

# Elevating drones as first-class citizens in the cloud-edge-IoT continuum

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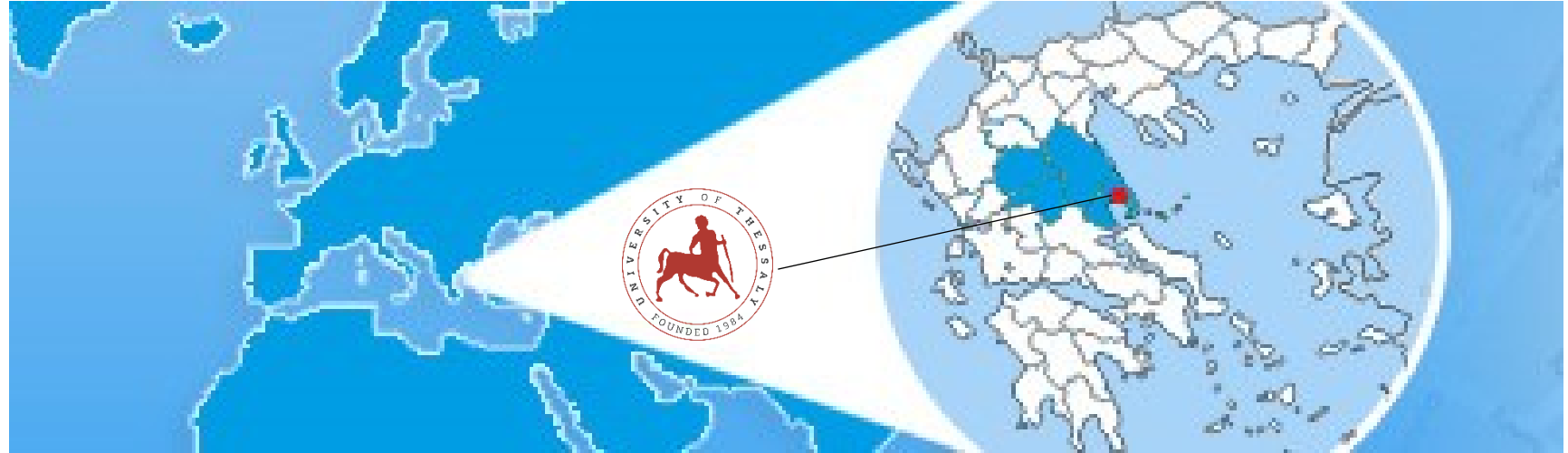
Spyros Lalis



Computer Systems Laboratory  
University of Thessaly,  
Volos, Greece

# Electrical & Computer Engineering Dept. @ UTH

- Founded 2000
- 5-year eng. diploma
- 25 faculty members
- 200 students annually

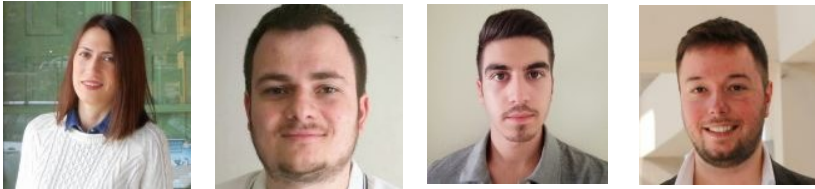


# Computer Systems Lab @ ECE.UTH

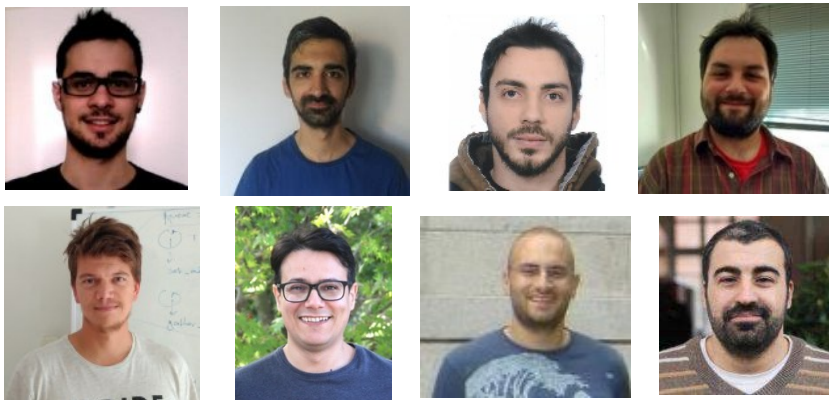
- Profs + PostDoc



- PhD students



- Alumni



- System software (OS, runtime environments) from embedded to HPC systems
- Approximate computing
- Accelerated & Reconfigurable computing
- Energy-aware computing
- Power / performance optimization
- Distributed & ubiquitous computing

- Significant EC & national funding
- Several international collaborations

# Special acks for the work that follows



Manos  
Koutsoubelias



Nasos  
Grigoropoulos



Giannis  
Badakis



Giorgos  
Polychronis



Foivos  
Pournaropoulos



Alexandros  
Patras



European  
Commission

HORIZON  
EUROPE

Co-financed by Greece and the European Union



# Overview

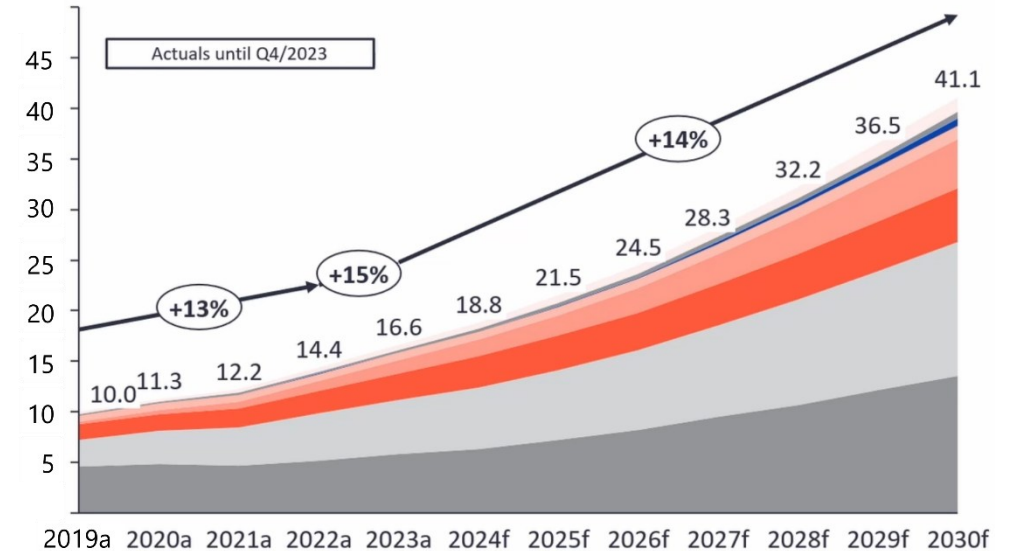
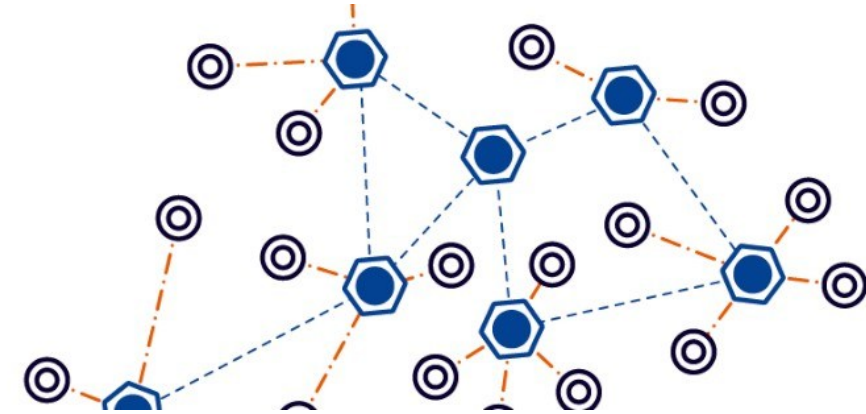
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- Motivation
- Selected Topics
  - Precision landing
  - Drone-based remote sensing architecture
  - Flexible application deployment & orchestration
  - Drone usage in the MLSysOps project
- Wrap-up

# Motivation

# IoT

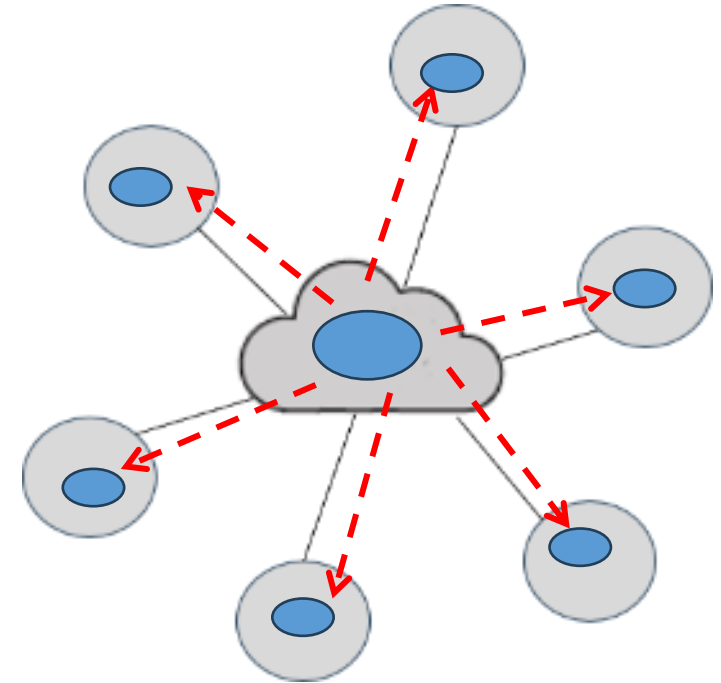
- Billions of connected devices
- Producing huge amounts of data
  - Some estimate 80 ZB by 2025
- The trend will increase
- Not possible (or desirable) to transmit & process everything in the cloud



<https://iot-analytics.com/wp/wp-content/uploads/2024/09/Global-IoT-market-forecast-Number-of-connected-IoT-devices-Sep-2024.mp4>

# Edge computing

- Move data processing **out** of the cloud
- Towards the so-called **edge**
- Close(r) to the data sources
- Regional or on-premise data centers
  - smaller clouds
- Standalone base stations / servers or the **IoT devices** themselves
  - resource-constrained, heterogenous



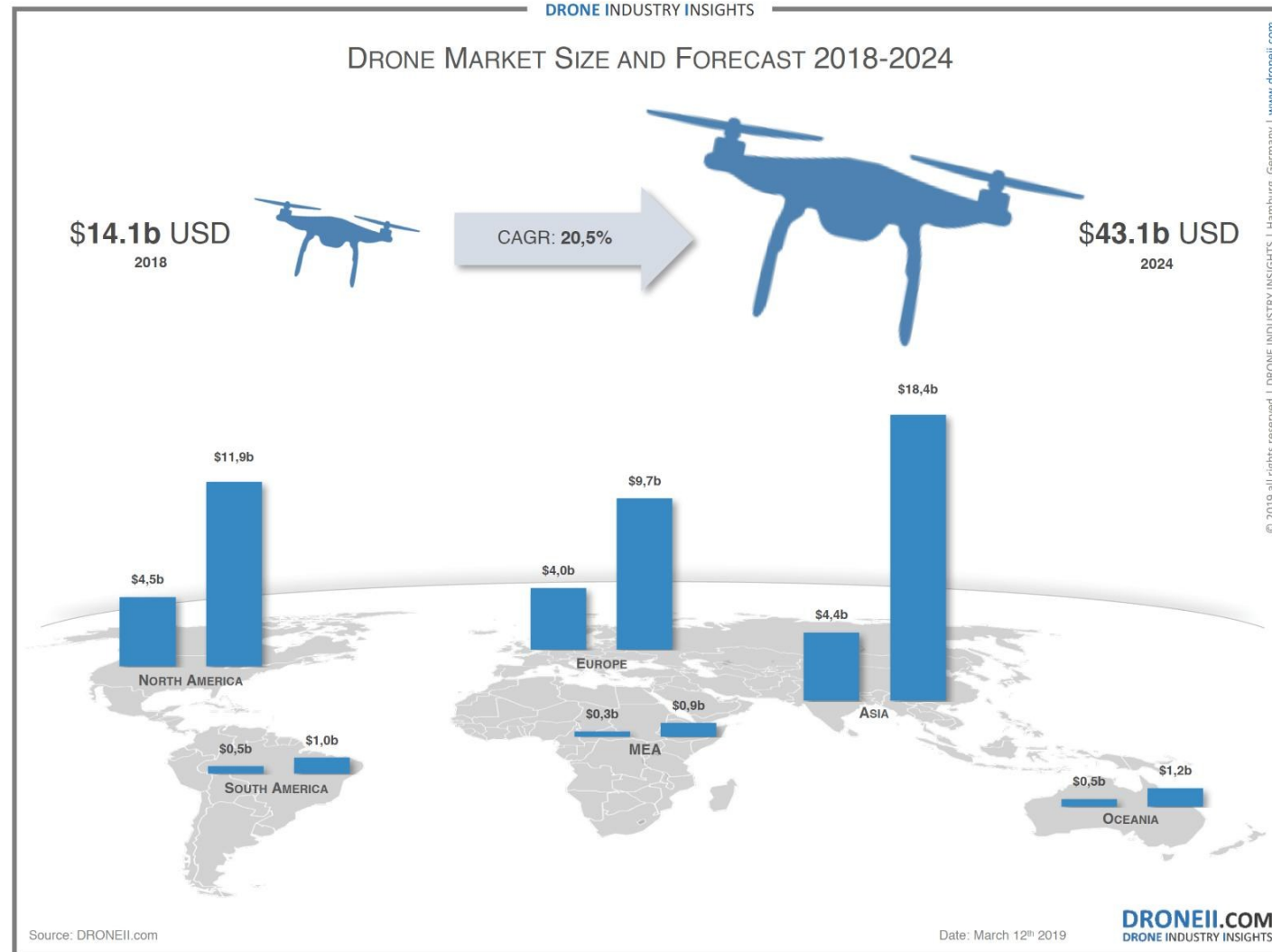


# Drones become increasingly popular

- More **affordable**
- Can be equipped with different **compute/communication HW**
- As well as different **sensors & actuators**
- Wide range of **civilian applications**
- **Polycopters**
  - Easy to operate
  - Vertical take-off/landing
  - Hovering over position of interest

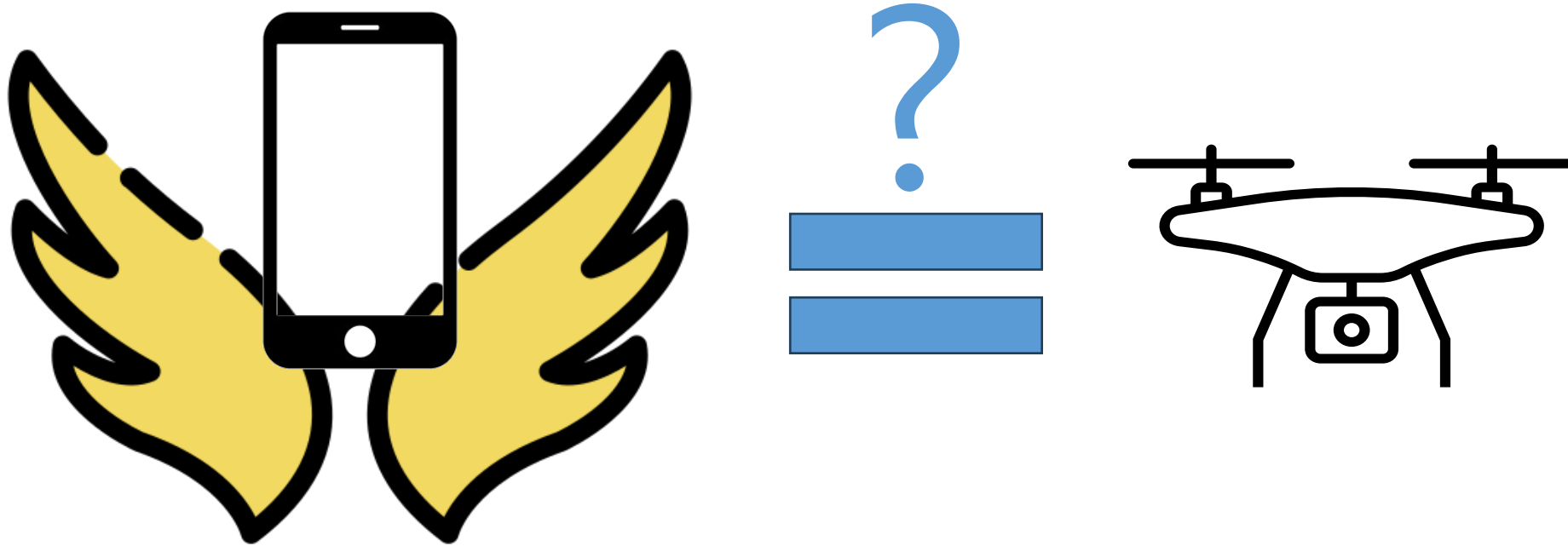


# Growing business sector

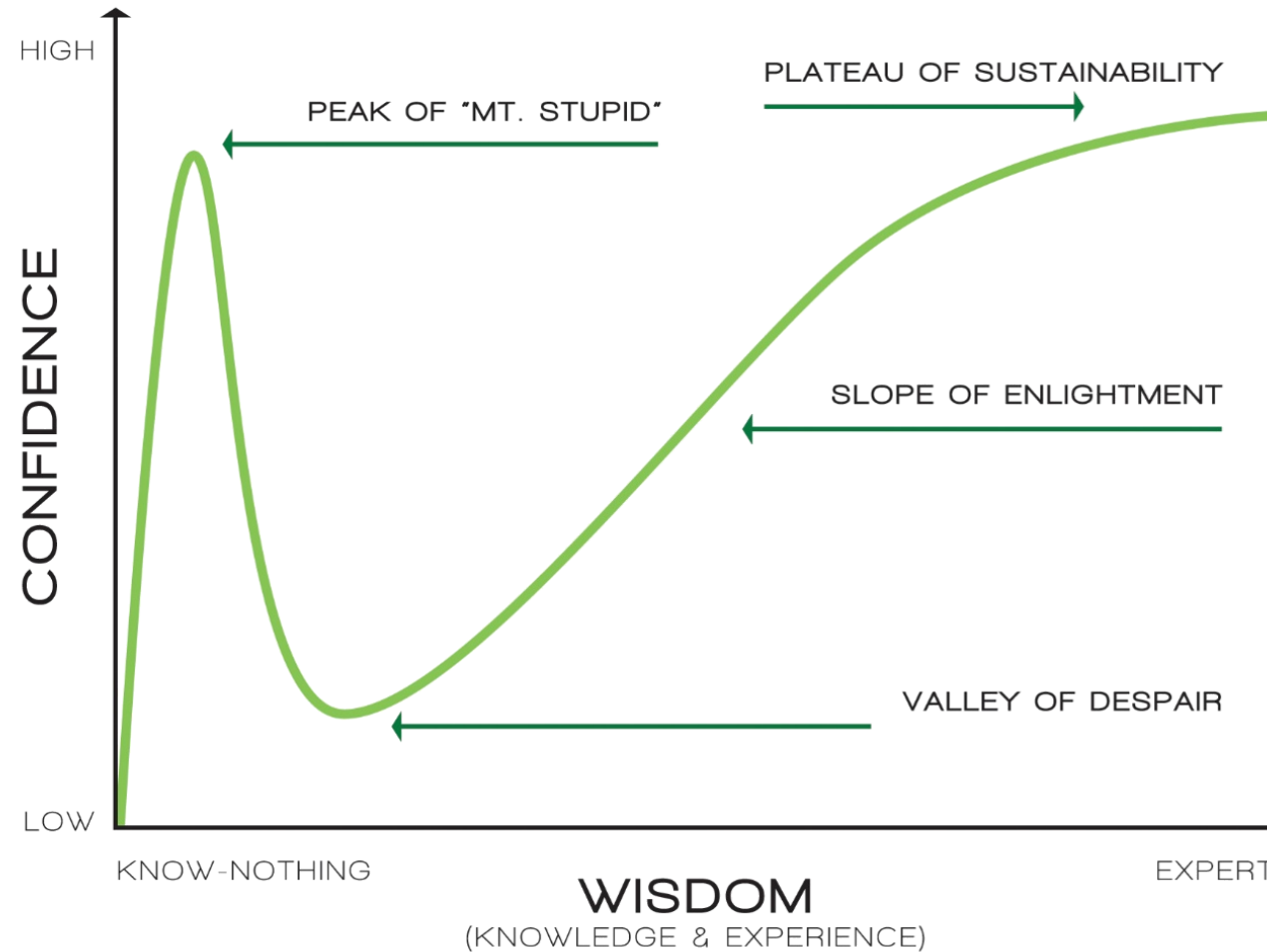


# The next ubiquitous IoT device?

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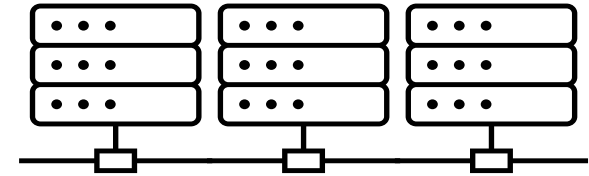
# Maybe ...



