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CYBER-PHYSICAL SYSTEM DESIGN SPACE EXPLORATION FOR AFFORDABLE PRECISION AGRICULTURE

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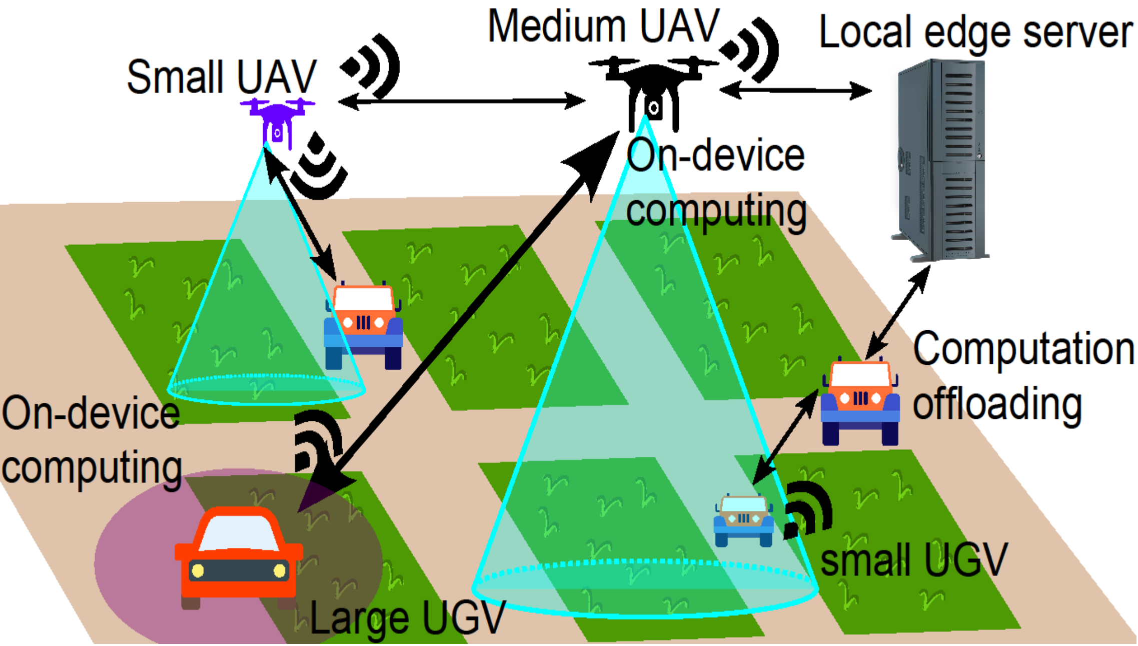
GitHub Repo: https://github.com/asu-kim/cps-dse-apa

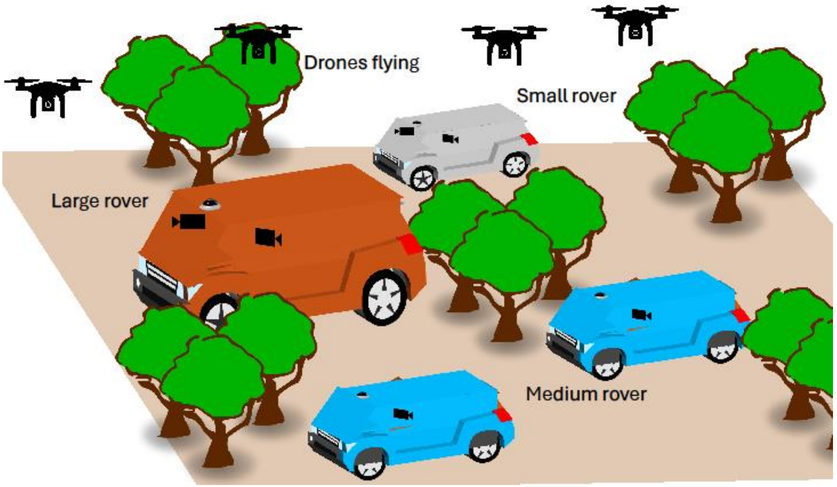
Motivation



- 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.

