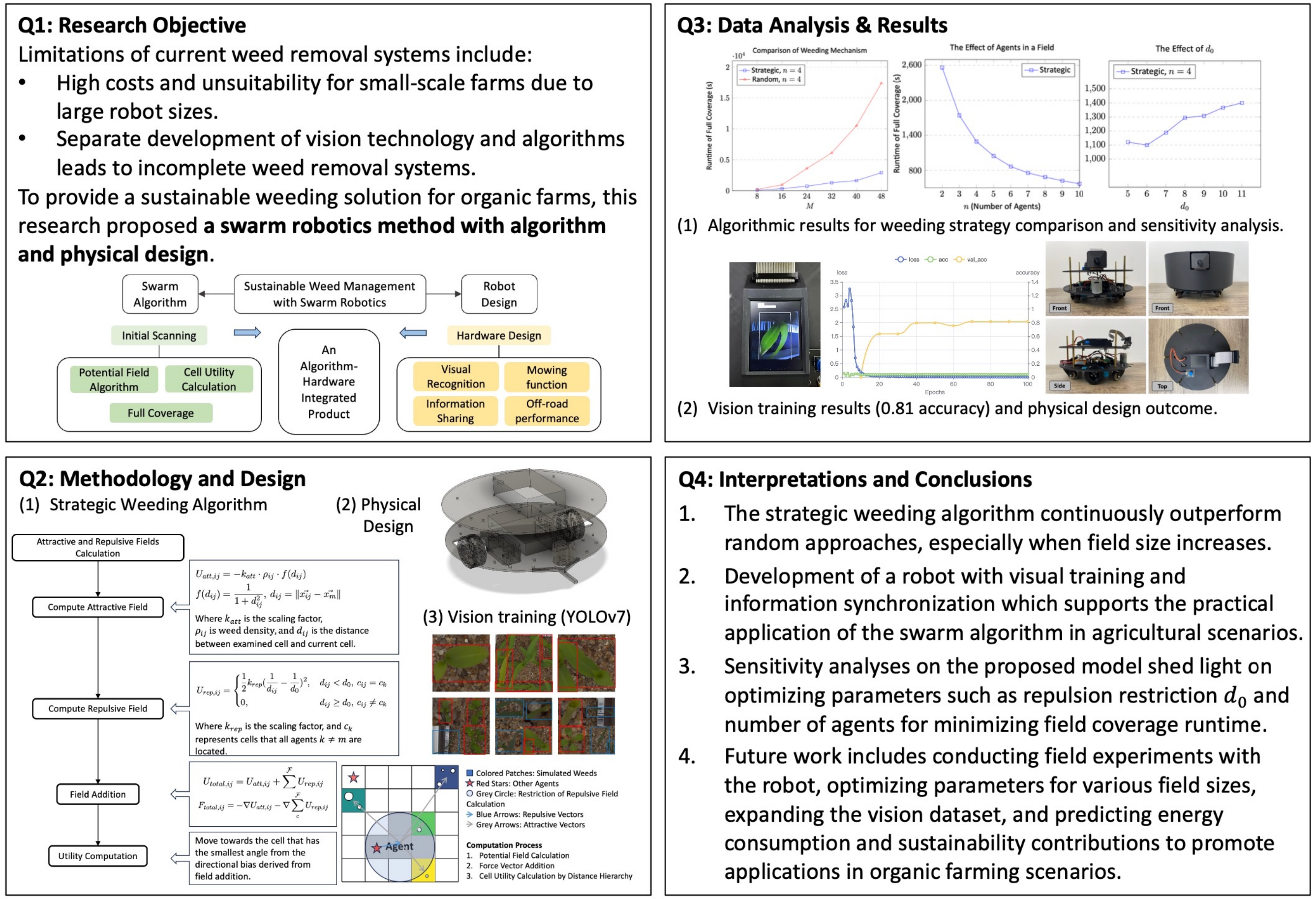

Q1: Research Objective
Limitations of current weed removal systems include:
• High costs and unsuitability for small-scale farms due to large robot sizes.
• Separate development of vision technology and algorithms leads to incomplete weed removal systems.
To provide a sustainable weeding solution for organic farms, this research proposed a swarm robotics method with algorithm and physical design.
Swarm Algorithm
Sustainable Weed Management with Swarm Robotics
Robot Design
Initial Scanning
Hardware Design
Potential Field Algorithm
Cell Utility Calculation
Full Coverage
An Algorithm-Hardware Integrated Product
Visual Recognition
Mowing function
Information Sharing
Off-road performance
Q3: Data Analysis & Results
Comparison of Weeding Mechanism
The Effect of Agents in a Field
The Effect of d0
(1) Algorithmic results for weeding strategy comparison and sensitivity analysis.
(2) Vision training results (0.81 accuracy) and physical design outcome.
Q2: Methodology and Design
(1) Strategic Weeding Algorithm
(2) Physical Design
(3) Vision training (YOLOv7)
Attractive and Repulsive Fields Calculation
Compute Attractive Field
Compute Repulsive Field
Field Addition
Utility Computation
Move towards the cell that has the smallest angle from the directional bias derived from field addition.
Computation Process
1. Potential Field Calculation
2. Force Vector Addition
3. Cell Utility Calculation by Distance Hierarchy
Q4: Interpretations and Conclusions
1. The strategic weeding algorithm continuously outperform random approaches, especially when field size increases.
2. Development of a robot with visual training and information synchronization which supports the practical application of the swarm algorithm in agricultural scenarios.
3. Sensitivity analyses on the proposed model shed light on optimizing parameters such as repulsion restriction d0 and number of agents for minimizing field coverage runtime.
4. Future work includes conducting field experiments with the robot, optimizing parameters for various field sizes, expanding the vision dataset, and predicting energy consumption and sustainability contributions to promote applications in organic farming scenarios.

