SAGE-Agri

SECURE AIR–GROUND EDGE INTELLIGENCE WITH SEMANTIC COMMUNICATIONS

FOR CROP MONITORING AND TARGETED IRRIGATION

A Cooperative UAV–UGV Platform for Practical Smart Agriculture in ASEAN

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SAGE-Agri: Secure Air–Ground Edge Intelligence

Background :

From fixed agricultural IoT to mobile air–ground intelligence



Previous stage
Fixed sensing

→

Next stage
Mobile cooperative sensing

✓ **Fixed sensing:** IoT sensors → edge gateway → crop monitoring → irrigation support

✓ **Mobile sensing:** UAV wide-area survey → semantic hotspot → UGV close inspection → targeted action

✓ **Research transition:** from monitoring selected points to finding where attention is required

The proposed extension adds mobility while keeping edge processing, low-bandwidth operation, and farmer control.

Field Scenario & Technical Bottleneck

One field, two observation scales, one constrained mission link



Wide-area coverage

UAV rapidly surveys the field and screens abnormal regions.

Close-range information

Lower leaves, disease symptoms and soil conditions require proximity.

Constrained uplink

Continuous RGB/video transmission consumes wireless resources.

Physical action

Irrigation requires payload, energy and stable ground operation.

Neither UAV nor UGV alone is efficient for the full monitoring–decision–action cycle.

Research Objectives

Objective 1: Cooperative Air–Ground Crop Monitoring

Develop a small UAV–UGV sensing architecture for autonomous field survey, hotspot localization, close-range inspection, and edge-based crop-state estimation.

Objective 2: Secure Semantic Communication & Mission Control

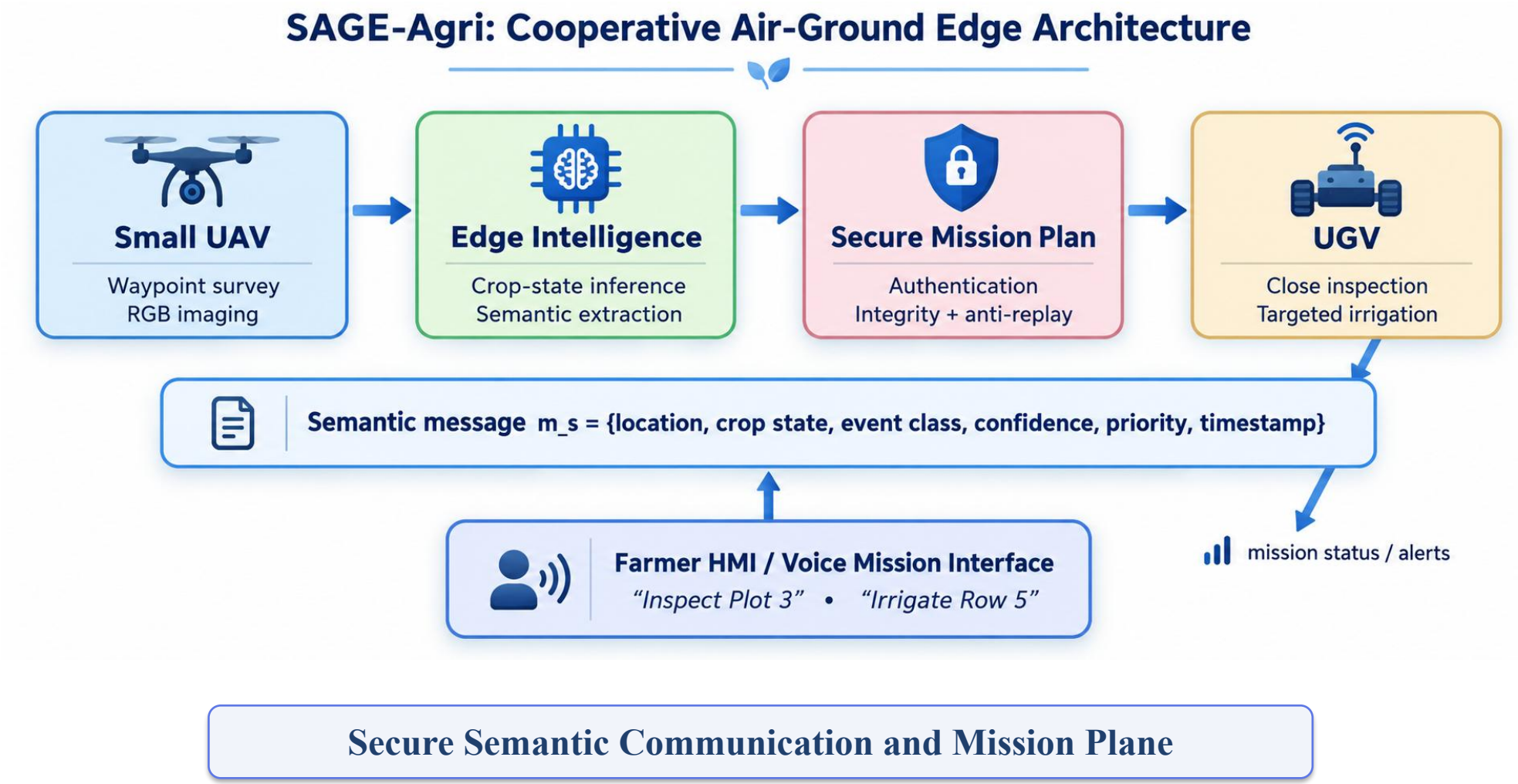
Transmit task-relevant crop and robot information instead of continuous raw visual data, while protecting identity, command integrity, telemetry, and mission requests.