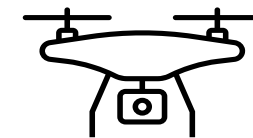


# Drones as part of the system infrastructure

- Server machines in datacenters
  - computing/storage resources
- IoT devices & standalone machines
  - sensing/actuation resources
  - computing/communication resources



- Drones
  - sensing/actuation resources
  - computing/communication resources
  - can fly directly above the region/points of interest
  - significant flexibility & coverage



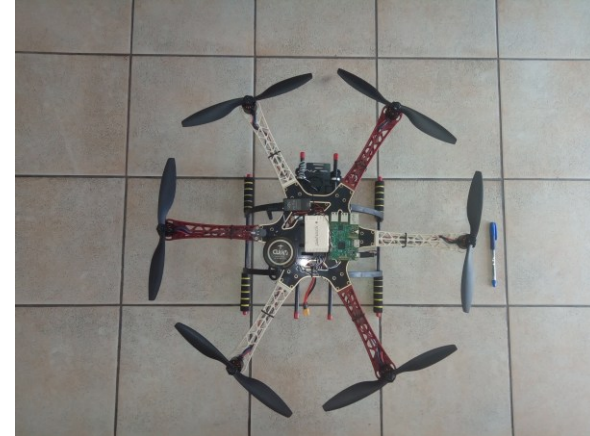
# Main goals of this talk

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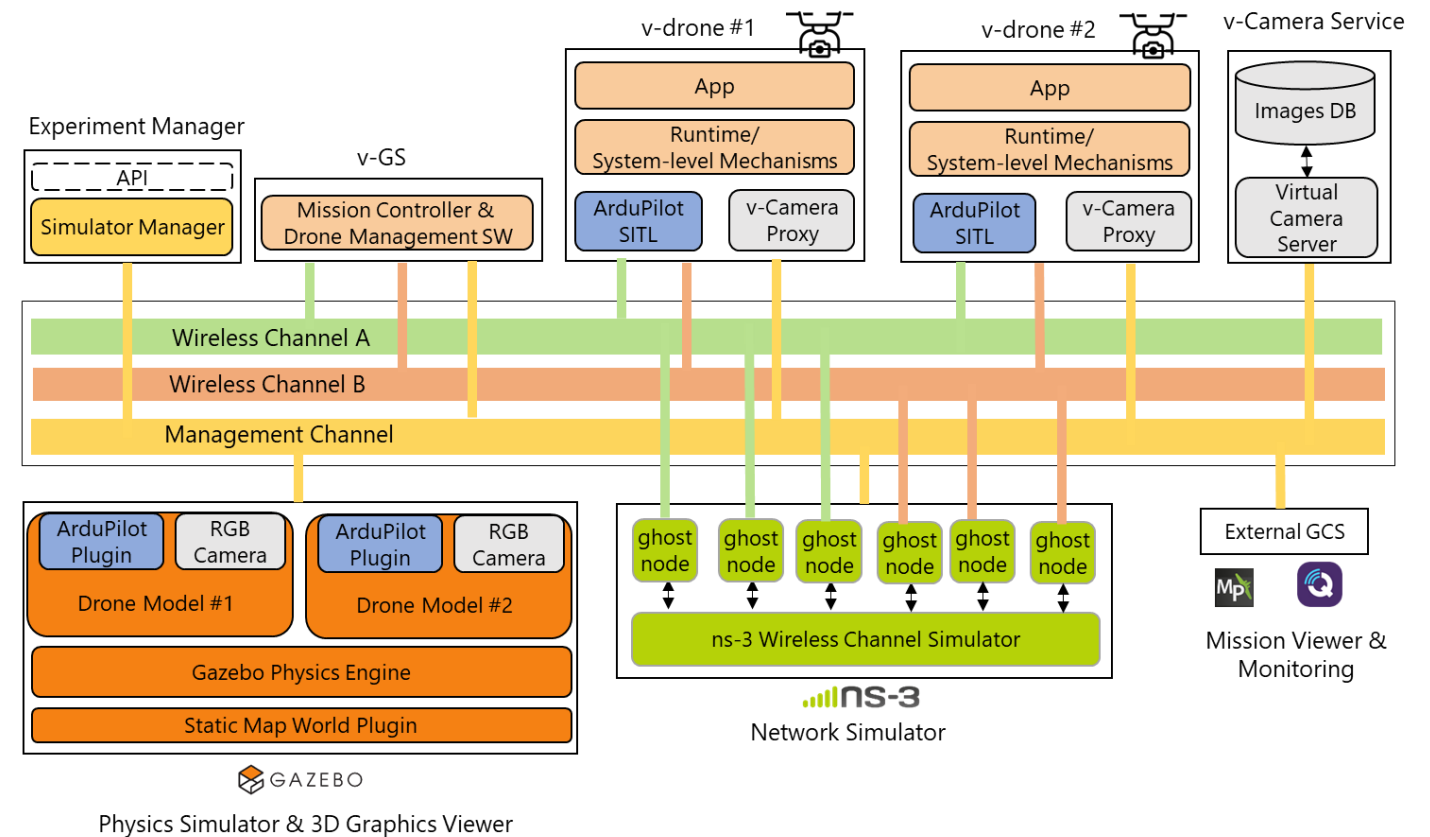
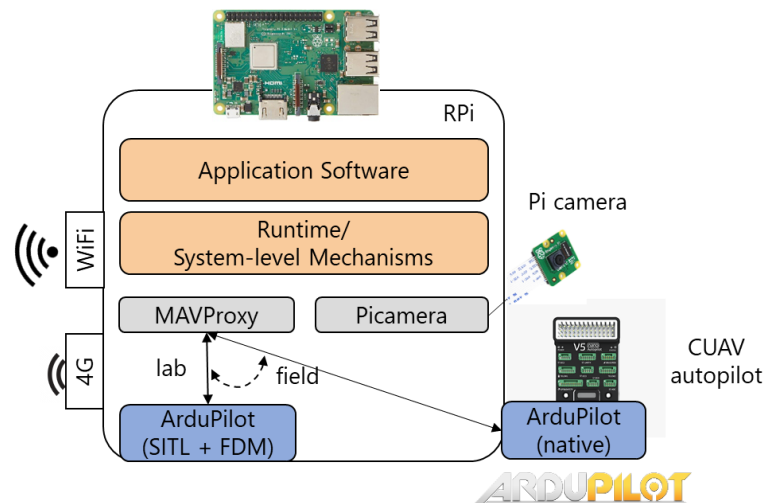
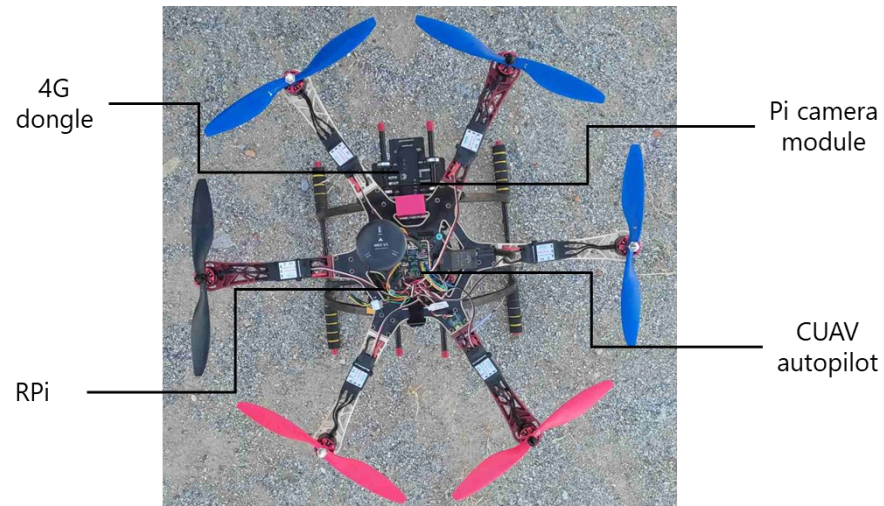
- Convince you that **civilian drones** are **interesting** IoT devices
- Show that these are **different “animals”** requiring extra care
- Indicate how these can be **exploited** as part of a greater **system infrastructure**
- Tease you to **consider** these animals in your **research** for **edge-centric systems**

# The players

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# Experimentation



Drones as first-class citizens in the cloud-edge-IoT continuum



# Topics

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- Precision landing
- Drone-based sensing architecture
- Flexible application deployment & orchestration
- Drone usage in the MLSysOps project

# Precision Landing

# Landing pads & hangars

- **Recharge** the drone's batteries
- **House** the drone between missions
- Important element for making drones part of the system **infrastructure**
- Support **multiple** (consecutive) takeoff-sense-land-recharge **cycles**
- **Reduce/eliminate** human intervention
- Potential for **remote** installations



# Need precision landing

- The drone must land inside a small area
- Conventional GPS can be (very) **inaccurate**
- RTK GPS, infrared beacons (IRLock)
- May have **issues** due to **interference**
- Any **single** precision landing **sensor** may **fail**



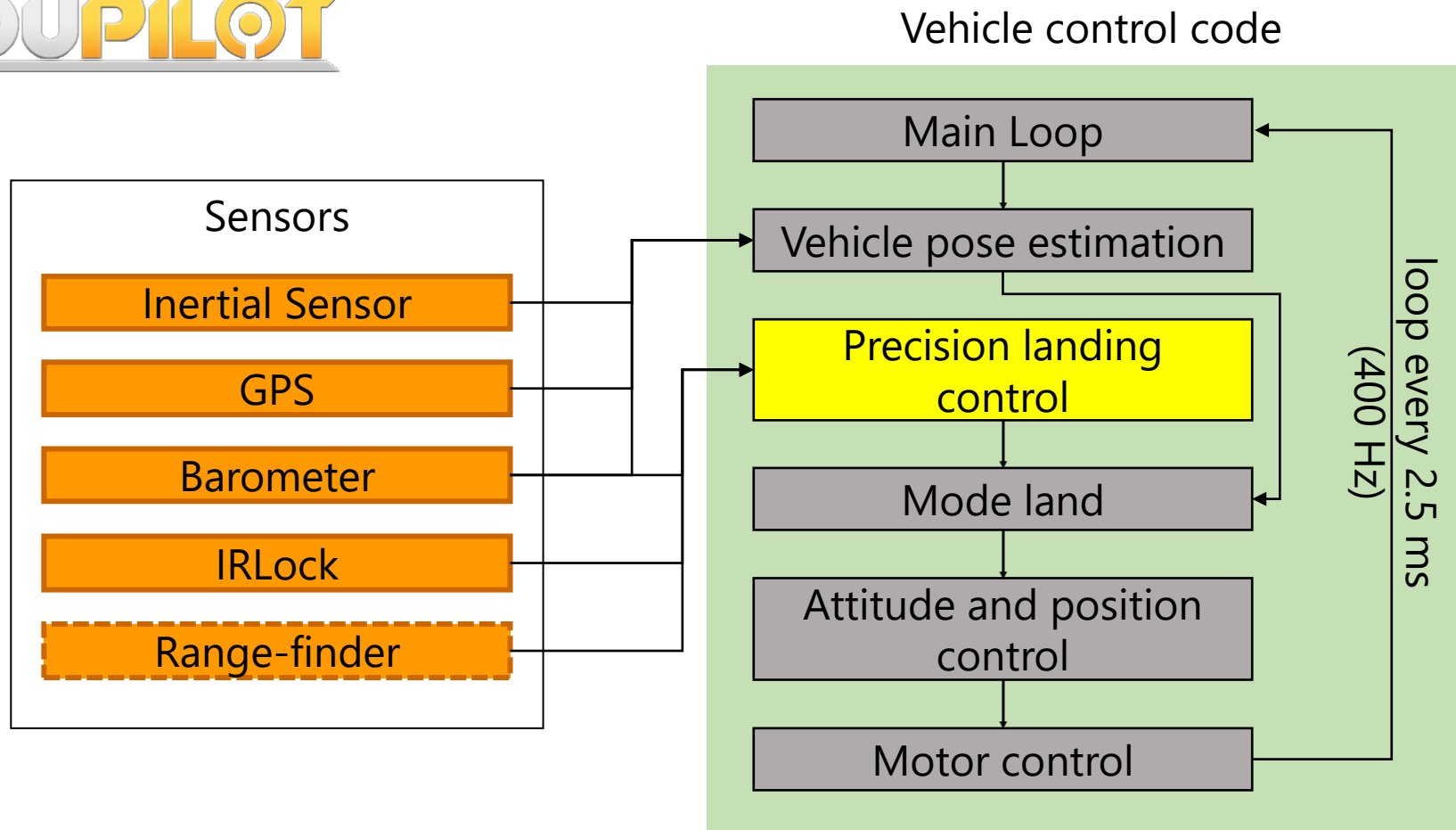


# Our work

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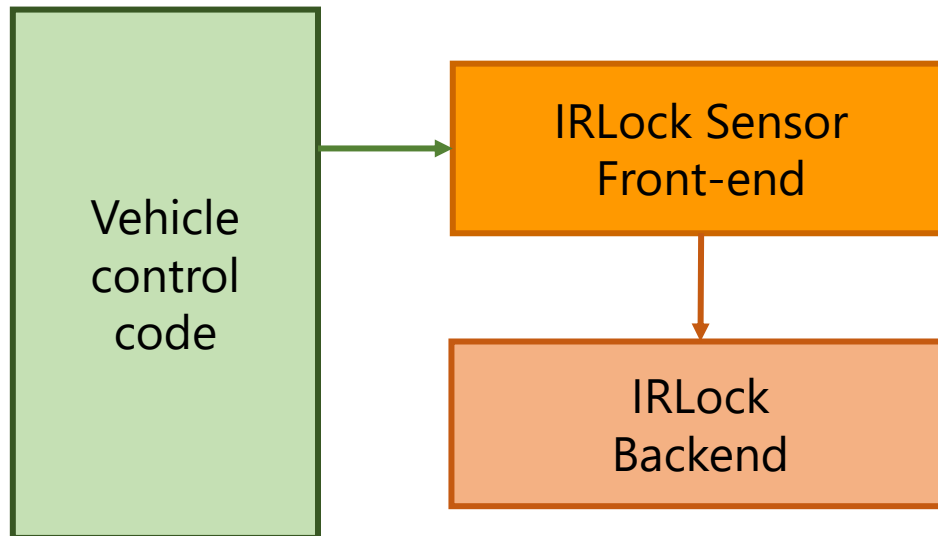
- As one more option, we investigate **visual markers**
- Use the drone's conventional camera to detect a specific **tag**
- Run the detection code on the drone's **onboard** computing platform (RPi)
- **Integration** with the autopilot framework
- **Combine/fuse** with another precision landing sensor (IRLock)
- **Fault tolerance** to individual sensor failures
- New landing modes to exploit new capability

# Control flow with precision landing enabled



# IRLock subsystem

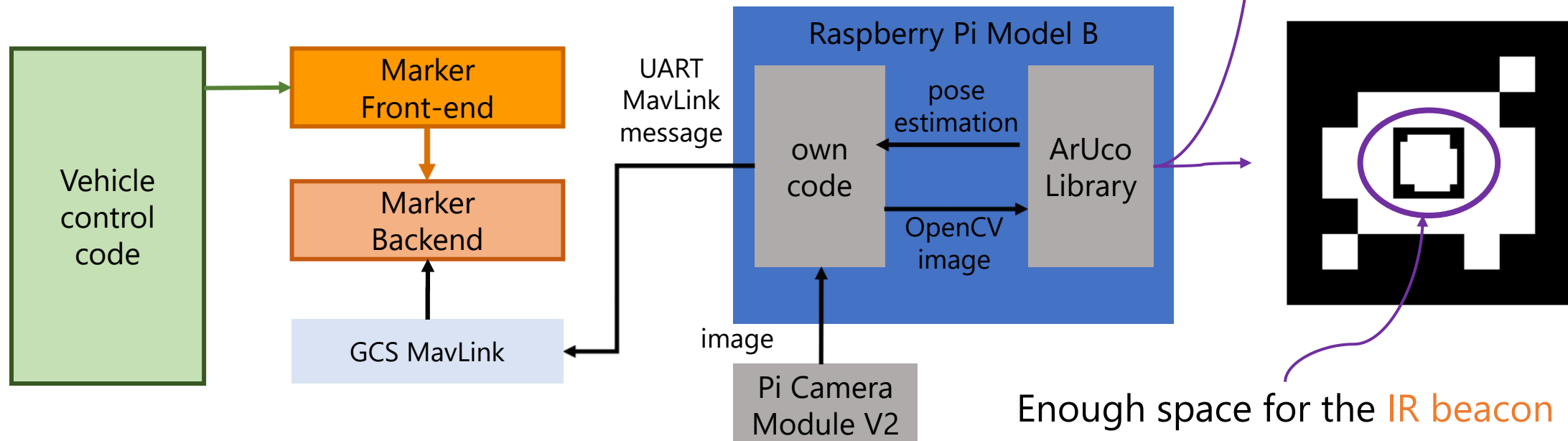
- I2C protocol
- 1 frame every 20ms (50Hz)
- Detection range 12-15 meters



Bytes	16-bit words	Description
0, 1	0	Sync (0xaa55)
2, 3	1	Checksum (sum of all words 2 – 6)
4, 5	2	Signature number
6, 7	3	X center of object (pixel)
8, 9	4	Y center of object (pixel)
10, 11	5	Width of object (pixels)
12, 13	6	Height of object (pixels)

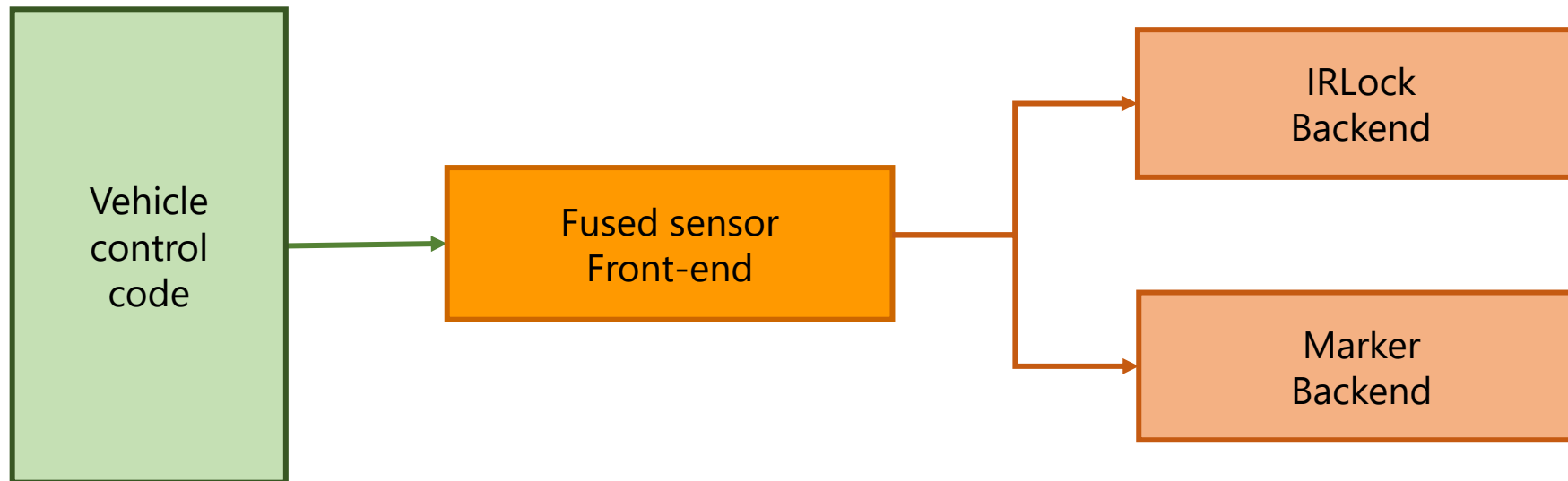
# Marker sensor subsystem

- Pi camera configured at 640x480
- Pose estimation every ~50ms (20 Hz)
- Send information using the MavLink protocol over serial/UART
- ArUco custom **fractal marker**
- Enables detection from **different heights**

