

An Edge-Enabled Smart Livestock Monitoring Framework in Mountainous Crete: The AGRARIAN Approach

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Abstract

We describe a livestock monitoring platform deployed in Western Crete, where approximately 200 sheep and goats range over steep terrain with unreliable cellular coverage. The platform has three computing layers (edge, fog, cloud) orchestrated by K3s, a lightweight Kubernetes distribution. Sensing relies on a DJI Mavic 3M drone for aerial video and a network of IoT weather stations for ground-level environmental data. A hybrid communication subsystem combines terrestrial 5G with satellite links and switches between them when signal quality drops. The farmer accesses the system through an Agricultural Decision Support System (ADSS), which aggregates sensor readings, AI-generated alerts, and satellite-derived indices into pilot-specific dashboards. Six test scenarios validate the chain from aerial capture to mobile alert delivery. A KPI framework ties fifteen technical measurements to five governance outcomes, including herd safety, infrastructure resilience, and farmer autonomy. The work was conducted under the AGRARIAN project (EU Horizon Europe).

Keywords: smart agriculture, livestock monitoring, edge computing, UAV, satellite IoT, hybrid communications, Kubernetes.

Introduction

Crete supports more than 500,000 sheep and goats, a large share of which are managed by small livestock operators under extensive grazing practices [1]. In mountainous parts of the island, herds move across steep communal pastureland, fragmented access routes, and areas with weak or absent terrestrial connectivity. Under these conditions, routine supervision still depends heavily on physical inspection by the herd owner. This mode of operation is labor-intensive, spatially inefficient, and inherently discontinuous. As a result, hazardous events such as animal dispersion, proximity to roads or cliff-like terrain, and delayed recognition of abnormal movement or possible health-related behaviour are often detected only after the risk has already materialised [2], [3]. The problem is therefore not only one of sensing, but of timely situational awareness in geographically and digitally constrained environments.

A wide range of enabling technologies already exists in isolation. UAV platforms can survey large and inaccessible grazing areas far faster than on-foot inspection and can provide imagery suitable for detection, counting, and behaviour analysis [4]. Edge computing enables low-latency processing close to the point of data acquisition, reducing dependence on distant cloud resources and supporting time-sensitive inference workflows [5], [6]. IoT devices extend environmental observability through local measurements and contextual sensing [5]. At the network level, non-terrestrial connectivity can complement terrestrial infrastructure in coverage-limited rural regions, offering an alternative path for data delivery when conventional mobile links degrade or fail [7]. However, the central challenge in real livestock operations is not the availability of these components individually, but their reliable integration into a single operational chain. Heterogeneous data streams, intermittent connectivity, constrained edge resources, and the need for application portability across distributed nodes create a systems-

integration problem that remains insufficiently addressed in most field-oriented smart livestock studies.

The AGRARIAN project addresses this gap by treating livestock monitoring as a distributed, edge-enabled service rather than as a standalone sensing task. Within the Greek pilot, deployed in Western Crete, the objective is to connect aerial sensing, ground-level data acquisition, hybrid terrestrial-satellite communications, distributed processing, and user-facing decision support into one coherent platform. In practical terms, this means that drone-acquired data from real grazing operations are not simply stored offline for later analysis, but are transmitted through a hybrid communication layer, processed by containerized services across edge, fog, and cloud resources, and exposed to the end user through an Agricultural Decision Support System (ADSS). The significance of this architecture lies in operational continuity: the platform is designed to remain functional under field conditions where connectivity is unstable, computational resources are unevenly distributed, and actionable outputs must still reach the herd owner with sufficient timeliness to support intervention [8], [9], [10].