Introduction and Goal

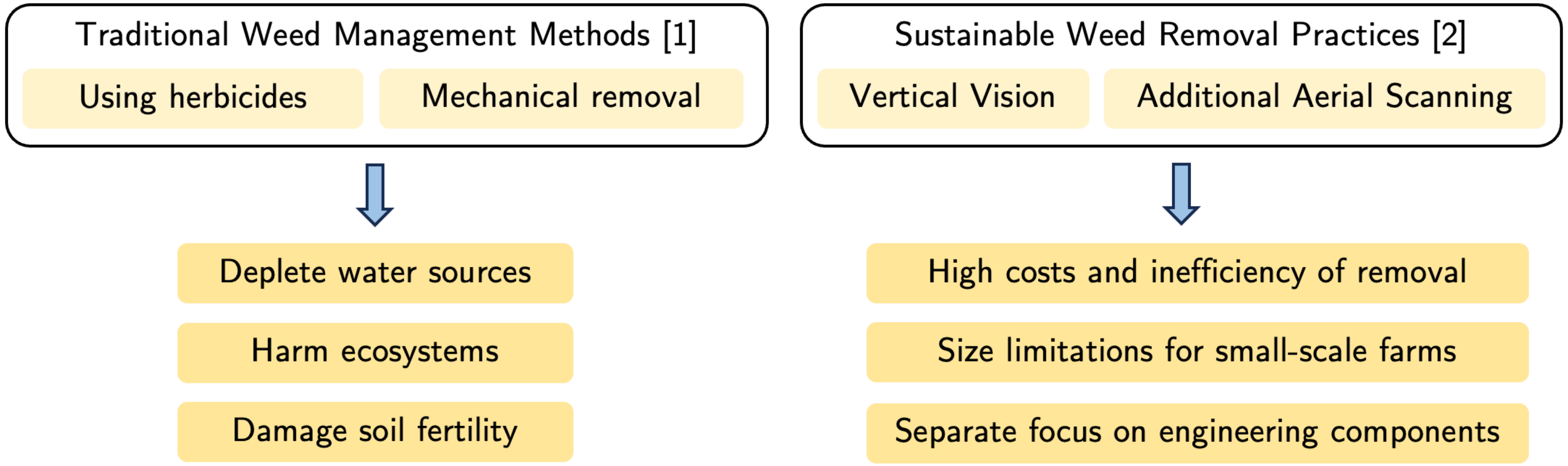

Figure 1: Comparison and drawback of Traditional and Sustainable Weed Management Methods.

- Environmental problems associated with traditional weed management methods
- Concerns about sustainable weed management (SWM) practices

Swarm a large group of locally communicating individuals with common goals [3]

Swarm robotics in SWM low cost, high efficiency, collective weeding behavior

Introduction and Goal

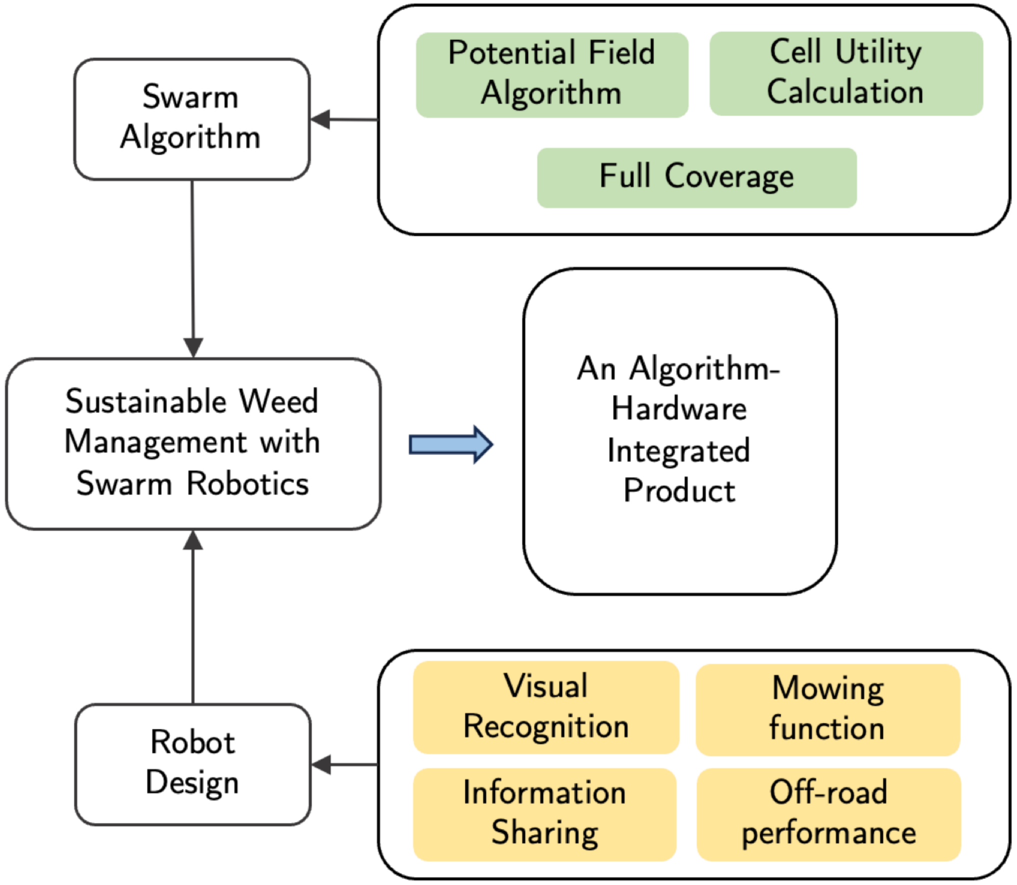

Figure 2: A schematic diagram of the work done in the research.

Completeness, Practicality

The work of this research includes:

(1) Developing **a strategic weed removal algorithm** that facilitates collective weeding behavior with low energy costs.