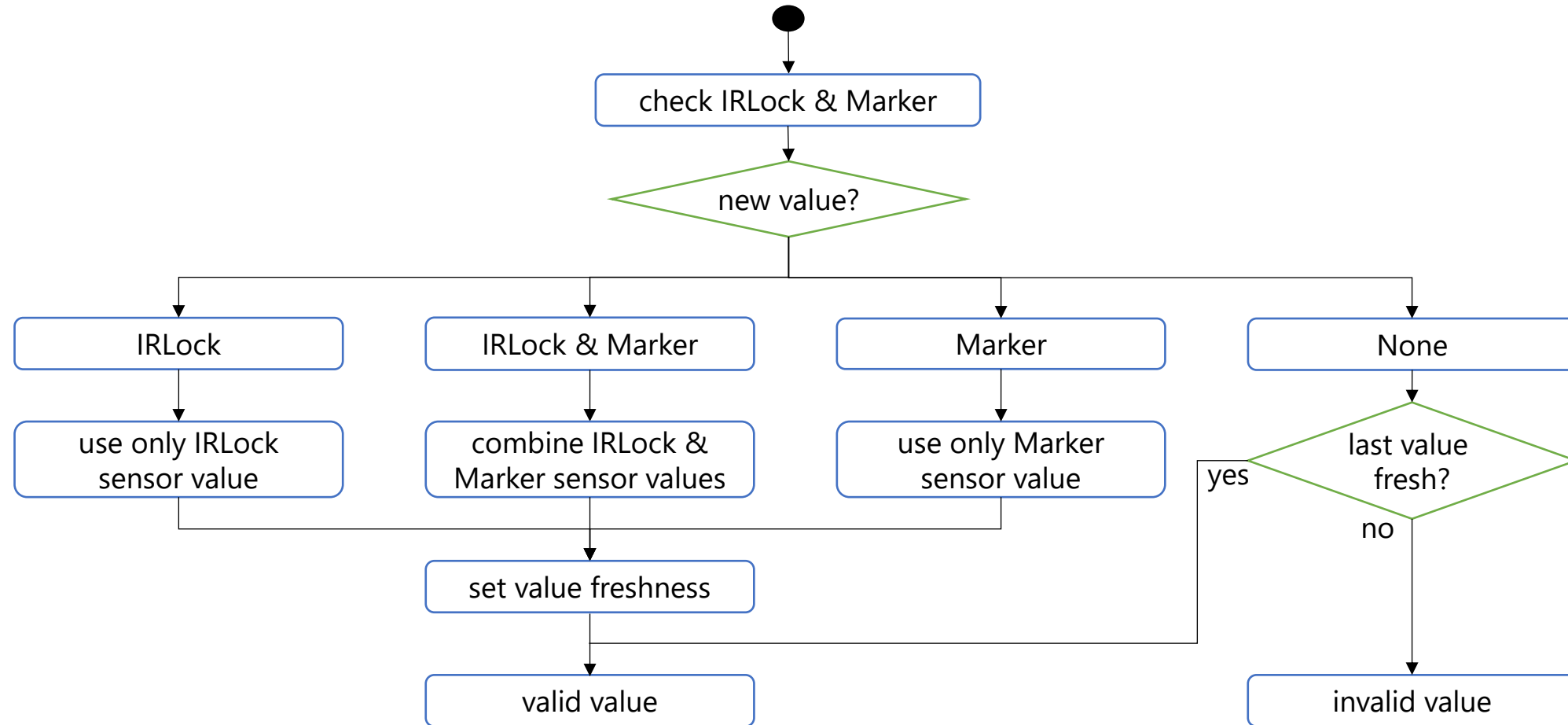


# Fused sensor

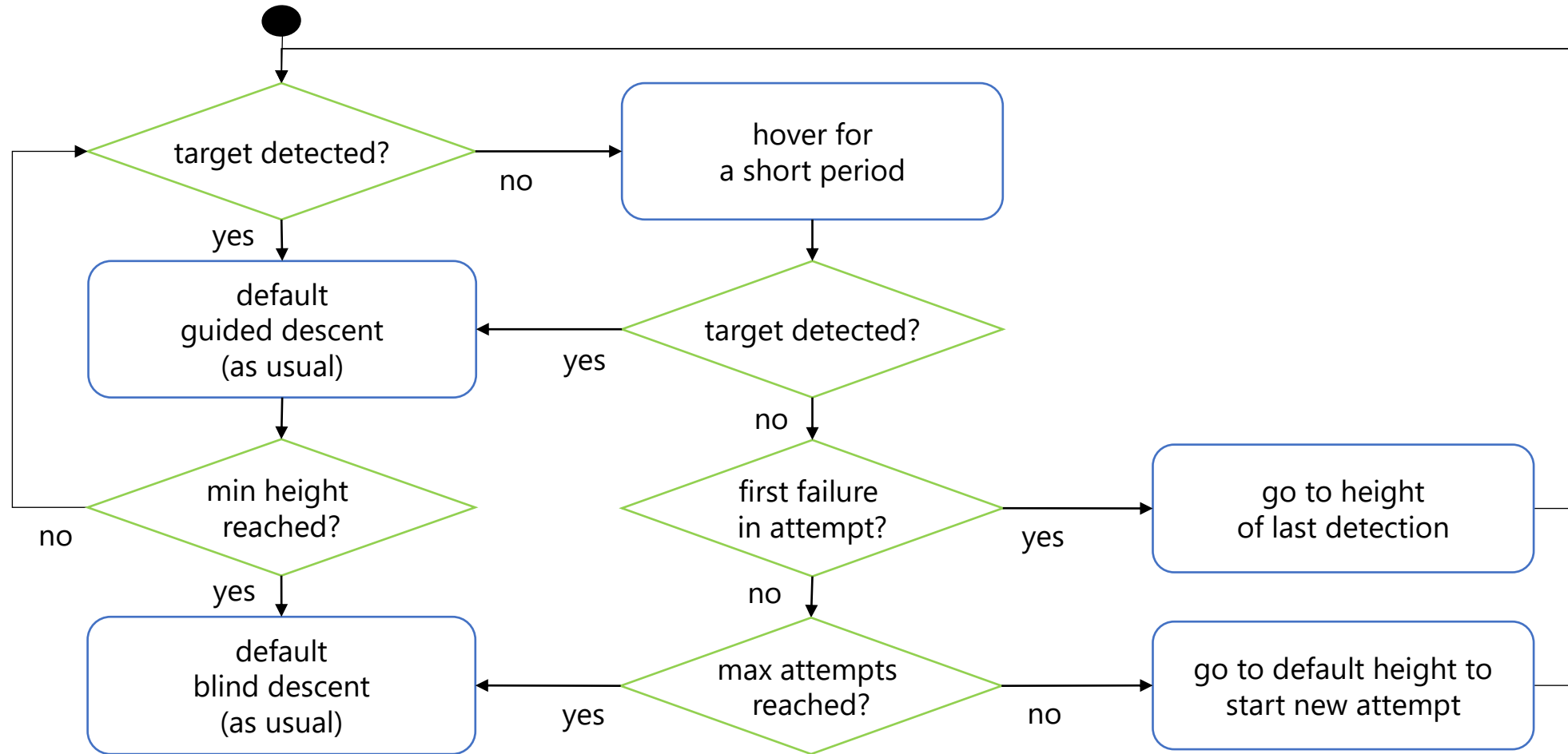
- Front-end hides all back-end details
- Does not have its own back-end
- Connects to the back-ends of the IRLock and Marker sensor subsystems



# Fusion logic



# Cautious land mode





# Controlled (artificial) failures

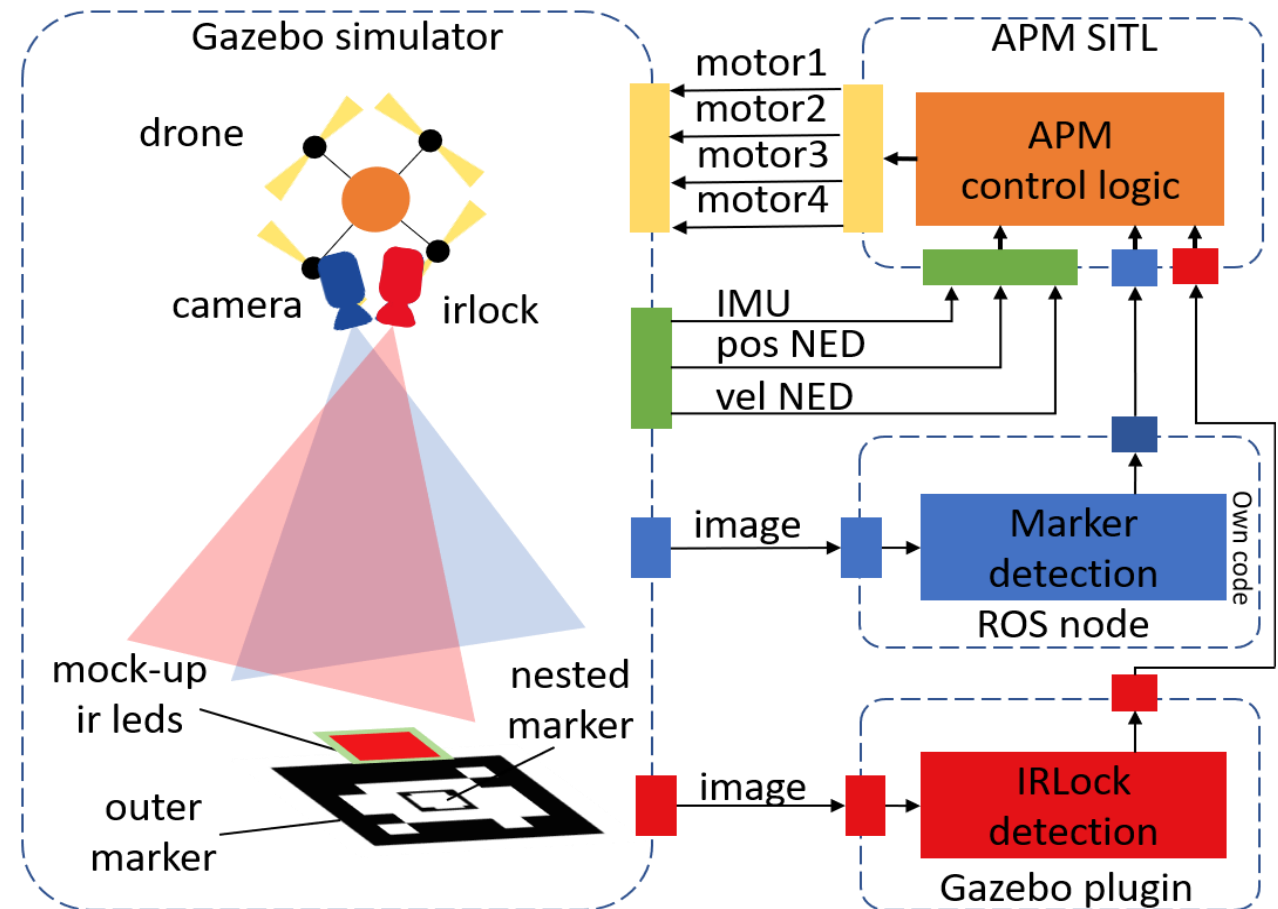
- Drop modes
  - random
  - periodic
- Modified the front-ends of the respective precision landing sensor subsystems
- Drop sensor values produced by the respective back-ends
- Configuration at runtime via a MavLink command

Field	Type	Description
target	uint8_t	Target sensor subsystem (IRLock: 1, Marker: 2, both: 3)
r_drop	float	Probability for dropping a new sensor value
p_keep	uint16_t	Number of consecutive new sensor values to keep
p_drop	uint16_t	Number of consecutive new sensor values to drop

*MavLink message*

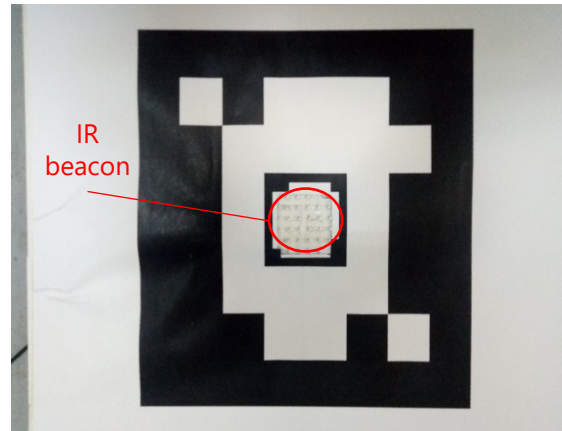
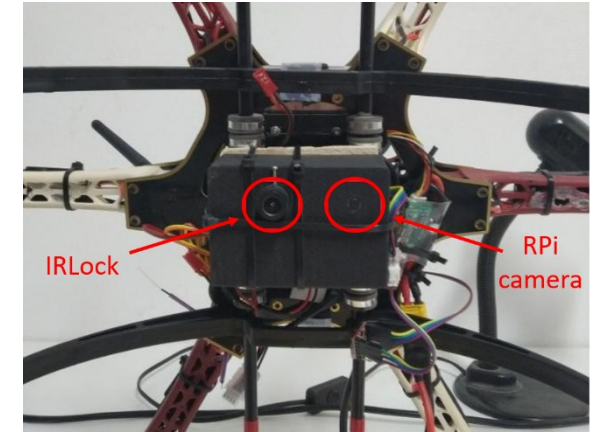
# Simulated setup

- Gazebo acts as a flight-dynamics simulation engine for the APM autopilot
- SITL platform configuration for the APM autopilot, derived from the same code base that targets real controllers
- Gazebo and APM communicate via UDP/IP



# Drone setup

- Autopilot CUAU Nano v5
  - ICM20689 accel/gyro
  - ICM20602 accel/gyro
  - BMI055 accel/gyro
  - IST8310 magnetometer
  - MS5611 barometer
- Neo v2 GPS/Compass
- Raspberry Pi & camera
- IRLock target tracking system

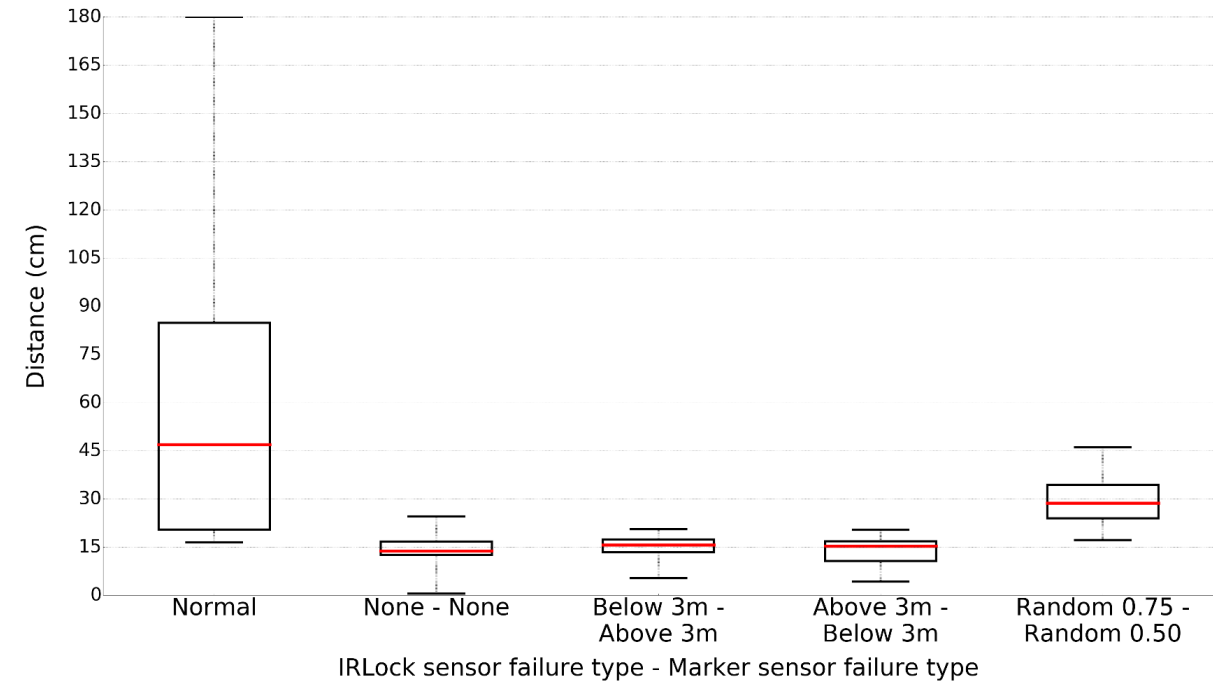
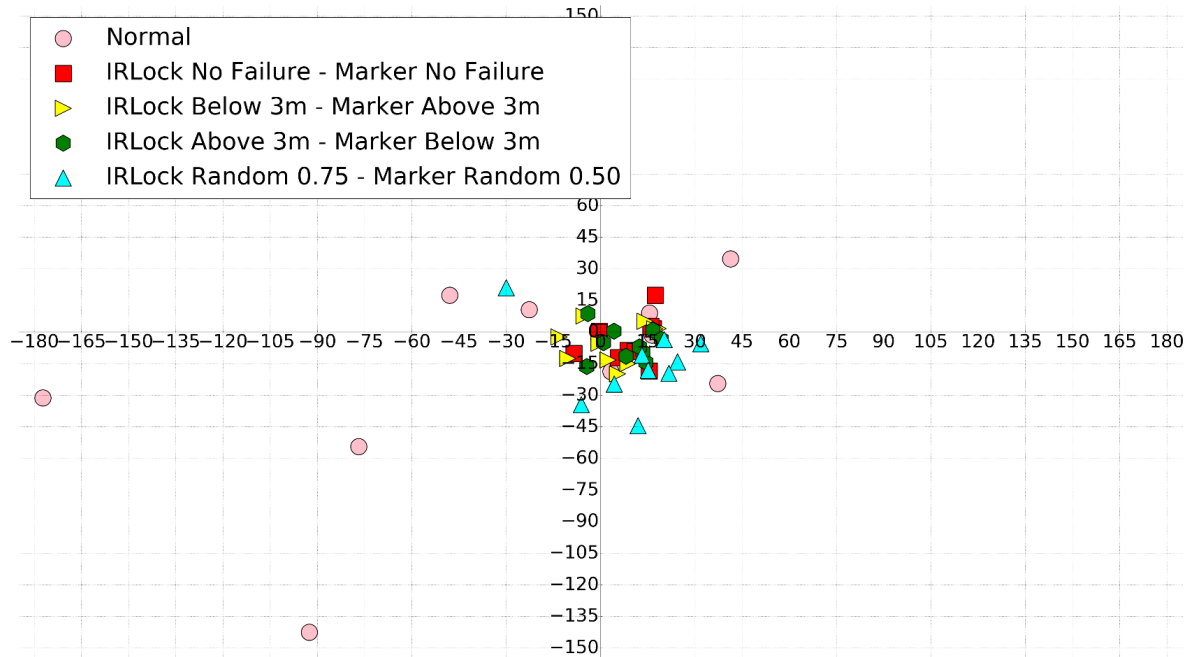


# Field tests

- The drone takes-off from a position outside the landing area
- Makes a small tour
- Returns to the home waypoint
- Once this is reached, precision landing is activated
  - guiding the drone on top of the visual marker and IR beacon
- Experiments are performed for **different** failure scenarios
  - values are dropped from one or even both sensors in a controlled way



# Results



# Drone-based remote sensing architecture



# Drones as a flexible remote sensing resource

- Target area to be monitored **periodically** or **on demand**
- Use **one or more drones** to perform the required sensing
- **Process** the results to detect events/phenomena of interest

## Application use case

- Panel inspection in a solar park
  - periodically
  - when receiving a user request
  - when receiving a signal from the park's electrical monitoring system
- Process IR images to detect issues on panels (e.g., cracks, hotspots)



