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Gas transmission asset resilience through network transitions

Autonomous Intelligent Asset Surveillance System (AIASM)

End-Point Monitoring Meeting

10th September 2025

Agenda

Agenda item	Presenter
Welcome and Introductions	NGT
Project Overview Recap	NGT
Discovery Key Findings & Lesson Learnt	Digital Catapult
Summary of Work Packages	Digital Catapult
Barriers, Risks and Issues Encountered	Digital Catapult
Project Plan & Finance Update	NGT
Project Specific Conditions	NGT
Comms And Engagement Plan	NGT
Alpha Plan	NGT

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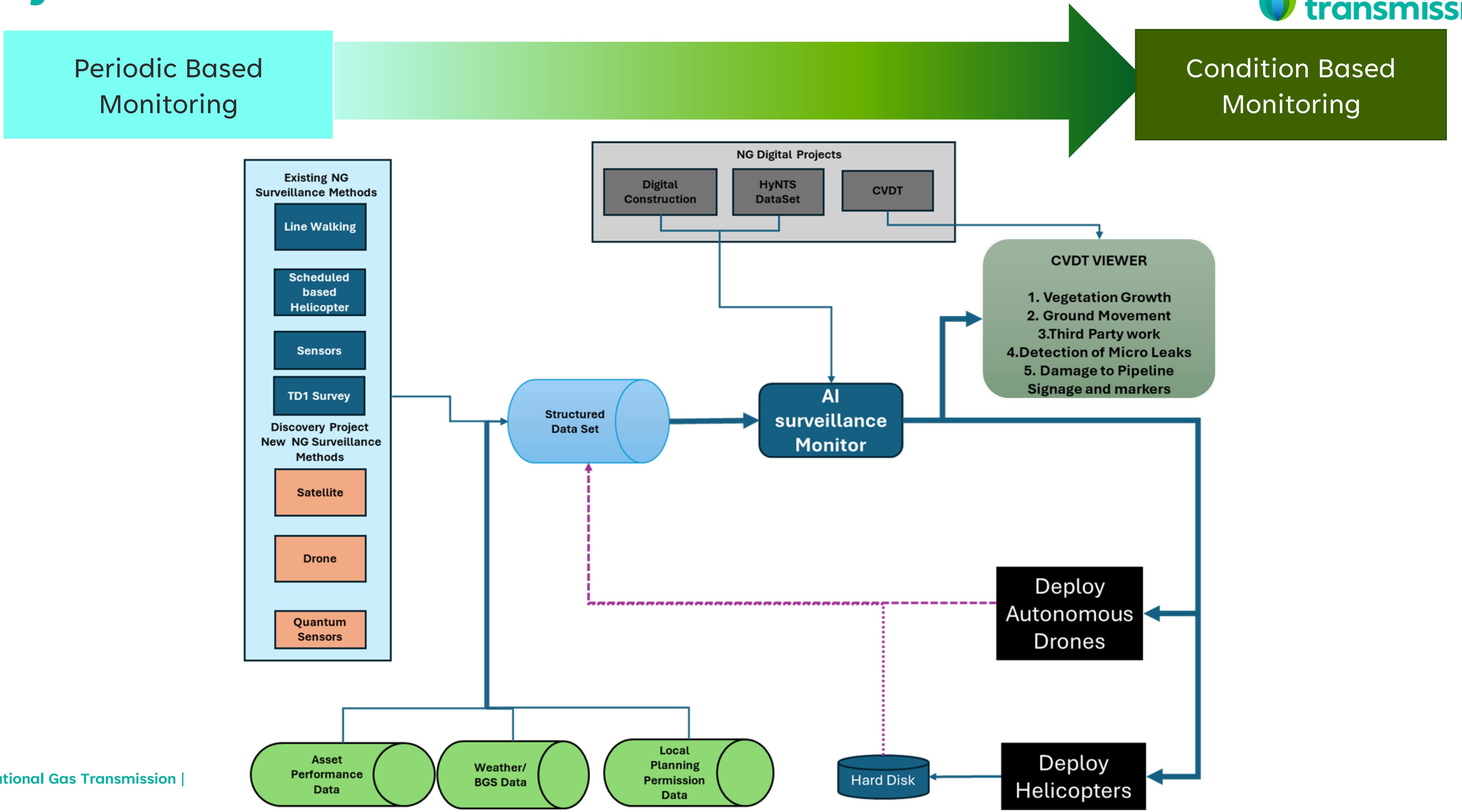
Project Overview



Project Outputs and lessons learnt

Project Outputs

WP 1	• Defined project scope, success criteria, and stakeholder roles. • Conducted structured workshops to gather business needs, operational challenges, and surveillance goals. • Established alignment between National Gas, Digital Catapult, and Satellite Applications Catapult.
WP 2	• Mapped existing systems, data sources, and integration points. • Identified gaps in data architecture, storage, and processing capabilities. • Documented AS-IS architecture and operational workflows.
WP 3	• Evaluated feasibility of various surveillance technologies. • Designed AI surveillance system with data pipelines, alerts, viewer integration, cybersecurity, and compliance. • Created workflows for vegetation monitoring and detecting external interference.
WP 4	• Recommended modular, scalable architecture with edge AI for remote deployments. • Outlined vendor engagement strategy and data governance principles. • Prepared for Alpha phase proposal and stakeholder workshop

Lessons Learnt

WP 1	• Early stakeholder engagement is critical for surfacing hidden operational inefficiencies. • Multidisciplinary workshops enabled a shared understanding of surveillance gaps and future needs. • Clear scoping helped avoid misalignment in later phases
WP 2	• Surveillance operations are reactive and fragmented, with duplicated reporting and manual data handling. • Lack of standardised data formats and integration APIs hinders automation. • Existing systems require better interoperability for AI readiness.
WP 3	• Satellite EO allows scalable monitoring but is expensive and weather-sensitive. • Hydrogen drones provide long flight times but require infrastructure. • Security and data sovereignty are critical for infrastructure monitoring—UK-based storage preferred
WP 4	• AI models need customization and robust data pipelines with MLOps support..

Work Package Update

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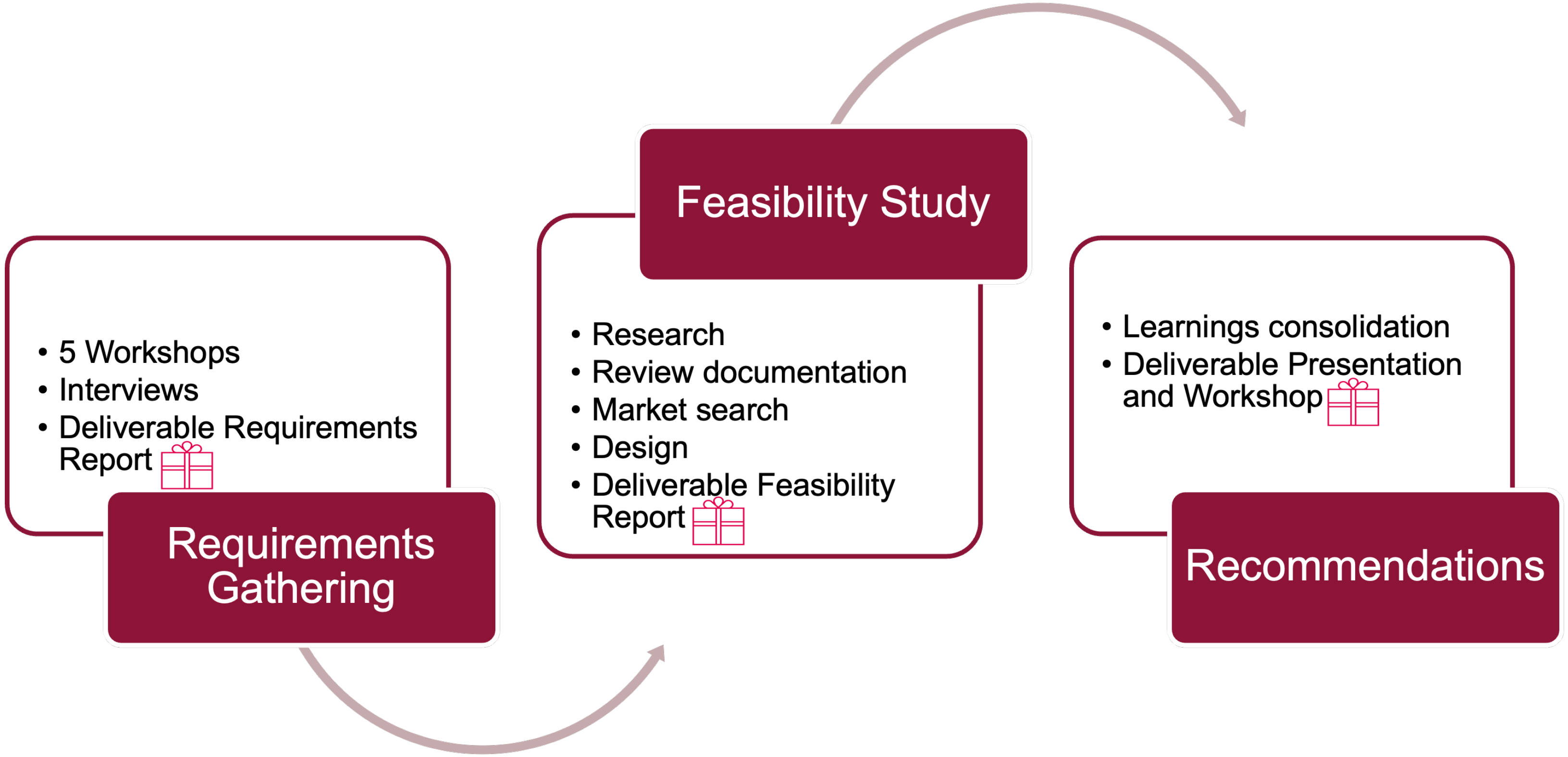
Activities and Deliverables in a Nutshell

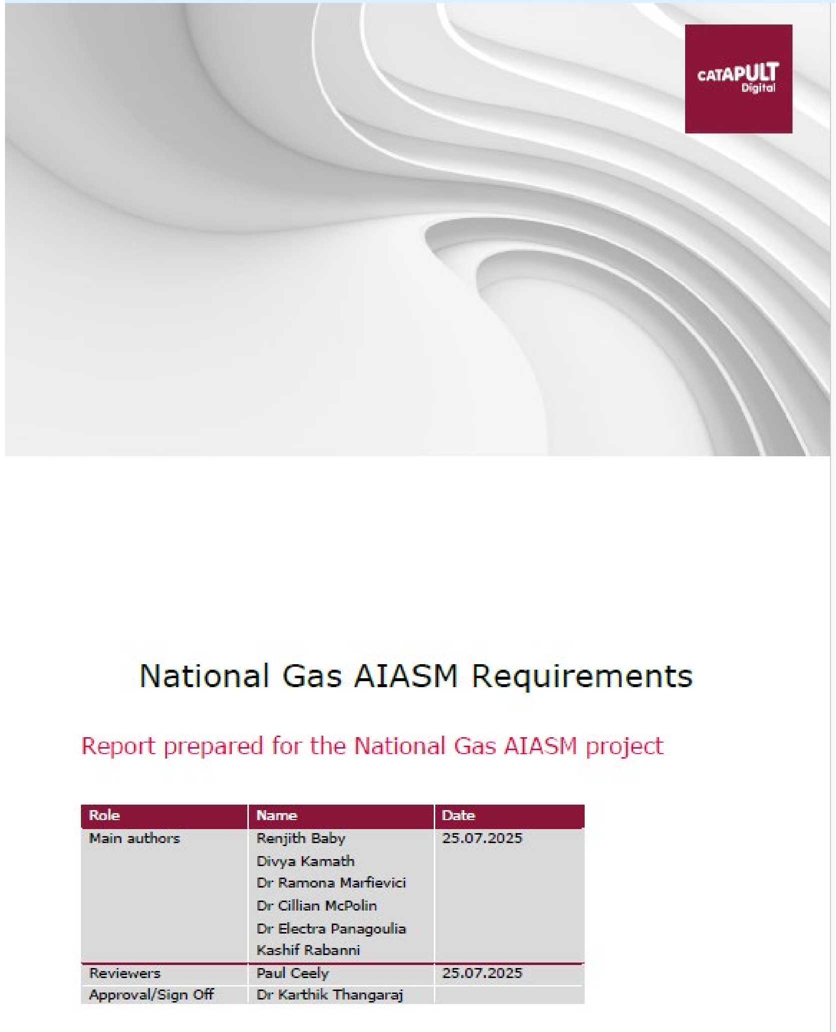


WP1: Assessment Scoping and Planning

Workshops		Desired participants	Desired outcomes
01	Discovery of business needs at National Gas Solutions sought Business goals (Including RIIO, ED2 plans)	• Asset Management • Data & digitalization • Strategy/Innovation	• Understand the key operational, regulatory, and financial challenges managing assets, infrastructure • Understand the immediate, long term business needs, performance targets and investment strategies
02	Discovery of existing systems, network, asset data, and visualisation	• Asset Management • Data & digitalisation	• Develop clear understanding of systems in use, existing data practices- data accessibility, data management, decision making process • Assess the current AI readiness
03	Understanding of communication needs, environmental conditions, availability of power, network infrastructure, devices and operational costs (at high level)	• Asset management • Data & digitalisation • Network operations team • IT infrastructure management	• Have a clear understanding of high-level network coverage and availability alongside any environmental constrains • Covering security, integration, and compliance issues
04	Discovery of critical, non-critical applications day to activity with field operations, emergency or incident response team	• Field operations & emergency response services • Network operations team	• Map how best technologies should be utilized and how does the digitalisation stack should align
05	Current Practice and change management framework – Gap analysis Reporting, data & information systems	• IT infrastructure management • Data & digitalisation	• Comprehensive assessment of existing data and digitalisation: evaluating readiness for change management

WP1: Assessment Scoping and Planning

Requirements Gathering Report



CATAPULT Digital

National Gas AIASM Requirements

Report prepared for the National Gas AIASM project

Role	Name	Date
Main authors	Renjith Baby Divya Kamath Dr Ramona Marfievici Dr Cillian McPolin Dr Electra Panagoulia Kashif Rabanni	25.07.2025
Reviewers	Paul Ceely	25.07.2025
Approval/Sign Off	Dr Karthik Thangaraj	

Workshops and Interviews

- Methodology
- Findings

Technical Requirements

- General
- Infrastructure and Assets
- Surveillance
- Data Pipeline
- Integration
- Regulation and Security

Workshop and Interview Questions

- Business Context & Challenges
- Infrastructure & Monitoring
- System and Architecture AS-IS
- Data Management and APIS
- Security & Compliance
- Technical Requirements & Constraints
- AI & Automation
- Surveillance Methods & Operations
- Condition-based Monitoring & Alerts
- Business Models
- Integration

WP2: AI Surveillance Platform Assessment

Activities

- High level systems AS-IS diagnosis
- Understand current data architecture, map existing data sources, and identify gaps

Outputs

- Mapped existing systems, data sources, and integration points
- Identified gaps in data architecture, storage, and processing capabilities
- Documented AS-IS architecture and operational workflows.

Requirement code	Requirement description
BR1.1	Identify NG requirements, understand current data architectures, map existing data sources, identify gaps.
BR1.2	Assess feasibility of new surveillance technologies.
BR1.3	Review commercially available solutions on the market.
BR1.4	Explore where AI models could be used for autonomous surveillance.
BR1.5	Cyber, regulatory, and integration requirements for autonomous surveillance using AI models.