(2) Designing a compact **weeding robot** equipped with communication, data synchronization and vision capabilities.

Algorithmic Design

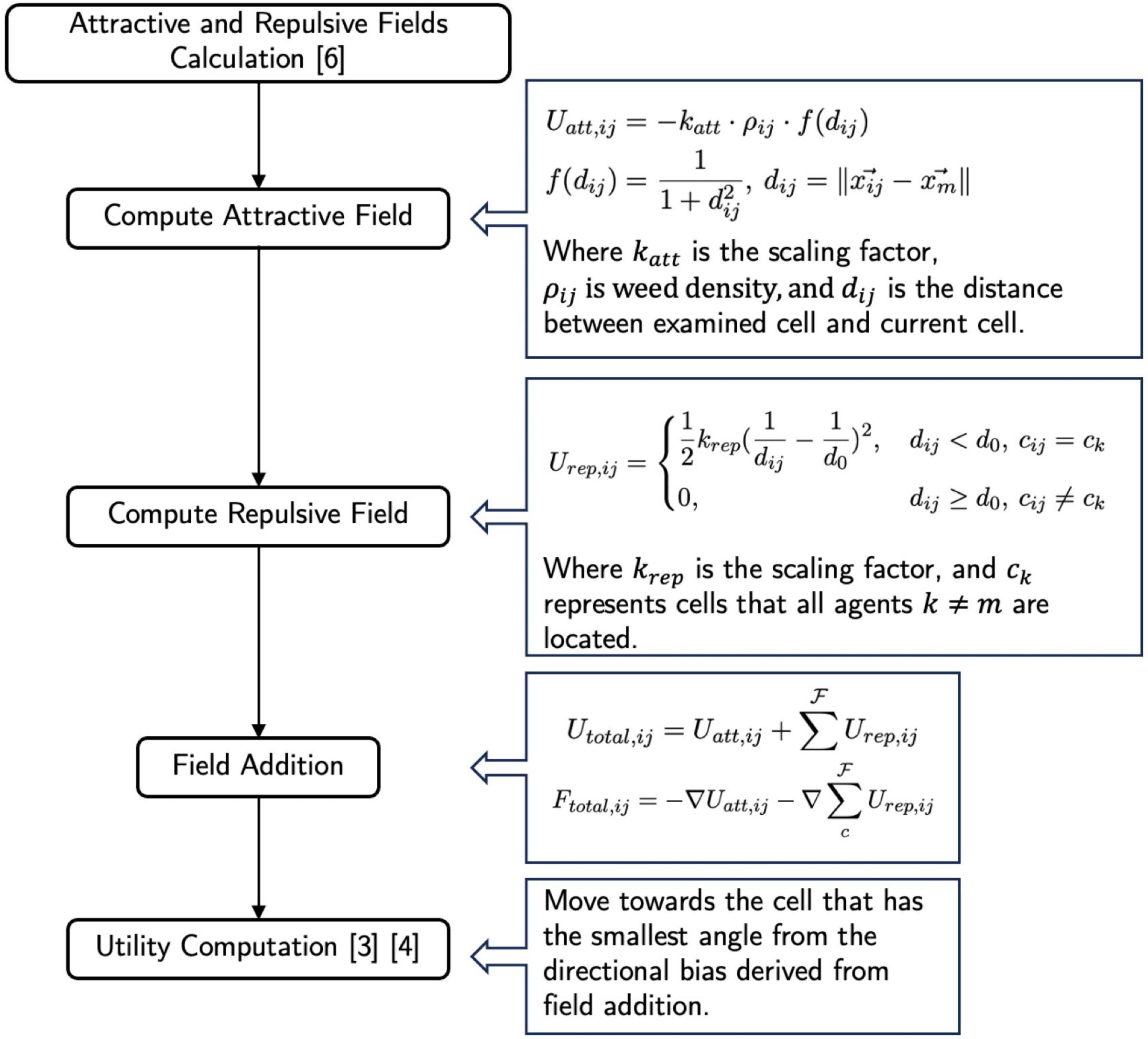

Figure 3: The execution process of strategic collective weeding algorithm.

Potential Field [4] Algorithm:
Attraction-Repulsion System

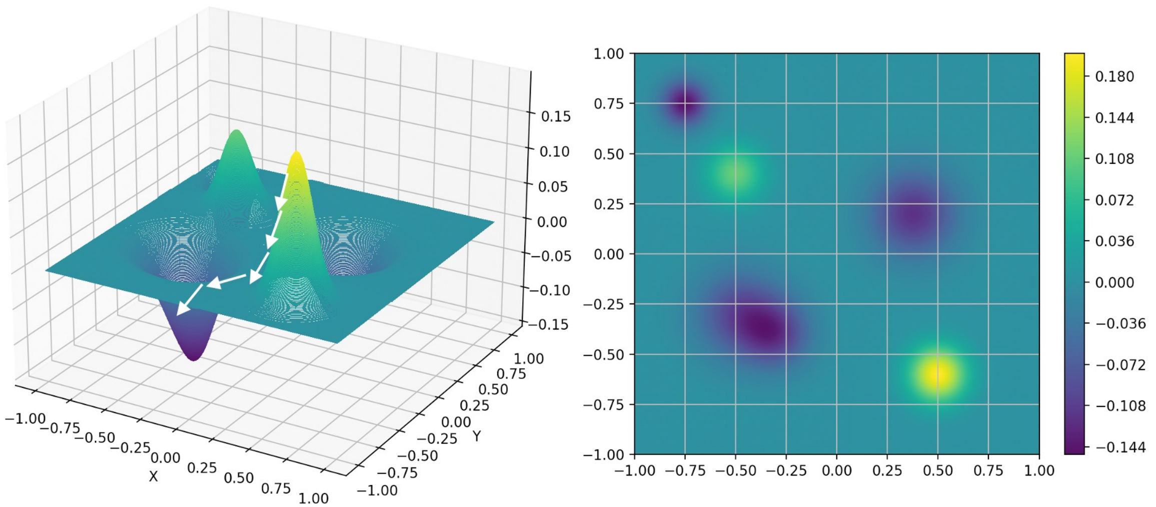

Figure 4: Demonstration of a sample potential field.