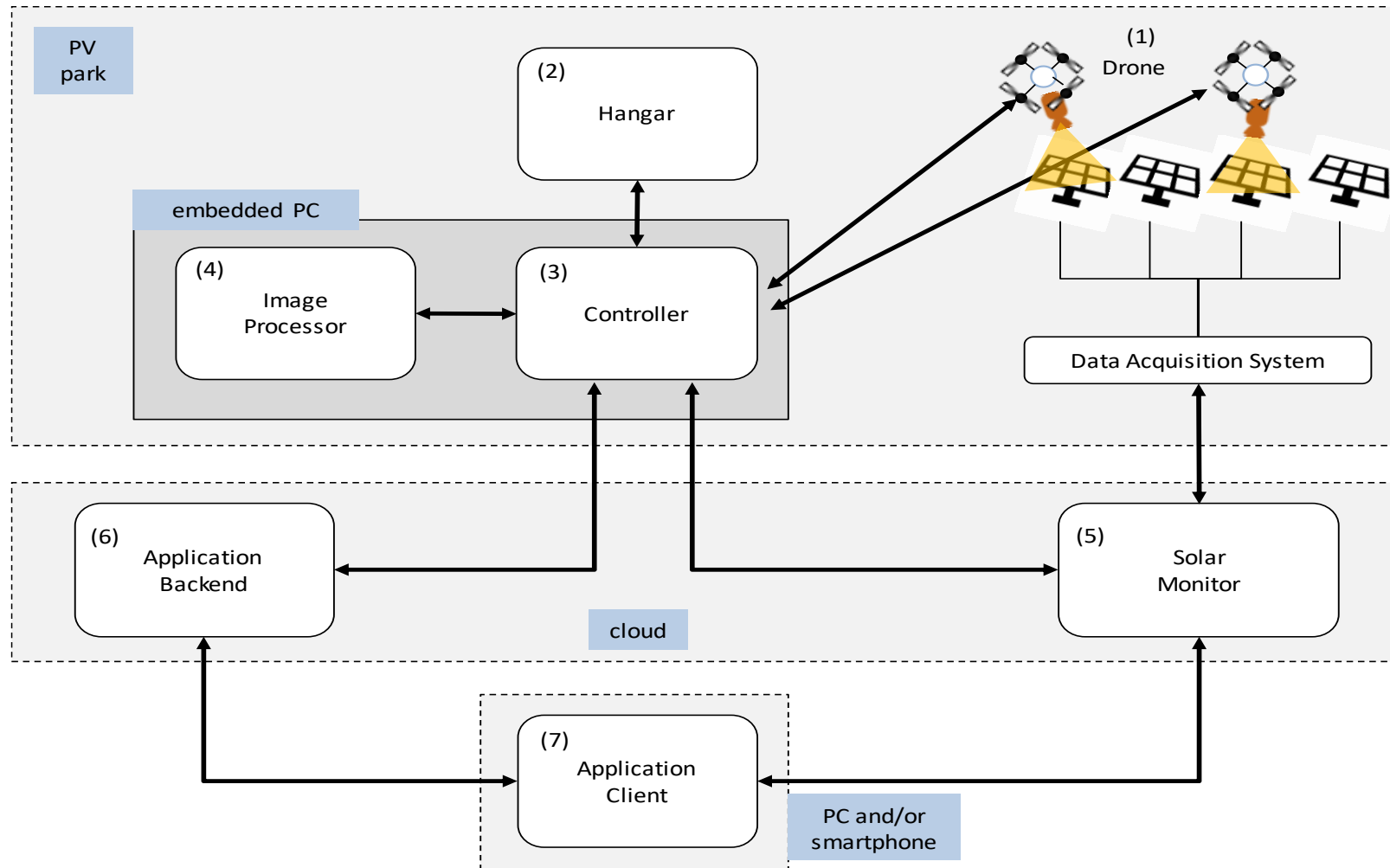


# Edge-oriented approach

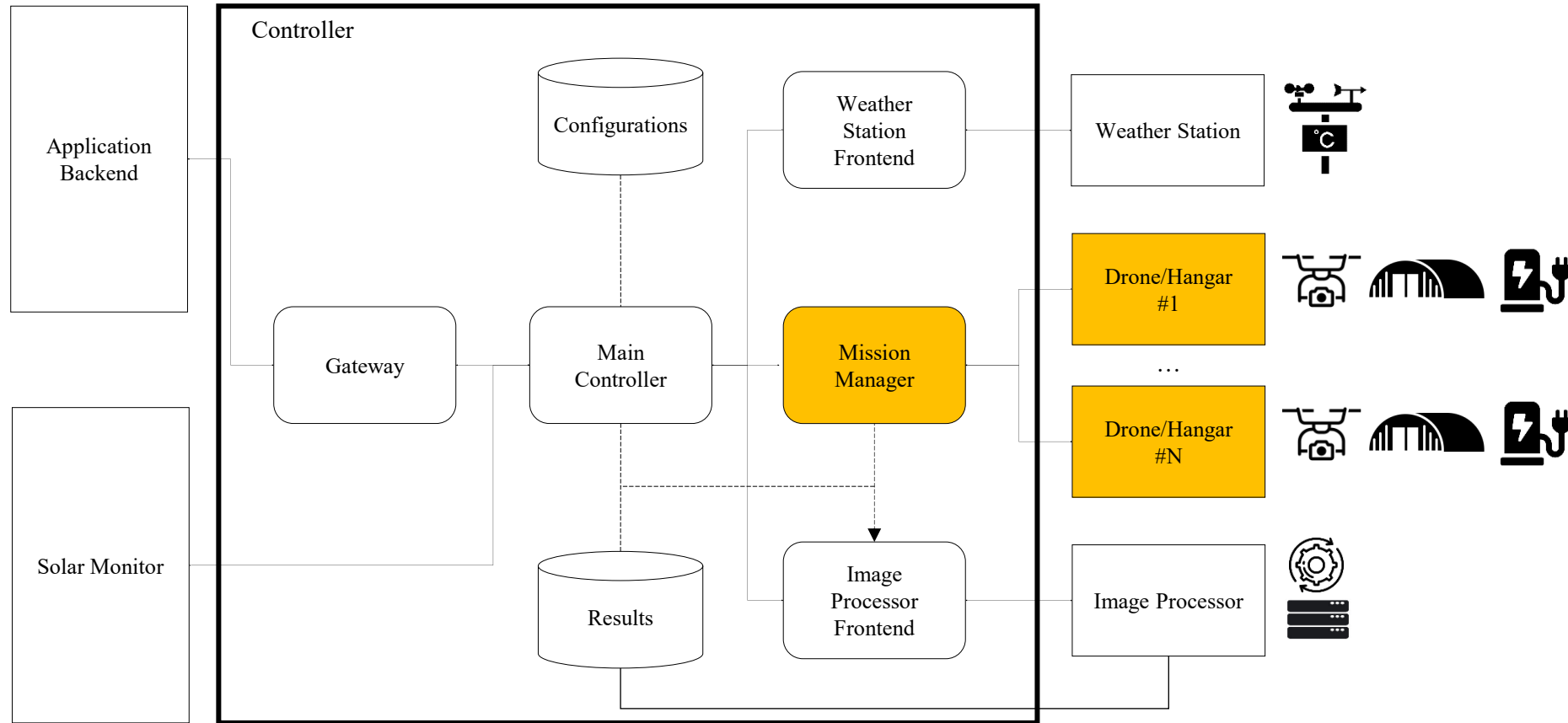
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- Drone housed in a **hangar**, also used to charge the drone's batteries
- The drone & hangar are **part** of the park **infrastructure**
- The entire management logic runs in an **embedded computer**
  - can be placed inside the hangar
- Even image **processing** runs **locally**

# Top-level architecture



# Internal Controller architecture

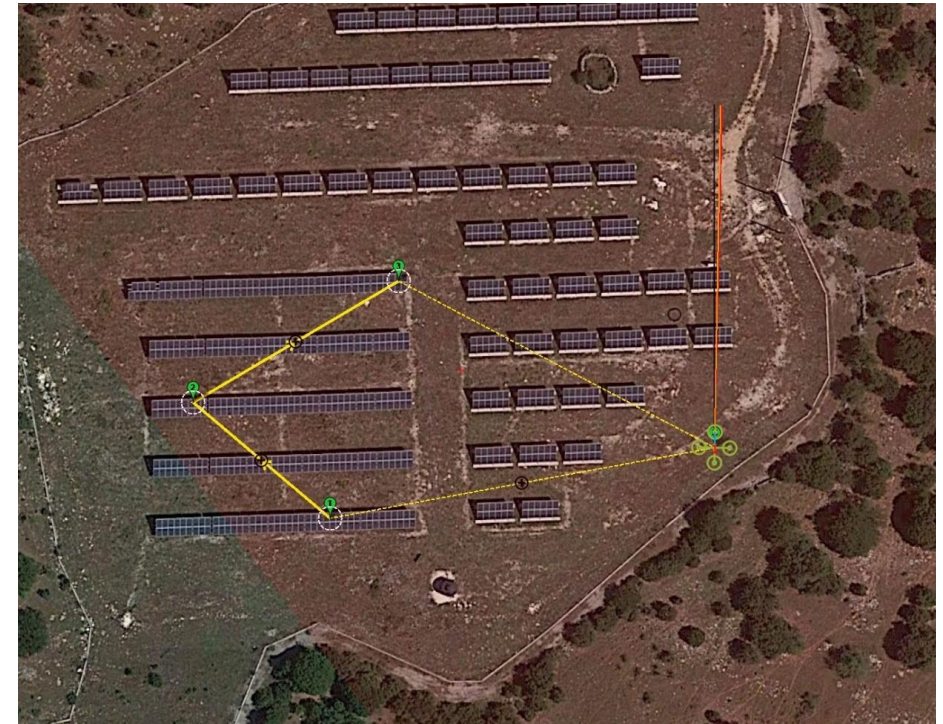


# Mission plans

Full inspection



Partial/focused inspection



# Multi-drone mission execution

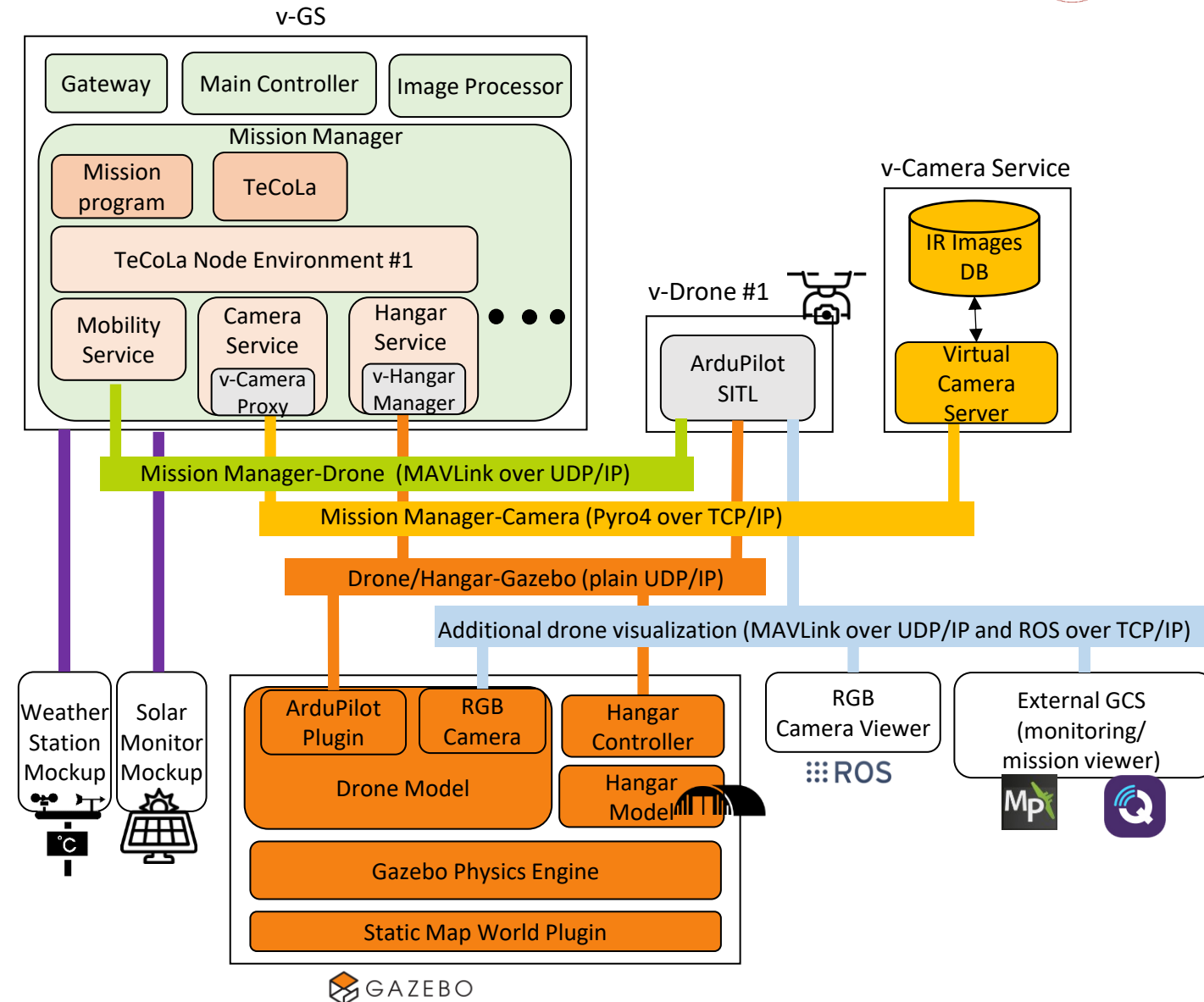
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- A mission can be parallelized using **multiple** drones **concurrently**
- The mission plan is **partitioned** into disjoint plans, one for each drone
  - number determined based on availability and/or via a configuration parameter
- At runtime, drone may experience **flight problems**
- It may also **run out of batteries** earlier than expected
- It will be instructed to return to land
- The rest of its plan is **distributed** to the remaining drones



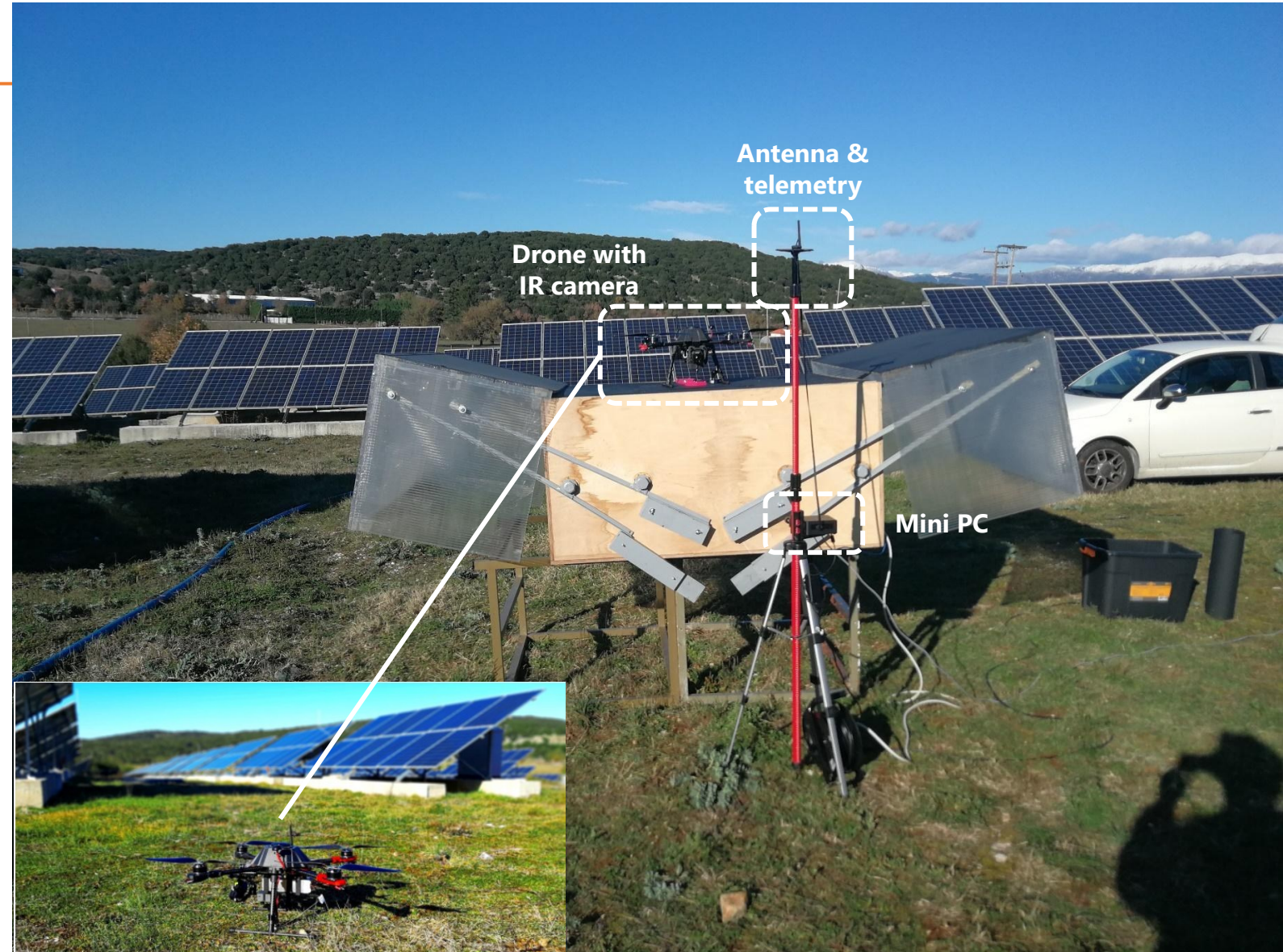
# Simulation setup

- Field tests are **time consuming**
  - preparations, travel time
  - weather, safe perimeter
- Even more so for tests that involve **multiple** drones
  - stand-by pilot for each one!
- Use a SITL setup to test the SW
  - Ardupilot/SITL
  - Mission Planner
  - Gazebo
  - ROS



# Field setup

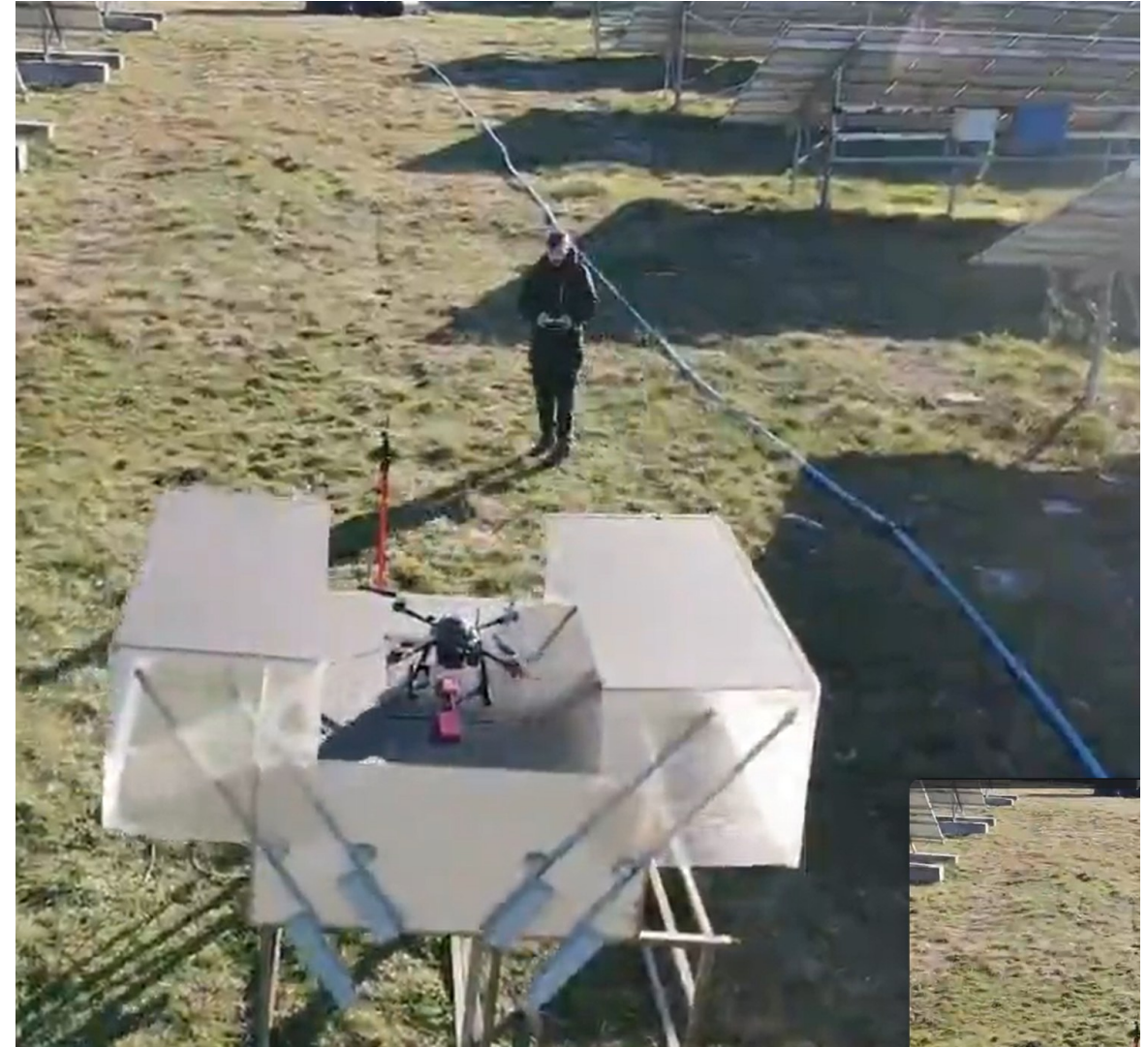
- Custom hangar with minimal functionality
  - open/close hatch
  - charging plate
  - IRLock beacon
- Portable mast with
  - drone telemetry link
  - WiFi
  - embedded PC (running the entire control & image processing SW)