Research Problem

- Design affordable multimodal CPS platforms for precision agriculture.
- Missing domain-specific constraints in existing CPS design space exploration (DSE).
- Lack of a unified design formulation for agricultural CPS.
- Applications introduce non-linear interactions



Challenges and Goals

Challenges

- Modeling intertwined constraints.
- Large and complex design space.
- Feasibility is hard to guarantee.
- Limited domain awareness.
- Application-driven non-linearity

Goals

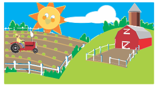
- Develop a unified DSE formulation tailored to precision agriculture CPS.
- Incorporate crop- and application-specific constraints directly into the design process.
- Guarantee feasible, deployable CPS designs through constraint-aware optimization and verification.

Proposed Approach

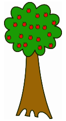
Inputs

$

Budget



Farm area size



Target crop

Application

Output

Proposed Approach

(Design Space Exploration)

- Cost < Budget
- Coverage > Farm area size
- Payload capacity
- Runtime > 0.2 hours for drones
- Crop–Application Parameterization

drone–rover configurations

- Total cost
- Area covered
- Sensors
- Communication
- Edge server
- Body
- Battery

Design Space Exploration

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

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

  - $\widetilde{C}_i$ - 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.

Design Space Exploration

- 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.

- Area Function

$$A_i \cdot x_i \geq S$$

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

- More Details in our paper

Application-Platform-Computation Mapping

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

Application	Computation Mode	Platform
Livestock monitoring	Onboard	Both
Beehive inspection	Onboard	Rover
Frost & pest early-warning systems	Onboard	Both
Fertilizing	Onboard	Rover

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

Evaluation & Case Studies

- Ablation study of the proposed approach.
- Compare the proposed approach with the state of the art.
- Feasibility verification using SAT-based constraint checking.
- This evaluation validates the effectiveness and robustness of the proposed framework.

- **Case Study 1**
  - Farm size: 4047m^2 (~1 acre).
  - Budget: $100K.
  - Crop type: Tree.
  - Application: Autonomous fruit and vegetable picking.

Small Apple tree farm

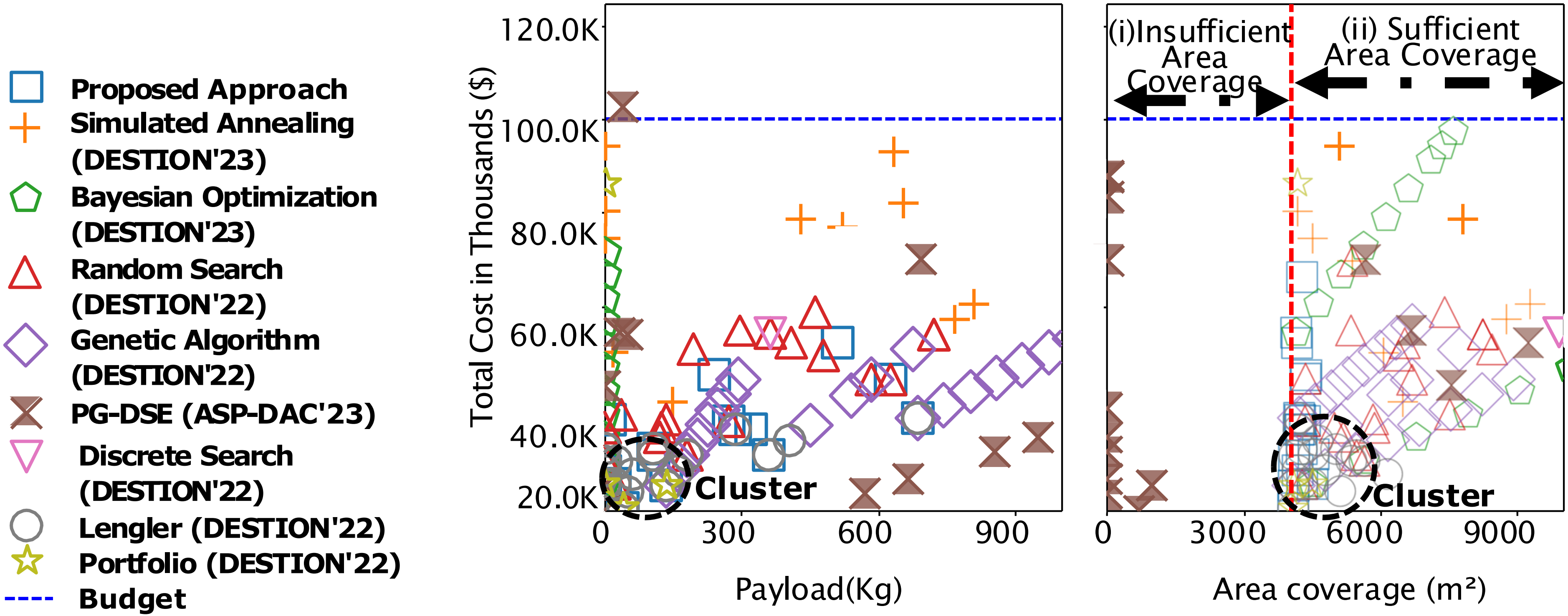
https://static.themarthablog.com/2017/08/DSC_6110.jpg