- **Attraction** guides the robots towards cells with a higher weed density.
- **Repulsion** prevents too many robots from congregating in a single patch.

Algorithmic Design

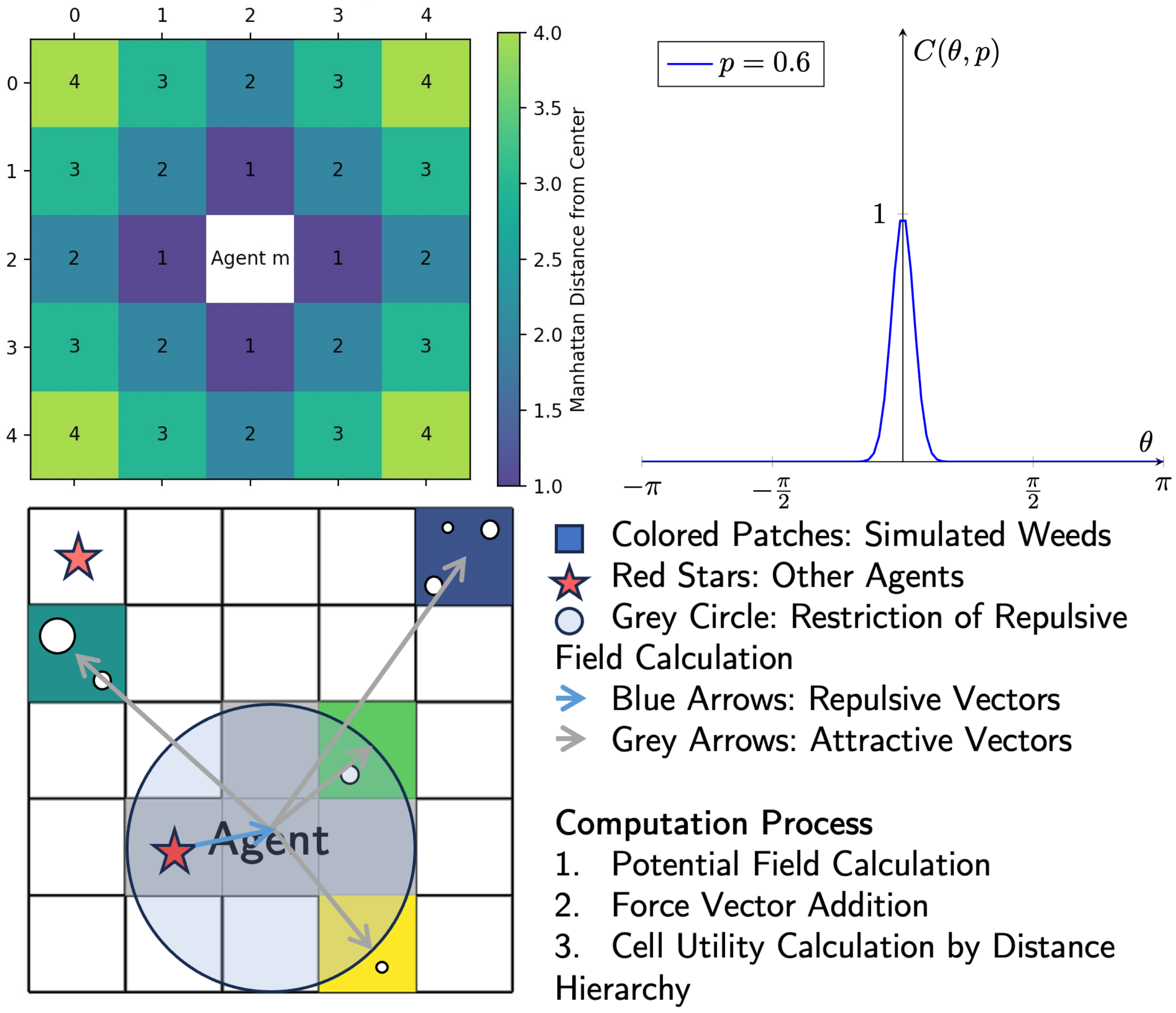

Figure 5: Hierarchy computation demonstration.

Hierarchy-based utility computation

- **Utility Computation**: The utility is computed by mapping the angle between the directional vector and the cell's positional vector onto a Cauchy distribution.
- **Hierarchy**: Priority is assigned to cells based on their Manhattan distance from the agent, with nearer cells receiving higher priority.

Integration of proximity prioritization and utility scores in the decision-making process