High level requirements

WP3: Technical Validation

Activities

- Assess feasibility of new surveillance technologies: satellite, drones, quantum and photonic sensing
- Market review
- Explore where AI models could be used to detect vegetation changes and third-party interference
- Design AI data pipeline architecture

Outputs

- Technical Report
  - Surveillance and monitoring technologies
  - Data pipeline architecture with services
  - AI-based workflows
  - Recommendations for technologies and services

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WP3: Technical Validation

Feasibility Study Report

National Gas AIASM – Feasibility Study

Report prepared for the National Gas AIASM project

August 2025
Version 1.0

Role	Name	Date
Main authors	Renjith Baby Divya Kamath Dr Ramona Marfievici Dr Cillian McPolin Dr Electra Panagoulia Kashif Rabanni	26.08.2025
Reviewers	Paul Ceely	28.08.2025
Approval/Sign Off	Dr Karthik Thangaraj	03.09.2025

Surveillance and Monitoring Technologies

- Satellite Earth Observations
- Drones
- Quantum & Photonic Sensing
- Fundamental Principles, Operational Characteristics, Data Formats and Outputs, Service Cost, Market Solutions, Secuity and Privacy
- Recommendations

AI-Based Surveillance Monitoring

- Data Pipelines Architecture
- Recommendations

AI-Based Workflows

- Vegetation Growth Detection
- Third-Party Interference

WP4: Roadmap & Recommendations

Activities

- Consolidate recommendations
- Workshop with National Gas stakeholders (in-person 08/09/2025 at National Gas office)

Outputs

- Recommendations Presentation

4.1 Data Pipelines Architecture

The proposed data integration framework is illustrated in Figure 6, which presents the conceptual architecture for integrating multiple data sources into the proposed AI monitoring system.

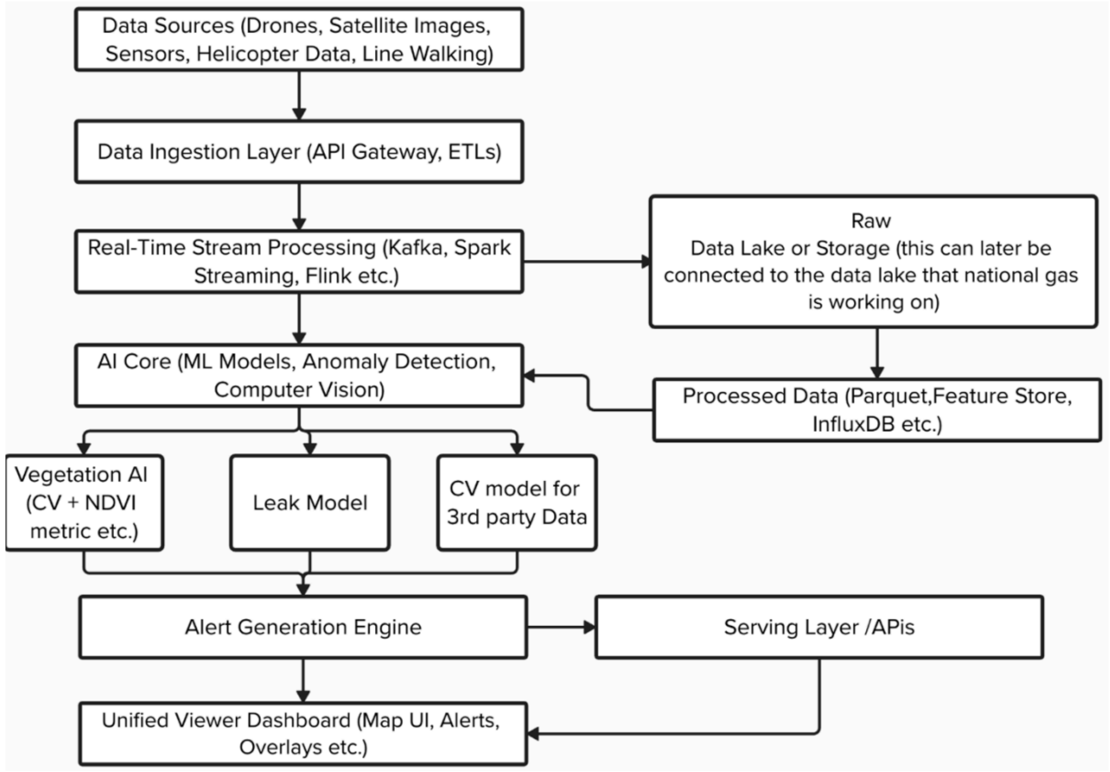

Figure 6. Data pipeline architecture for the AI-based surveillance monitor (Please note that examples provided are for understanding only and this may change in the future).

Risks, Achievements and Challenges (Digital Catapult)

Barriers, Risks and Issues Encountered

No	Risk	Probability	Impact	Mitigation
1	Risk that delayed access to required data and people with understanding of the data will impact timeline	Possible	Serious	We will engage with relevant stakeholders early in project to ensure data can be obtained in a timely manner and does not delay activities. We will leverage strong relationships with internal and external stakeholders to ensure to ensure information is obtained from a variety of sources. Finally, timelines will be shared with stakeholders for delivery to take place on time.
2	There is a risk that there is a lack of availability/capacity of National Gas internal subject matter experts to support	Possible	Serious	We will ensure milestone dates and deadlines are clear to all parties at the start of the project. We will provide continuous and consistent communication with key stakeholders to identify the best way to learn/gather the key information.
3	There is a risk that the short time frame for project means any delays will result in potential loss of value	Possible	Major	The project is structured in an agile approach ensuring that value is realised in short increments of activity. Weekly sprints can allow us to realise value early, continuously, and with quality assurance. Finally, we will be proactive on scope, deliverables and milestones review.

Please note that all mitigations were successful

Barriers, Risks and Issues Encountered

Technical

- There is a risk that the initial solution ideas and recommendations are unable to satisfy National Gas requirements.
- There is a risk that data that is necessary to streamline the user journey is locked in legacy systems and is disproportionately expensive to integrate or migrate to a new solution.

Managerial & Policy

- Challenges in implementing Drone in surveillance theme, CAA regulatory & framework ,BLOS, Data transmission, using drone in third party land.
- Cost challenges in embedding satellite applications.

Project Conditions

- Delays in providing obtaining feedback due to annual leave
- Risk that National Gas SME support is unavailable

Proposed Mitigation

- Adopt agile approach with short increments of work delivering solutions quickly and validating them through playbacks with key stakeholders.
- During the Discovery phase we will assess the feasibility of solutions as well as the usability.

- Work closely with Advisory group in alpha phase to understand the regulations challenges , find ways to mitigate it.
- Explore the cost-effective way of using satellite application , enable AI to make that decision.

- Agreed revised schedule for deliverables and adapted schedule accordingly
- We will provide continuous and consistent communication with key stakeholders to identify the best way to learn/gather the key information.

Project achievements and challenges

Key Successes

- **Multi-layer surveillance model established –** The study set out a clear framework combining satellites, drones, classical sensing, and emerging quantum sensing into a single, AI-driven surveillance architecture
- **Integration of cutting-edge technologies –** It successfully evaluated how diverse data sources (EO satellites, UAVs, fibre optics, and quantum sensors) can be integrated into one system, reducing dependence on helicopter patrol
- **AI-enabled monitoring and automation –** The report demonstrated how AI models can automate vegetation growth detection and third-party interference monitoring, improving operational efficiency and threat detection accuracy
- **Practical data pipeline design –** A data pipeline and architecture were proposed to ensure seamless ingestion, processing, and integration of both real-time and historical surveillance data
- **Enhanced safety and cost-effectiveness –** UAVs and remote sensing were shown to improve worker safety (by reducing hazardous inspections) and cut operational costs through earlier detection of issues
- **Clear strategic pathway –** The feasibility study not only provided technical evaluations but also developed **recommendations for implementation and next steps**, ensuring alignment with National Gas' operational needs

Key Challenges

- Access to data sources
- Working around multi stakeholder availability
- Multispectral EO imagery can be limited by cloud cover and adverse weather conditions, while hyperspectral imagery is still immature and expensive. This creates risks around consistent monitoring and potentially prohibitive costs if National Gas were to rely too heavily on commercial satellite data

Project Plan & Finance Update

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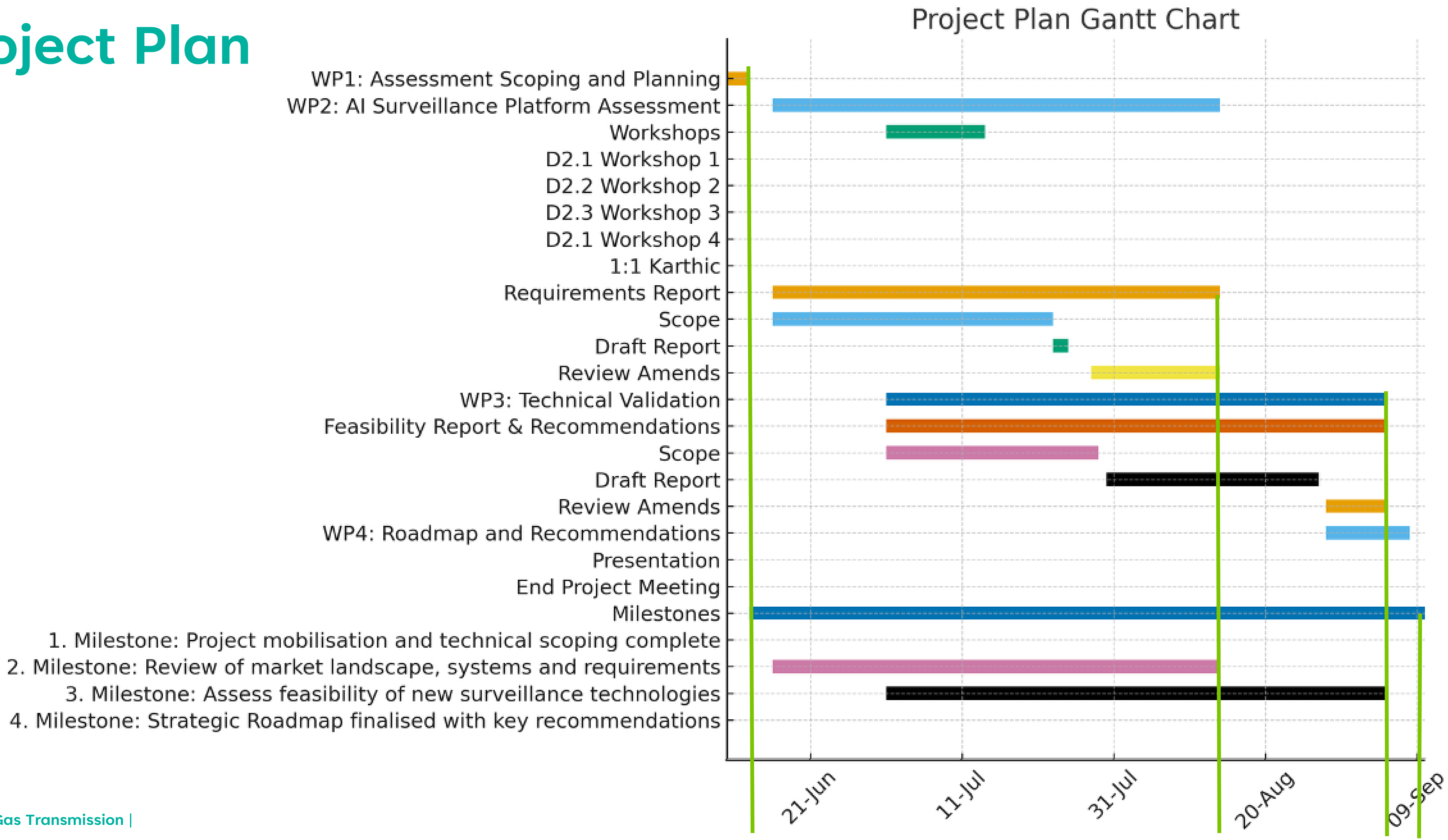
Project Plan



Finance Update

Description of deliverable	Due date	Responsible party	Forecast Cost	Actual date	Actual cost
M1 Assessment Scoping and Planning	31/08/2025	All Party	£ 41,548	31/08/2025	£ 35,051.23
M2 AI Surveillance Platform Assessment	31/08/2025	All Party	£ 19,704.60	31/08/2025	£ 19,704.60
M3 Technical Validation	31/08/2025	All Party	£ 23,579.80	31/08/2025	£ 23,579.80
M4 Roadmap and Recommendations	31/08/2025	All Party	£ 12,817.60	31/08/2025	£ 12,817.60

No changes to the **Project Plan and Project Outcomes**.

	Forecast			Actual		
	Milestone Total Costs	Legal	Total	Milestone Total costs	Legal	Total
Digital Catapult	£ 78,426	N/A	£ 78,426	£ 78,426	N/A	£ 78,426
NG Internal Total Cost	£ 16,524	£ 2,700	£ 19,224	£ 8,870.23	£ 3,857	£ 12,727.23
Total	£ 97,650.00	£ 2,700	£ 97,650	£ 87,296.23	£ 3,857	£ 91,153.23

Final cost – underspend of £6,496.77

Project Specific Conditions

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Project Specific Conditions

CONDITION 1

The Funding Party must not spend any SIF Funding until contracts are signed with the Project Partners named in Table 1 for the purpose of completing the Project.

STATUS CLOSED

CONDITION 2

The Funding Party must report on the financial contributions made to the Project as set out in its Application. Any financial contributions made over and above that stated in its Application should also be reported and included within the Project costs template.

STATUS CLOSED

CONDITION 3

The Funding Party must make reasonable endeavours to participate in all meetings related to the Project that they are invited to by Ofgem, UKRI and DESNZ during the Discovery Phase.

STATUS CLOSED

CONDITION 4

The Discovery phase will last for a period of up to five months from the date the Project Direction is issued; the Project will be allowed a flexible start date within the five-month period. The Project must provide the monitoring officer with the start date of the Project and must be completed before the end of the five-month period.

STATUS CLOSED

Comms and Engagement plans

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Comms and Engagement Plan

Workshop

In-person workshop with NG internal team to present the discovery phase finding

Scheduled 08/09/205

Show and Tell

Session to be organised by NG comms team , inviting wider audience .

Date TBC

Social Media

End of Project and Findings will be shared as a blog in LinkedIn.

STATUS TBC

Alpha Phase Preparation

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Work Package for Alpha

The project will be focussed around 5 work packages that will continue into Beta whilst developing our understanding in greater detail and eventually demonstrating this opportunity for the UK.

WP1 –Management of projects timelines, cost and risk aligned to UKRI requirements and determination of the Beta application activities

WP2- AIASM Requirements Definition

- Gather additional uses cases from stakeholders.
- Define requirements for the AIASM to be implemented in CIN's IT infrastructure.
- Review of commercially available surveillance methodologies.
- CBA for Beta application

WP3 - AIASM MVP Model Development for Third-Party Detection

- Develop and train MVP to detect third-party work near pipelines using multimodal data
- Deploy the MVP in a controlled environment and test real-time alerting capabilities.
- Propose ways to visualise the output in Digital twin viewer platform.

WP5 –Compliance, Security and Data Governance

- Ensure the MVP meets regulatory, cybersecurity, and data governance standards.
- Conduct cybersecurity assessment .
- Establish secure APIs for external data sources

WP 5- Stakeholder Engagement, Strategy & Implementation Planning
Detailed approach to deploy AIASM within UK/EU energy sector

Alpha Requirement: Additional partners

Project Scope	Alpha Project Partner Requirements	Possible Partner	Notes
Transition planning for an energy system with reducing natural gas demand	1. Energy network licensee in addition to the project lead. And	(TBC)	In discussion with GDN and National Grid
	2. A consumer representative group	Energy System Catapult (TBC)	Advisory: Regulations and Compliance in implementing surveillance measures, AI and Data Sharing (Ofgem's framework). Wider stakeholder engagement, potential with industry/government bodies (ex CAA).