- **Case Study 2**
  - Farm size: 40468 m^2 (~10 acre).
  - Budget: $1M.
  - Crop type: Vine.
  - Applications: General crop monitoring and yield estimation.

Large Grape vine farm

https://www.blueridgenow.com/gcdn/authoring/2003/09/29/NHTN/ghows-NC-91ca0fdd-8201-4b3d-a76b-70479f0f1dab-02483142.jpeg?width=660&height=441&fit=crop&format=pjpg&auto=webp

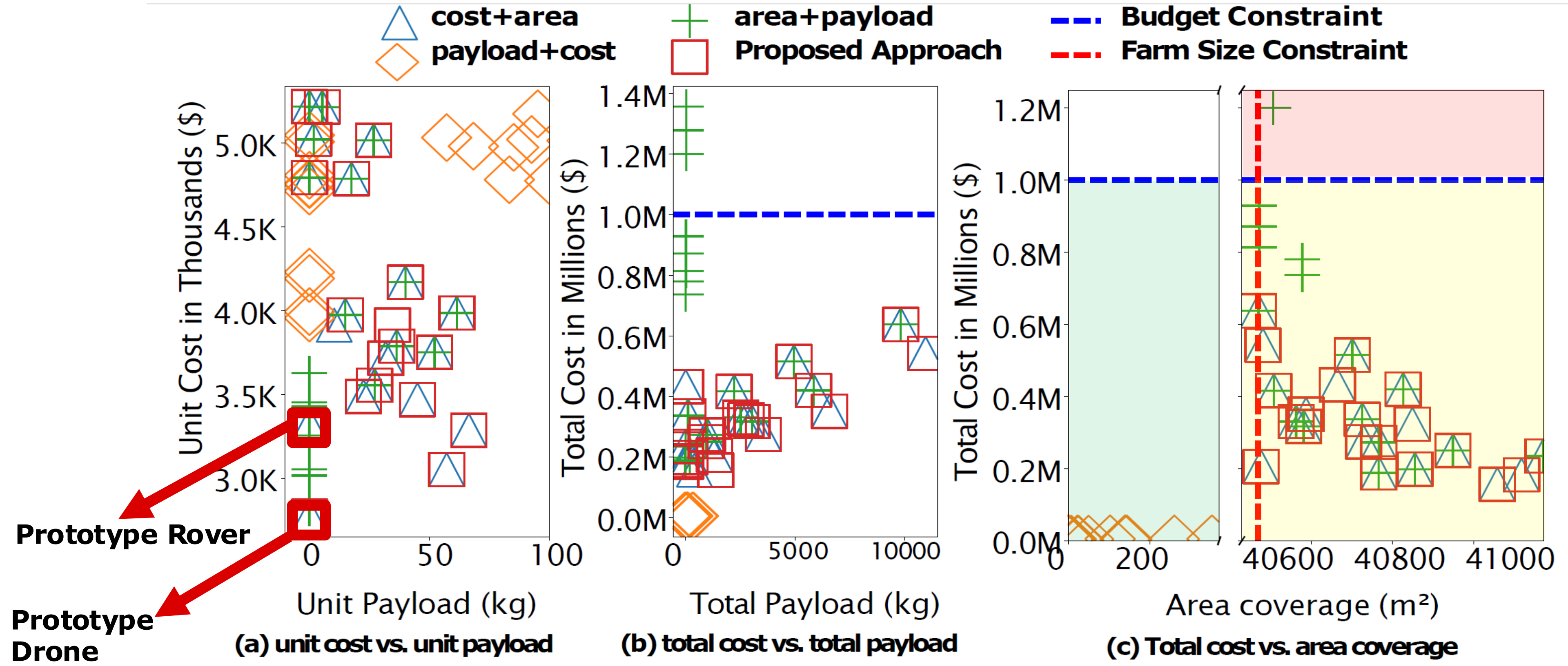
Evaluation of Design Aspects Case Study 1



