Cyber-Physical System Design Space Exploration for Affordable Precision Agriculture

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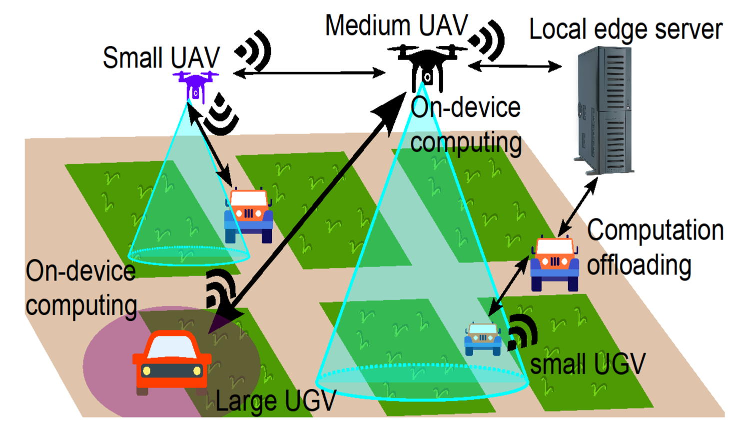
Motivation

- High cyber-physical system (CPS) cost limits broader adoption of precision agriculture.
- Farmers and system designers require tools that explore feasible alternatives.
- Choosing inappropriate hardware leads to expensive systems that fail to meet farm coverage or application needs.



Proposed Approach

INPUTS

- Budget
- Farm area
- Target crop
- Application

Proposed Approach (Design Space Exploration)

- Cost <= budget
- Coverage >= farm area
- Payload requirement
- Runtime >= 0.2 h (drone)
- Crop/application constraints

OUTPUT

Drone–Rover Configuration

- Total cost
- Area covered
- Sensors
- Communications
- Battery

Application	Computation Mode	Platform
General crop monitoring	Off-board	Both
Thermal imaging	Off-board	Both
Image stitching	Off-board	Both
Soil monitoring	Off-board	Rover
Yield estimation	Off-board	Both
Quality control	Off-board	Rover
Autonomous fruit/vegetable picking	Onboard	Rover
Mechanical weeding	Onboard	Rover
Soil pH sampling	Onboard	Rover
Climate mapping	Off-board	Rover
Fence/Infrastructure inspection	Off-board	Drone
Livestock monitoring	Onboard	Both
Beehive inspection	Onboard	Rover
Frost & pest early-warning systems	Onboard	Both
Fertilizing	Onboard	Rover

- Applications determine computation mode and platform selection.
- Computation mode – Off-board or Real-time onboard

Area Function

$$A_i \cdot x_i \geq S$$

- A_i - Area covered by each UAV or UGV.
- S - Farm size specified by user.
- A_i = 5 square m, area covered = 100 square m.

Objective – Minimize cost, maximize area coverage, and ensure sufficient payload capacity.

$$\min x \sum_{i=1}^{N} (\alpha\, \widetilde{C}_i\, x_i + \beta\, \widetilde{A}_i\, x_i - \gamma\, \widetilde{P}_i\, x_i)$$

- $\widetilde{C}_i$ - Normalized Cost.
- $\widetilde{A}_i$ - Normalized Area.
- $\widetilde{P}_i$ - Normalized Payload.
- x_i - Number of units of UAV and UGV.
- α, β, and γ - Weights reflect user priorities and are derived using a Rank Order Centroid weighting scheme.

Cost Function

$$(C_i + extra\_cost) \cdot x_i + edge\_cost \leq B$$

- C_i - Monetary cost of UAV or UGV.
- $extra\_cost$ - Monetary cost for application-specific part.
- $edge\_cost$ - Monetary cost of the local edge server.
- B - Budget defined by the user.
- Configuration A - x_i = 20 Drones, C_i = \$100, $extra\_cost$ = \$10, $edge\_cost$ = \$1000, Total cost = \$3200.