Physical Design

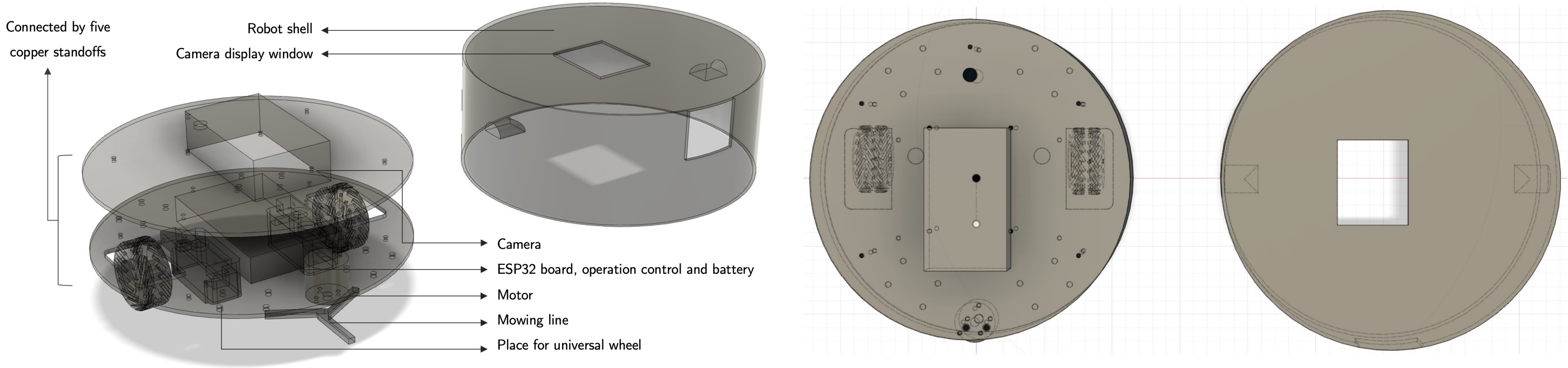

Figure 6: Design sketches of the robot prototype.

Three Objectives

- **Off-road performance**: Ensures the robot operates stably under various road conditions.Algorithms
- **Deployment**: Enables the execution of the algorithm's functions.
- **Vision Training**: Allows the robot to identify weeds.

Design and Product Sketch completed by Fusion360; robot body made by 3D printing with eco-friendly materials **cost-effective and sustainable**

Physical Design

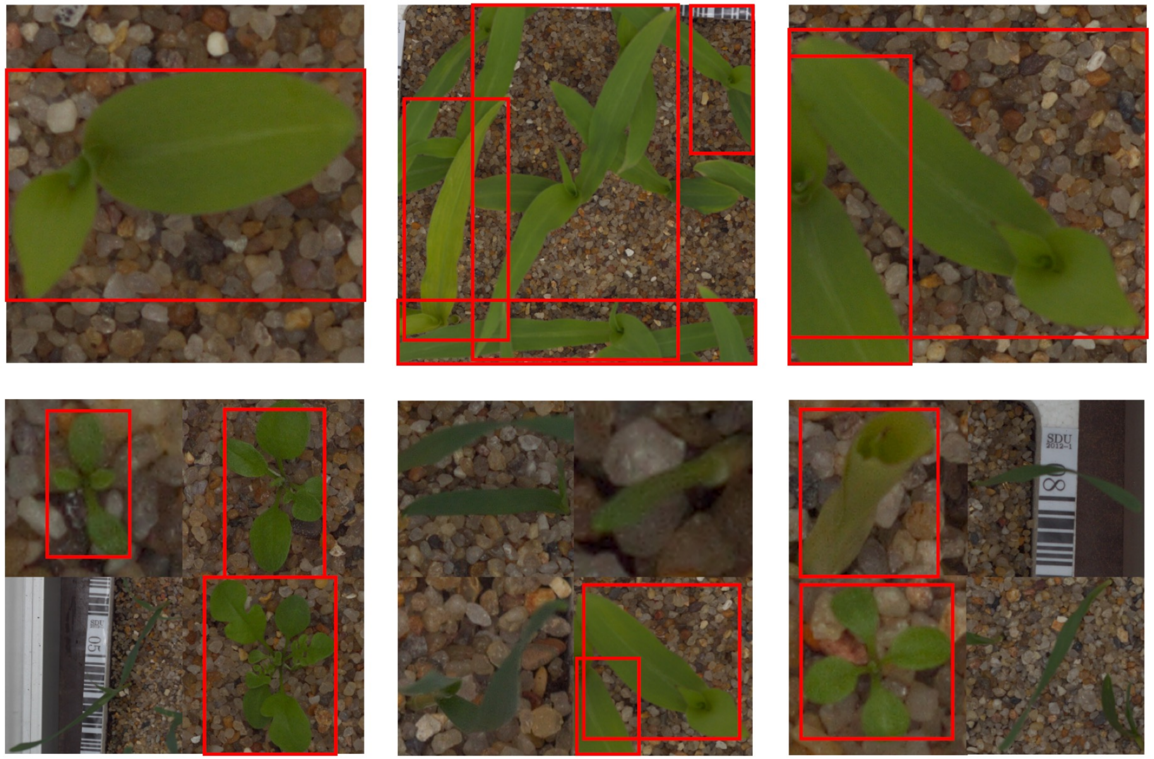

Figure 5: Bounding boxes for the V2 Plant Seedling dataset.

- V2 Plant Seedling dataset [4] *Rationale of using a seedling dataset
- YOLOv7 [5]
- Manually annotated, flipped, blurred, and resized.

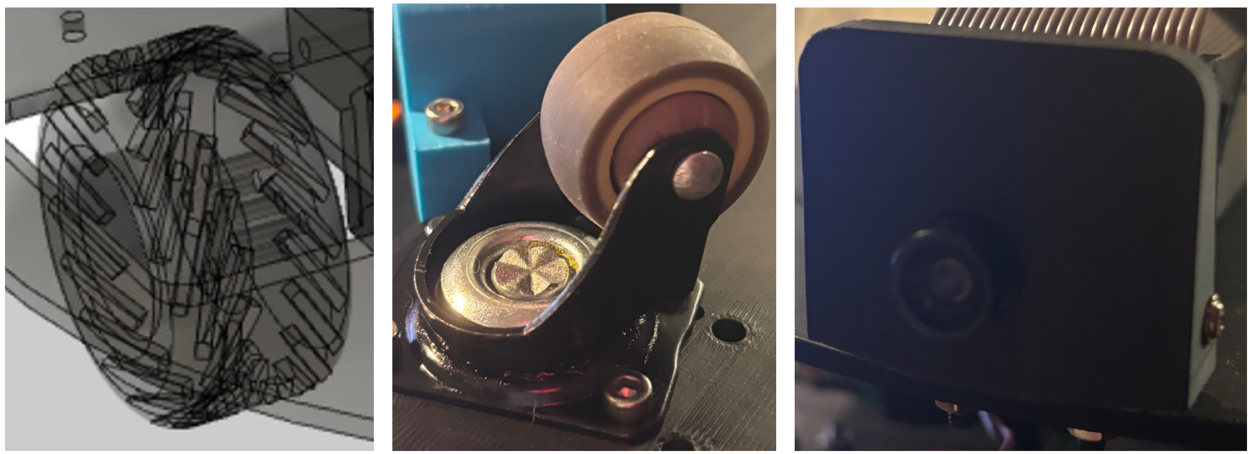

Figure 6: Robot components of key functionalities.