APPENDIX

Satellite Integration

Table 1. Satellite imagery technologies: performance characteristics, applications, integrations requirements, regulatory and security considerations, and market solutions

Technology	Applications	Performance, advantages, limitations	Integration considerations	Regulatory and security considerations	Maturity of available systems on the market
Multispectral EO satellite imagery	Anomaly detection (e.g., vegetation discolouration), encroachment (e.g., from vegetation or buildings), change detection, environmental monitoring	Object and change detection on land and environmental monitoring are well-established use cases for multispectral satellite imagery. Thanks to the historical archive and future data availability, monitoring is possible over long time periods. Ground data/human expertise needed to correctly interpret satellite imagery. Cloud coverage limits data availability.	Satellite imagery can be quite big in size; if this is to be used in itself, need to ensure sufficient storage capacity. Otherwise, need to ensure that the final output is in a format that is compatible with existing National Gas systems. For high-resolution satellite imagery, there will be a data cost.	UK-based data storage where possible.	Highly mature solutions available from multiple companies, including satellite operators. Some examples: - AiDASH, - Maxar, - Environment Systems Planet, - Terrabotics, - Satelytics
Hyperspectral satellite imagery	As for multispectral EO satellite imagery but might be able to obtain more detail in terms of e.g. the type of vegetation encroaching on a pipeline (this level of detail may not be needed).	As for multispectral EO satellite imagery, however as the technology is less mature, there will be an element of prototyping to any work. Also, the historical archive of hyperspectral EO satellite imagery is much poorer, and there are far fewer hyperspectral satellites, meaning data availability is patchier. In addition, hyperspectral imagery is likely to be generally more expensive than multispectral imagery.	As for multispectral EO satellite imagery, with the added complication that as hyperspectral imagery is a much newer technology, there might be extra complications when integrating with existing systems.	Using UK-based data storage where possible.	Much less mature than multispectral EO satellite imagery. Available sensors include: PRISMA, Planet's Tanager, and Pixxel

Satellite Integration

SAR EO satellite imagery	Structural health monitoring through ground movement monitoring, identify encroachments, environmental monitoring (limited).	Object detection and environmental monitoring are developed applications of SAR EO satellite imagery, however the information provided is less detailed than that from multispectral/hyperspectral imagery. For this reason, change detection with SAR is trickier than with multispectral/hyperspectral imagery. SAR interferometry (InSAR) can be used to monitor millimetric ground movements from space, possibly giving an early warning on the integrity of the gas pipeline (e.g. if ground movement causes pipeline cracks). SAR sensors are not as badly affected by cloud coverage and adverse weather conditions. There is also a rich historical archive of SAR data, and guaranteed coverage into the future.	As for multispectral EO satellite imagery. SAR images are less easy to interpret by themselves, if these were to be used by themselves it is likely that upskilling would be needed.	UK-based data storage to be used where possible.	Fairly mature solutions available, though as mentioned, these might be less effective than those using multispectral EO satellite imagery and harder to transfer to gas infrastructure monitoring. Often SAR data is used in conjunction with multispectral imagery for environmental monitoring. Examples include ASTERRA and SatSense.
Greenhouse gas (GHG) EO satellite imagery	Monitoring of pipelines to detect leaks and ensure these have been addressed.	Affected by adverse weather conditions (e.g., clouds). As well as dedicated satellites, hyperspectral satellites can also be used to monitor GHGs. Monitoring GHGs using EO satellites is a mature application, especially when using dedicated GHG-measuring satellites.	As for multispectral EO satellite imagery. There is currently no EO satellite imagery that is of a high enough resolution for the challenge that National Gas are facing; therefore, the EO satellite imagery would need to be purchased.	UK-based data storage where possible.	Specifically for commercial GHG EO datasets, there are a handful of specialised companies, such as GHGSat, MethaneSat (satellite launch expected later in 2025 or in 2026). As for hyperspectral EO satellites, some examples include PRISMA and the GHOSt constellation from Orbital Sidekick.

Drone Integration

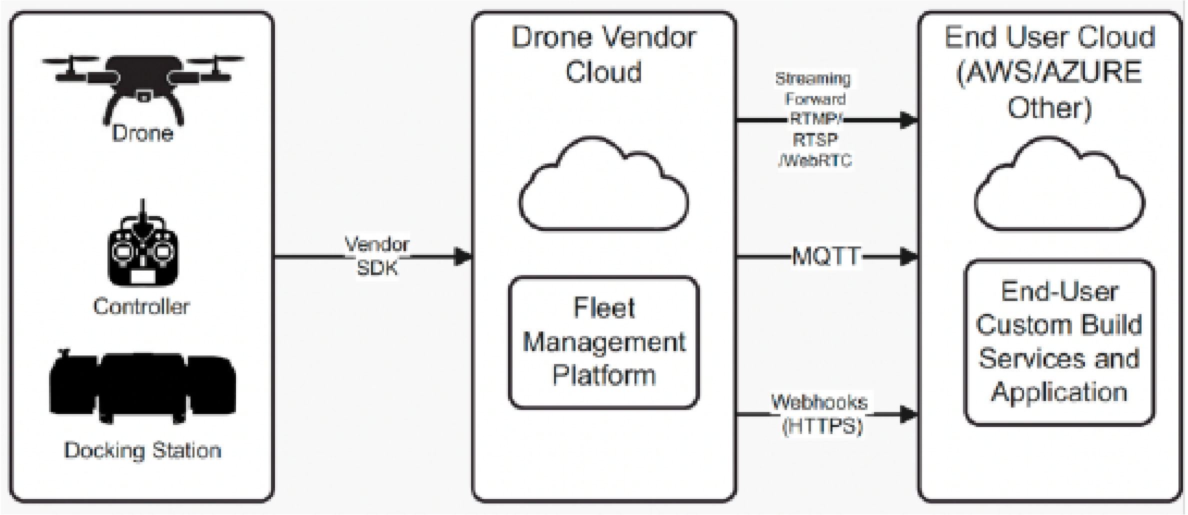

Figure 3. Drone vendor cloud to end-user cloud architecture.

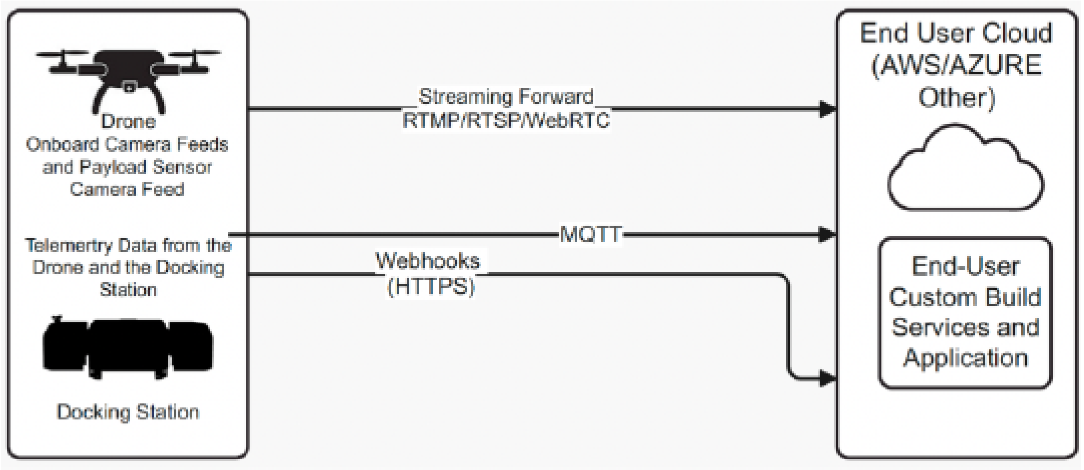

Figure 4. Drone and docking station to end-user cloud architecture.

National Gas AIASM – Feasibility Study

Report prepared for the National Gas AIASM project

August 2025

Version 1.0

Role	Name	Date
Main authors	Renjith Baby Divya Kamath Dr Ramona Marfievici Dr Cillian McPolin Dr Electra Panagoulia Kashif Rabanni	26.08.2025
Reviewers	Paul Ceely	28.08.2025
Approval/Sign Off	Dr Karthik Thangaraj	03.09.2025

Change history

Version	Summary of Changes	Approver
1.0	Document published	Paul Ceely

Table of Contents

List of Abbreviations

AI	Artificial Intelligence
AES	Advanced Encryption Standard
API	Application Programming Interface
AWS	Amazon Web Services
BGS	British Geological Survey
BVLOS	Beyond Visual Line of Sight
CAA	Civil Aviation Authority
CAGR	Compound Annual Growth Rate
CCTV	Closed-Circuit Television
CHM	Canopy Height Model
cm	Centimetre
CO2	Carbon dioxide
CROME	Crop Map of England
CSV	Comma Standard Values
CV	Computer Vision
DAG	Directed Acyclic Graph
DSM	Digital Surface Model
DTM	Digital Terrain Model
ENVI	Environment for Visualizing Images
EO	Earth Observations
ESA	European Space Agency
EVLOS	Extended Visual Line of Sight
FIPS	Federal Information Processing Standards
GBM	Gradient Boosting Machines
GDPR	General Data Protection Regulation
GHG	Greenhouse Gas
GRU	Gated Recurrent Units
HDFS	Hadoop Distributed File System
IAM	Identity and Access Management
IMU	Inertial Measurement Unit
IR	Infrared
ITT	Invitation to Tender
JPEG	Joint Photographic Expert Group
kHZ	kilo Herz
km	Kilometre
KML	Keyhole Markup Language
KMZ	Keyhole Markup Language Zipped
LiDAR	Light Detection and Ranging
LLM	Large Language Models
LSBUD	Line Search Before U Dig
LSTM	Long Short-Term Memory

LTE	Long-Term Evolution
m	Meter
ML	Machine Learning
MLOPs	Machine Learning Operations
MQTT	Message Queuing Telemetry Transport
NASA	National Aeronautics and Space Administration
NDRE	Normalized Difference Red-Edge
NIST	National Institute of Standards and Technology
OGI	Optical Gas Imaging
PIG	Pipeline Inspection Gauge
PPK	Post-Processed Kinematic
RGB	Reg, Green, and Blue
ROW	Right-of-Way
RTK	Real-time Kinematic
RTMP	Real-Time Messaging Protocol
RTSP	Real-Time Streaming Protocol
SAC	Satellite Applications Catapult
SAR	Synthetic Aperture Radar
SDK	Software Development Kits
SVM	Support Vector Machine
TBytes	Terra Bytes
TEE	Trusted Execution Environment
TIFF	Tagged Image File Format
TLS	Transport Layer Security
TPI	Third-party interference
TRL	Technology Readiness Level
UART	Universal Asynchronous Receiver-Transmitter
UAV	Unmanned Aerial Vehicle
VLOS	Visual Line of sight
WebRTC	Web Real-Time Communication

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1. Introduction

National Gas is developing an advanced multi-layered asset surveillance system that leverages artificial intelligence (AI) to establish a more effective and efficient monitoring system for critical infrastructure. This initiative seeks to integrate cutting-edge technologies into existing surveillance methodologies, enhancing capabilities across data collection, processing, and alerts. The proposed system will explore the integration of multiple technologies, including satellite-based monitoring, unmanned aerial vehicles (UAVs), and advanced (quantum) sensing. National Gas aims to evaluate the feasibility of creating an AI-driven autonomous surveillance model specifically designed for monitoring critical national infrastructure assets.

2. Scope of Document

This document contains the technical feasibility study conducted by Digital Catapult and Satellite Applications Catapult for National Gas's development of an advanced multi-layered asset surveillance system.

The proposed system explored in this study integrates multiple complementary surveillance and monitoring technologies, including satellite Earth observations with comprehensive data types and formats, autonomous drone platforms with diverse energy sources and sensor configurations, and emerging quantum and photonic sensing capabilities. The technical analysis contains drone integration architectures and specialized drone docking station integration for persistent monitoring operations, along with security and privacy frameworks specifically developed for drone operations.

The feasibility assessment further investigates AI-based surveillance monitoring through data pipelines architectures, including data ingestion layers, real-time processing systems, AI core workflows, automated alert generation and rule engines, and integrated viewer platforms.

This study provides recommendations for the selection and integration of different technologies and components, along with practical steps for the design and implementation of the AI-driven autonomous surveillance model.

3. Surveillance and Monitoring Technologies

National Gas aims to develop a robust multi-layer asset surveillance system embedded with AI to create a more efficient surveillance regime. The project explores opportunities to integrate innovative technologies into NG surveillance methods for data collection, processing, and alert deployment. These technologies include satellite monitoring, drones, and classic and quantum sensing capabilities, as potential updates or additional to traditional surveillance methods, helicopter surveillance and line-walking techniques.

This section provides an assessment of key enabling technologies that form the foundation of the proposed multi-layer surveillance architecture. We look at satellite imagery systems, drone-based platforms, classical sensing technologies, and emerging quantum sensing capabilities. Each technology is evaluated across multiple dimensions to inform strategic decision-making and system design. For each technology this assessment covers: technology overview: fundamental principles, capabilities, and operational characteristics, including their specific advantages for monitoring, market solutions: commercially available services and vendors currently operating in the technology space, data formats: data output formats, resolution capabilities (where applicable), service cost (where available), technology readiness level (TRL) focused on quantum sensing.

3.1. Satellite Earth Observations

3.1.1 Technology Overview and Capabilities

Earth Observation (EO) encompasses the collection, analysis and interpretation of data about the Earth's physical, chemical and biological systems. Satellite EO specifically refers to the use of various satellite-based imaging equipment to carry out EO activities.
Broadly speaking, EO satellite sensors can be split into passive (optical) and active (Synthetic Aperture Radar (SAR)) sensors, with the active satellites picking up the reflection of the radiation they have emitted, while passive satellites pick up reflected sunlight. SAR satellites operate in the microwave section of the electromagnetic spectrum, while optical satellites operate in the optical and infrared (IR) part. Due to the nature of the sensors, SAR satellites can capture images during the daytime and nighttime, and are mostly unaffected by cloud cover, whereas optical satellites can only capture images in the daytime and the quality and availability of the images is affected by weather conditions, including cloud cover (SAR satellite imagery is impacted by weather conditions too, though to a much lesser degree). Optical satellites capture data in multiple spectral bands, while SAR satellites only capture data in a single spectral band.

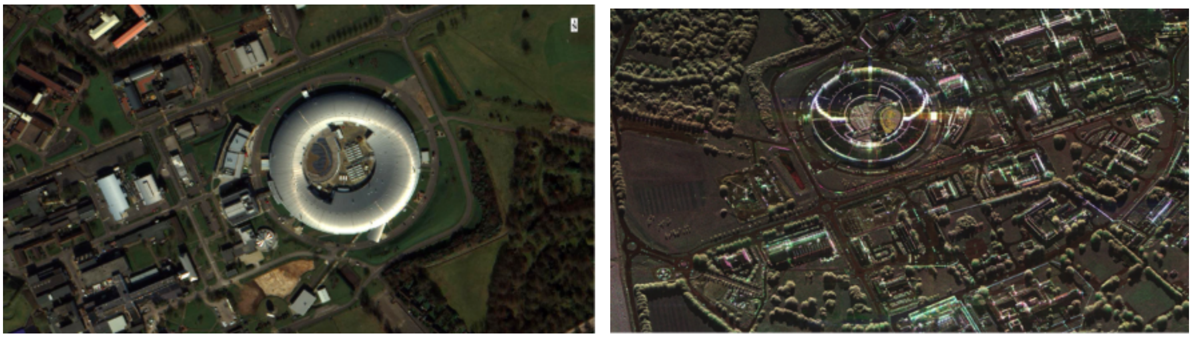

Figure 1. Multispectral optical (left) and SAR EO satellite imagery (right) over Harwell Campus.

Due to the fact that these satellites operate in different parts of the electromagnetic spectrum, they are sensitive to different characteristics of the Earth's surface; for example, SAR imagery is very good at picking up metallic objects and is extensively used to map flooding, because water appears much darker than its surroundings in SAR images. On the other hand, optical EO imagery is very commonly used to map vegetation health and is better than SAR imagery for object detection, for example.