Evaluation Results

Case Study 1

Farm size: ~1 acre.
Budget: \$100K.
Crop type: Tree.
Application: Autonomous fruit and vegetable picking

Case Study 2

Farm size: ~10 acres.
Budget: \$1M.
Crop type: Vine.
Application: General crop monitoring and yield estimation

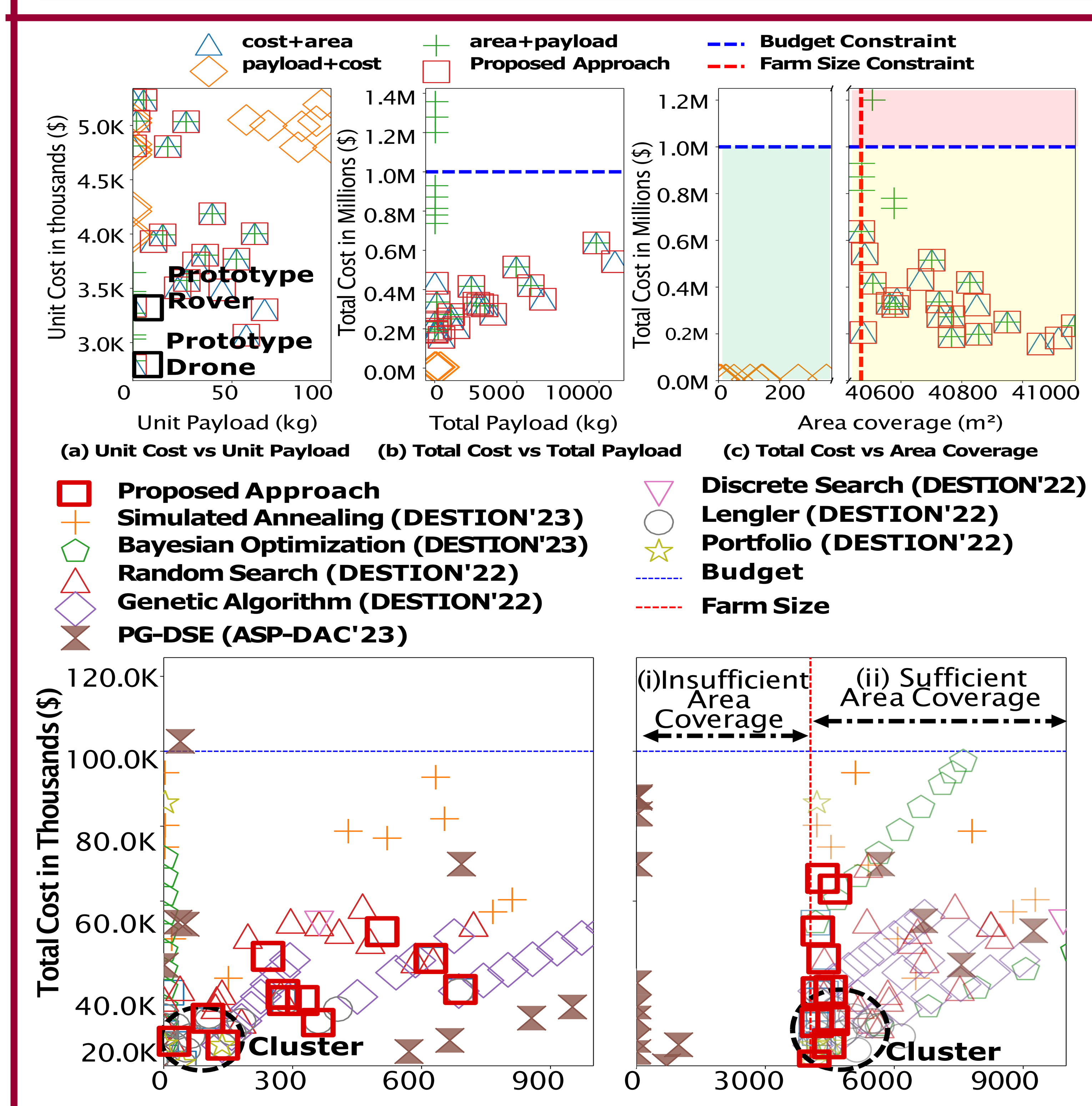
Method verified by SAT	Total configs	Valid configs	Invalid configs
Proposed approach	18	18	0
Cost+Area	18	18	0
Simulated Annealing	12	12	0
Bayesian Optimization	20	20	0
Random Search	20	20	0
Genetic Algorithm	20	20	0
Discrete	1	1	0
Lenglar	18	18	0
Portfolio	4	4	0
Payload+Cost	13	0	13
Area+Payload	20	17	3
PG-DSE	20	4	16