- Wheels with regular rectangular groves
- Omnidirectional wheels
- Arduino ESP32 Board for Bluetooth and wireless connection
- Camera for weed recognition

Results: Physical Design

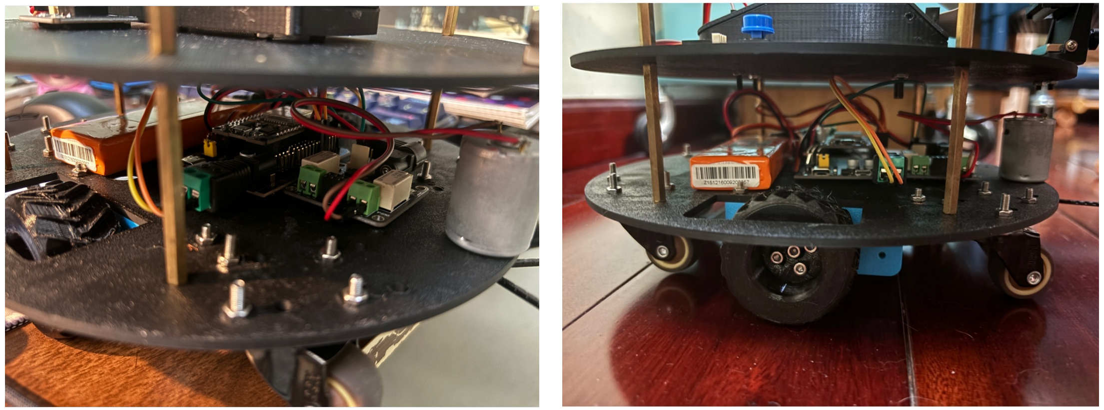

Figure 7: Inner configuration of the robot.

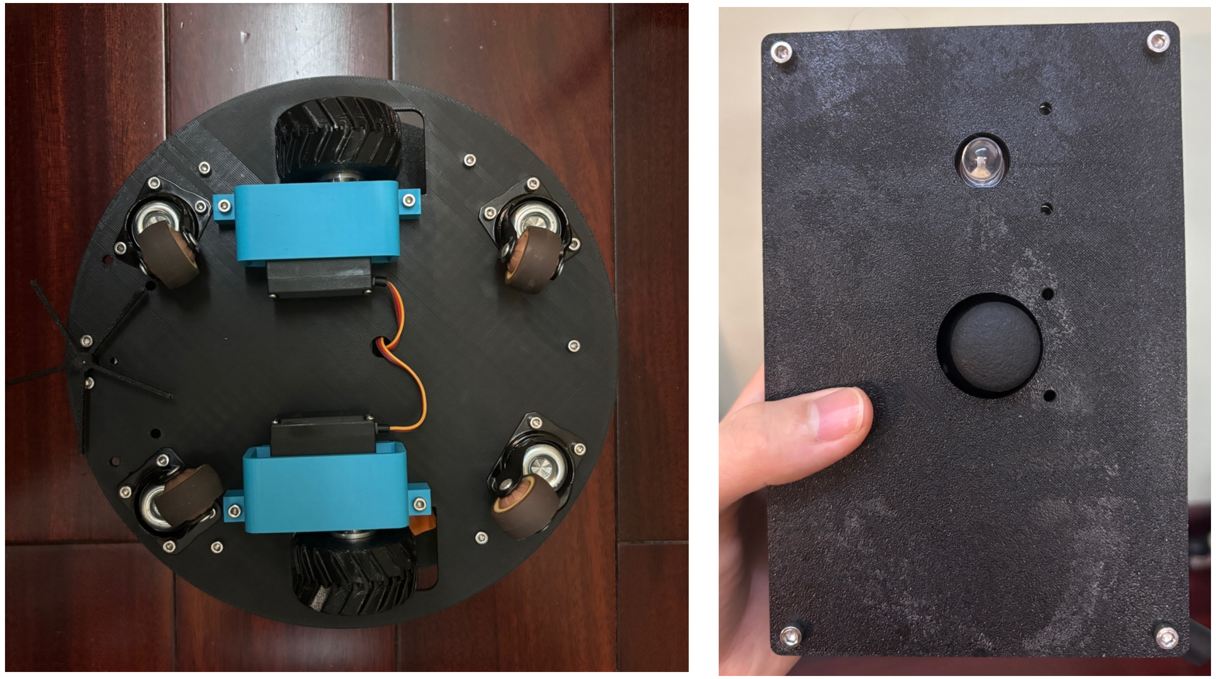

Figure 8: Bottom view and external remote controller for testing.