This paper presents the Greek livestock pilot as a concrete implementation of that architecture. It focuses on four tightly coupled components. First, it describes the distributed computing backbone based on K3s, used to orchestrate containerized services across resource-constrained and heterogeneous infrastructure layers [11], [12]. Second, it details the sensing subsystem, which combines UAV-based observation with complementary in-situ and satellite-enabled data pathways. Third, it examines the hybrid communication layer through which terrestrial and non-terrestrial links are combined to maintain data transfer under low-connectivity conditions [7]. Fourth, it presents the ADSS layer through which alerts, processed outputs, and pilot-relevant insights are delivered to the user. Beyond describing the technical stack, the paper also proposes a KPI framework that links system-level measurements to governance-relevant outcomes such as herd safety, infrastructure resilience, operator autonomy, and practical field usability. This is important because the contribution of the work is not limited to demonstrating that individual components function, but to showing how an integrated digital chain for mountainous livestock monitoring can be structured, deployed, and evaluated under realistic operational constraints.

A companion paper [13] describes the AI methods, data collection protocol, danger detection pipeline, and health-monitoring design, the algorithm-level detail that the present integration-focused account does not develop. The present paper concentrates on the system integration: K3s orchestration, three-tier edge-fog-cloud architecture, hybrid terrestrial-satellite connectivity, ADSS implementation, and the KPI-to-governance framework. The two papers are designed to be read independently but derive from the same project.

Data and Method

Study area and pilot design

The pilot site is located in Western Crete (35.4°N, 23.9°E), near the town of Chania. Terrain is hilly to mountainous, with slopes frequently exceeding 30°. The Mediterranean Agronomic Institute of Chania (MAICh) operates the pilot. MAICh manages a test herd of approximately 200 sheep and goats on communal pastureland and has defined test corridors that cross public roads and steep drops, producing conditions representative of real herding operations.

The aerial sensor is a DJI Mavic 3M equipped with an RGB camera and a 4-band multispectral camera (red, green, red-edge, near-infrared). Flights are conducted at three altitudes: 15, 25, and 50 m. These altitudes were selected to test detection performance across scales. During each mission, video and telemetry data are transmitted through the hybrid communication subsystem for near real-time processing by containerized AI applications.

Distributed computing architecture

The AGRARIAN platform is structured into three infrastructure layers (Fig. 1). The cloud layer hosts high-capacity processing nodes, a centralised data store that underpins the ADSS, and three user-facing interfaces. A Grafana-based System Management Dashboard allows network operators to monitor cluster health, node availability, and per-pod resource consumption (CPU, memory). A Development Dashboard, implemented as a private GitHub repository with a CI/CD pipeline (GitHub Actions), automates testing, Docker image building, and publication to the container registry. A Customer Portal allows farmers to browse available applications, request deployments, and access running services. The fog layer sits between cloud and edge. It incorporates gateway nodes and satellite nodes that perform intermediate data processing closer to the point of acquisition. This layer is particularly relevant for the hybrid communication architecture, where satellite connectivity supplements or replaces terrestrial links. The edge layer consists of IoT devices deployed in the field: weather stations, soil sensors, and small processing units connected to actuators (e.g., irrigation controllers). These devices run lightweight containerized applications for data collection and basic local processing.