Objective 3: Targeted UGV Actuation & Field Validation

Integrate local sensing and targeted irrigation on the UGV and evaluate accuracy, latency, communication load, mission completion, and secure operation.

Proposed Air–Ground Cooperative Architecture

UAV LOCATES ATTENTION; UGV VERIFIES AND ACTS



UAV as an Autonomous Aerial Scout

WIDE-AREA MONITORING WITH LIMITED ONBOARD RESOURCES

Waypoint mission → RGB acquisition →
Edge inference→ Hotspot detection → m_s

$m_s = \{ l, c, q, p, t \}$

l: location
c: crop/event class
q: confidence
p: mission priority
t: timestamp

UAV functions

Autonomous waypoint flight
Crop image acquisition
Abnormality screening
Semantic hotspot generation

Scope control

No spraying payload on the UAV. This reduces payload, battery demand, control complexity and flight-safety constraints.



UAV role: detect where to inspect — fast, repeatable, and communication-aware.

Optional Multi-UAV Mission: Verify Only When Needed

CORE: ONE EXISTING UAV + UGV | EXTENSION: ONE SMALL VERIFYING UAV

1. Wide-area scout

Existing UAV
RGB waypoint survey
Georeferenced hotspot

→

2. Selective verification

Small UAV-2
Extra view only if uncertain
Multi-view decision fusion

→

3. Ground action

UGV
Local RGB + soil moisture
Interlocked irrigation

Gateway controls task allocation, evidence level, message freshness, authorization, and mission logs.
UAV-3 / persistent relay / autonomous formation flight are NOT required for the first field pilot.

Testable question: Does a second viewpoint improve correct hotspot decisions enough to justify added radio traffic, energy and mission time?

UGV as Ground Inspector and Actuator

CLOSE-RANGE SENSING WHERE THE UAV NEEDS SUPPORT

Semantic hotspot → Navigation → Close-range imaging→ Local sensing → Decision → Targeted irrigation

Inspect → Verify → Irrigate

UGV payload

RGB camera
Soil-moisture sensor
Edge processor
Water tank
Pump + controllable nozzle
Wireless module

Future extension

Fertilizer delivery
Targeted spraying
Soil sampling
Not required for the initial prototype.



UGV role: detailed verification and physical action at the selected hotspot.

Edge Intelligence: From Image to Crop State

PROCESS DATA CLOSE TO THE SENSOR

$$I \rightarrow f\theta \rightarrow z \rightarrow g\varphi \rightarrow (\hat{c}, q) \rightarrow \pi \rightarrow a$$

Model variables

I: captured image
fθ: lightweight feature extractor
z: feature sequence
gφ: crop-state classifier
ĉ: crop condition
q: confidence
a: communication/control action

Why edge?

Lower uplink traffic
Shorter decision path
Operation during intermittent cloud connectivity
Fast local robot coordination

Keep the demonstrator at edge-AI scale
no cloud-scale LLM training is required.