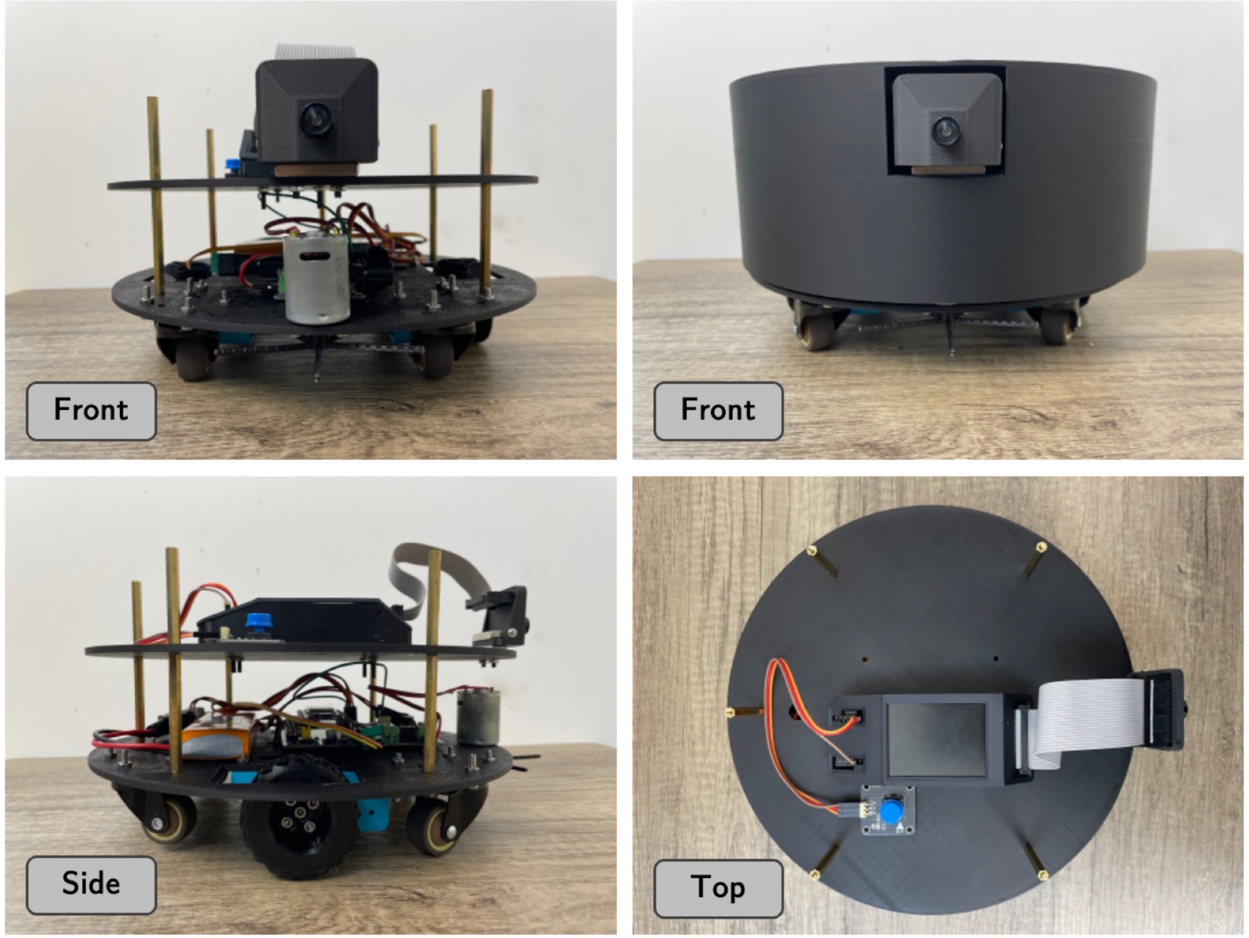

Figure 8: Final product.

Three-view diagram of the robot.

Results: Physical Design

Figure 9: Vision training results.

The training results over 100 epochs diagram shows that the test set has achieved an accuracy of 81%.

Results: Algorithmic Design

No.	Dependent Variable	Independent Variable	Value Specification
1	Total Runtime (In a single operation)	Method, M	Strategic, $n=4$; Random, $n=4$; $M=8,16,24,32,40,48$ $d_0=M/4$
2		n	$n=$2, 3, 4, 5, 6, 7, 8, 9, 10
3		k_{rep}	$k_{\text{rep}}=$ 0.02, 0.05, 0.08, 0.11, 0.14, 0.17, 0.20
4		d_0	$d_0=5,6,7,8,9,10,11$

Table 1: Simulation parameter specification.

- **Group 1**: Strategic Weeding Algorithm vs Segmented Random (traversing the field by columns)
- **Group 2, 3, 4**: Sensitivity analysis on key parameters (number of agents, repulsive force coefficient, repulsion distance restriction)