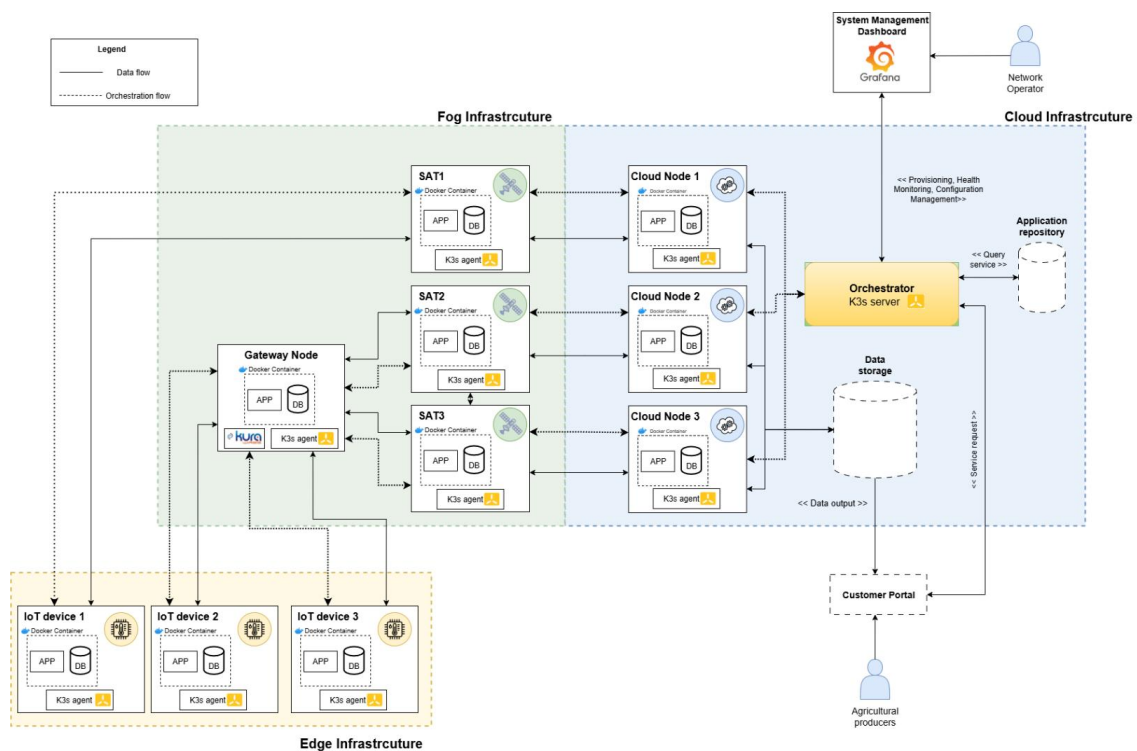


Fig. 1. AGRARIAN orchestration architecture: the K3s server distributes containerized applications across cloud, fog, and edge nodes.

Orchestration across all three layers is handled by K3s, a certified Kubernetes distribution designed for resource-constrained environments. K3s packages a full control plane into a binary under 100 MB and runs on hardware with as little as 512 MB of RAM, including ARM-based devices such as Raspberry Pi boards. Applications are packaged as Docker containers and stored in a private image registry hosted alongside the K3s server node. The registry uses the official Docker Registry 2 (lightweight HTTP API v2 image).

The Customer Portal communicates with the orchestration layer through a dedicated REST API (Fig. 2). When a farmer selects an application, the system checks whether it is already running. If so, the API returns the application's endpoint. If not, the API queries the image registry, retrieves the corresponding Docker image, and sends deployment instructions to the

K3s server, which places the container on the appropriate node based on metadata embedded in the image manifest. The API also handles user registration, authentication, and application discovery with filtering by testbed.

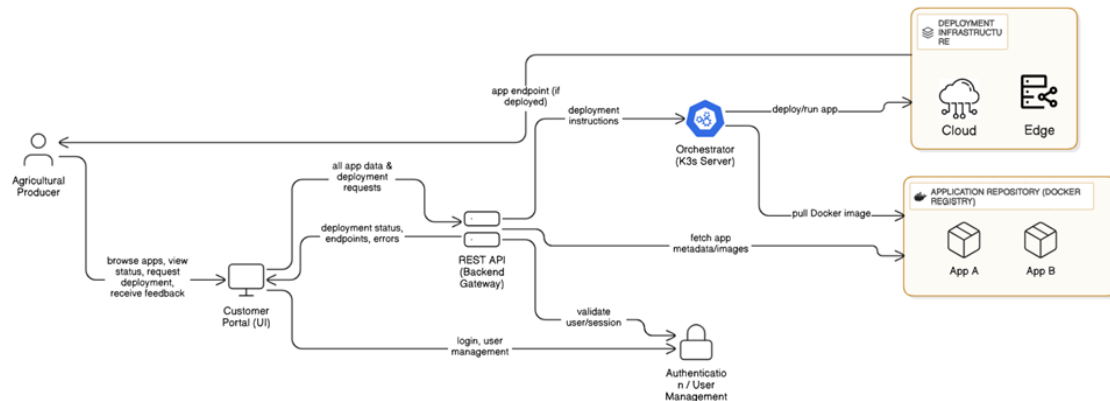


Fig. 2. Customer Portal and REST API workflow: application discovery, on-demand deployment, and user access.