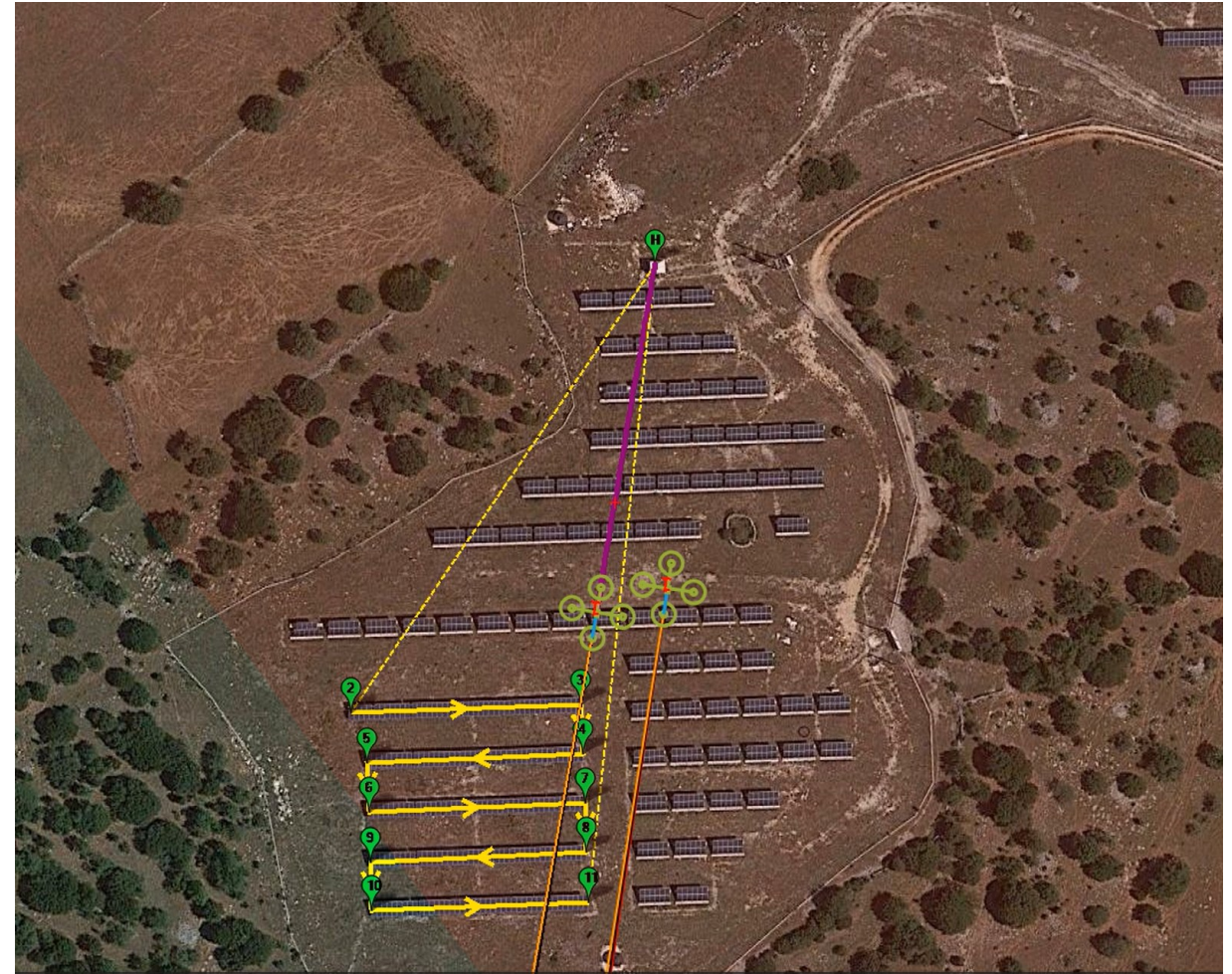
# Full cycle of operation in the field

- Controller SW runs the **full cycle**
  - open hangar & arm the drone
  - instruct the drone to take off
  - instruct the drone to goto specific waypoints and take pictures
  - when done, instruct the drone to return to the home position
  - instruct the drone to land (using the precision land mode)
  - when the drone lands, start downloading and processing the images take during flight
  - close the hangar
- Everything runs **automatically**
  - no human in the loop
  - the pilot seen in the video is merely stand-by, to takeover just in case something goes wrong – fortunately, this was not needed



# SITL tests with multiple drones

- Similar scenarios as for the single drone
- Using **multiple** (two) drones
- Controller SW automatically **splits** the mission into parts, one for **each** drone
- **Concurrently** runs and monitors the full cycle of operation for each drone
- Such scenarios have also been **tested in the field** – not captured in video because we did not have a third drone ...

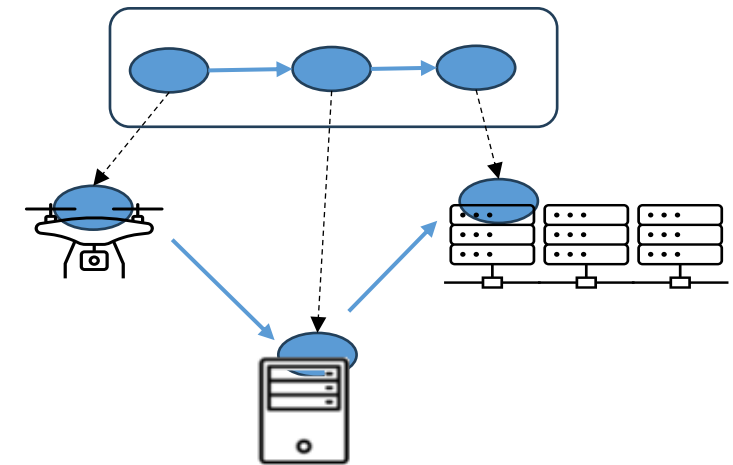
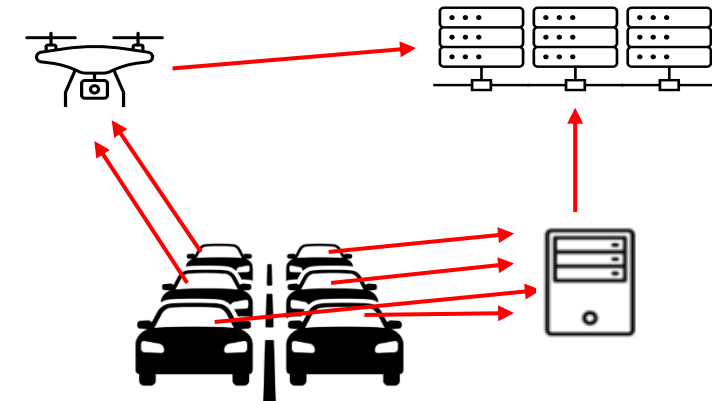




# Flexible application deployment & orchestration

# Drones as **hosts** for application code

- Many works focus on using drones as access points & service providers for ground vehicles
  - complementary to base-stations & edge servers
- We consider a largely orthogonal scenario
- Use drones as **application hosts**
  - run application-specific on-board sensing, computation, actuation tasks
- On demand
- Perhaps in conjunction with other infrastructure that can host **other** parts of the application, at the **edge** and/or in the **cloud**

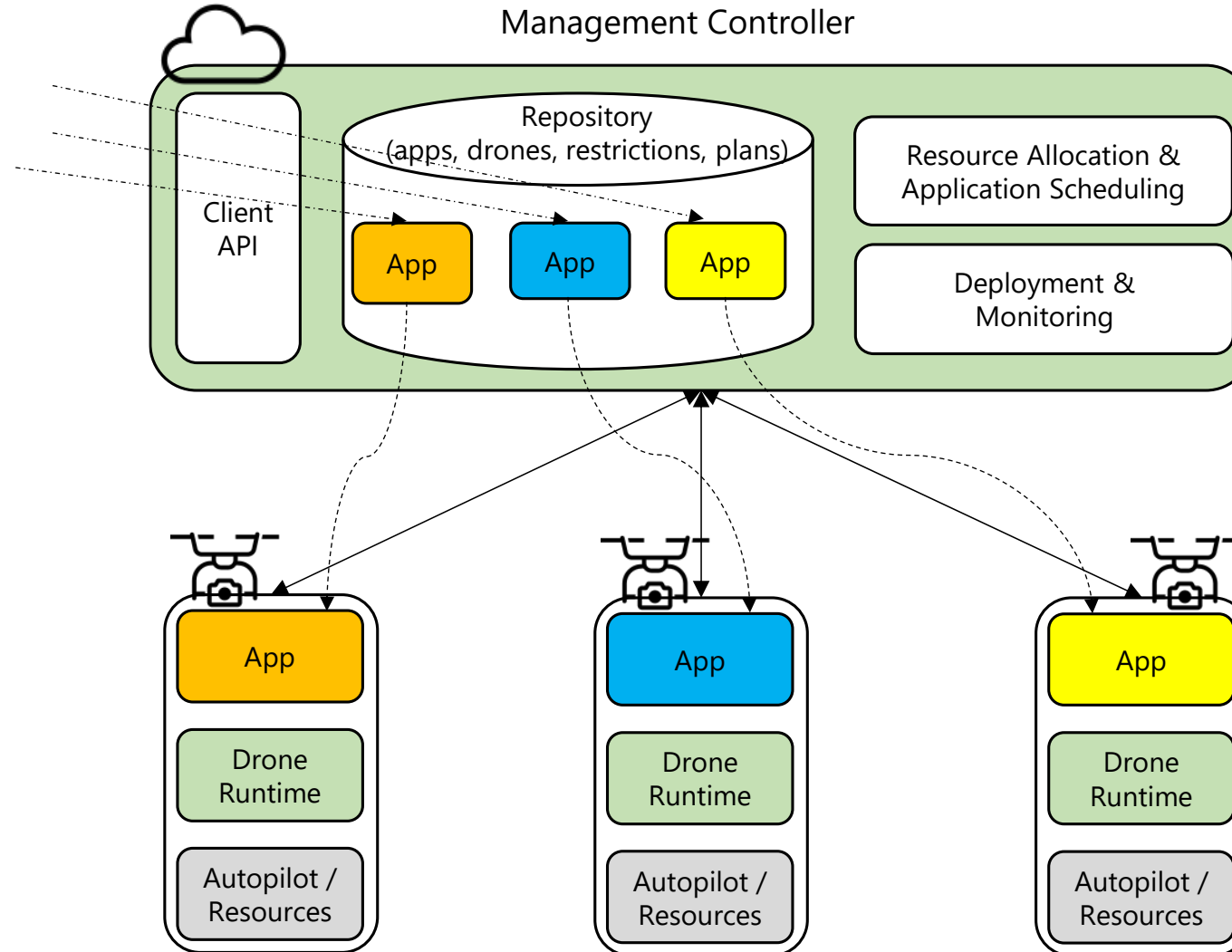


# Key aspects

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- Support **flexible** application deployment
- Enforce **flight/privacy restrictions**
- Support **distributed** application deployment

# Application deployment support



# Drone & application descriptions

```
id: 123
model: custom
type: quadcopter
category: small
```

## -- physical features

```
dimensions: {height=30cm,length=50cm, width=50cm}
weight: 1200g
```

## -- flight features

```
autopilot: ArduCopterV3.6.11
max-speed: 15m/s
max-alt: 50m
max-time: 15min
capabilities: [hover]
```

## -- computing & communication resources

```
platform: RaspberryPi3
cpu: ARMv7l
ram: 1GB
storage: 5GB
os: Raspbian
networking: [WiFi, 4G]
```

## -- sensor resources

```
camera: {type=RGB, res=1920x1080, model=ModelX}
```

```
id: 456
class: surveillance
navigation-type: waypoint-based
```

## -- flight requirements

```
max-speed: 10m/s
alt: 20m-30m
capabilities: [hover]
```

## -- computing & communication requirements

```
cpu: ARMv7l
ram: 512MB
storage: 1GB
os: Raspbian
networking: [4G]
```

## -- sensor requirements

```
camera: {type=RGB, res=1280x720}
```

```
-- configuration
waypoints
```



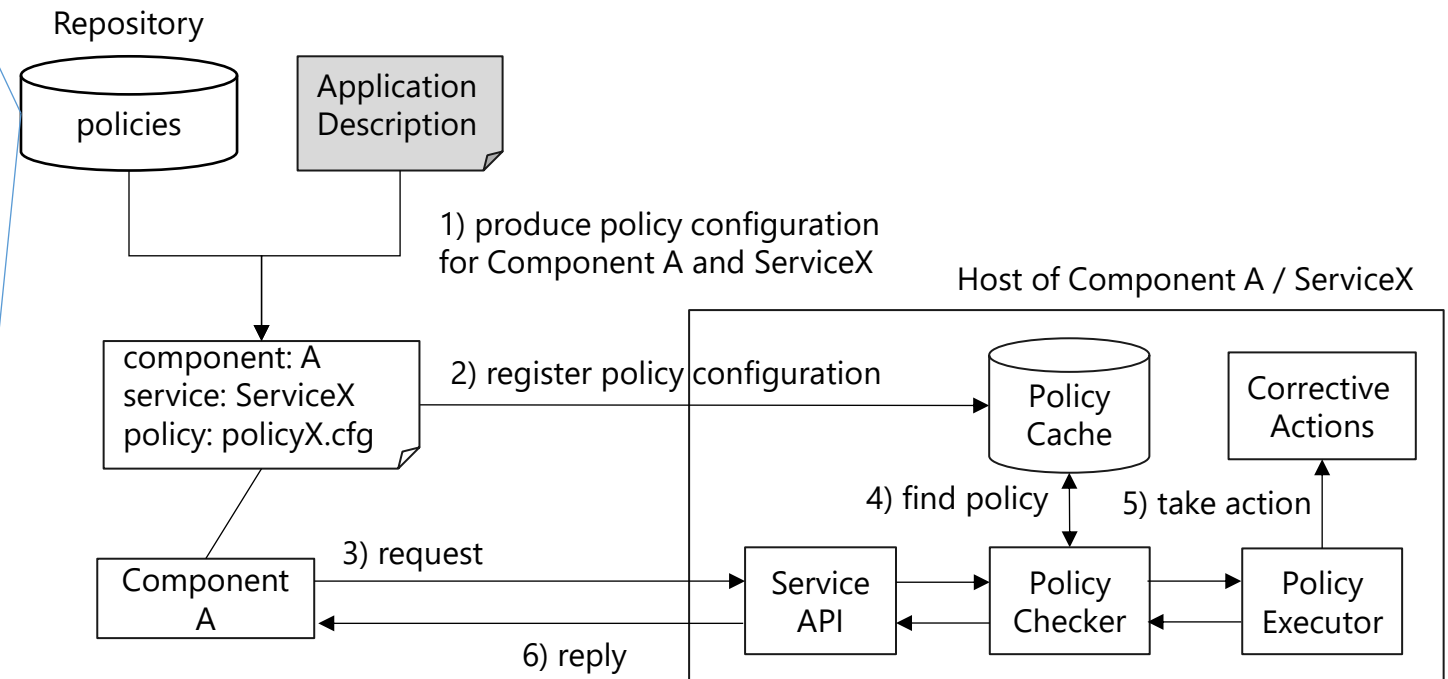
# Service-based access control

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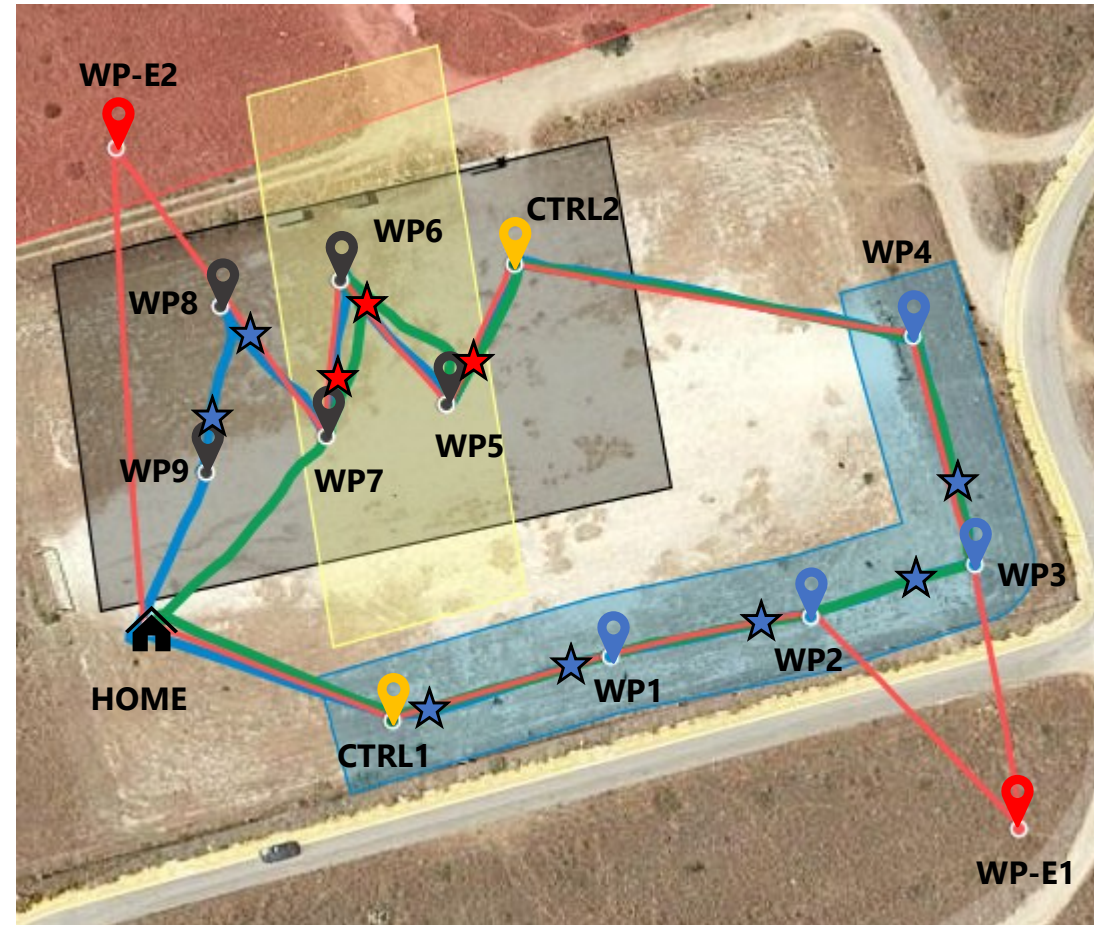
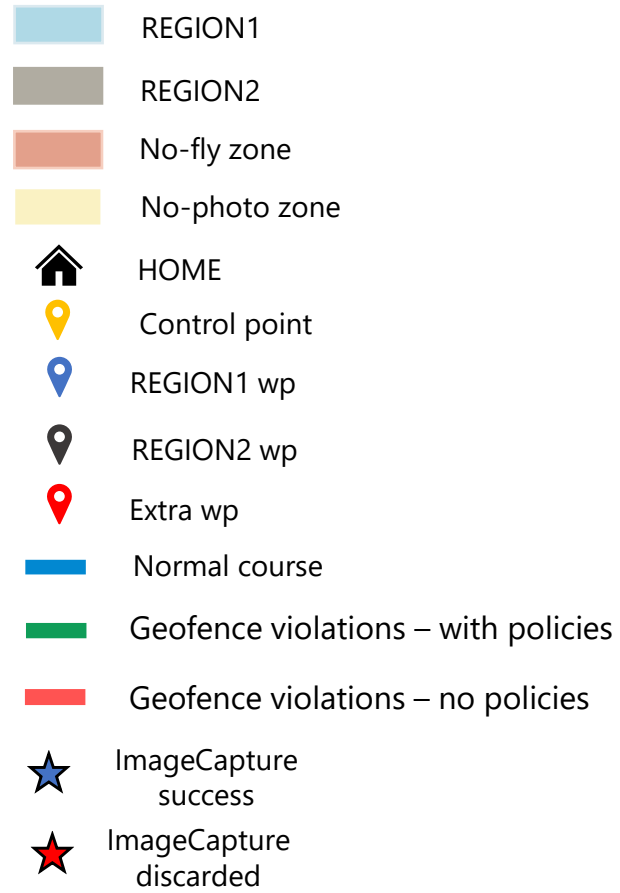
- Not all applications/drones are equal
- Need to **specify** & **enforce** the desired **behavior/limits**
- Capture the capabilities of a drone through **services**
  - mobility service, camera service, sprayer service, ...
- Applications **declare** the service methods used
- Authorities/operators **specify** the desired behavior through **policies**
- These policies are **checked** & **enforced** through **controlled service access**