Results: Algorithmic Design

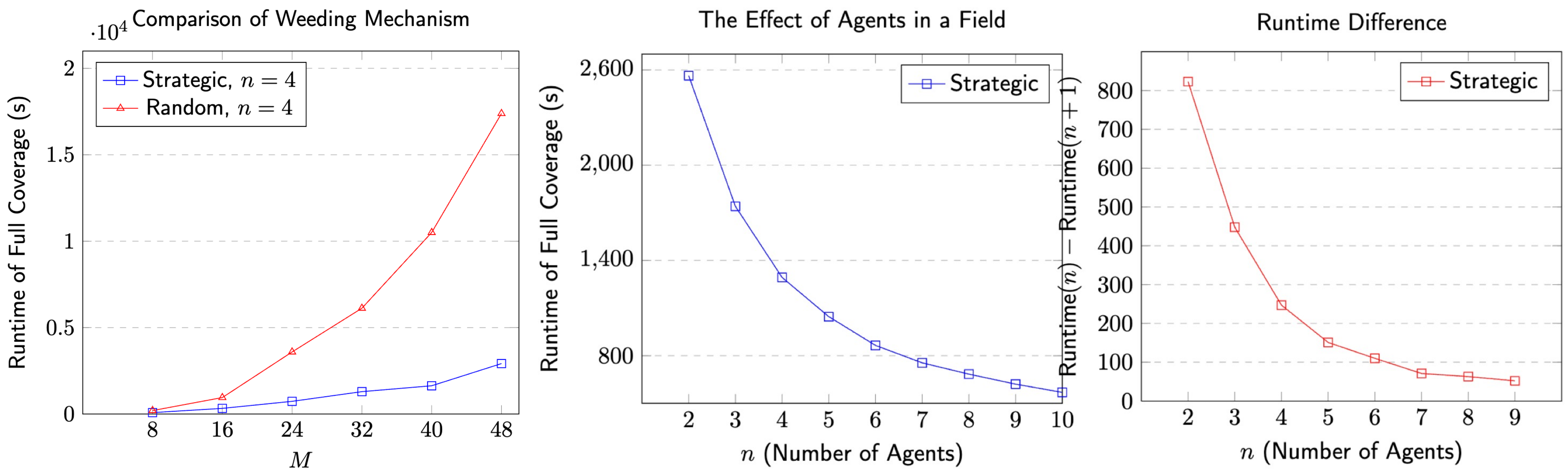

Figure 10: Algorithm comparison (I) and sensitivity analysis on number of agents (II, III).

Group 1 As the field size M increases, strategic weeding algorithm consistently outperforms the random walk method. The difference in performance between the two methods becomes more transparent as the task complexity grows.

Group 2 As the number of agents increments, the rate of runtime decrease slows down, indicating a diminishing return on the addition of more agents.

Results: Algorithmic Design

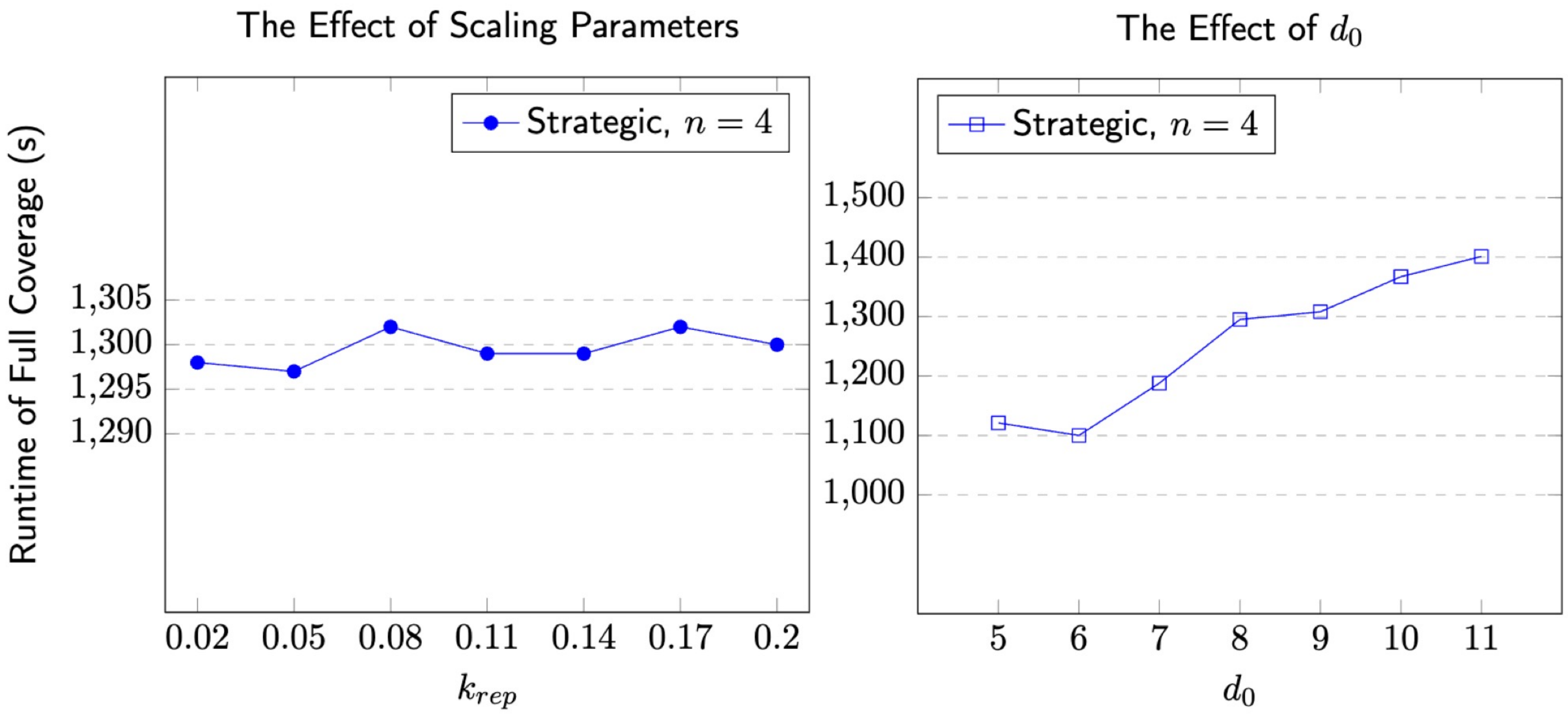

Figure 11: The effect of scaling parameters and repulsive force calculation restriction.

Group 3 For a small number of agents, the scaling factors are not critical in the strategic coverage time.

Group 4 As d_0 increases from 5 to 11, there is a general trend that the total runtime increases. In this scenario, robot might be taking into account agents that are farther away, which are not as relevant to avoiding high agent density areas.

Conclusions

1. The strategic weeding algorithm outperforms random approaches especially when field size increases.
2. The research develops of a robot with visual training and information synchronization which supports the practical application of the swarm algorithm in agricultural scenarios.
3. Sensitivity analyses on the proposed model shed light on optimizing parameters such as repulsion restriction d_0 and number of agents for minimizing field coverage runtime.
4. Future work can focus on: Conducting field experiments to refine and optimize parameter settings for various field sizes, expanding the vision dataset to include more crop and weed species for broader applicability, and predicting energy consumption and sustainability contributions in organic farms. This will provide quantitative insights for future applications in organic farming.

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