(a) total cost vs. payload

(b) Total cost vs. area coverage.

Evaluation of Design Aspects Case Study 2

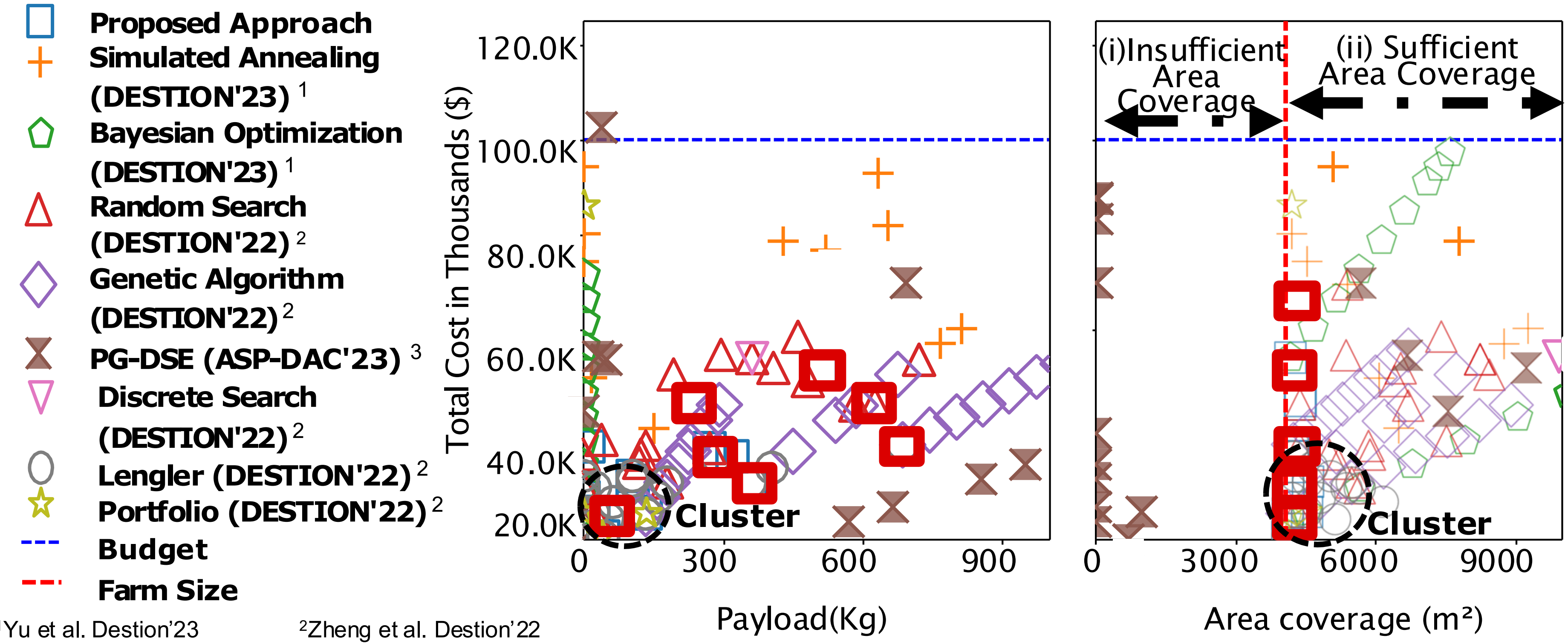


(a) unit cost vs. unit payload

(b) total cost vs. total payload

(c) Total cost vs. area coverage

Optimizer Model Evaluation Case Study 1



(a) total cost vs. payload (b) Total cost vs. area coverage.