# Policy-based service invocation

```
- type: AccessControl # method access
  kind: denial # forbid access
  methods: [CaptureImage, RetrieveImage]
  selector: # for all drones/edge nodes in a given area
    area: region1
- type: LimitControl # speed limit
  kind: speed
  upperLimit: 10.0
  action: enforce # adopt bound
  selector: # for all drones flying above a certain area
    area: region2
- type: LimitControl # altitude limits
  kind: altitude
  upperLimit: 50.0
  lowerLimit: 5.0
  action: enforce # adopt corresponding bound
  selector: # for a given area and certain drone classes
    area: region2
    drone: { key: class, operator: In, values: [C2, C3]}
- type: GeofenceControl # mobility limits
  kind: exclusion # prevent from entering
  action: land # take over and land the drone
  selector: # for drones exceeding a specific weight
    area: region3
    drone: { key: mtom, operator: Gt, value: 2000}
- type: PrivacyControl # for sensors
  kind: camera # for the camera
  action: blurFaces # use suitable filter
  selector: # for all drones/edge nodes in a given area
    area: region3
```



# Field test



# Toward distributed applications

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- Monolithic applications cannot exploit the full potential (and heterogeneity) of the continuum
- Explore the concept of **distributed** applications
- Consisting of **distinct components** that can be deployed on different parts of the system infrastructure
  - in the spirit of application-specific microservices / service pipelines
- **Deploy and orchestrate** the execution of application components
- **Across the continuum**: in the cloud, at the edge, on drones

# Approach

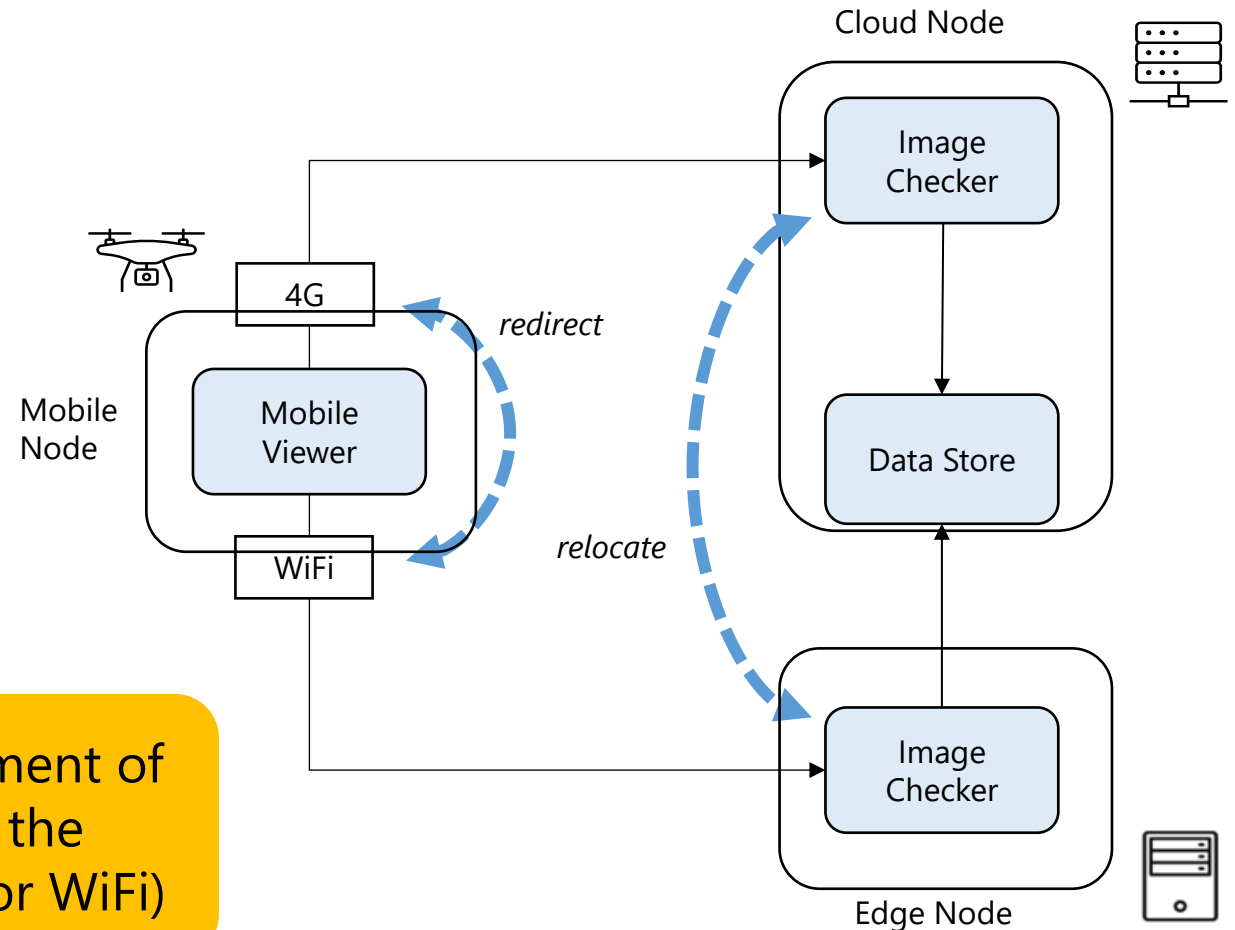
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- Allow the user to express the deployment of such distributed applications in a **declarative** way (e.g., similar to cloud-based deployments)
- Support the deployment & orchestrated execution of such applications in the **cloud-edge-drone continuum** in a transparent way
- Support the **relocation** of application components
- Support the **redirection** of application traffic
- Make it easy to **experiment** with different deployment & configuration policies, or even change them at runtime

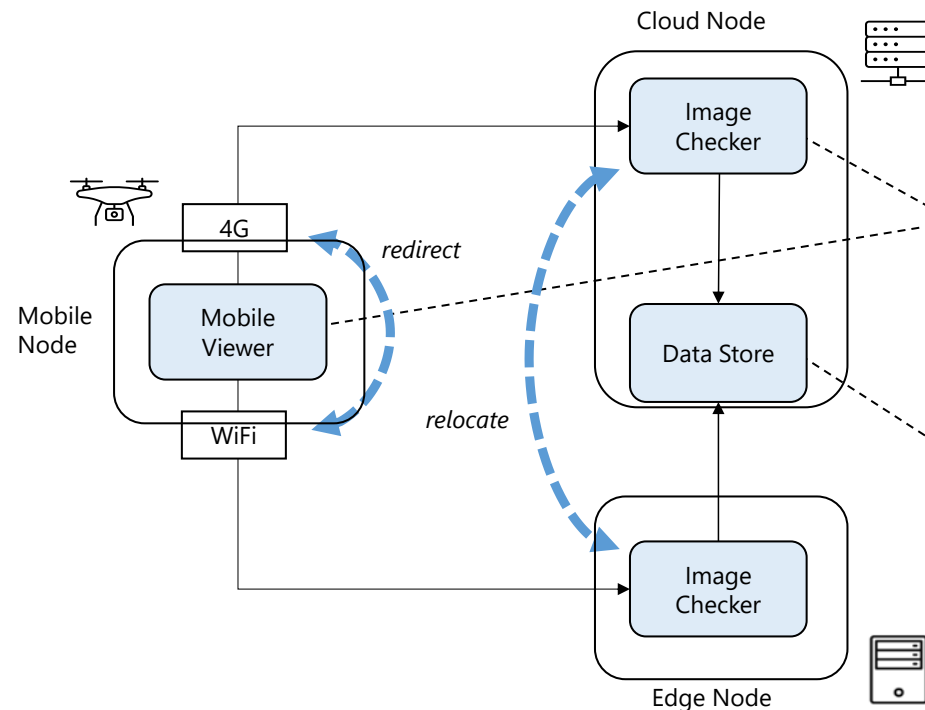
# Application example

- MobileViewer
  - takes photos via the drone's camera & possibly preprocesses them
  - may also include mission logic, controlling the drone's autopilot
- ImageChecker
  - performs heavyweight computation on images to detect objects of interest
- DataStore
  - stores images of interest

**Objective:** Support (i) the flexible deployment of the ImageChecker (cloud or edge) and (ii) the redirection of application traffic (over 4G or WiFi)



# Application description

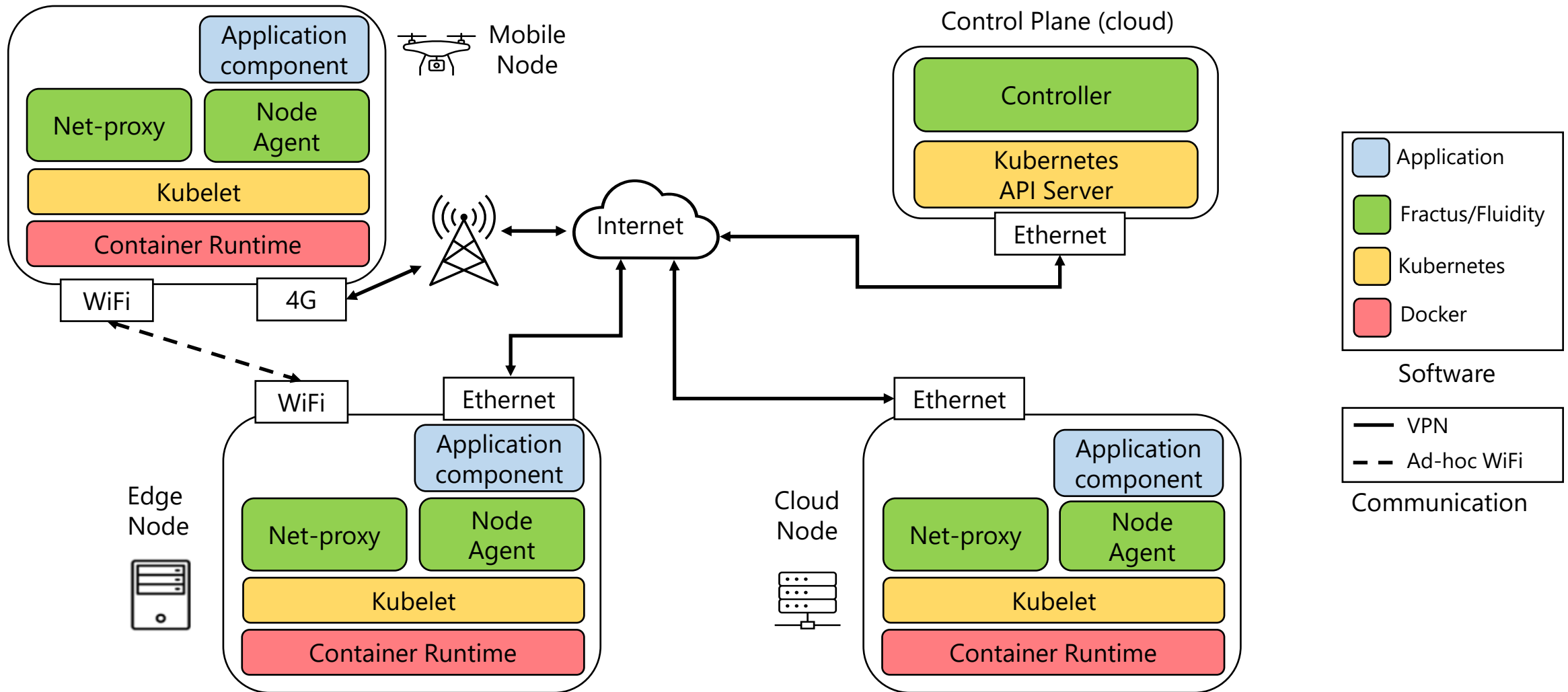


```
kind: Application
name: ObjectDetectionApp
components:
- name: MobileViewer
  podSpec: PodMobileViewer.yaml
  placement: mobile
  systemServices:
    camera:
      methods: [CaptureImage, RetrieveImage]
      sensorType: RGB
  egress: [ImageChecker]
- name: ImageChecker
  podSpec: PodImageChecker.yaml
  placement: hybrid
  ingress: [MobileViewer]
  egress: [DataStore]
- name: DataStore
  podSpec: PodDataStore.yaml
  placement: cloud
  ingress: [ImageChecker]
Policy:
- name: simple_policy.py
```