Some important concepts when talking about EO satellites are:

- spatial resolution: the smallest distance possible between two objects so that a satellite sensor can distinguish between them. Note that for optical satellites the spatial resolution can vary between different bands, while for SAR satellites it can vary based on the data capture mode;
- temporal resolution/revisit time: the frequency with which a satellite passes over the exact same area on Earth; in ideal conditions, this would be how often an image over that area is available (note that due to optical sensors being affected by cloud cover, this is not often the case);
- swath: this is the size of the area covered in a single overhead pass by a satellite, and the geographical size of the dataset.

Figure 2. Optical multispectral satellite imagery at 0.5m (top left), 2m (top right), 5m (bottom left), and 10m (bottom right) over Harwell Campus.

Currently, there are satellites available whose images are available for free, and ones whose images are paid for (commercial satellites).

Freely-available satellite data: these satellites are generally operated by national space agencies (e.g., NASA, ESA) and due to one of their main goals being ongoing monitoring of the Earth's surface and climate, their historical archives stretch back to the 1970s and these satellites (or their replacements) are expected to provide data well into the future, covering the entire Earth. Some of the most frequently used satellites in this category are NASA's LandSat-8 and –9 (optical), and ESA's Sentinel-1 (SAR) and Sentinel-2 (optical). The spatial resolution of these satellites ranges from hundreds of metres or kilometres up to 10m, and they generally have a fixed observation schedule, meaning they have a fixed temporal resolution. LandSat-8 and –9 have a spatial resolution of up to 15m and a revisit time of 8 days as a constellation of two satellites, with a swath of 185km. Sentinel-1 and Sentinel-2 have spatial resolutions of up to 5m and up to 10m, temporal resolutions of 6 days and 5 days over the UK and swaths of at least 250km (depends on observation mode) and 290km, respectively.

Commercial satellites: these satellites are operated by private companies (e.g., Maxar[1], Airbus) and to reduce operating costs, only acquire images over areas and at times requested by their customers. For this reason, the historical archive of these commercial satellites is not as rich as that for freely available satellite imagery. However, it is possible to task such satellites, meaning that future acquisition of imagery can be requested, as frequently as is required (if it is within the satellite's temporal resolution). Commercial satellites offer much higher resolution than freely available satellites (up to 31cm for optical and 25cm for SAR) and their temporal resolution is also generally higher (often sub-daily). Their swaths are smaller than those of freely available satellite imagery due to the higher resolution; generally, the swaths are <100km. The cost of commercial satellite data varies, with archive data being cheaper than tasking data; the cost depends on the size of the area covered, the level of data processing required.

To summarise, satellites provide an unbiased way of monitoring assets anywhere around the globe on a regular basis, allowing for ongoing monitoring but also historical trend analysis.

3.1.1.2 Surveillance Applications

As described above, EO satellites can provide frequent coverage for assets anywhere on the globe, at different resolutions and using different types of sensors. As such, they offer a huge range of potential surveillance applications, especially when combined with machine learning (ML) and computer vision (CV) technologies. In this section, we will focus on the ones most relevant to National Gas, based on the information provided in the Requirements Gathering Report.

[1] https://www.maxar.com/maxar-intelligence/who-we-serve/environmental

The main goal of National Gas' surveillance work is to detect changes in the immediate surroundings of their pipeline infrastructure that could compromise the pipeline's integrity. These changes can include, for example, the parking of farm machinery, the building of garden/farm sheds and creation of new footpaths on or near National Gas pipelines.
Here we explore the suitability of different satellite EO technologies to helping solve this challenge; note that typical data formats are covered in a section below and broadly apply to any EO satellite imagery and derived geospatial data.

Table 1. Satellite imagery technologies: performance characteristics, applications, integrations requirements, regulatory and security considerations, and market solutions

Technology	Applications	Performance, advantages, limitations	Integration considerations	Regulatory and security considerations	Maturity of available systems on the market
Multispectral EO satellite imagery	Anomaly detection (e.g., vegetation discolouration), encroachment (e.g., from vegetation or buildings), change detection, environmental monitoring	Object and change detection on land and environmental monitoring are well-established use cases for multispectral satellite imagery. Thanks to the historical archive and future data availability, monitoring is possible over long time periods. Ground data/human expertise needed to correctly interpret satellite imagery. Cloud coverage limits data availability.	Satellite imagery can be quite big in size; if this is to be used in itself, need to ensure sufficient storage capacity. Otherwise, need to ensure that the final output is in a format that is compatible with existing National Gas systems. For high-resolution satellite imagery, there will be a data cost.	UK-based data storage where possible.	Highly mature solutions available from multiple companies, including satellite operators. Some examples: - AiDASH, - Maxar, - Environment Systems Planet, - Terrabotics, - Satelytics
Hyperspectral satellite imagery	As for multispectral EO satellite imagery but might be able to obtain more detail in terms of e.g. the type of vegetation encroaching on a pipeline (this level of detail may not be needed).	As for multispectral EO satellite imagery, however as the technology is less mature, there will be an element of prototyping to any work. Also, the historical archive of hyperspectral EO satellite imagery is much poorer, and there are far fewer hyperspectral satellites, meaning data availability is patchier. In addition, hyperspectral imagery is likely to be generally more expensive than multispectral imagery.	As for multispectral EO satellite imagery, with the added complication that as hyperspectral imagery is a much newer technology, there might be extra complications when integrating with existing systems.	Using UK-based data storage where possible.	Much less mature than multispectral EO satellite imagery. Available sensors include: PRISMA, Planet's Tanager, and Pixxel

SAR EO satellite imagery	Structural health monitoring through ground movement monitoring, identify encroachments, environmental monitoring (limited).	Object detection and environmental monitoring are developed applications of SAR EO satellite imagery, however the information provided is less detailed than that from multispectral/hyperspectral imagery. For this reason, change detection with SAR is trickier than with multispectral/hyperspectral imagery. SAR interferometry (InSAR) can be used to monitor millimetric ground movements from space, possibly giving an early warning on the integrity of the gas pipeline (e.g. if ground movement causes pipeline cracks). SAR sensors are not as badly affected by cloud coverage and adverse weather conditions. There is also a rich historical archive of SAR data, and guaranteed coverage into the future.	As for multispectral EO satellite imagery. SAR images are less easy to interpret by themselves, if these were to be used by themselves it is likely that upskilling would be needed.	UK-based data storage to be used where possible.	Fairly mature solutions available, though as mentioned, these might be less effective than those using multispectral EO satellite imagery and harder to transfer to gas infrastructure monitoring. Often SAR data is used in conjunction with multispectral imagery for environmental monitoring. Examples include ASTERRA and SatSense.
Greenhouse gas (GHG) EO satellite imagery	Monitoring of pipelines to detect leaks and ensure these have been addressed.	Affected by adverse weather conditions (e.g., clouds). As well as dedicated satellites, hyperspectral satellites can also be used to monitor GHGs. Monitoring GHGs using EO satellites is a mature application, especially when using dedicated GHG-measuring satellites.	As for multispectral EO satellite imagery. There is currently no EO satellite imagery that is of a high enough resolution for the challenge that National Gas are facing; therefore, the EO satellite imagery would need to be purchased.	UK-based data storage where possible.	Specifically for commercial GHG EO datasets, there are a handful of specialised companies, such as GHGSat, MethaneSat (satellite launch expected later in 2025 or in 2026). As for hyperspectral EO satellites, some examples include PRISMA and the GHOSt constellation from Orbital Sidekick.

			Note that integration using hyperspectral data might be trickier than when using a dedicated GHG data provider.		

3.1.2 Data Types and Formats

Satellite EO imagery is generally made available in raster data type, in GeoTIFF or Tagged Image File Format (TIFF) file format (`*.tiff` or `*.tif` file suffixes), which are standalone file formats. As satellite imagery can be bulky, it often comes in zipped files or tarballs.

Geospatial data (e.g., derived from EO satellite imagery) generally comes in vector data type, and some of the most commonly used data formats are geoJSON (`*.geojson` or `*.json` file suffix), shapefile (these consist of multiple files, with the mandatory files needed being those with `*.dbf, *.shp and *.shx` file suffixes; however there can be more than these associated with a single shapefile[2]) and Keyhole Markup Language/Keyhole Markup Language Zipped (KML/KMZ), with `*.kml` and `*.kmz` file suffix respectively).

3.1.3 Recommendations

Based on the requirements and National Gas' pain points as detailed in the requirements report and the maturity and potential cost of the EO satellite-based solutions detailed above, **the main recommendation is to use a combination of multispectral and SAR EO datasets to carry out ongoing monitoring of National Gas' pipelines and the areas immediately surrounding them.**

These datasets would be combined with ML algorithms to enable ongoing change detection. The benefits of this are:

- regular updates on the area above and surrounding the pipeline on a more regular basis than afforded by helicopter flights, with savings on helicopter flight costs and carbon footprint;
- due to their wide swath (the area covered in a single data capture) relative to the narrow area covered by helicopter flights, the National Gas pipeline network can be imaged in its entirety on a more frequent basis than what is achieved through helicopter flights (which are repeated every two weeks). This would enable the optimisation of ground staff visits, increase efficiency and reduce carbon footprint.
- through the use of a change detection algorithm, duplicate reports would be minimised (e.g., if a farmer had left a piece of farm machinery near a pipeline for several months, this would only get flagged once, rather than every single time the helicopter flew over the area) and ground staff time could be used more efficiently.
- conversely, if ground staff had visited an area of concern and provided some recommendations, change detection would provide information on whether these have been implemented or not, again allowing ground staff to be resourced more effectively.
- limitations to this recommendation include the possibly prohibitive cost, and the fact that multispectral EO satellite data availability is limited in adverse weather conditions (though combining this with SAR data offers some mitigation).

[2] https://desktop.arcgis.com/en/arcmap/latest/manage-data/shapefiles/shapefile-file-extensions.htm

To test the applicability, effectiveness and efficiency of EO satellite data when monitoring the National Gas pipeline network as compared to monitoring using helicopter flights, it is suggested that a trial is run incorporating learnings from the previous trial carried out by Orbital Eye. These include:

- using a larger trial area to ensure enough incidents of concern occur across the trial period. This area should also cover more densely populated areas, where incidents are more likely to occur,
- using a trial area that is more geographically diverse, to highlight how the two technologies perform across the National Gas network.

If EO satellite data availability allows it, the trial can be run using historical incidents, as well as newly reported incidents, on the National Gas network; this would also improve the training of the change detection ML algorithm. If using only newly reported incidents, the trail needs to be of a sufficient time duration to allow the creation of a large enough sample so that the change detection ML algorithm can be sufficiently trained.

For the purposes of this trial, we recommend running an open invitation to tender (ITT), to select a delivery partner with the following expected level of service for the company selected :

- procurement and acquisition of EO satellite imagery, both archival and tasking, based on the requirements identified by National Gas
- storage and processing of the acquired satellite imagery, in accordance with National Gas requirements
- development and training of a ML algorithm to carry out the tasks identified in the ITT, e.g. object detection using the acquired satellite imagery
- carrying out the tasks identified in the ITT, e.g., object detection, using the acquired satellite imagery and ML algorithm
- generation of output datasets from the above process based on National Gas requirements
- incorporation of feedback from National Gas into their work where possible (within the scope of the ITT)
- meetings with National Gas throughout the pilot project to provide updates on progress and receive feedback
- final written report and presentation to National Gas.

3.2 Drones

National Gas aims to extend its surveillance and monitoring capabilities through use of Unmanned Aerial Vehicles (UAV)/Drones technologies and AI. The surveillance in this report cover's vegetation growth monitoring but can be also extended to infrastructure monitoring, structural integrity such as tampering with systems like iDetect365, authorised/unauthorised construction around the pipeline, ground movement such as terrain mapping alongside satellite data and other sensor data. Drones are remotely controlled autonomous aircraft capable of executing various missions. In general, there are three types of drones, remote controlled drones operated manually via remote control, autonomous drones which are pre-programmed to perform task and hybrid drones which can be controlled both remotely and can perform autonomous operations.

3.2.1 Energy Source

These drones primarily rely on lithium-ion batteries primarily and recently there is an increase of hydrogen fuel cells for power. Each offer distinct advantages and constraints. Below shown in Table 2 demonstrates side by side comparison for decision maker to take strategic decisions when it comes to the choice of the power source for the drones.

Table 2. Comparison table for energy source for drones.

Parameters	Hydrogen Fuel	Battery Power
Endurance and Performance	• Hydrogen fuel cell drones in contrast to battery power drones are about 4-5 times higher energy density with no payload. • Another advantage is quick turnaround times for refuelling a hydrogen drone take only few minutes.	• Lithium-ion battery drones are generally limited to short flights with no payload and battery energy density remains a limiting factor. • Lithium-ion battery requires either a spare battery or extended charging period.
Application areas	• Well-suited for long range infrastructure surveillance. Can power multiple sensors simultaneously.	• This is currently the industry standard for most drones used in inspections and mapping tasks due to easy deployment and maturity in the technology.
Sustainability and Environmental Impact	• Zero operational emissions. The hydrogen cell emits only water vapour as a byproduct. • Hydrogen must be produced and transported. If hydrogen is generated via renewable energy (green hydrogen). Then the fuel cell of the drones and its operation can be nearly carbon neutral. In contrast to hydrogen sourced from natural gas (grey hydrogen) which carries a Carbon Dioxide (CO2) footprint upstream in the supply chain. Which then partly offsets the zero-emission benefit. • Hydrogen Fuel cells have longer service life. • The upfront cost of the hardware infrastructure for hydrogen fuel cell is far higher but have longer	• Zero operational emissions. • Charging batteries for the drones draw electricity that may have come from fossil fuels. Thus, considering the broader environmental footprint which depends on energy production. • Shorter Service life compared to hydrogen fuel cells. • Batteries involve the mining of critical minerals and face recycling challenges. This a drone's carbon footprint is tied to how clean the electric grid is and how the battery is produced and disposed. Currently, initiatives are undertaken to develop clear battery disposal techniques and cleaner battery chemistries to minimise environmental impact.

	lifespan and less downtime can improve ROI through quick refuelling. Thus, the hydrogen drone's footprint depends on the hydrogen production method and fuel logistics. • This sector is growing rapidly to make hydrogen drones for long endurance missions. Hydrogen Fuel Cell Drone Market to Soar to USD 2085 Million by 2031, Growing at 76.3% Compound Annual Growth Rate (CAGR) [1].	• Automated battery swap stations and ultra-fast charging systems are being developed to minimise downtime [2]. Thus, unless battery breakthrough meets the extreme range requirements, hydrogen fuel cells or hybrid solutions are likely to play an important role for ultra long-range use-cases in this sector. Regulators are more likely to permit Beyond Visual Line of sight (BVLOS) missions with battery-powered drones that are safer and use more reliable batteries

Recommendations

Choosing the appropriate energy source for drones in the natural gas sector is highly dependent on the task, which requires a balance of endurance, payload capacity, cost, and operational efficiency. Hydrogen fuel cell drones are superior for long-range inspections, leak detection, and heavy-payload operations, including Light Detection and Ranging (LiDAR) mapping and vegetation management, where extended flight durations and reduced downtime are essential. On the other hand, battery-operated drones are the optimal selection for brief, routine, and localised assignments, like facility perimeter surveillance, short evaluations task, or rapid visual assessments, where ease of use and reduced initial expenses take priority over endurance needs.

3.2.2 Drones Integration

To operationalise these drones and utilise their maximum potential, one must address how aircraft and payload data is transmitted to the cloud, how docking stations are managed, and how field communication systems work during deployment with minimal impact on existing connectivity. Three integration methods address these challenges, and they are presented next.

3.2.2.1 Drones Integration Architectures

Vendor-mediated cloud architecture

Figure 3 depicts the fastest integration architecture, enabling direct connectivity from the drone vendor cloud environment to the end-user environment. This architecture establishes connectivity from the drone units and their associated controller/docking infrastructure through vendor-specific cloud platforms to end-user cloud environments. The operational framework centralizes flight operations management and docking system control within proprietary vendor fleet management platforms, for example DJI FlightHUB [68], DroneSense [20], FlytBase [69], etc.