In-situ IoT network

Within the Romanian pilot (Pilot 2), the Forum of Professional Farmers and Processors of Romania (FAPPR) has deployed 10 smart weather stations across 10 farms in the Bărăgan Plain, one of the country's most productive agricultural regions. Each station is equipped with a rain gauge, an air temperature and relative humidity sensor, and a soil temperature and moisture sensor.

From these raw measurements, the system derives four virtual indicators through data processing algorithms: leaf wetness (relevant for disease risk), vapour pressure deficit or VPD (indicator of plant transpiration stress), Delta T (evaporative demand, used to optimise spraying), and dew point (condensation threshold, relevant to disease onset prediction). Data collected in situ are transmitted via IoT protocols to a central server, where they are aggregated, stored, and made available through the ADSS dashboards.

Satellite observation and edge AI

Satellite imagery provides large-area coverage that ground sensors and drones cannot match: vegetation indices, soil moisture estimates, and crop health indicators at field scale. Within AGRARIAN, satellite data are augmented by on-board AI processing. Ubotica's CogniSAT-XE2 module, built around the Intel Movidius Myriad X processor, runs inference directly on CubeSat platforms (Fig. 3). Raw imagery is reduced to compact result packets before downlink, which lowers both bandwidth requirements and delivery latency.

These CubeSat AI nodes are integrated into the same K3s orchestration framework used on the ground. Developers build containerized satellite applications and deploy them through the AGRARIAN platform in the same manner as edge or cloud workloads. Communication between the CubeSat and the orchestrator uses gRPC for task deployment and module management.

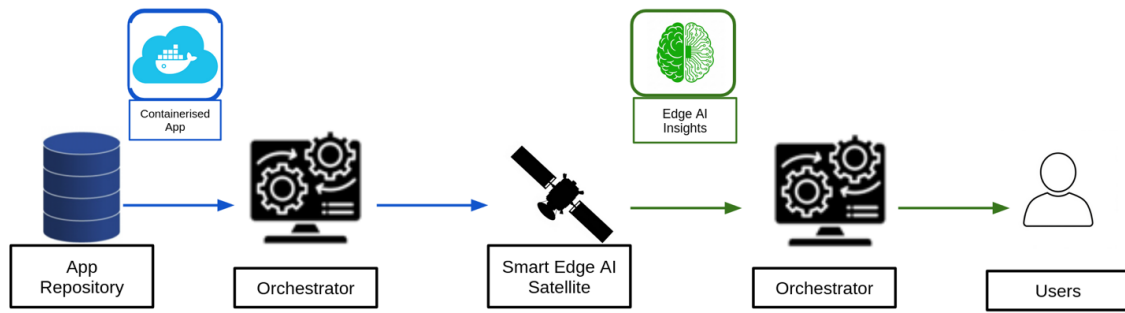


Fig. 3. In-space IoT network: CubeSat edge AI compute nodes within the AGRARIAN orchestration.

Hybrid communication infrastructure

Terrestrial cellular coverage across the pilot area in Western Crete is intermittent. The platform addresses this with a hybrid communication layer that combines 5G terrestrial links with satellite connectivity and performs automatic handover when signal quality degrades (Fig. 4). Three testbeds implement the hybrid layer.

The NCSR D testbed pairs a real 5G base station with an emulated GEO satellite link. The hybrid communication node is deployed as a K3s worker node, so the orchestrator can place containerized applications directly at the network edge. At the Greek pilot site, this node is installed at a field command point with local power and physical security. During drone flights, the MAICH team records throughput, latency, and handover events along the planned flight corridor and tags each measurement with the corresponding mission identifier [9].