Satisfiability (SAT) verification

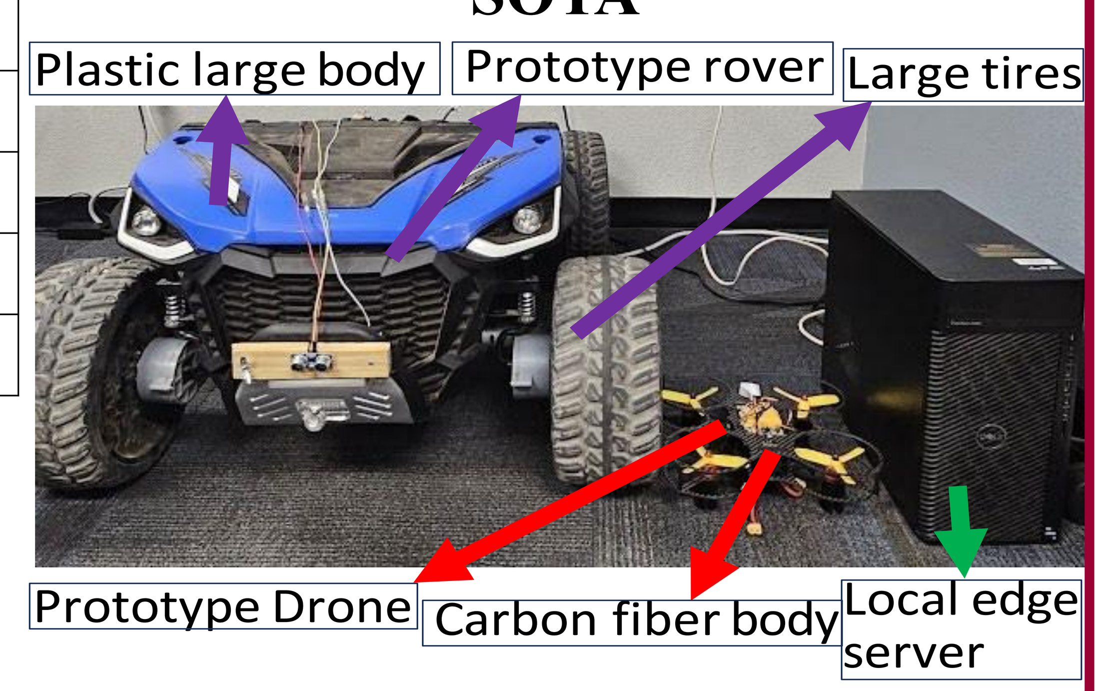
Ablation study of the proposed approach.
Compare the proposed approach with the state of the art.
Feasibility verification using SAT-based constraint checking.

SOTA and Proposed optimizer	Case Study 1	Case Study 2
Simulated Annealing	0.325	0.465
Bayesian Optimization	0.498	N/A
Random Search	0.496	0.475
Genetic Algorithm	0.503	0.527
Discrete Search	0.307	0.600
Lengler	0.634	0.686
Portfolio	0.634	0.686
PG-DSE	0.619	0.360
Proposed Approach	0.634	0.686

Weighted score comparison with SOTA



Total Cost vs. Payload **Total Cost vs. Area Coverage**



Hardware Prototype Implementation