Device provisioning and enrollment processes for payloads, sensors, and other proprietary components are executed through the vendor-provided Software Developments Kits (SDKs). Following successful enrollment, data transmission to end-user cloud infrastructure can be done using standard protocols including Real-Time Messaging Protocol (RTMP), Real-Time

Streaming Protocol (RTSP), Web Real-Time Communication (WebRTC), Message Queuing Telemetry Transport (MQTT), and HTTPS-based webhook implementations.

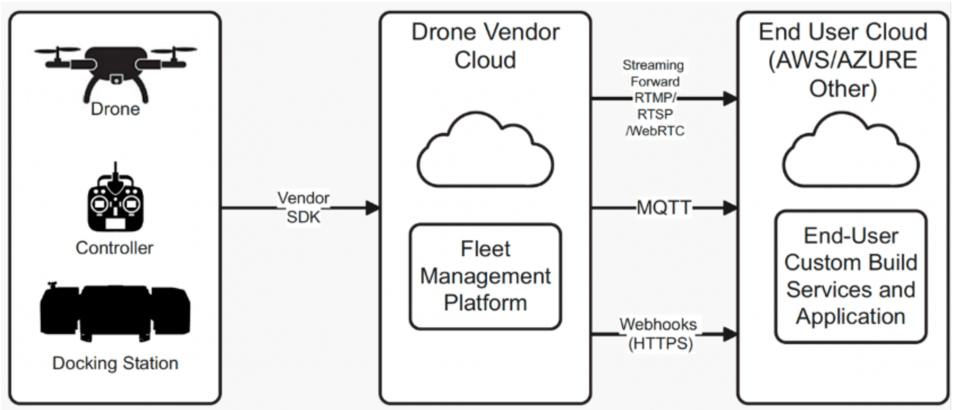

Figure 3. Drone vendor cloud to end-user cloud architecture.

This architectural approach provides accelerated deployment capability by leveraging pre-existing vendor platform infrastructure and commercially available SDKs, thereby reducing implementation complexity for drone fleet integration.

Direct-to-cloud architecture

The architecture illustrated in Figure 4 enables direct connectivity between drone platforms and docking infrastructure to end-user cloud environments. This configuration provides end users with complete data sovereignty and ownership of all information assets residing in their cloud tenancy. The drone and the docking stations stream live data feeds directly to end-user cloud environment through RTMP/RTSP/WebRTC. Concurrently, telemetry data, system events, and operational status information are transmitted via HTTPS webhook implementation and MQTT.

Withing the designed AWS or Azure cloud tenancy, organizations can deploy custom ingestion services to process these data streams while implementing security frameworks like Identity and Access Management (IAM) policies, IP-based access controls, and other enterprise-grade security measures.

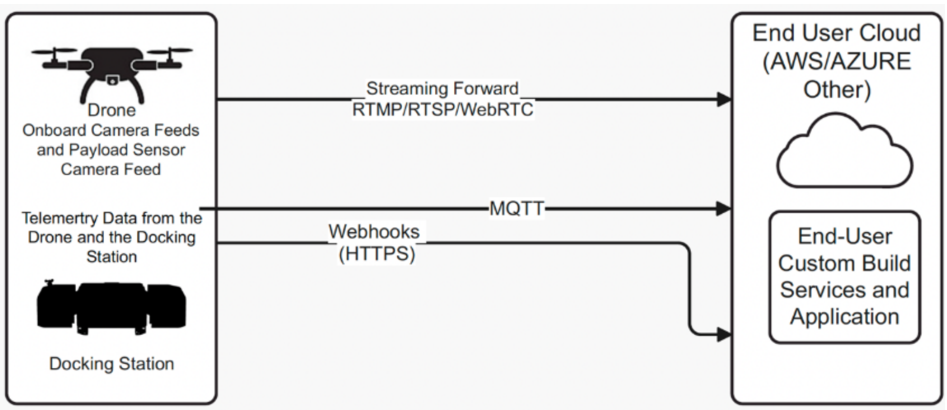

Figure 4. Drone and docking station to end-user cloud architecture.

This architectural pattern enables organisations to maintain full control over data processing, storage, and access management within their own cloud infrastructure boundaries.

Edge-Cloud hybrid architecture

The architecture depicted in Figure 5 enables connectivity optimized for offline edge processing capabilities while maintaining bidirectional connectivity with the end-user cloud environments. This leverages vendor-provided SDKs adapter interfaces to establish connections between edge gateway and drone platforms, controllers, and docking stations.

The edge gateway component can be deployed either onboard the drone platform or integrated within the docking station infrastructure. Physical connectivity is established through Ethernet, USB, or Universal Asynchronous Receiver-Transmitter (UART) interfaces, enabling real-time extraction of telemetry data, payload/sensor information, and system status metrics. The gateway can perform lightweight computational processing and local storage of pre-processed data files, which can be shared with the end-user cloud environment for advanced analytics when required.

System connectivity to drone platforms is done through docking station infrastructure, with the docking station maintaining direct communication links to the edge gateway. Data transmissions to and from end-user cloud environments can use cellular 4G/5G, Starlink satellite, or private Wi-Fi connections through integrated stream manager and MQTT Bridge components.

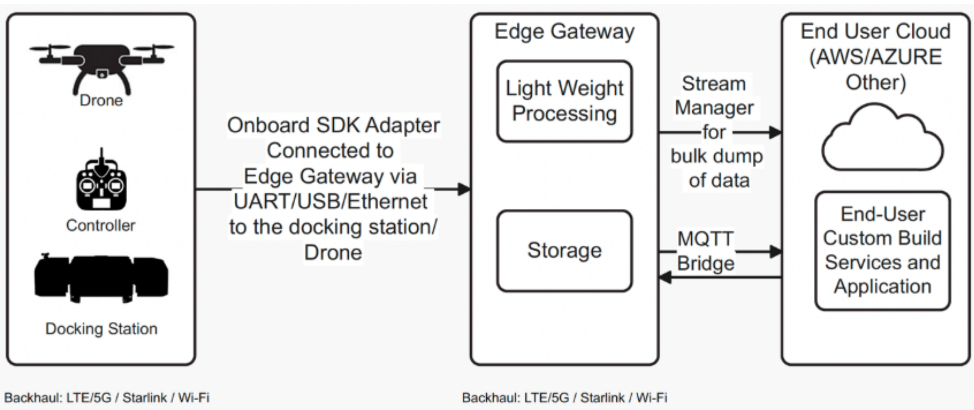

Figure 5. Edge-cloud hybrid architecture.

This architecture implements intelligent connectivity switching mechanisms during network interruptions and optimized bandwidth utilization through prioritized data transmission protocols. This approach provides viable solutions for BVLOS operations and remote site deployments where network connectivity may be intermittent, or bandwidth constrained.

Recommendations

This technical assessment recommends implementing a practical deployment architecture cantered on the DJI Enterprise platform, utilizing standardized data pipeline infrastructure supported by DJIDeveloper Kit components and communication protocols. The proposed deployment can integrate two to three architectural frameworks to address the identified use-cases: vegetation management, leak detection, and on-demand inspection operations. The system can be deployed with the DJI M350 RTK drone platforms, selected for their multi-payload/sensor attachment capabilities, IP55 environmental rating, and extended 55-minute flight duration. These platforms will be enhanced with DJI 4G transmission modules to ensure BVLOS operational resilience.

The solution architecture can combine DJI Cloud infrastructure utilizing DJI FlightHUB 2+ Cloud API with integrated Streaming Manager functionality and NVIDIA Jetson Nano edge computing modules for localized data processing. Processed data can be transmitted to AWS or Azure cloud environments where specialized services will perform advanced analytics and AI model execution for intelligent decision-making processes.

All data handling can utilize standardized open formats including GeoTIFF (`.geotiff`), JavaScript Object Notation (`.json`), `.jpeg`, and MPEG-4 file formats withing appropriate standardized schema frameworks. The complete payload and sensor configuration, detailed in the Annex 1 – Powerful DJJ Payload/Sensors List, will ensure that operational procedures, data management protocols, and communication systems maintain full compliance with UK Civil Aviation Authority (CAA) regulatory requirements and industry best practices.

3.2.2.2 Drone Docking Station Integration

Table 3 shows a list of docking stations. Several docking solutions are marketed as fully integrated "drone-in-a-box" platforms with evident streamlined deployment advantages. While they bring benefits such as simplified implementation process, reduce integration complexity, and faster time-to-deployment, they also come with risks like vendor lock-in, migration cost, and closed ecosystem limitations. Organisations should carefully evaluate the long-term implications of integration versus modular approaches when selecting docking solutions, considering both immediate deployment benefits and future scalability requirements.

Table 3. Docking stations characteristics, data types, market maturity, and cost.

Docking Station	Communication	Data Types and Formats	Maturity	Cost	Most Compatible Drones
DJI Dock 2 	Built in FlightHub 2 with cloud API and FlightHub Sync which has webhook and MQTT integration, this also comes with direct transfer connectivity to the RTMP server. Own weather station	.mp4, .jpeg, json these files contain live video, telemetry data, mission logs, dock status and health	High	~[redacted] (from COPTRZ)	DJI Matrice 3D/3TD
DJI Dock 3 	Built in FlightHub 2 with cloud API and FlightHub Sync which has webhook and MQTT integration, this also comes with direct transfer connectivity to	.mp4, .jpeg, json	High	[redacted] VAT incl. (from DJI)	DJI Matrice 4D/4TD

	the RTMP server. Own weather station and enhance dust water resistance and can operate 24/7. Vehicle Mount. Operating at lower temperature				
Skydio Dock 	Cloud API and it has its own Dock API	.mp4, .jpeg, json, .csv	High	Vendor enquiry needed	Skydio X10/X10D
Percepto Base 	AIM Platform for exporting media files and has LTE backhaul connection	.mp4, .jpeg, json, .csv	Medium-High	Vendor enquiry needed	Percepto Air
Hextronics Universal 	Integration via flytbase. Has provision for LTE and it has its own inbuilt wifi. Battery integration available	.mp4, .jpeg, json	High in US due to coverage could not find any deployment in UK	Vendor enquiry needed	DJI Mavic 3 (Enterprise) Anzu Raptor, Parrot Anafi AI
HEISHA D135 	Vendor SDKs and custom build communication can be ordered. It has its own weather station system on the dock.	.mp4, .jpeg, json	Medium	Vendor enquiry needed	DJI Matrice 300/350

Alternative commercial solutions, including Azure Drones Skeyetech E2 [5], Iron dome American Robotics [6], Easy Aerial EG202 (drone in a box) [7], represent proprietary platforms with significant integration limitations. A quick evaluation of the systems from the available documentation, indicated several critical constraints that would impact long-term operational viability: limited technical documentation and restricted software development kits, constraining customization capabilities and integration with existing systems, along with proprietary hardware implementations and payload configurations, limiting operational flexibility. Moreover, the API integration is limited constraining system integration with existing data pipelines and operational workflows.

Recommendations

[redacted] is recommended, configured with application-specific sensor payloads informed by operational requirements. Technical justification: cloud infrastructure with native private cloud integration capabilities, good technical support framework with documentation, implements standardized data transmission protocols and data formats, enabling integration with existing enterprise data flows and interoperability with third-party systems, 24/7 autonomous operations with weather-resistant hardware specifications designed for outdoor deployments. An operational advantage is the system's modular design, enabling vehicle-mounted deployment configurations, i.e., field operators can transport and deploy the docking stations using their standard utility vehicle, thus expanding operational coverage with minimal infrastructure investment.

3.2.2.3 Communication technologies and backhaul for the overall system

BVLOS operations [8] require remote pilot control without direct visual contact with the drone. Regulatory compliance requires demonstration to CAA that aircraft separation is maintained within controlled airspace, communication links remain stable throughout flight operations, and risk mitigation protocols protect personnel, equipment, and assets during mission execution. For this reason, the communication backhaul is the critical infrastructure component for the drone deployment infrastructure. Current market solutions provide dual- and multi-link communication capabilities, using cellular networks (e.g., multi-SIM LTE/4G, and 5G), satellite communications (e.g., SATCOM integration including commercial providers), and radio frequency links ranging from unlicensed ISM bands 2.4GHz to 5.8GHz (short-range applications), long-range unlicensed (i.e., 868-915MHz), licensed spectrum (i.e., 5.03-5.091GHz CCA allocation, to private LTE/5G networks.

Drone communication architectures typically implement point-to-point, mesh, or hybrid topologies combining P2P radio bridges with cellular and satellite communication links.

The DJI platform (Enterprise + Dock) utilizes the Cellular Enhanced Transmission dongles [9] integrated with docking station infrastructure. Starlink satellite connectivity can enhance coverage for remote deployments.

The Skydio X10 platform along with its docking system uses a combination of P2P radio and 5G communication capabilities which is built in. This also can be paired with Starlink for remote operations and areas of less network coverage.

Percepto Air and its docking station uses multi-SIM LTE backhaul with direct cloud platform integration.

Thou Autel EVO Max 4T platofrm [10] and its docking station, not mentioned earlier in the report, implements mesh networking topology with optional 4G backhaul and integrated multi-drone network communication capabilities.

Specialized vendors including Elsight Halo [11], Iridium Certus 97770 [12], and uAvionix mulLTElink [13] provide multi-link communication modules including inbuilt 4G/5G, satellite communication including Starlink [14], and private network capabilities (Wi-Fi/Ethernet). However, these solutions require integration engineering effort and may not represent optimal choices for standardized deployment scenarios.

Recommendations

The primary system stack recommendations are the [redacted] complemented by Starlink satellite connectivity for field deployment operations. These platforms leverage native cloud service integration across major platforms (e.g., AWS: Kinesis Video Stream for real-time video data processing, IoT Core for telemetry data ingestion and device management, Microsoft Azure: IoT hub for device connectivity and messaging, Event Hub for high-throughput data streaming, and Blob Storage for persistent data archival and retrieval).

3.2.3 Drones Security and Privacy Layers

A secure and compliant enterprise drone depends on full stack security deployment from device to application to cloud. Each enterprise drone comes with their own set of device security, application security, data privacy and security, encrypted communications, cloud security, Security certifications, audits and calibration. Below discussed is generic, not extensive and vendor agnostic.

1. Device Security: All enterprise drones in the current market employ hardware root of trust to the chip level following the guidelines of Trusted Execution Environment (TEE) [15, 16] and certified to meet the Federal Information Processing Standard (FIPS) 140 [17, 18] validated cryptographic module standards and standard laid by the National Institute of Standards and Technology (NIST). This is used to protect the keys, secure boot and device identification.

2. Application Security: Flight applications and SDKs are made secure through code signing, permission scoping, and secure update channels. Vendors release developer documentation and security [19] upgrades for Cloud/Open/Onboard/Payload SDKs so that developers can gauge risk and follow best practices.

3. Data Security and Privacy Controls: Industry standards allow end-users and customers control over data flows and retention. For example, some drones use TLS1.2/1.3 for sharing data while it's moving over a network and Advanced Encryption Standard (AES)-256 for stored data in default cloud or internal storage. Drone applications commonly offer a mode that allows to synchronize and share data between there cloud or end-customer cloud through means explain above in Section 3.2.2 Drones Integration. There is provision for on-prem option for data sovereignty through fleet management platforms such as DJI FlightHub 2, DroneSense [20] and FlytBase .

Trasport Layer Security: Transport Layer Security (TLS) relies on TLS Protected protocols such as MQTT [21]/HTTPS/WebSocket [22] for telemetry and control. These protocols secure the data for example the live stream video form the drone to cloud environment or private NGINX RTMP servers and others. Also to note some of the common live protocol for live streaming of data are RTMP, RTSP [23], WebRTC [24], etc. MQTT/Webhooks are used mainly for telemetry/event-based data streams.