The DLR testbed emulates a LEO satellite constellation at a configurable altitude between 500 and 1200 km. Data from agricultural applications enter the testbed through IP-based interfaces and traverse the emulated satellite network. A K3s agent embedded in the testbed communicates with the remote K3s server, linking the testbed to the wider orchestration framework.

The Sateliot testbed emulates a 5G Non-Terrestrial Network (NTN) based on 3GPP Release 17 standards. It supports workload placement at three points: on the device edge for immediate sensor processing, on the satellite for in-orbit inference, and in the cloud for computation-heavy tasks. Integration with the Ubotica AI module creates a dual-mission payload that handles both Earth observation imagery and IoT sensor data in orbit.

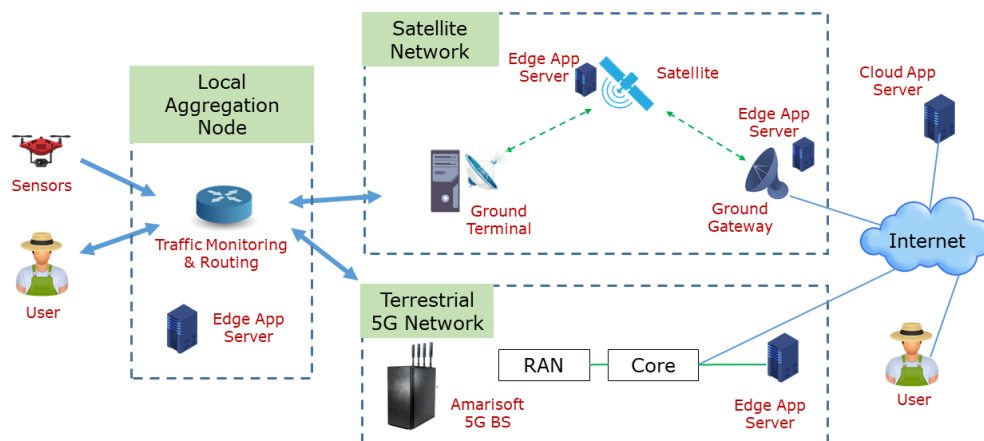


Fig. 4. Hybrid 5G and satellite communication architecture with automatic handover.

Agricultural Decision Support System

The ADSS is the interface through which farmers, communities, and local authorities interact with the platform. It retrieves pre-processed data from multiple backend databases (sensor readings, weather forecasts, AI-generated alerts, satellite-derived indices) through a REST service and presents them in pilot-specific dashboards (Fig. 5). The backend uses a standardised data ingestion layer that harmonises formats across all three pilots.

Each pilot deployment has its own dashboard. The Greek dashboard displays livestock alerts, animal counts, danger-proximity warnings, and connectivity status. The Romanian dashboard shows soil conditions and weather data from the 10 weather stations. The Spanish dashboard presents vineyard yield forecasts, disease stress indicators, and soil moisture maps. The platform also generates automated recommendations based on contextual analysis and integrated predictive models. Access control is managed through Keycloak, with role-based permissions that separate farmer, operator, and developer views.

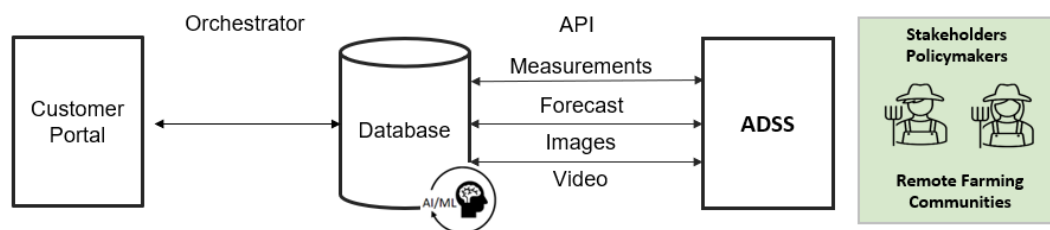


Fig. 5. ADSS architecture: data ingestion, backend services, and pilot-specific dashboard interfaces.