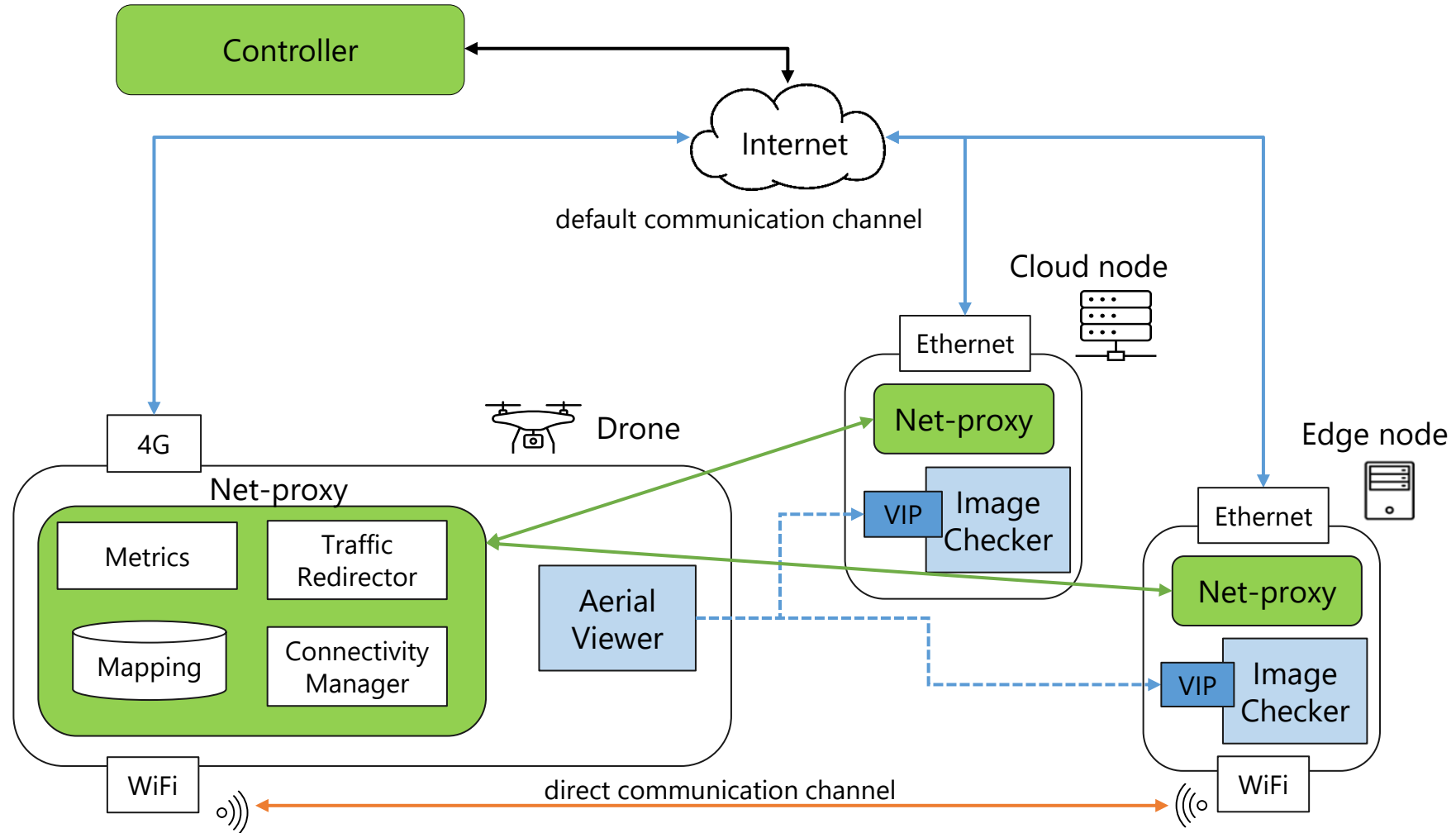
place in the cloud  
or at the edge



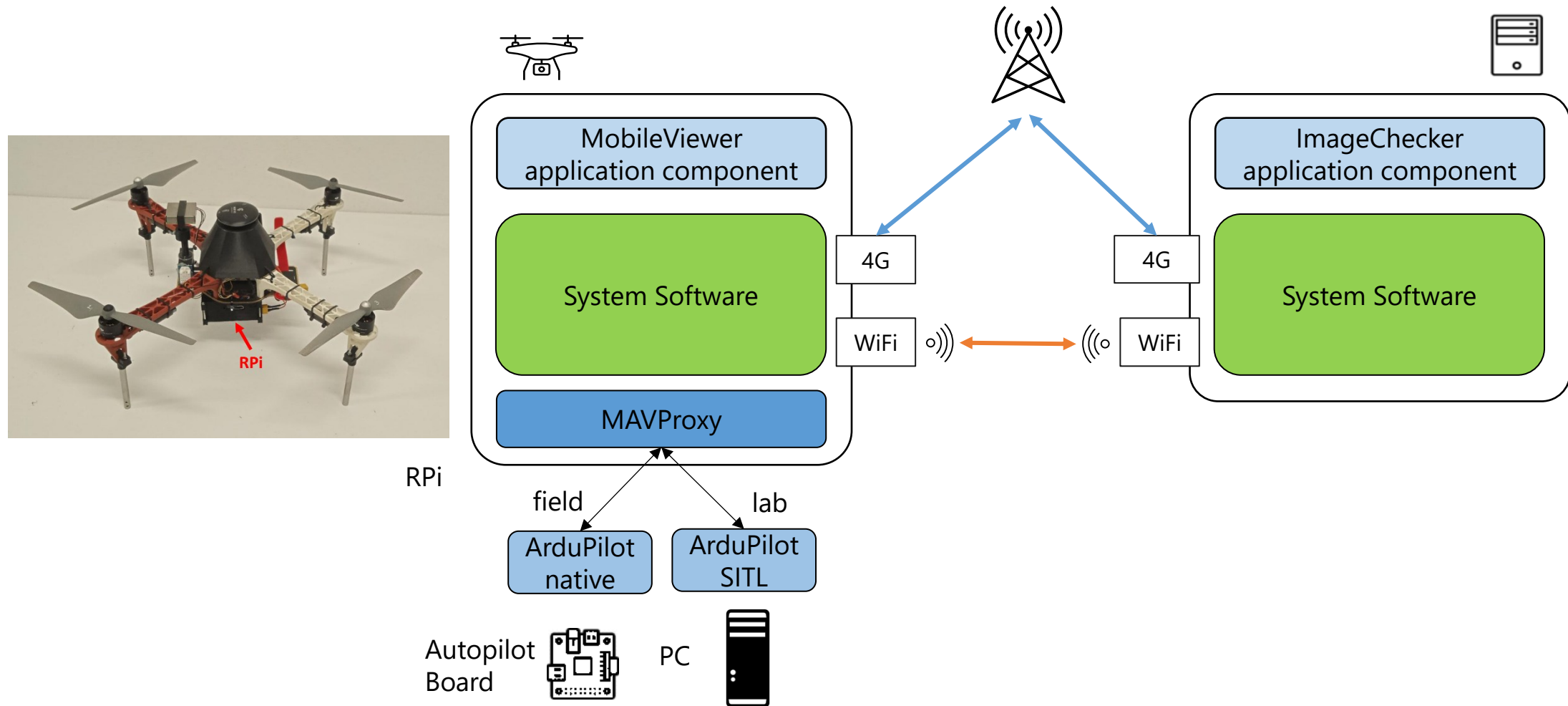
# Architecture & test setup



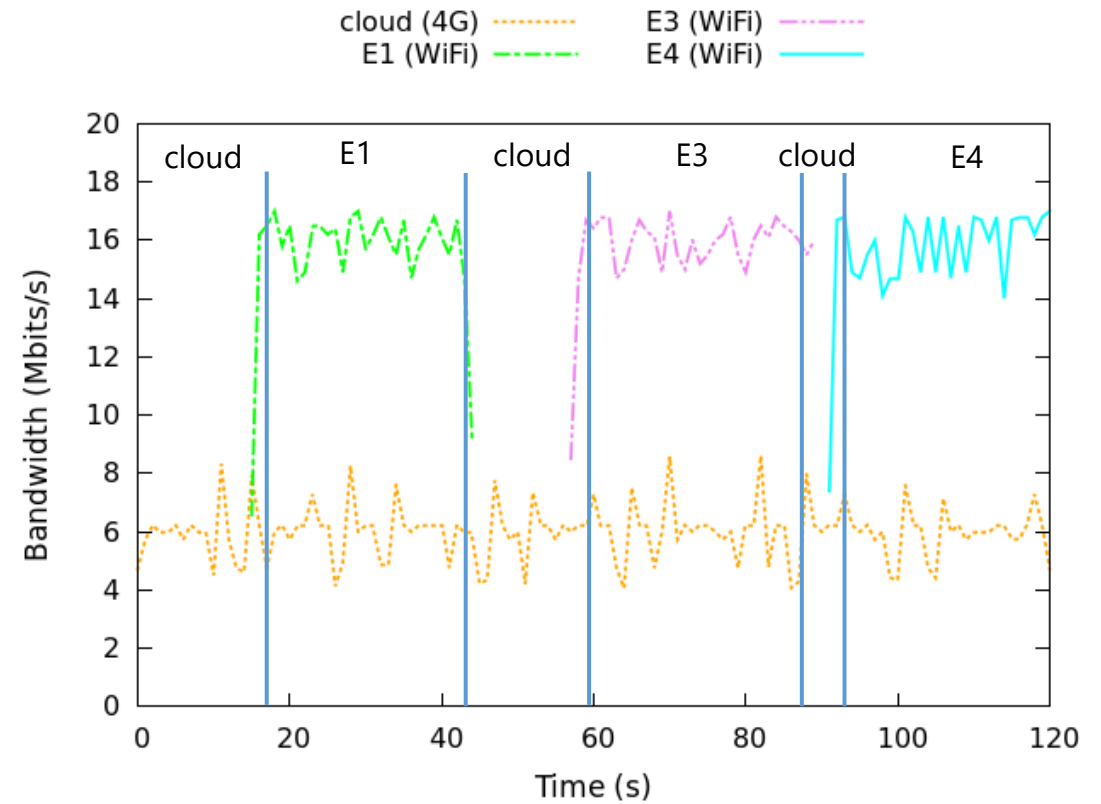
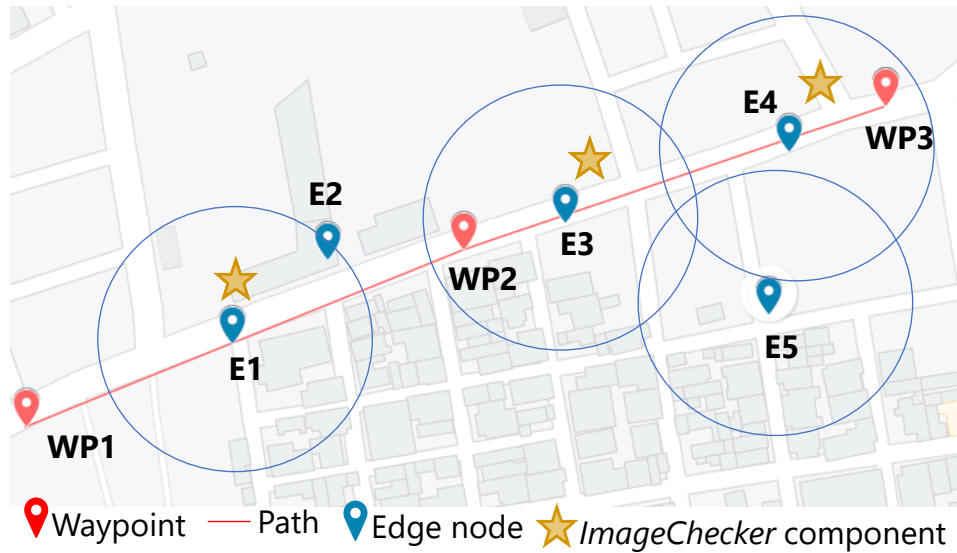
# Application traffic redirection



# Experimental node setup



# Results



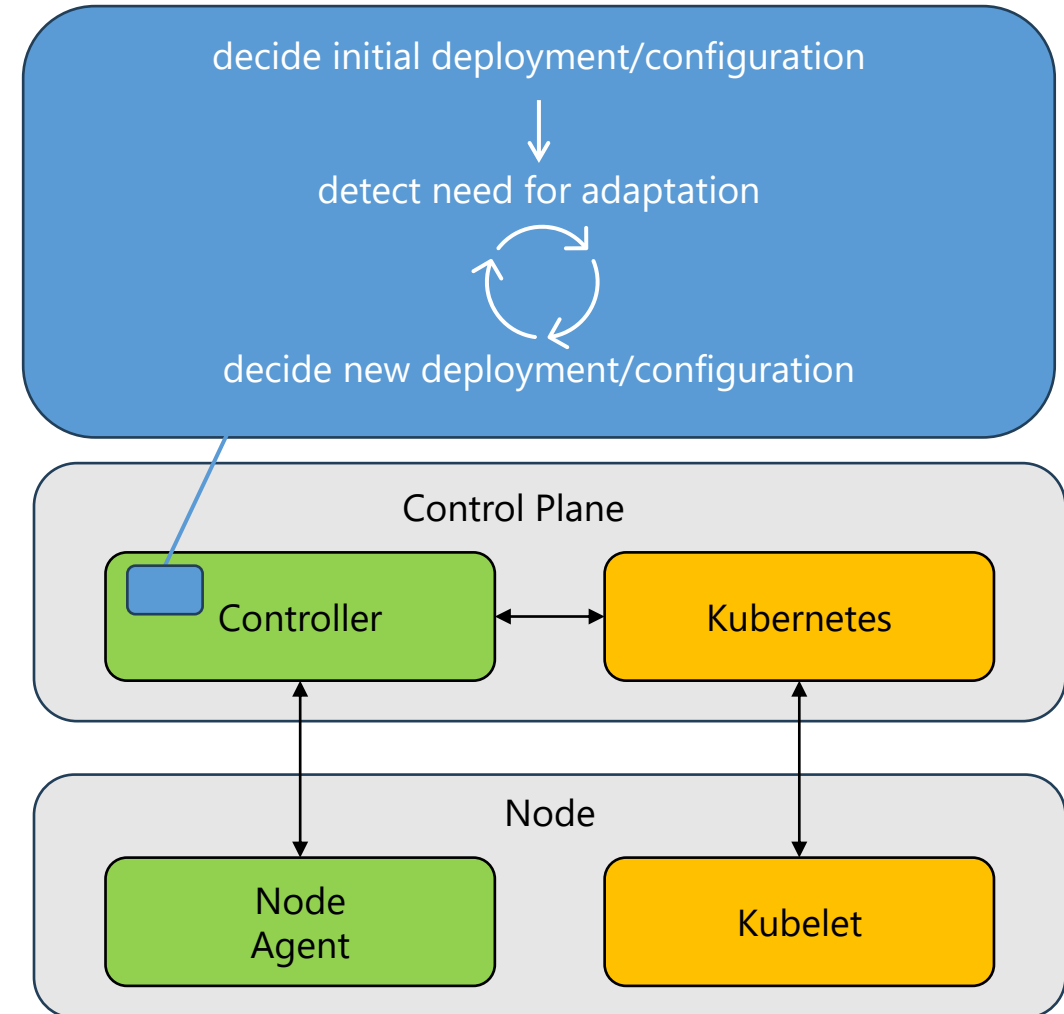
# Separation between mechanisms and policy

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- Various configuration choices
  - Where to deploy (hybrid) application components?
  - Over which network interface / link to redirect application traffic?
- Can adopt **different** decision approaches
- Can have **different** objectives / optimization targets
- Make it easy to experiment with **different** policies

# Pluggable policies

- The application deployment/configuration **policy** is a **plug-in**
- Interacts with the rest of the framework (Controller) via a **well-defined API**
- Can access/process arbitrary **telemetry** and maintain its own **state** (data)
- Produces deployment **plans**
  - for execution by the Controller
- The plan can be **adapted** at runtime
- The policy itself can be **changed at runtime**, while the application is running



# Different policies for component relocation

## Naïve (blind)

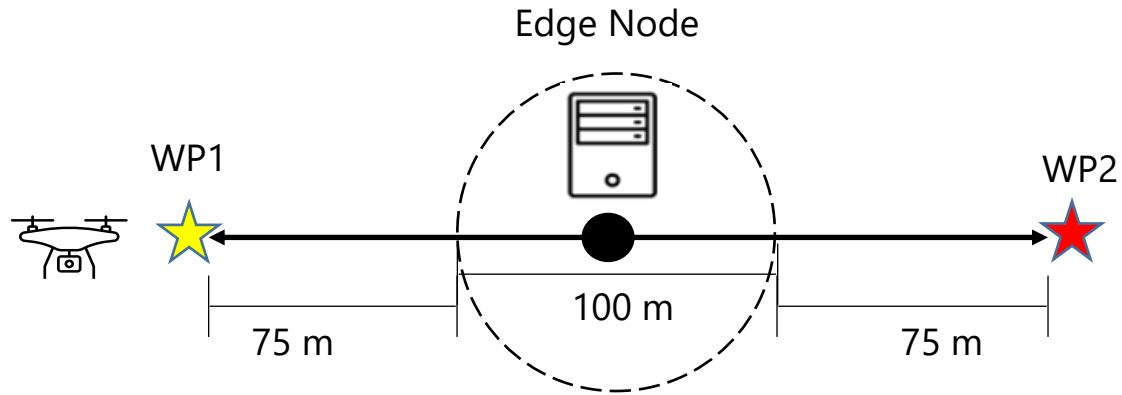
- Place the ImageChecker application component by default in the cloud
- Relocate ImageChecker to the edge when the drone enters the range of the edge node
- Relocate the ImageChecker back to the cloud when the drone exits the range of the edge node

## Data-driven (learning)

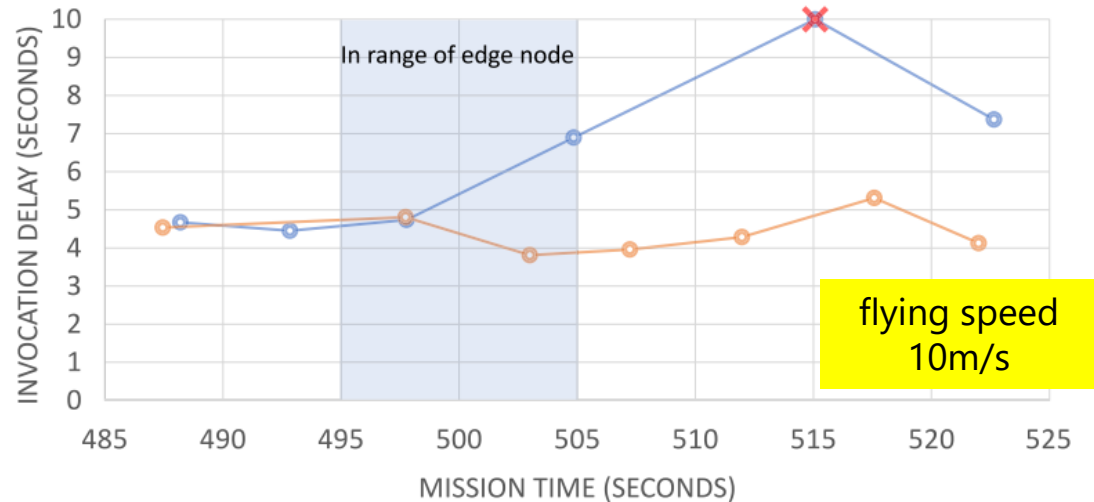
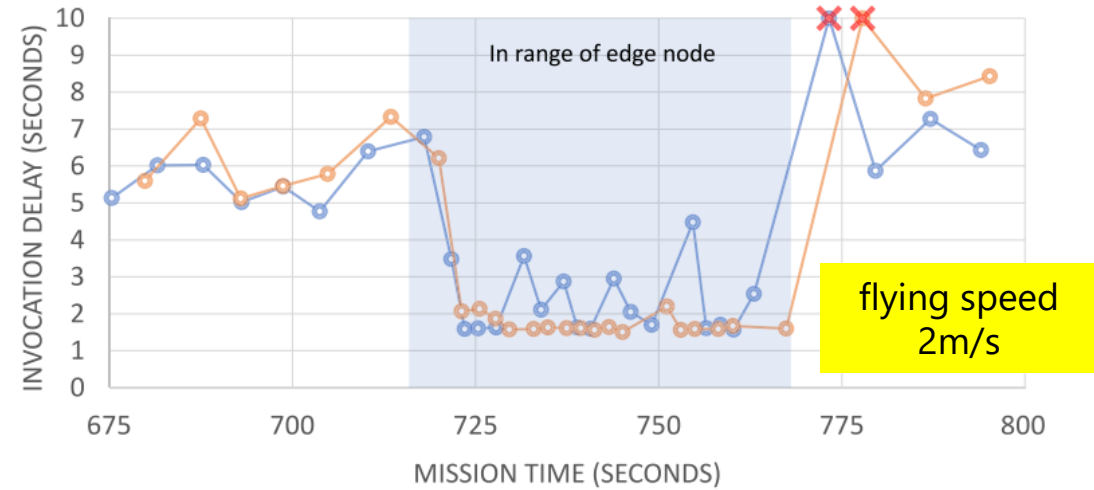
- Place the ImageChecker application component by default in the cloud
- Initially adopt the naïve policy
- Record the relocation delays and invocation time for cloud and edge
- Relocate ImageChecker only when the edge invocation times are **expected** to outweigh the relocation overhead



# Test scenario & results



Phase number	Round-trips	Velocity (m/sec)
#1	1	2
#2	5	10
#3	1	2



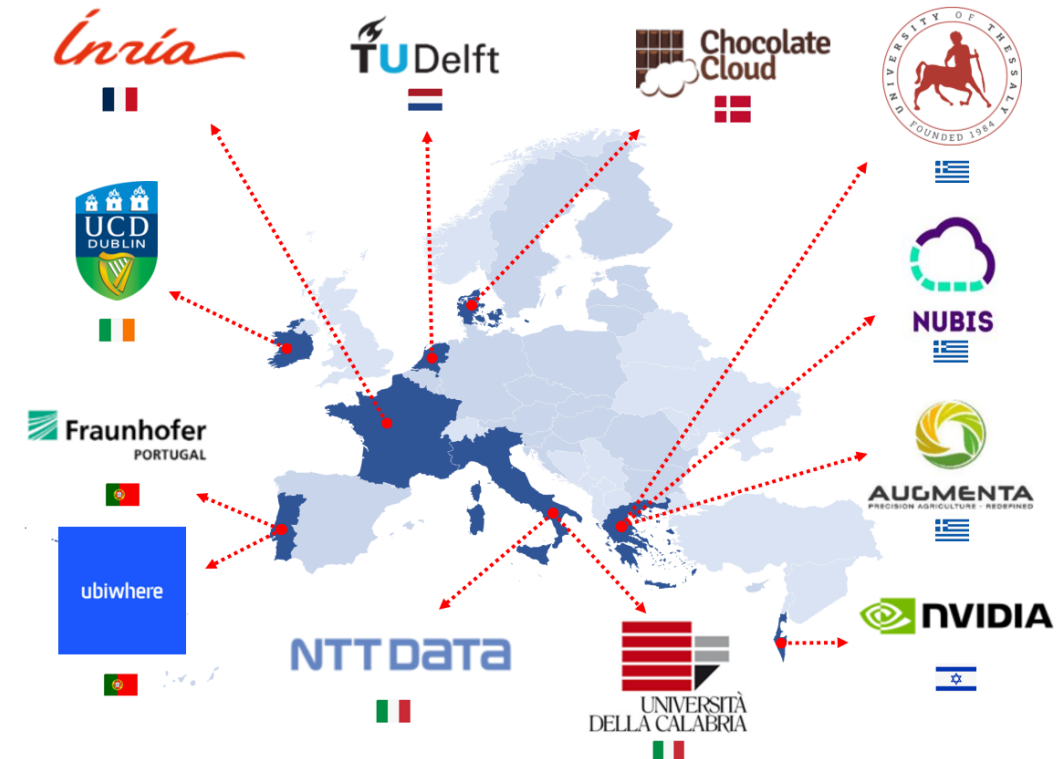
Naive Policy Data-driven Policy Failed Invocations

# MLSysOps project

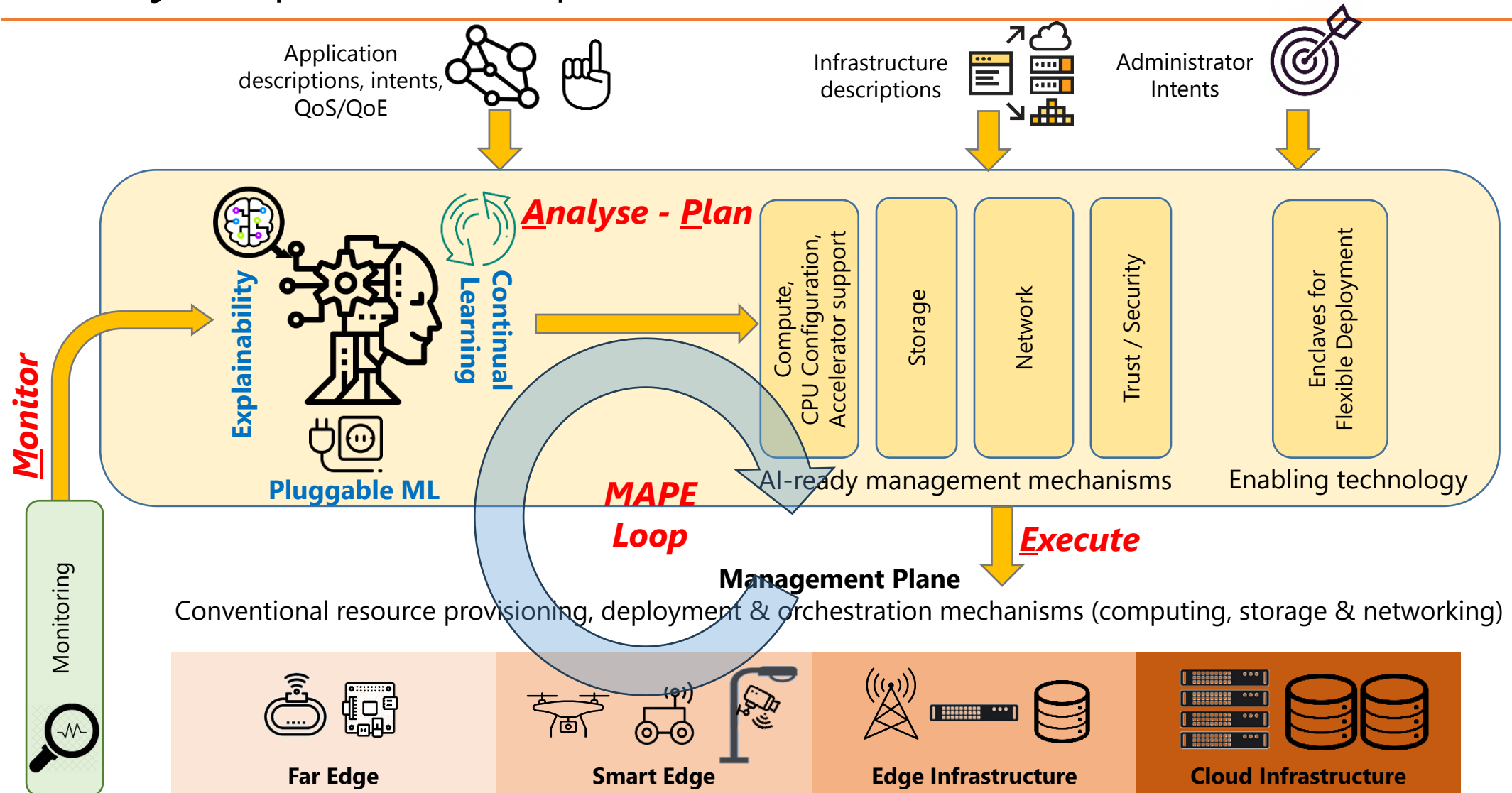
# Project focus

*Autonomic system management and configuration  
in the **cloud-edge-IoT continuum** using **AI/ML methods***