Cloud Security: Enterprise cloud environments such as Azure or AWS stack can offer public cloud options, private cloud options and on-premises choices that all have the same features when it comes to storage of data from drones or mounted payload sensors. These environments give full control over storage, sharing/access, keys etc. [25]

Security certifications, audits and calibration: Drones and Sensor vendors list and share audit guidelines and certifications through there platform and portals. Some of the independent security and privacy certifications are ISO/IEC 27001 [26] and ISO/IEC 27701 [27] by ISO, and SOC 2 (type I/II) [28], CAP 722 [29] performed by CPA. Also, under the guidelines by UK CAA for calibration of drones the operators/end user should maintain them in suitable conditions and keep records. Some of the calibration include Inertial Measurement Unit (IMU) calibration (gyroscope/accelerometer), onboard camera calibration, parts calibration, docking station and system calibration, payload/sensor calibration as per their requirements. There are also bug bounty program run by various vendors that helps to remove any ongoing vulnerability that helps to activity remove any [30].

3.2.4 Drones Sensors and Imaging Technologies

National Gas uses send helicopters to video inspect their transmission pipeline and on ground line man for foot patrols. This can be an expensive process and potential safety risks in case of adverse conditions. Using drones is a safer and cheaper option. UAVs can get to inaccessible places, find breaches, and send live data without putting personnel in danger. Drones also enable more frequent inspections (even daily or weekly if needed), which means earlier detection of issues like leaks or structural problems, thereby preventing small issues from escalating. Drones can carry both passive sensors (e.g., optical Reg, Green, and Blue (RGB), multispectral, hyperspectral, thermal IR) and active sensors (e.g., LiDAR etc.). Unlike satellites, drones can be tasked on demand, fly below cloud and collect centimetre-level detail data from target site. Some limitations which include endurance, extreme weather such as wind, and airspace/regulatory constraints for BVLOS. The essential data sources to consider when designing, developing and deploying an AI model for manual, autonomous and hybrid drone-based surveillance for BVLOS, Visual Line of Sight (VLOS), Extended Visual Line of Sight (EVLOS) are as follows in Table 4:

Table 4. Commercial drone sensors/payloads including data output characteristics, supported formats, market maturity, integration complexity, and cost considerations.

Drones Sensors and Imaging Technologies	Data Produced/ Typical Data Rate	Common Formats/Key Metadata	Market Maturity	Integration	Cost *	Primary Use-Cases	Ref.
RGB (Visual): The high-resolution colour data allows defect recognition, photogrammetric reconstruction and contextual situational awareness.	2D images and videos High Frequency 1080p: 2-6 Mb/s 4K: 8-15 Mb/s	.jpeg, .png, .tiff, .raw, .mp4, .mov Exchangeable image file format (EXIF) and Extensible Metadata Platform (XMP) (Contains: GPS, altitude, timestamp, camera settings)	Very mature solution available in the market such as below: DJI Mavic mechanical shutter camera, Zenmuse P1, Autel EVO II Pro 6K Enterprise, Phase One iXM-100	DJI Mavic camera Plug and play data and data can be transferred via the cloud API and Webhooks. DJI Zenmuse P1 easy mountable on the DJI drones DJI M300/M350 and data can be shared via cloud API, storage on SD card. Autel EVOII can be mounted on the Autel drones and can transfer data via RMTP from the Live DECK 2. This can also be connected to private cloud Phase One iXM-100: The data can be transferred using the Phase One SDK via Ethernet/USB3.	Mavic DJI: ~[redacted] (from DJI) Zenmuse P1: ~[redacted] (from DJI) Autel Evo II: ~[redacted] (from autel store) Phase One iXM-100: ~[redacted] (from dronenerds)	Visual inspection, crack/defect detection, 3D model generation	[31] [32] [33]
Environmental Sensors: An array of sensors to measure ambient pressure, temperature,	Gas concentrations (CH_4, CO_2, VOCs), temp, humidity, wind,	.txt, .csv, .json, .xml Sensor ID, sensor type, GPS,	Highly mature solutions available in the market such as below: Pergam Laser Falcon	DJI U10 UAV: this is mounted on drones like DJI M300/M350 powered by the I/0 available on the drone. Data collected via FlightHub Sync and Cloud API and then	Pergam Laser Falcon: ~[redacted] (from 3DMapping tools)	Weather correlation scenario, leak confirmation, atmospheric profiling,	[34] [35] [36] [70] [71] [72]

humidity, wind, ambient air for target gases and particulates. All of them together help to provide good quality of data to build atmospheric profiles for risk assessment and dispersion modelling for various decision-making scenarios.	pressure, particulates Event Driven Transm.	timestamp, unit value,	Soarability Sniffer4D Nano2 DJI U10 UAV-Based Laser Methane Leakage Detector	can be integrate to Azure/AWS. Processing can be done locally on an Edge Jetson device using the 12V/5V option data can be UART or the USB2.0 wiring and then to the MQTT broker. Sniffer4D: Can be mounted on the DJI M300/M350/M30/M3E. Power by USB-C 5V Max input. Built in LTE connectivity supports Global 4G, 3G, Edge and GPRS network. Payload SDK for data extraction to the cloud and the Edge. Have MQTT broker option to cloud environment and UDP Json to a target IP on a private network. Pergam Laser Falcon: Standard I/O like U10 above but lighter <300g and has standard DJI communication protocols and service. Integrable to	Soarability Sniffer4D Nano2: Price on request available. This is the best in the market in terms of software, data pipeline, multi-gases, services and integration with a wide range of drones. DJI U10 UAV-Based Laser Methane Leakage Detector: [redacted] approx. (from Heliguys)	Digital twin modelling,	

				Cloud and Edge devices with small dev time.			
Thermal IR: Enables non-contact surface temperature detection etc. That are invisible in the visual spectrum	Radiometric temperature per pixel High Frequency and Low Frequency 1-3 Mb/s	.r-jpeg, .tiff, .dat, .csv, .mp4 Temperature map; GPS; timestamp	Mature solutions available for commercial use. Some of them are DJI M3T, DJI Zenmuse H20T, Teledyne FLIR Vue TZ20-R,	Teledyne FLIR Vue TZ20-R can transfer its data via the RTMP video pipeline to private cloud and stored in SD card. DJI Zenmuse H20T data can be transferred via Webhooks and stream manager via the FlightHub 2. This can be also directed to the private cloud via the RTMP path. DJI M3T data can be transferred to cloud using webhooks and kinesis video stream using the RMTP Server.	Teledyne FLIR Vue TZ20-R: ~[redacted] (from drones) DJI Zenmuse H20T: ~[redacted] (from cliftoncameras) DJI M3T: ~[redacted] (from Heliguy)	Leak detection, overheating/stress monitoring, nighttime operation and surveillance.	[37] [38] [39]
Hyperspectral: Captures discrete bands of visible spectrum to highlight material properties and vegetation growth.	We have found generally the Full-spectrum signatures ranges from 50–300+ bands High Frequency	.hdr, .envi, .bil, .bip, .hdf5, .mat Wavelength metadata, GPS data, timestamp	Moderately Mature. One of solution is VNIR (400-1800nm) from Headwall, Resonon and Hyspex. Across the board it gives you access to share data via the edge devices configured to process data and	Across the board it gives you access to share data via the edge devices configured to process data and synchronised to S3 or Blob	VNIR Cost Headwall Nano: ~[redacted] (from surfaceoptics) Resonon: ~[redacted] Cubert: obtains from vendor	Degradation of surface material, Detecting Gas unique absorption and emission spectral signature, Detecting vegetation	[40] [41]

	and Low Frequency		synchronized to S3 or blob		HySpex: obtains from vendor	growth and monitoring. Also, change detection	
Multispectral: Also, helps in vegetation growth detection and monitoring.	Band reflectance ranges from 4-8 Low Frequency	.tiff, .raw, .csv Band wavelength, GPS, timestamp	Highly Mature. Multispectral is standard in precision agriculture, vegetation monitoring, and material analysis. Some of the examples are DJI M3 Multispectral, MicaSense RedEdge, Parrot Sequoia	Across the board the data can be accessed through could API and telemetry data via MQTT.	Mica Sense RedEdge: ~[redacted] DJI M3 Multispectral: ~ [redacted] (from dronepilotacademy) MicaSense [redacted] (from thebioniceye) [redacted] (from enterpriseuav)	Material health, Change detection and vegetation monitoring	[42]
LiDAR: Used for precise 3D point cloud (XYZ) mapping which helps in creating a 3D model of the terrain/surface/asse	3D point clouds, Digital Surface Model (DSM) and Digital	.txt, .ply, .laz, ..ply, .xyz Band wavelength, GPS, timestamp	Highly Mature. DJI Zenmuse L1, YellowScan, GeoCue, Reigl, mdLidar1000HR	DJI Zenmuse L1: Direct cloud API for processing of data. YellowScan, GeoCue, Reigl, mdLidar1000HR they also show Cloud API availability	DJI Zenmuse L1: ~[redacted] (from dronesales)	Terrian Mapping, 3D modelling.	[43] [44] [45]

t thus helping in detecting structural deformation in the digital model and can also be used for predictive models.	Terrian Model (DTM) High Frequency And Low Frequency			and also edge processing data pipelines	YellowScan: Price available from vendor GeoCue: Price available from vendor mdLiDAR: [redacted] (from precision capture)		
Optical Gas Imaging (OGI): Using the absorption and emission characteristics in the infrared spectrum they can facilitate the visualisation of gas leaks such as methane and other volatile organic compound (VOC) emissions	Gas emission image and video High Frequency	.mp4, .dat, .mov, in some cases it also has seen proprietary FLIR format which stands for forward Looking InfraRed. GPS, timestamp and Radiometric temperature measurement per pixel. Note: The cameras [20] mentioned in the reference can be mounted on the	Moderately Mature but growing in oil and gas pipeline uses cases as this is a specialist market. Some of the examples are as below: Workswell GIS-320	This can be mounted on drones including the DJI airframe. This can then record the radiometric video and take still images and support RTSP for live viewing and data transmission. It has its own vendor software and but webhooks or MQTT can be used be used for transmitting other form of telemetry/events data parallel to the RTSP. The vendor provides on-prem tools to run local apps and then push the data to their own cloud.	Workswell GIS-320: [redacted]not including shipping and custom charges (from volatus drones)	Methane and VOC leak visualisation and Safety monitoring for line walking survey.	[46] [47]

		drones additionally for comparison and sensitivity.					
Ultrasonic: These can help in measuring thickness and corrosion by sending high frequency sound pulses through material. This is ideal for checking internal wear in material for Non-destructive testing (NDT)	Thickness and Corrosion readings High Frequency, Adaptive Frequency	.csv, .txt, in some cases proprietary format like .dat Location and distance values along with timestamps.	Extremely Mature. But UAV adaption is emerging. There are only three examples that were found on commercial level maturity. Tritex Multiguage 6000, Voliro UT, Flyability Elios 3UT, Skygauge drone.	Tritex Multiguage 6000 that can be attached to any enterprise drone and is wireless to 500m. Voliro UT which will need attachement as per the drone and Flyability Elios 3UT which comes with the entire enterprise system including the drone. For the Elios and Voliro this can live stream data through bulk upload to private cloud in .csv format and json format. Both have local apps and dashboard for the edge.	Tritex Multiguage 6000: [redacted] (from alphageo) Voliro UT- price is available from the vendor. Flyability Elios 3UT- price is available from the vendor. Skygauge drone: price is available from the vendor.	Contact based wear detection and thickness inspection	[48] [49] [50] [51] [52] [53]
Ground Penetrating Radar (GPR): Uses radar pulses (electromagnetic waves) to detect and image	Subsurface return signal variation mapping (profiling)	.txt, .csv, .dat, .dxt, .segy Antenna frequency, co-	Very mature Market but adapting to UAV. Compatible examples Zond Aero 500 RadarTeam Cobra SE-150	Zond Aero 500 can be mounted on enterprise drone. Also, this can be mounted on M300/M350 from DJI. This comes with vendor software to provide	Zond Aero 500: [redacted] excluding vat and other charges (from alphgeo)	Underground pipeline location and various types of anomalies detection.	[54] [55] [56]

underground objects and features thus assessing subsurface anomalies without excavation. They have two types low-frequency (unshielded) and high-frequency (shielded to reduce noise)	High Frequency, Adaptive Frequency	ordinates (X, Y, Z) and timestamp		the slice layer and volumetry visualisation. The acquired parameter from the system such as freq. trace rate and altitude etc. can be pushed from the edge to the cloud. No vendor cloud available. It has three types of data raw, processed and .csv metadata. The SDK is compatible with DJI. RadarTeam cobra SE-150 operating time is 12 hours and can also be integrated with drone power source. Works with both DJI M300 and M350	RadarTeam cobra SE-150: [redacted] (from stockrc)	Note: Not suitable for confined spaces and areas with tall vegetation	
Magnetometer: This measures the magnetic flux density and can determine the direction, strength or relative variation in the magnetic field at certain locations. This is also used to detect anomalies in the earth magnetic	Magnetic field strength reading High Frequency, Event Driven and Adaptive Frequency	.csv, .txt, .dat Sensor orientation, GPS, timestamp	Mature Market. Some of the examples are SENSYS MagDrone R3/R4, Geometrics MagArrow II, GEM Systems DRONEmag Perimeter 8 drone & MagniPhy magnetometer	All the three systems can be mounted on the DJI Drones but also other compatible drones. Sensys MagDrone R3/R4 can be powered from its own battery pack or from the drone itself but for optimal usage battery pack is preferred. The data can be pushed to a edge device in the .csv/,txt format or pushed to the end-user	SENSYS MagDrone R3: [redacted] including vat and shipping and custom charges (from infinitedrones) R4 price is available from the vendor.	Tracing buried metallic pipes, ferrous anomaly detection	[57] [58] [59] [60]

field caused by ferrous objects.				cloud. No vendor cloud is available. Similar method can be used for the GEM System DRONEmag	Geometrics MagArrow II- [redacted] rental but buying price need to check with vendor GEM Systems DRONEmag- price need to check with vendor Perimeter 8 drone & MagniPhy magnetometer: Vendor Quote needed		
Acoustic Microphone Arrays: An acoustic microphone array is a group of microphones that are set up in a certain way to pick up, locate, and analyse sound	Sound and ultrasonic waveforms Event Driven and Adaptive Frequency	.wav, .flac, .csv Sampling rate, timestamp	Emerging to Mature. Examples: CRYSound 2626G UAV	CRYSound 2626G UAV is Lightweight and rugged design. 64 MEMS microphones which provides accurate leak localization from the air using a wide detection frequency range of 2–65 kHz. This is also compatible with enterprise drones and has been	CRYSound 2626G UAV - price need to check with vendor and might come with integration cost or additional	Leak detection and sub-surface leak localisation, structure monitoring	[61] [62]

sources in the environment.				commercially available for the DJI drones. This has edge processing capabilities and images, video and .csv data can be exported from the app provided by the vendor. It does should evidence that the vendor might provide private cloud integration for processing of the media outputs and events Json files which can be then either pushed to client cloud environment either from the vendor cloud or from the ground edge compute unit.	attachments cost.		
Synthetic Aperture Radar (SAR): This is an advanced radar imaging technology which emits microwaves pulses and analyses the return echoes and produces high resolution images.	2D/3D images High Frequency	.ceos, sicd, .geotiff, .nitf, .img Angle, polarisation, wavelength, direction, acquisition time	Overall mature market. DJI offers CSM radar but it's not SAR but third-party SAR payload can be integrated on M300/M350 through the port available on the drone. Example: IMSAR NSP-3/5/7 other Radar are for fixed wing drones and are around 18kg	The weight of the overall IMSAR system is in the range of 3.5kg and can be mounted as the payload for the drone. This has its own SDK and platform (Lisa 3D) and can be powered by the drone and data can be shared via the Ethernet on the module which can then be pushed to the cloud API endpoint via the edge GPU Server (needs further investigation).	IMSAR NSP-3: need to contact vendor. DJI radar cost around £562 approx. not including mounting charges and integration (from heliguy)	All weather terrain mapping, vegetation structure analysis	[63] [64]

			payload which is not ideal for this scenario				
Telemetry: These are collection of sensors that are housed inside the drones to capture flight relation information of the drone.	Acceleration, orientation, angular rates High Frequency 2-70 MB/hr and Adaptive Frequency	.txt, .bin, .csv and some proprietary file structure Timestamp, calibration, time sync data with a network clock or GPS	Very Mature. Inbuild into the drones	Various ways to collect the telemetry data but generally can be push to the cloud via MQTT payload	Inbuild comes with the drone price.	Flight stability, motion correlation with sensor outputs	[65] [66]
Global Position system (GPS) and Global Navigation Satellite System (GNSS): Used in drone navigation.	Latitude, longitude, time, speed, altitude Event Driven Transm. and Adaptive Frequency	.gpx, .kml, .csv, .nmea, .rinex Timestamp, horizontal and vertical precision, real-time kinematic, precision point positioning	Very Mature. These come inbuild into the drone for real time kinematics (RTK) for knowing the real time position of the drone but can be attached as well. DJI D-RTK 2 Mobile Station, Emlid Reach M2, Septentrio Mosaic X5.	The DJI series comes with the RTK but mobile station can be attached such as DJI D-RTK 2 Mobile Station and can be placed on the survey point. Emlid Reach M2 which has a range of 100 km. Septentrio Mosaic X5. The raw data from all of them can be uploaded to the cloud via API.	DJI D-RTK 2: ~[redacted] (from talosdrones) Emlid Reach M2: ~[redacted] (from emlid) Septentrio Mosaic X5: ~[redacted] (from arkelectronics)	Geotagging, flight path mapping, georef. all sensor data	[67]