[1]Yu et al. Destion'23 [2]Zheng et al. Destion'22

[3]Liao et al. ASP-DAC'23

Weighted Score

Design Aspects	Case Study 1 $100K, 1 Acre	Case Study 2 $1M, 10 Acres
Area+Payload	0.404	0.377
Payload+Cost	0.611	0.611
Cost+Area	0.417	0.389
Proposed Approach	0.417	0.389

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

- Proposed approach ranks among the top performers.
- Consistent results in both case studies.

Satisfiability (SAT) Verification

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

Method verified by SAT	Total configs	Valid configs	Invalid configs
Payload+Cost	13	0	13
Area+Payload	20	17	3
PG-DSE	20	4	16

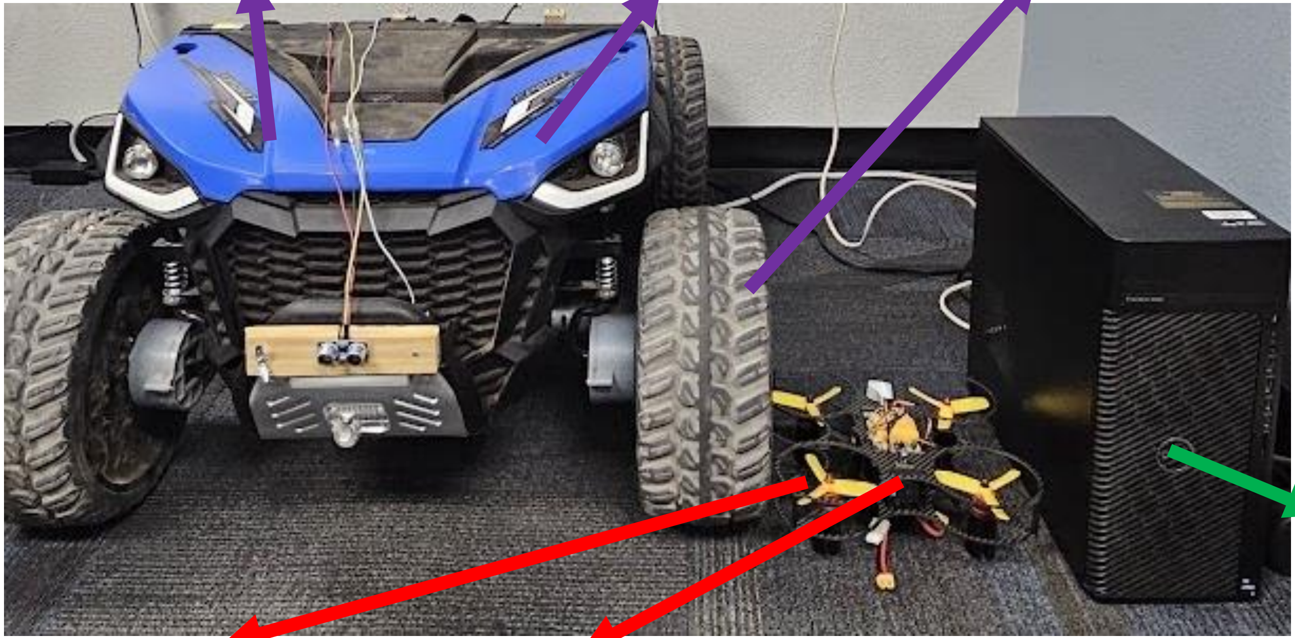
- Ensures robustness to model changes.
- Most methods achieve full feasibility.

Hardware Prototype Implementation

Plastic large body

Prototype rover

Large tires



Local edge server

Prototype drone

Carbon fiber body

Conclusion & Acknowledgment

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- Introduced a cost-aware DSE framework for multimodal UAV–UGV CPS in precision agriculture.
- Optimized cost, area coverage, and payload under realistic farm, crop, and application constraints.
- Achieved consistent feasibility and trade-offs compared to SOTA's.
- Validated feasibility through SAT-based verification and implemented hardware prototype.
- Extend our framework to other CPS domains with non-linear trade-offs, such as warehouse monitoring and disaster response.

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- **GitHub Repo:** https://github.com/asu-kim/cps-dse-apa
- **ASU KIM Lab Page:** https://labs.engineering.asu.edu/kim/

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