Semantic Communication: Transmit What Matters

TASK-ORIENTED INFORMATION INSTEAD OF RAW IMAGE/VIDEO STREAMS

Conventional link
Camera → Image/Video → Wireless link → Remote processing
High source data rate

Proposed link
Camera → Edge inference → m_s → Wireless link → Mission decision
Task-relevant information only

$$\eta_B = 1 - B_{sem} / B_{raw}$$

$$A_{task} = P(\hat{c} = c)$$

Research question: How much source data can be removed before crop-state and mission decisions degrade?



Voice-Based Mission Interface

VOICE COMMANDS STAY AT MISSION LEVEL, NOT MOTOR-CONTROL LEVEL

Farmer: “Inspect Plot 3.”

ASR → intent extraction
MISSION = INSPECT
TARGET = PLOT_3

User authentication + command validation
authorized mission only

Mission planner
select UAV / UGV task

Autonomous execution
navigation and actuation remain in robot control

Voice defines the mission. Autonomous control executes the mission.



Secure Mission and Semantic Data Plane

SECURITY PROTECTS PHYSICAL AGRICULTURAL ACTIONS, NOT ONLY DATA PACKETS

1. Device trust
UAV ↔ gateway ↔ UGV authentication

2. Communication trust
Encrypted telemetry
Message integrity
Anti-replay protection

3. Mission trust
Voice/user authorization
Anomaly detection
Safe command execution

4. Threat examples
Spoofed UAV data
Modified hotspot coordinates
Unauthorized UGV actuation
Replay of old irrigation command

Research metrics
- Authentication latency
- Command success rate
- Attack detection rate
- False alarm rate
- Communication overhead



A compromised message can trigger a physical action; therefore security sits inside the control path.

Research Questions & Evaluation Metrics

FOUR QUESTIONS — FOUR MEASURABLE OUTCOMES

RQ1

UAV–UGV spatial crop inspection

- ✓ F1-score
- ✓ localization error
- ✓ coverage
- ✓ mission completion

RQ2

Semantic extraction under wireless constraint

- ✓ transmitted bytes
- ✓ η_B
- ✓ latency
- ✓ task accuracy

RQ3

UGV actuation at target location

- ✓ irrigation localization
- ✓ delivered volume
- ✓ soil-moisture response

RQ4

Secure and usable mission control

- ✓ command recognition
- ✓ authorization delay
- ✓ threat detection
- ✓ false alarms

Observation → Communication → Decision → Action

NEXT STEP — baseline experiments define quantitative performance targets.

Minimum Viable Field Demonstrator

ONE INTEGRATED LOOP, NOT DISCONNECTED FUNCTIONS

1. **Farmer mission**
   "Inspect Plot A."
2. **UAV survey**
   Predefined route
3. **Edge AI**
   Abnormal region
4. **Semantic hotspot**
   m_s transmitted
5. **UGV inspection**
   Image + soil sensing
6. **Targeted irrigation**
   If control condition is satisfied
7. **Secure log**
   Mission report



Reliable loop first;
additional agricultural functions later.

Adaptive Semantic Evidence and Bounded ISAC

RESEARCH CONTRIBUTION AND MATCHED EXPERIMENTAL COMPARISON

B0	**Compressed RGB**	Image uplink → inference
B1	**Fixed event**	Class + location + confidence
B2	**Adaptive semantics**	Event / ROI / image selected by uncertainty and link
P	**Cooperative semantics**	B2 + conditional second-UAV verification

Optional ISAC feasibility: obtain RF channel / echo observations from a shared OFDM link to test UGV presence or link obstruction. Report detection error AND link overhead. Not a prerequisite for irrigation.

ASEAN–Japan Collaboration & Research Roadmap

A MODULAR PLATFORM FOR JOINT RESEARCH AND PILOT VALIDATION

Air–Ground Edge Sensing
UAV/UGV platform
crop observation
edge models

Semantic and Secure Communications
semantic message design
wireless-link evaluation
secure mission control

Field Integration and Validation
targeted irrigation
pilot deployment
end-to-end performance

Proposed Collaboration Roles

PTIT, Vietnam
- System architecture
- Semantic communication
- Edge intelligence
- Integration

Agricultural partners (Thailand, Malaysia, Lao)
- Crop scenarios
- Field measurements
- Validation

ASEAN ICT/robotics partners
- Robot platform
- Connectivity
- Local pilot scenarios

NICT / Japan
- Communication and security research
- Technical evaluation
- Coordination

From sensing everything to communicating what matters — and acting only where needed.