Results

Test scenarios

The livestock pilot is validated through six test cases that span the full data chain from sensing to user notification.

TC001 (Autonomous mission execution) verifies that the drone can fly a pre-planned route safely and repeatedly at 15, 25, and 50 m. The camera is set to nadir, illumination is restricted to late morning through early afternoon, and the drone repositions slightly every minute to increase spatial variability in the captured imagery.

TC002 (Detection and counting) tests accuracy across three scene compositions: mostly sheep, mostly goats, and mixed. Scenes are divided 75/25 between static and moving animals (the latter herder-assisted in spring). Frame sampling is set at 3 s for static scenes and 1.5 s for moving scenes.

TC003 (Danger-proximity alerts) validates timely, geo-referenced alerts near hazards. Road and vehicle cues are extracted from video; slope buffers are computed from a Digital Elevation Model.

TC004 (Hybrid connectivity) forces a satellite fallback by degrading the terrestrial signal and verifies that video, telemetry, and alert streams continue without interruption.

TC005 (Real-time notification) confirms that alerts reach the farmer's mobile device with GPS coordinates and an evidence frame, and that acknowledgements are logged in the platform.

TC006 (Dataset pipeline) validates the end-to-end path from field capture to curated, annotated frames with complete metadata (altitude, timestamp, subject class, motion status, GPS location), intended for AI model training.

KPI framework and governance outcomes

Each test case feeds into one or more Key Performance Indicators. The KPIs in turn map to five governance outcomes through attribution scores ranging from 1 (indirect link) to 3 (strong, direct link). A Key Value Indicator (KVI) for each outcome is computed as the weighted average of its linked KPI measurements relative to their targets (Table 1).

Table 1. KPI-to-governance outcome mapping for the Greek livestock pilot.

Governance outcome	Linked KPIs	Attribution (1–3)	Target
GO1. Herd safety	KPI 1.1 Detection accuracy	3, 3, 3	F1 $\geq$ 0.91 MAE < 0.8/frame
	KPI 1.2 Counting MAE		
	KPI 1.3 Hazard alert precision/recall		
GO2. Infrastructure resilience	KPI 2.1 Uplink throughput	3, 2, 3	$\geq$ 150 Mbps
	KPI 2.2 Satellite fallback rate		$\geq$ 85 % fallback
	KPI 2.3 Connectivity uptime		97.5 % uptime
GO3. Farmer responsiveness	KPI 3.1 Alert latency	3, 3, 2	Median 2.8 s
	KPI 3.2 Delivery success		94 % delivery
	KPI 3.3 Acknowledgment rate		80 % ack
GO4. Data reproducibility	KPI 4.1 Dataset volume	2, 3, 3	$\geq$ 4 datasets
	KPI 4.2 Metadata completeness		98 % metadata
	KPI 4.3 Flight datasets ($\geq$ 4)		
GO5. Farmer empowerment	KPI 5.1 Operator autonomy	3, 3, 2	72 % autonomous
	KPI 5.2 Greek UI coverage		100 % Greek
	KPI 5.3 Usability (SUS)		SUS $\geq$ 80

The 150 Mbps uplink target derives from the requirement for near real-time 4K video streaming. The Greek-language UI target reflects the fact that the herd owner does not read English. The System Usability Scale (SUS) target of 80 corresponds to an adjective rating of “good”.

It is important to distinguish between KPI targets (design-time specifications, reported in Table 1) and KPI measurements (field-collected values). The measurement campaign is ongoing, and measured values for detection accuracy, latency distributions under hybrid connectivity, and operator autonomy will be reported after completion of the simultaneous-testbed validation phase. The latency measurement protocol has been defined: during each flight, the hybrid communication node records per-packet round-trip times tagged with the active link (5G or satellite), and the system logs the interval from alert generation to delivery confirmation on the farmer’s mobile device. These data will allow the construction of latency distributions stratified by connectivity mode, which directly inform the KPI 3.1 (alert latency) and KPI 3.2 (delivery success) targets reported in Table 1.