***Note: All pricing data represents approximate estimated compiled from multiple market sources and should not be considered definitive. Official vendor quotations must be obtained to verify current pricing, availability, and specifications prior to procurement decisions.**

Recommendations

Sensor set should align with core operational requirements identified during the discovery phase engagement with National Gas, specifically: vegetation growth detection, leak detection capabilities, and rapid incident response processes. The following use-case analysis defines the required sensor mounting configuration necessary to achieve specific operational objectives:

Use-Case 1 Vegetation Detection: Multispectral, RGB, LiDAR, Hyperspectral
Use-Case 2 Leak Detection: Optical Gas Imaging, Thermal IR, Environmental Sensors
Use-Case 3 Rapid Incident Response: RGB, Thermal IR, LiDAR.

Additional sensors identified in the above table may be deployed for other use-cases or implemented in combination configurations as specified within primary use-cases column. The selection and deployment rules for the above-mentioned scenario patrol would look like this for the above-mentioned sensors:

Mounted on the drone for **Daily Patrol:** RGB+ Thermal + Optical Gas Imaging (OGI)
Mounted on the drone for **Weekly Patrol:** Multispectral, and Hyperspectral
Helicopter for **By-Weekly Patrol:** Images (RGB Camera on the Raspberry Pi)
Satellite as per **Schedule Patrol**.

For the use cases:

Vegetation detection: LiDAR (for borderline cases to analyse the built-up in vegetation), Multispectral
Suspected Leak: OGI, other can also be used along with it
On-demand Major Incident: thermal, RGB, Lidar, Multispectral and Hyperspectral.

Some of the benefits for deploying drones are as below:

- early surface issues detection, lowering risk and early remedy means lower cost,
- autonomous drones provide in detail and higher quality of data of the area looking at recent built up and terrain change detection,
- unmanned flights mean avoidance of hazardous conditions, weather conditions and faster detection time as multiple sites can be patrolled, event driven activities, thus reducing over operational cost in long term,
- richer evidence grade data with strict data standards for processing and cross-sensor data validation/fusion,

3.3 Quantum and Photonic Sensing

3.3.1 Technology Overview and Capabilities

There are a multitude of quantum and photonic technologies with application in the monitoring of pipelines – they can be grouped into mature, off-the-shelf solutions, and emerging techniques that require more testing and/or integration efforts. General advantages include high sensitivity, speed, flexibility of implementation and multiparameter sensing, albeit at potentially higher costs compared to conventional systems. High data rates, particularly from hyperspectral and optical fibre systems, must be considered when implementing many of the technologies.

Table 5. Quantum and photonics sensing: performance characteristics, applications, integrations requirements, regulatory and security considerations, and market solutions.

Technology	Applications	Performance, advantages, limitations	Typical data formats, integration considerations	Regulatory and security considerations	Maturity available systems on market
Quantum magnetometry – atomic and diamond-based systems	Anomaly detection, encroachments, pipeline damage	Ultrahigh sensitivity for magnetic fields, potential noise challenges (thermal/vibration)	System dependent, e.g., Twinleaf outputs 1kHz signal with field amplitude, export to standard formats (e.g., columns of time, amplitude, exported in .CSV)	Export controls, US/Japan- based manufacturer. Defence applications result in high regulation	Emerging - small number of commercialised systems. Many academic systems in UK, lower Technology Readiness Level (TRLs). Example system: Magnetic sensing - QANT
Optical fibre sensing (including quantum-enhanced	Intrusion detection (tampering/damage to pipeline). Structural health monitoring (integrity of pipeline) and environmental monitoring (ground movement, temperature)	versatile methods of monitoring multiple parameters, including temperature, strain and vibrations. Real-time, continuous data on condition of pipeline/surrounding	Output data covers parameters - phase, amplitude, amplitude – standard formats (e.g., columns of time, amplitude)	Potential future supply chain issues due to current use of fibre in defence applications	Mature - deployed for, e.g., Distributed Acoustic/Temperature Sensing. Quantum-enhanced are lower TRL Example system: Pipeline link detection - OptaSense
Single photon techniques (quantum imaging)	Structural health monitoring, identify encroachments	Detection in difficult weather conditions (e.g., fog, with foliage)	Image data - depth data across an entire optical field of view, time stamping of photon arrivals to specific pixels	Examples export license controlled, e.g., the PF32 Camera Range	Emerging - and commercial systems available. References: [73, 74]

Hyperspectral / multispectral imaging (land/aerial)	Monitor vegetation density, composition along pipelines, identify encroachments	High spectral resolution (e.g., in terms of nanometres), albeit at high cost and high data volumes. Satellite imagery - tens of metres resolution, airborne ~ 1 cm, drone-based ~ sub-cm	Datacubes (x, y, wavelength) - each datapoint corresponding to intensity/amplitude - e.g., ENVI data format	No immediate considerations	Lightweight drone-based systems available, high cost for infrared systems in particular Example system: Spectral Imaging Platform
Visible light sensors/imaging	Visual inspection – e.g. monitor vegetation, threats, encroachments	Versatile, general technique, limited spectral resolution compared to hyper/multispectral imaging – spatial resolution	Conventional image formats (e.g., JPEG)	N/A	Mature, deployed widely
Thermal imaging	Abnormal temperature signatures – pipeline damage	High temperature/spatial resolution	Thermal image format – e.g., JPEG	Export restrictions vary based on specifications	Maturing technology, widespread availability
Neuromorphic imaging	Motion detection	High speed, low energy consumption	Image data - pixel-level brightness changes	N/A	Emerging technology with some commercial availability Example system: Prophesee Metavision Technology

3.3.2 Discussion, Comparison, and Summary

The above table contains various forms of imaging (neuromorphic, thermal, conventional imaging, hyperspectral), together with sensing technologies (quantum and fibre optics), which have their respective benefits and limitations.
Quantum technologies typically have lower TRLs, with a small number of examples commercialised; single-photon (quantum) imaging has specific advantages in this regard around monitoring through atmospheric obscurants, while magnetometry potentially provides an ultrasensitive means of, e.g., detecting machinery encroaching on pipelines. Typically, these techniques involve more integration considerations (software and hardware) by virtue of their emerging nature, and there is the need demonstrate, in the field, their advantages over competing non-quantum technologies, which include in terms of sensitivity, size, weight and power, stability and calibration requirements.

In addition, imaging technologies share similar data integration challenges, although it is important to note the volumes associated with hyperspectral imaging in particular. Many are sufficiently miniaturised to be drone-based (including magnetometry), as discussed, which benefits their use for monitoring pipelines and their immediate environment, providing greater flexibility. Multimodal sensing, harnessing multiple of the above imaging technologies, integrating diverse data streams, would thus enhance breadth of data collected and likely provide a means of more rapid detection of anomalies, yielding greater insights by combining an array for data sources. For example, thermal imaging and convectional (visible light) imaging are complementary, providing benefits for inspecting vegetation and highlighting temperature fluctuations.

Moreover, the broad applicability of fibre optics sensors, enabling the monitoring of temperature/vibration/acoustic signals, together with facilitating communication channels, makes them highly useful for monitoring the conditions around pipelines in this context. Trials of optical fibre systems have already been undertaken for event detection and classification - e.g., pipeline intrusion, ground disturbance by third parties, agricultural or construction activities in close proximity, seismic activity, Pipeline Inspection Gauge (PIG) detection, fluid disturbances within the pipeline; case studies are available from the Fiber Optic Sensing Association[3] . The costs of fibre deployment must be taken into account, together with the data volumes (e.g., OptaSense pipeline case study ~30 TBytes per day).

Recommendations

Considering costs, ease-of-use, implementation challenges, maturity and availability, the following steps would be potentially beneficial:

- Investigation of multimodal sensing, including multiple of the addressed imaging technologies (both quantum and photonic), to access their collective benefits, harnessing their complementary aspects. As many of the technologies have similar data formats and integration considerations, there would not be considerable software challenges in this respect. A small-scale investigation, including drone-based systems, would be advantageous in this context. Moreover, the costs of more mature technologies (e.g., visible light imaging) are also typically lower than those that are emerging (e.g. quantum magnetometry).
- Optical fibre sensing (including quantum-enhanced) has significant potential to prevent environmental damage to pipelines, due to its breadth of applications, sensitivity and ease-of-use when deployed. A limited potential trial would be greatly

[3] https://fiberopticsensing.org/page/fosa-case-studies-papers

beneficial – it would access how effective the test system is for an array of use cases (e.g. construction activities, ground disturbance), address the challenges of deployment (in terms of hardware and software) whilst also providing an estimate for the costs involved in wider deployment. Moreover, this form of sensing is also complementary to the above imaging techniques, enabling continuous monitoring of pipelines and their immediate vicinity, as opposed to periodic assessment. This form of sensing has been developed and deployed in infrastructure monitoring more broadly, including in terms of bridges, railways and road, enabling, e.g., structural health monitoring and perimeter monitoring.

4. AI-Based Surveillance Monitoring

The primary objective of implementing an AI-based surveillance system is to fundamentally transform how National Gas monitors and its critical infrastructure assets. This transformation is driven by three core design goals: automation for operational efficiency, enhanced accuracy in event/threat detection and asset assessment, and continuous long-term monitoring capabilities that extend far beyond the temporal and spatial limitations of traditional snapshot methods such as helicopter inspections.

Previous sections explored opportunities to integrate new technologies into National Gas surveillance methods for data collection, processing, and alert deployment. In this section, we propose a data pipeline and architecture designed to integrate the diverse data sources outlined before. This integration framework will incorporate enabling technologies and services necessary for seamless data flow and processing, together with an intelligent AI model for autonomous surveillance. The AI model is expected to monitor assets using both real-time data and historical data streams, incorporating existing surveillance infrastructure, new data sources that may include satellite monitoring, classical and quantum sensing, drones, together with condition monitoring sensors, and other relevant data sources. Two specialized AI models tailored for distinct operational use-cases, vegetation growth detection and third-party interference monitoring, are presented as well.

4.1 Data Pipelines Architecture

The proposed data integration framework is illustrated in Figure 6, which presents the conceptual architecture for integrating multiple data sources into the proposed AI monitoring system.

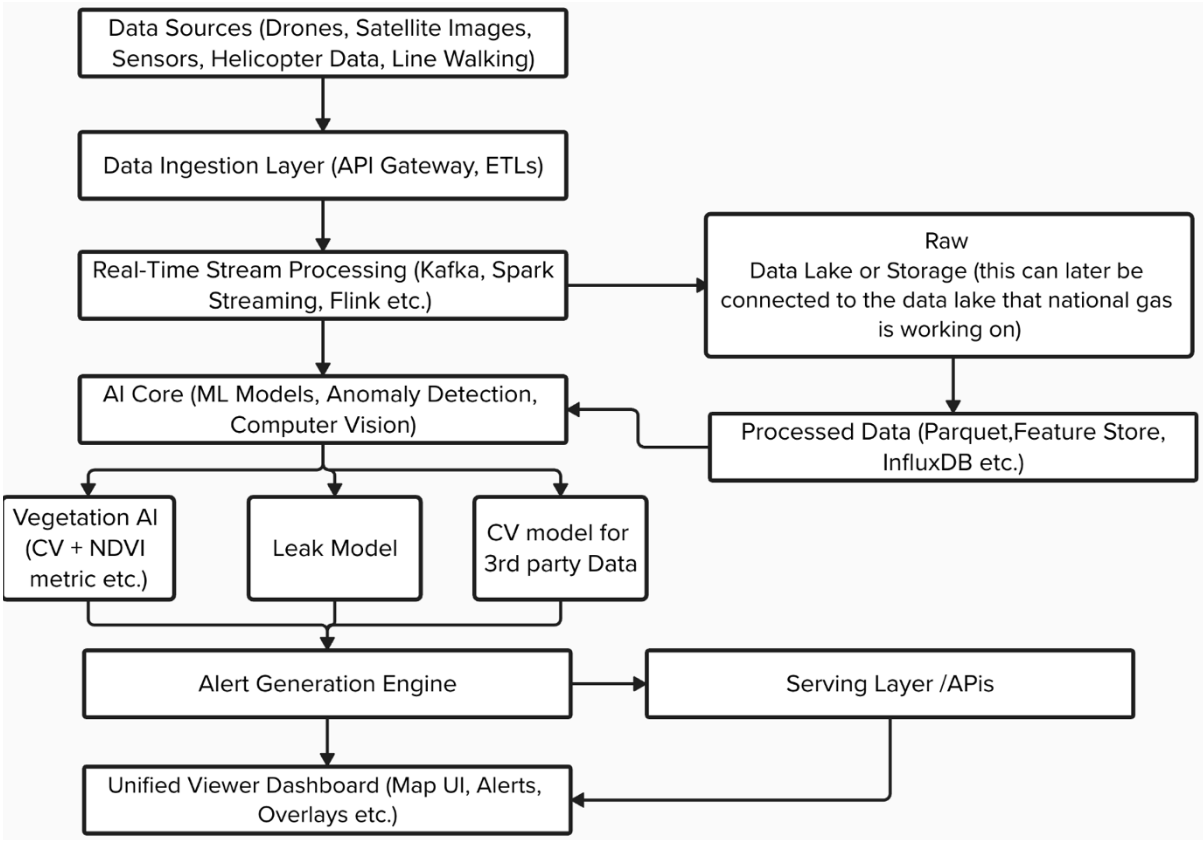

Figure 6. Data pipeline architecture for the AI-based surveillance monitor (Please note that examples provided are for understanding only and this may change in the future).

4.1.1 Data Ingestion Layer

The data ingestion layer will get data from aggregated diverse streams via Application Programming Interfaces (APIs), these could be Restful APIs, or ingestion pipelines for real time and historical data processing. These sources are through Drones (e.g., video, thermal, LiDAR), Satellites (e.g., imagery, NDVI), Quantum sensors (e.g., seismic, microleak detection), Ground-based IoT sensors (e.g., pressure, temperature) and Public APIs (e.g., weather, planning permissions). The existing and new data sources that were highlighted are listed below:

a. Current:
   i. Line walking images, inputs, etc.
   ii. Helicopter data and autonomous drones stored in hard disk
   iii. Sensor's data

iv. Asset performance data
v. Weather/ British Geological Survey (BGS) Data
vi. Local Planning Permissions data
vii. National Digital Projects (digital Construction Data, HyNTS dataset and CVDT

b. New data sources in the future:
   i. Satellite images
   ii. Drones
   iii. Quantum and classic sensors

Once the data is received this must be processed so that it is in the required format for the AI surveillance to process as necessary.