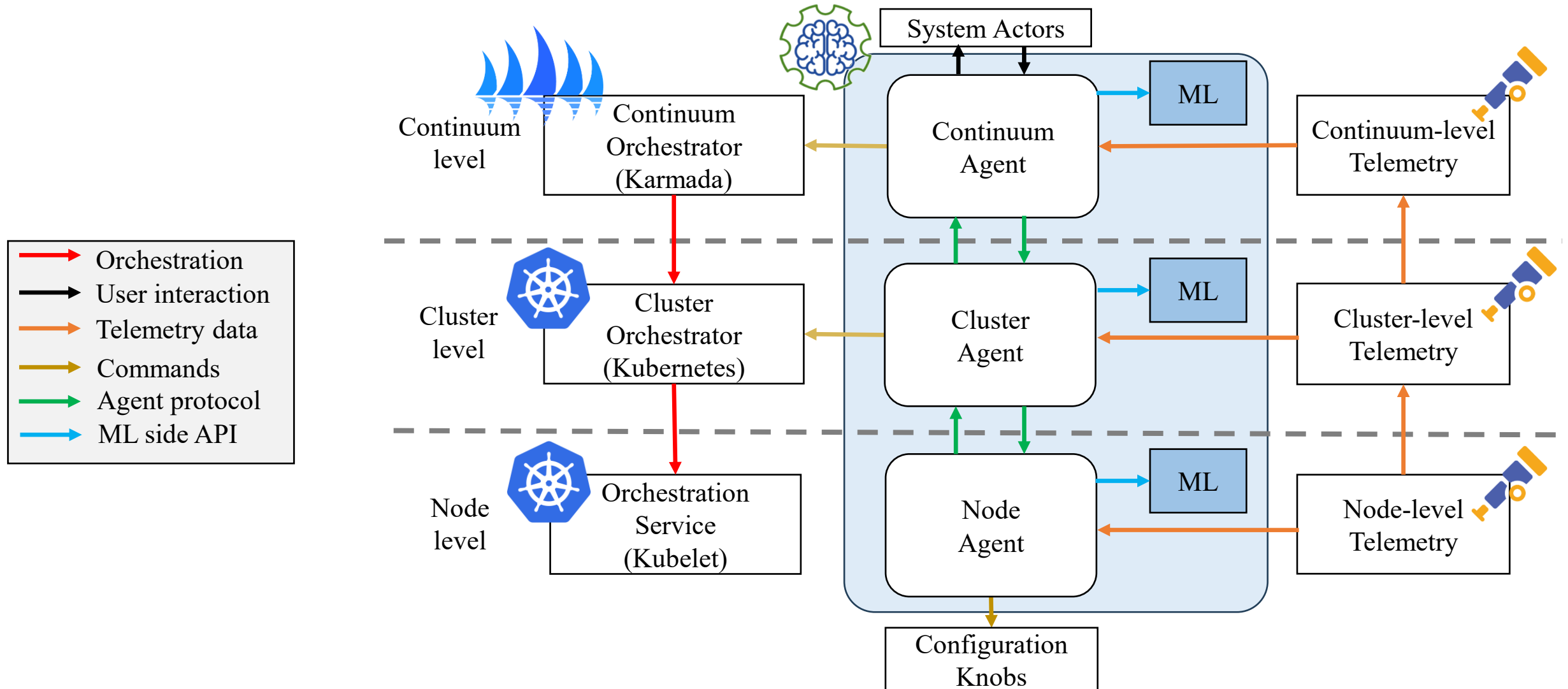
- Modular, distributed applications
  - different (interacting) components
- Explore different management aspects
  - deployment, computing/acceleration, storage, communication/networking, trust
- Disassociate management from control
  - AI/ML-ready (policy-neutral) mechanisms
  - take decisions using suitable ML models
- Key AI/ML features
  - distributed / hierarchical agent-based approach
  - different agent may use different ML models
  - continual learning, efficient retraining, explainable ML



# MLSysOps concept



# MLSysOps architecture



# Edge-oriented application use cases

## Smart City



Use AI/ML-driven control to manage/configure application modules that can be deployed on smart lampposts for object/incidence detection

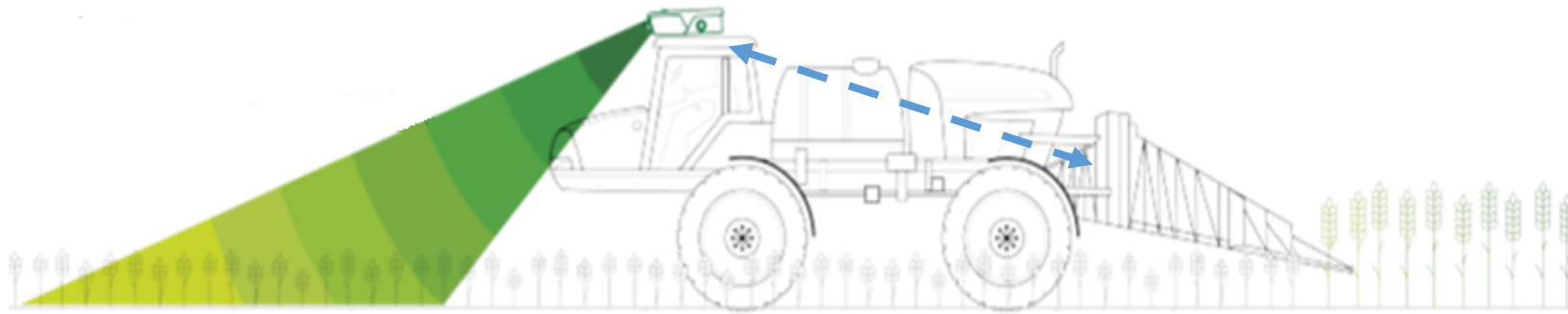
## Smart Agriculture



Use AI/ML-driven control to jointly manage/configure the image processing application pipeline in camera-based devices mounted on a tractor and a companion drone.

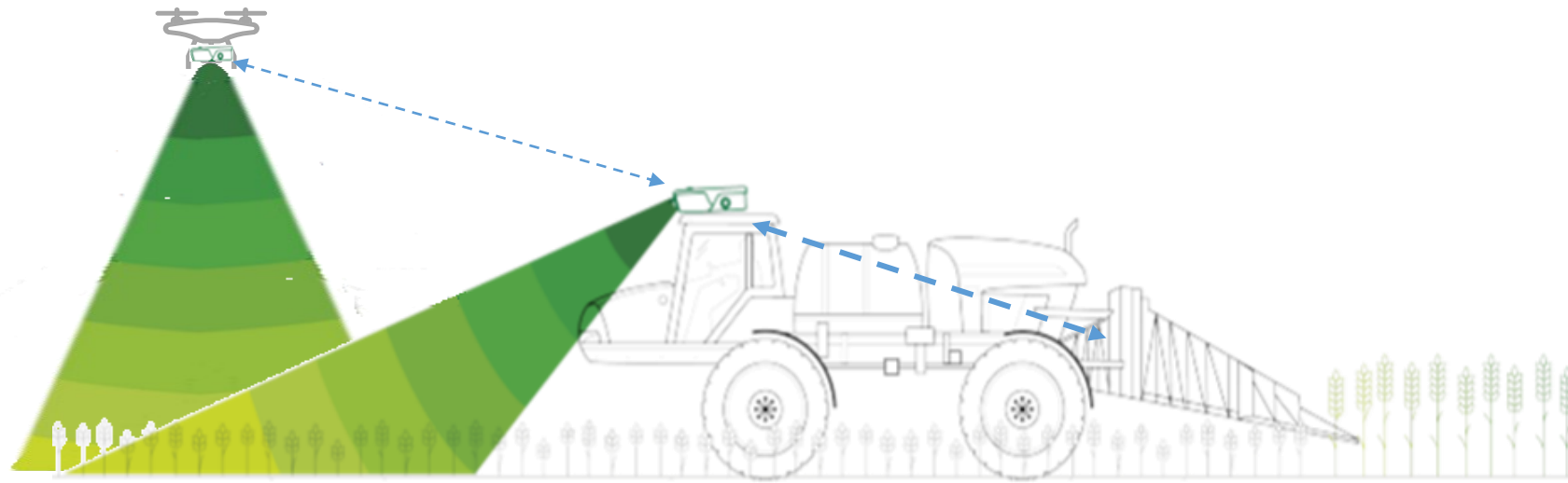


# Tractor operation



- On-tractor device is used to **detect weeds** in the field
- This information is used to **control the sprayer** at the back of the tractor
- Significant **savings in herbicides** and **reduced soil pollution**
- However, image processing may face issues due to shadows, glares, bumps, etc.

# Tractor operation with drone

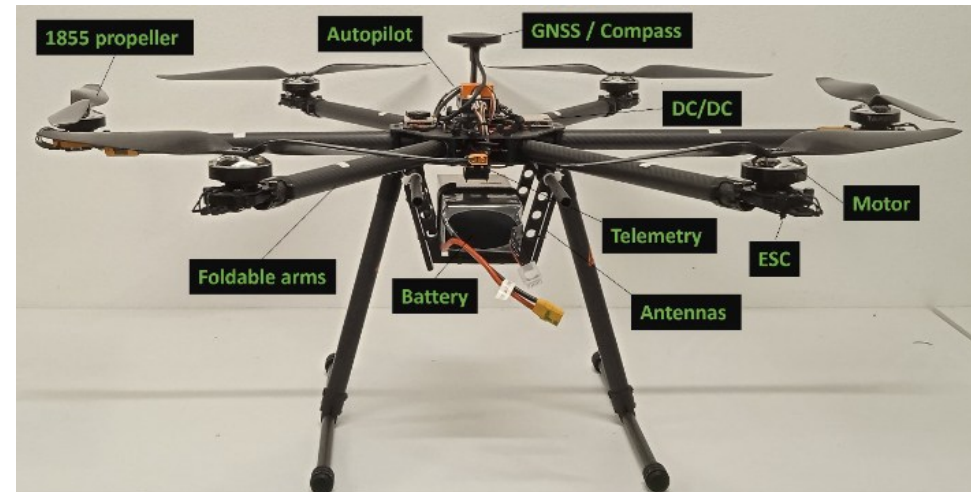


- Use a companion **drone** to aid the tractor featuring a similar device
- Vertical view may **resolve** some of the previous issues
- However, the drone must be engaged in a **smart** way
- **Only** if the tractor is not doing well and this is **expected** to continue “sufficiently long”

# The nodes



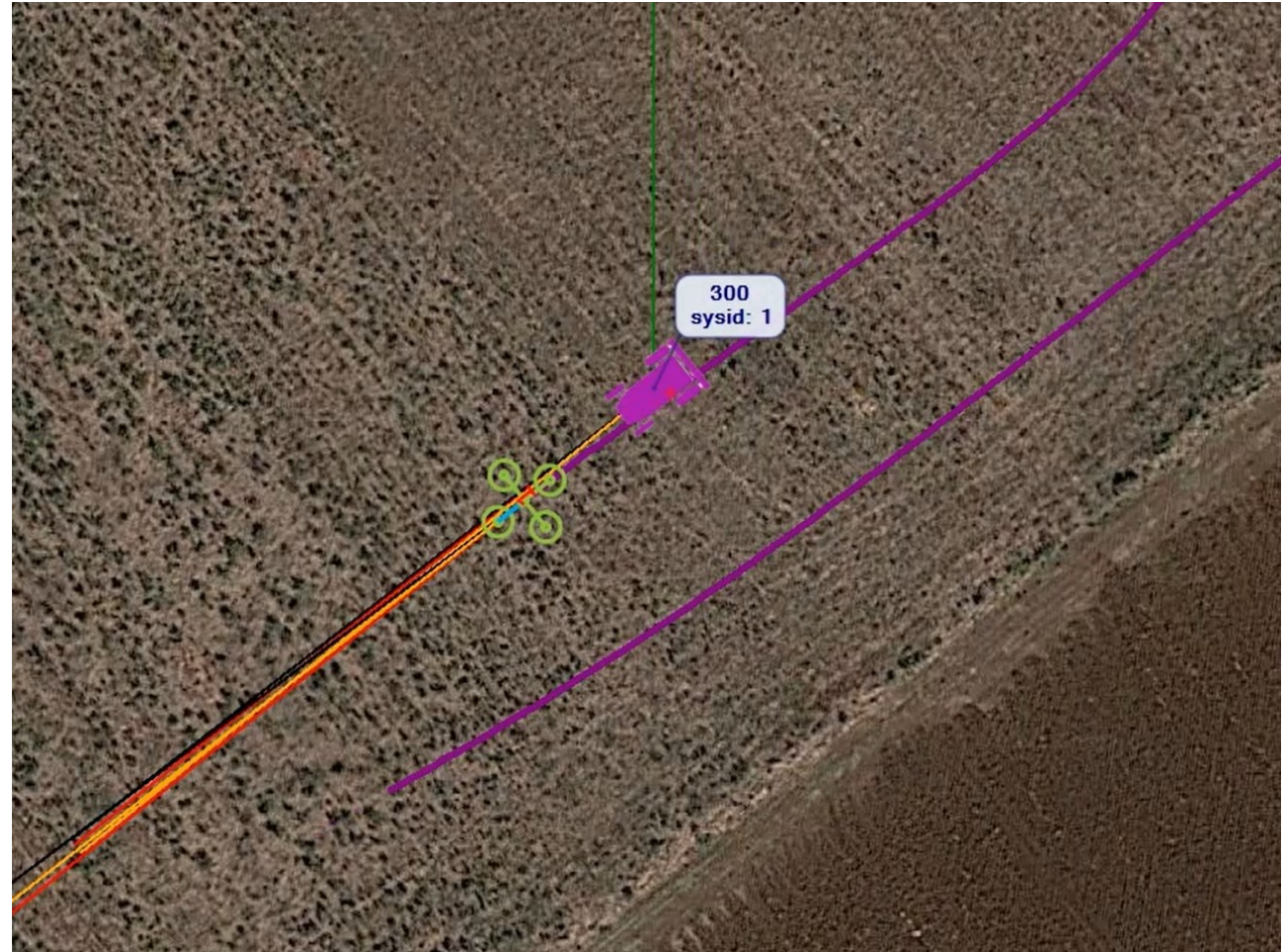
Tractor Node



Drone

# SITL tests

- Tractor and drone as **virtual** vehicles
- Each vehicle runs a separate SITL autopilot configuration
- Tractor starts scanning the field
- Drone is **engaged/disengaged** to start/stop following the tractor
- For testing purposes, drone (dis)engagement is triggered manually via suitable commands
- Ultimately, these decisions will be taken automatically via AI/ML





# Field tests

- Similar scenarios as in SITL tests
- Using a real tractor and drone
- Confirm basic drone operation without human intervention under real conditions
- Standalone and tandem operation of the image processing pipeline
- Collect real data for system and application performance



# Possible extensions/variations

- Same drone supports multiple tractors
  - in an alternating way



- Several drones used in parallel
  - each supporting a different tractor



- Several drones support a single tractor
  - in relay





# Wrap-up

# Summary

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## Motivation

- Use drones as **first-class resources** in next-generation applications

## Work presented

- **Automation** of the full operation cycle, including landing/housing/charging
- Flexible **application deployment/orchestration** in conjunction with the edge/cloud
- Manage, **check & enforce** flight and sensing/actuation **restrictions**

## Testing, testing, testing

- Field tests with drones are very **time-consuming**
- **Multi-drone** tests are an even bigger challenge
- Using a suitable **SITL/HITL environment** is of key importance

# Further directions

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## Hangars as a **shared** resource

- Suitable planning, scheduling, reservations, etc

## Drone **multi-tenancy**

- SW-wise not such a big issue
- Must support sharing also in the flight/mobility dimension
- Need appropriate conventions (e.g., driver-passenger relationship)

## Coordinated application deployment/execution on **multiple** vehicles

- Swarm-based applications (UAV + UAV + ... UAV)
- Heterogeneous unmanned systems (UAV + UGV, UAV + USV)

# Related publications

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- F. Pournaropoulos, A. Patras, C. D. Antonopoulos, N. Bellas, S. Lalis, “**Fluidity: Providing Flexible Deployment and Adaptation Policy Experimentation for Serverless and Distributed Applications Spanning Cloud–Edge–Mobile Environments**”, *Future Generation Computer Systems*, vol. 157, 2024.
- S.-F. Pournaropoulos, C. D. Antonopoulos and S. Lalis, “**Supporting the Adaptive Deployment of Modular Applications in Cloud-Edge-Mobile Systems**”, *International Conference on Embedded Wireless Systems and Networks (EWSN)*, September 2023.
- N. Grigoropoulos and S. Lalis, “**Fractus: Orchestration of Distributed Applications in the Drone-Edge-Cloud Continuum**”, *IEEE Computers, Software, and Applications Conference (COMPSAC)*, June 2022.
- M. Koutsoubelias, N. Grigoropoulos, G. Polychronis, G. Badakis and S. Lalis, “**System Architecture for Autonomous Drone-based Remote Sensing**”, *International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services (Mobiquitous)*, November 2021.
- G. Badakis, M. Koutsoubelias and S. Lalis, “**Robust Precision Landing for Autonomous Drones Combining Vision-based and Infrared Sensors**”, *IEEE Sensors Applications Symposium (SAS)*, August 2021.
- N. Grigoropoulos and S. Lalis, “**Simulation and Digital Twin Support for Managed Drone Applications**”, *IEEE/ACM International Symposium on Distributed Simulation and Real Time Applications (DS-RT)*, September 2020.
- N. Grigoropoulos and S. Lalis, “**Flexible Deployment and Enforcement of Flight and Privacy Restrictions for Drone Applications**”, *International Workshop on Safety and Security of Intelligent Vehicles (SSIV), IEEE/IFIP International Conference on Dependable Systems and Networks (DSN)*, June 2020.

# Publications on planning/scheduling & FT

- G. Polychronis, M. Koutsoubelias, and S. Lalis, “***Should I Stay or Should I Go: A Learning Approach for Drone-based Sensing Applications***”, *Workshop on Wireless Sensors & Drones in IoT (Wi-DroIT), International Conference on Distributed Computing in Smart Systems and the Internet of Things (DCOSS-IoT)*, April 2024.
- G. Polychronis and S. Lalis, “***Flexible Computation Offloading at the Edge for Autonomous Drones with Uncertain Flight Times***”, *International Conference on Distributed Computing in Smart Systems and the Internet of Things (DCOSS-IoT)*, June 2023.
- G. Polychronis and S. Lalis, “***Joint Edge Resource Allocation and Path Planning for Drones with Energy Constraints***”, *International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services (Mobiquitous)*, November 2022.
- G. Polychronis and S. Lalis, “***Planning Computation Offloading on Shared Edge Infrastructure for Multiple Drones***”, *International Workshop on Wireless Sensor, Robot and UAV Networks (WiSARN), IEEE International Conference on Distributed Computing Systems (ICDCS)*, July 2022.
- G. Polychronis and S. Lalis, “***Safe Optimistic Path Planning for Autonomous Drones under Dynamic Energy Costs***”, *IEEE International Conference on Intelligent Transportation Systems (ITSC)*, September 2021.
- T. Kasidakis, G. Polychronis, M. Koutsoubelias and S. Lalis, “***Reducing the Mission Time of Drone Applications through Location-Aware Edge Computing***”, *IEEE International Conference on Fog and Edge Computing (ICFEC)*, May 2021.
- N. Grigoropoulos, M. Koutsoubelias and S. Lalis, “***Byzantine Fault Tolerance for Centrally Coordinated Missions with Unmanned Vehicles***”, *ACM International Conference on Computing Frontiers (CF)*, May 2020.
- N. Grigoropoulos, M. Koutsoubelias and S. Lalis, “***Active Replication for Centrally Coordinated Teams of Autonomous Vehicles***”, *IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS)*, June 2019.

# Pointers

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<https://csl.e-ce.uth.gr/>



<https://mlsysops.eu>



<https://exeliigence.tech/>

**Feel free to ping  
for more info!**

**lalis@uth.gr**