Target data flow

The intended operational data flow proceeds through six stages. (1) The drone captures video and flight telemetry over designated grazing areas. (2) The hybrid communication node relays the data, falling back to the satellite link when terrestrial signal quality drops below threshold. (3) The platform’s ingestion layer receives and time-aligns the video and telemetry streams. (4) Containerized AI services perform livestock detection, counting, and danger assessment, producing annotated video and structured alerts in msgpack format (fields: frame ID, alert text, timestamp, image dimensions, compression flag, evidence frame bytes). (5) Dashboards and the mobile application present alerts with GPS coordinates and evidence frames; user

acknowledgements and comments are recorded. (6) Raw and derived data are stored with full metadata for model retraining and pilot evaluation.

Conclusion

This paper has presented the AGRARIAN Greek pilot as an integrated edge-enabled framework for livestock monitoring in the mountainous terrain of Crete. Its main contribution is not the use of drones, sensors, or satellite links in isolation, but their orchestration into a single operational chain that couples field sensing, distributed processing, hybrid connectivity, and user-facing decision support. Within this architecture, K3s provides a lightweight but fully Kubernetes-compatible orchestration layer, enabling deployment across edge, fog, and cloud resources without sacrificing portability or extensibility. In parallel, the coexistence of the NCSRD, DLR, and Sateliot communication testbeds establishes the basis for resilient service continuity under connectivity degradation, which is a central requirement in remote grazing environments.

A second contribution of the work is methodological. The proposed KPI framework does not evaluate the platform only at the level of technical performance, but explicitly links fifteen measurable indicators to five governance-oriented outcomes. This creates a transparent chain from system behaviour to operational relevance: detection quality informs herd safety, connectivity metrics inform infrastructure resilience, notification performance informs farmer responsiveness, dataset quality informs reproducibility, and autonomy/usability metrics inform farmer empowerment. Such a structure is important because it allows the pilot to be assessed not merely as a technology demonstrator, but as a digital intervention whose field value can be traced, quantified, and critically examined. Equally important, the same framework makes deficiencies visible. When a KPI underperforms, the affected governance outcome and the responsible test scenario can be identified directly, which supports iterative refinement rather than one-off validation.

At the same time, the present work should be read with clear boundaries. The platform architecture and validation workflow are in place, but full simultaneous field operation of all communication testbeds has not yet been completed. The herd owner has not yet executed missions independently, meaning that the autonomy and empowerment dimensions remain only partially validated at this stage. Simultaneous field operation of the NCSRD, DLR, and Sateliot testbeds is scheduled, at which point throughput, latency, and handover metrics under realistic field conditions will be measured concurrently across all three communication paths. Operator autonomy trials, in which the herd owner executes missions independently over a full grazing season, are planned for the second field campaign and are contingent on herder availability and drone certification completion. In addition, although the architecture is designed to support third-party applications through the AGRARIAN open-call mechanism, this integration pathway has not yet been exercised with external developers under real pilot conditions. These limitations do not weaken the architectural contribution; rather, they define the next validation steps required to move from system readiness to robust operational evidence.

These planned activities are not speculative. The testbed hardware is deployed, the communication nodes are integrated as K3s worker nodes, and the measurement protocols have been defined. The remaining work is a scheduling and execution challenge rather than a design gap. We report the current validation status candidly because the distinction between architectural readiness and field-verified performance is central to how this work should be evaluated.

The AGRARIAN Greek pilot shows that livestock monitoring in rugged, connectivity-constrained environments can be framed as a distributed systems problem and addressed through a modular, edge-to-cloud architecture with hybrid terrestrial-satellite support. Beyond the specific case of Crete, the significance of the approach lies in its transferability. The same architectural logic, with pilot-specific sensing and analytics layers, can be adapted to the Romanian and Spanish AGRARIAN scenarios and, more broadly, to other remote agricultural settings where resilience, low-latency decision support, and interoperability are more critical than raw computational scale alone.

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