4.1.2 Real-Time Data Processing and Data Architecture

Real time data processing will pull data in real-time from all the different data sources into streaming engines which can preprocess the data (e.g., georeferencing images, cleaning sensor data, filter the data or manipulate) to normalise formats and timestamp the data. Listed below are examples of technologies that can be used:

- Apache Kafka[4], Apache Flink[5], or Apache Spark Streaming[6], etc.
- Functions that may be performed on the data:
  - Time-series anomaly detection
  - Real-time computer vision inference
  - Filtering and preprocessing sensor and satellite image data

The data collected could be stored and processed as outlined below before being handed over to the AI software for use. This is the plumbing on how and where data lives, and how it flows between layers.

The raw or unprocessed data collected is varied in nature consisting of images, video and sensor data and can be stored in a data lake for processing in scalable storage such as (Amazon S3[7], Hadoop Distributed File System (HDFS)) or in the cloud as is currently being done for existing sensor data. This would help keep historical records for model retraining and auditing as well as help with inspection of anomalies in data.

[4] https://kafka.apache.org/
[5] https://flink.apache.org/
[6] https://spark.apache.org/streaming/
[7] https://aws.amazon.com/s3/

The processed data could be in the form of curated datasets in structured formats (e.g., Parquet[8]) or time-series DB (e.g., TimescaleDB[9]/InfluxDB[10]) for sensor data or Geospatial DB (e.g., PostGIS[11]) for spatial queries.

4.1.3 AI Core/Intelligent Workflows

The AI core currently refers to more AI intelligent workflows that can be designed as per the use cases provided. Design AI models to detect vegetation growth (NDVI + computer vision), ground movement (LiDAR/vibration anomaly detection), third-party activity, microleaks (sensor fusion), and signage damage. Use both rule-based and ML/AI alert generation. There should also be a feature store such as feast for reusing the ML/AI data and also a model registry such as MLflow[12]/Amazon SageMaker[13] for version control of AI models.

AI models per task:

- Vegetation Overgrowth: NDVI from satellite + Computer Vision from drone video
- Ground Movement: LiDAR & seismic data → anomaly detection
- 3rd-party Activity: CV + object detection from drone & Closed-Circuit Television (CCTV) feeds
- Microleaks: Sensor fusion of acoustic, quantum, pressure data
- Signage Damage: Image classification from drone passes

The recommendation is to leverage ML for anomaly detection (e.g., random forest, Support Vector Machine (SVM)), fusion with acoustic/pressure sensing, and attention mechanisms for temporal dependency detection. The design should include AI models optimized for sensitivity, false-alarm reduction, and interpretability. An example of AI/ML Processing approaches:

1. **Computer Vision**
    a. Object detection (e.g., YOLOv8[14], Detectron2[15]) for vehicles/machinery near pipeline right-of-way.
    b. Image segmentation (e.g., U-Net[16], SegFormer[17]) for vegetation mapping.

2. **Time-Series Anomaly Detection**

[8] https://parquet.apache.org/docs/file-format/
[9] https://github.com/timescale/timescaledb

[10] https://www.influxdata.com/

[11] https://postgis.net/
[12] https://mlflow.org/
[13] https://aws.amazon.com/sagemaker/
[14] https://yolov8.com/
[15] https://github.com/facebookresearch/detectron2
[16] https://github.com/jakeret/tf_unet
[17] https://github.com/NVlabs/SegFormer

a. Long Short-Term Memory (LSTM) / Gated Recurrent Units (GRU) / Temporal Convolutional Networks for sensor readings.
b. Autoencoders for unsupervised detection of rare events.

3. **Sensor Fusion Models**
    a. Combine satellite, drone, and ground sensor data into a single ML model.
    b. Use Bayesian fusion, Kalman filters, or multimodal deep learning.

4. **Change Detection:** Compare recent imagery to historical baselines to detect new activity or landscape changes.

5. **Predictive Models:** Forecast maintenance needs or potential failure points based on historical patterns.

4.1.4 Alert Generation & Rules Engine

Based on the data provided and features that are needed the AI Surveillance Monitor can generate alerts as a combination of rule-based and AI-based fusion of conditions. Alerts can also be generated on a use case basis and below points:

- Severity (critical, high, medium, low)
- Prioritized for operator action or Human-in-the-loop (Tiered alerting (auto-resolve low-confidence; analyst review for medium; dispatch for high and critical))
- Scoring.

4.1.5 Viewer Platform

The alerts generated can be viewed on an external dashboard via API or a serving layer or connected to the CVDT Viewer Platform at a later stage as highlighted in the workshops. This could be map-based UI depicting different aspects of a use case such as vegetation growth or an alert management dashboard. The dashboard could have layers for: live drone feeds, satellite overlays, sensor alerts, historical data comparison.

A summary of examples of technology Stack that can be used for the different components of the architecture and can be seen in the table below.

Table 6. Examples of technology stacks for the architecture in Figure 6.

[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

Please note that the architecture diagrams and examples provided above are recommendations only and should not be considered as the final design for the AI Surveillance monitor. This is only a representation of what it may look like based on assumptions and can only be confirmed once the requirements and data for it are provided.

Recommendations

The following strategic aspects should be considered:

1. Data Governance & Compliance

- Define **data ownership** (especially for commercial satellite data).
- Ensure compliance with **local privacy laws** (e.g., General Data Protection Regulation (GDPR) for EU-based monitoring).
- Create **data quality standards** for ingestion pipelines.

2. Partnerships & Vendor Management

- Build agreements with satellite imagery providers for **on-demand high-resolution captures** during suspected events.
- Work with drone service companies for **scheduled and emergency aerial surveys**.
- Partner with IoT vendors for sensor installation and maintenance.

3. Reusable Data Pipelines

- Define small reusable data pipelines for data integration, cleansing and feeding to other ML pipelines. [75]

4. AI Model Lifecycle Management

- Implement **continuous model training** with fresh data.
- Use **model explainability** (e.g., SHapley Additive exPlanations (SHAP [18]), Local Interpretable Model-agnostic Explanations (LIME [19])) to justify AI decisions for regulatory reporting.

[18] https://shap.readthedocs.io/en/latest/
[19] https://c3.ai/glossary/data-science/lime-local-interpretable-model-agnostic-explanations/

- Deploy a **shadow mode** (monitoring without acting) before full automation to validate model accuracy.
- Implement Machine Learning Operations (**MLOPs)** best practises for data ingestion pipelines, model training/retraining and automation of ML workflows.
- Incorporate scalable (possible Directed Acyclic Graph (DAG)-based) workflow automation to implement the ML model data preprocessing, model training, evaluation, and maintenance [76].

5. Operational Readiness

- Create a central space to monitor AI alerts (this could be the CVDT viewer in the future).
- Train field teams to **verify and act** on AI-generated alerts. Have a human in the loop where necessary.
- Have a **failover plan** in case of AI system outage.

6. Scalability & Reliability

- Start with **pilot deployments** in high-risk pipeline sections.
- Build infrastructure that can **scale** if there is a need for more sensors or more imagery. This also applies to the data pipelines and the AI surveillance monitor.
- Use **edge AI** for remote areas with low connectivity — processing data locally on drones/sensors.

7. Security

- Use **end-to-end encryption** for sensor-to-cloud data.
- Harden APIs against unauthorized access.
- Monitor AI system logs for cyber-attack patterns.

4.2 An Example Workflow

Through structured discovery workshops conducted with National Gas stakeholders, critical risk scenarios requiring monitoring were identified as follows:

Vegetation-related:

1. **Vegetation hiding or blocking assets** that the gas pipeline monitoring team need to see or reach (e.g., signs, route markers, covers, valves, access points, etc), making it harder to carry out routine work or respond to emergencies.
2. **Vegetation roots changing the ground above the pipes** (i.e., rising, sinking, or disturbing the soil), potentially putting stress on the pipe or joints.

Third-Party Interferences (TPI) related:

3. **Digging, drilling or farming above the pipeline** without checking the plans, hitting or scraping the pipe (damages now or leaks later).
4. **Constructing or placing things on the pipeline route** (e.g., driveways, walls, sheds, stockpiles), which blocks access for inspection or emergency repairs.

This report focuses on the first risk scenario, specifically "vegetation hiding or blocking assets".

4.2.1 Summary of the Vegetation-related Workflow

An AI-based monitoring solution has been developed by the Digital Catapult team to address vegetation overgrowth detection, depicted in Figure 7, and summarized as follows:

1. **Helicopter pre-screening:** Aerial photos collected manually during helicopter survey serve as the first entry point. Observers flag pipeline Right-of-Way (ROW) sections with suspected vegetation issues. This ensures that detailed analysis is focused only on potentially problematic locations and assets.
2. **Satellite confirmation:** Optical and multispectral imagery of the flagged areas is used to compute vegetation indices (NDVI, Normalized Difference Red Edge (NDRE), etc.) and detect changes over time. This adds an objective second opinion on vegetation density and growth trends around the pipeline corridor. The reliability of satellite imagery is highly dependent on the weather conditions.
3. **UAV/drone high-resolution survey:** Targeted drone flights over flagged pipeline sections capture RGB (nadir + oblique), multispectral, and optionally LiDAR data. Outputs include orthomosaics, canopy height models (Digital Surface Model/Digital Terrain Model/Canopy Height Model (DSM/DTM/CHM)), and vegetation masks. These datasets provide detailed confirmation and can be reviewed manually by experts or fed to AI models. This could be optional if the alternative sources, satellite imagery and sensors are reliable.
4. **Sensors and CCTV (where available):** Local environmental sensors (humidity, soil moisture, vibration, acoustic, etc.) and fixed cameras add real-time context. These

inputs detect growth-favourable conditions, sudden disturbances, or direct visual evidence of encroachment, complementing aerial/satellite data.

5. **AI based analysis:** Multi-modal analytics apply object detection (YOLO/DETR) to locate assets, segmentation models (SegFormer/Mask2Former) to map vegetation, visibility classifiers to assess asset occlusion, canopy height estimation from LiDAR, and bi-temporal change detection. Each modality contributes features (e.g., NDVI, occlusion index, growth trends, moisture anomalies, etc.) into a fusion step.
6. **Data fusion & risk scoring:** Rule-based logic, weighted confidence scoring, or ML fusion models combine satellite, UAV, sensor, and CCTV evidence. Outputs are vegetation risk scores, asset visibility status, and growth urgency, along with supporting image/sensor evidence.
7. **Automated alerting:** Alerts are triggered when risk scores exceed thresholds. These can be routed to manual verification of processed imagery or other evidence, line walking team to follow up or even detailed drone/helicopter surveys.
8. **GIS dashboard integration:** All outputs are fed into the operator's GIS, showing pipeline corridors color-coded by vegetation risk, asset visibility (visible/hidden), and flagged points. Engineers can drill down to see drone orthomosaics, CCTV frames, or sensor graphs, and feedback loops help refine models over time.

A multi-tier monitoring system that leverages satellite imagery, ground-based sensors, and fixed camera installation as primary surveillance tools, with UAVs serving as secondary verification assets can be used. Upon successful validation and deployment this integrated approach has the potential to significantly reduce operational reliance on traditional helicopter-based routine monitoring processes.

Key terms used in the workflow diagram:

- **UAV -** Uncrewed Aerial Vehicle or drone used to capture images or LiDAR over the pipeline corridor.
- **Nadir / Oblique** - Nadir - camera pointing straight down; Oblique - angled shots to see under canopies and around objects.
- **NDVI** - Normalized Difference Vegetation Index; a simple ratio from red & near-infrared light that indicates how healthy/green vegetation is.
- **NDRE** - Normalized Difference Red-Edge Index; like NDVI but uses the “red-edge” band to better capture leaf chlorophyll in mid/late growth stages.
- **RTK** - Real-Time Kinematic; method that corrects GPS positions in real time for centimetre-level accuracy.
- **PPK** - Post-Processed Kinematic - like RTK but corrections are applied after flight during processing (often more reliable where radio links are weak).
- **Photogrammetry** - Turning overlapping photos into 3D models and accurate maps by matching features and solving camera geometry.
- **Orthomosaic** - A map-like image created from many photos that have been geometrically corrected so you can measure distances/areas accurately.
- **DSM / DTM / CHM** - Digital Surface Model (tops of everything), Digital Terrain Model (bare ground), Canopy Height Model (tree height = DSM − DTM).
- **ROW** - Right-of-Way; the corridor along the buried pipeline that must be kept clear for access and safety.
- **Bi-temporal change detection** - Comparing two dates of imagery to find what changed (e.g., new excavation, fresh ground disturbance, new vegetation cover).

AI models referenced

- **YOLO** - A fast object detector (finds valves, markers, machinery, etc., in images).
- **DETR** - Transformer-based object detector that simplifies the detection pipeline.
- **SegFormer / Mask2Former** - Segmentation AI models that produce pixel-accurate vegetation masks and can separate object/vegetation classes.
- **GBM –** Gradient boosting machines are an ensemble learning method that builds models sequentially, where each new model corrects the errors of the previous ones.

4.2.2 Summary of the Third-Party Interference Workflow

An AI-based monitoring solution has been developed by the Digital Catapult team to address the third-party interference detection, depicted in Figure 8, and summarized as follows:

1. **Helicopter pre-screening:** Routine helicopter survey remains the mandated entry to this monitoring workflow. Aerial video or still imagery is automatically analysed (and/or manually observed) to detect signs of unauthorised excavation, heavy machinery near the right-of-way or assets, or new structures. This ensures detailed analysis and follow-up are focused only on potentially risky pipeline sections.

   This helicopter pre-screening acts as the trigger for multiple other ways to monitor and verify the information. This can be automated or manual triggering.

2. **Satellite confirmation:** High-resolution optical and radar imagery of the flagged areas is used to detect third party activities near the assets, new access tracks, machinery presence, or structural changes. Additional seasonal land-use layers (e.g., Crop Map of England) help differentiate between normal farming cycles and suspicious third-party activity.
3. **UAV/drone survey:** Targeted drone flights over risk locations can confirm and provide highly detailed context. This may not be always needed in situations where the satellite imagery can verify the results. Eventually, in a condition-based monitoring approach where no helicopter survey is required, UAV survey can be used as the next layer of verification of activities after a satellite-based pre-screening.
4. **Ground sensors and CCTV** (where available): Local environment sensors and fixed cameras can be used for real time monitoring when needed at installed locations. Different sensors and fixed cameras can detect excavation activity, vehicle crossings, or repeated heavy loads over pipeline corridors or near other similar activities near assets. These inputs provide immediate warnings between scheduled aerial patrols but limited to the locations where the sensors or cameras are installed.
5. **Works and planning intelligence feeds:** This information can be used to verify activities at certain locations. It also adds ahead of time context to be vigilant about any planned activities at critical locations. Comparing helicopter/satellite/UAV detections against these sources helps filter legitimate vs. unauthorised activity.

   Here are some potential sources of information;

   1. Roadworks Service API (Street Manager)
      Available at: https://findtransportdata.dft.gov.uk/dataset/roadworks-service-api-street-manager
   2. One.network:
      Available at: https://one.network/
   3. Planning and housing data in England
      Available at: https://www.planning.data.gov.uk/
   4. Searchland, sourcing and evaluating land property opportunities
      Available at: https://searchland.co.uk/
   5. Planning Alerts for specific areas:
      Available at: https://planning.org.uk/
   6. Linesearch before U dig:
      Available at: https://lsbud.co.uk/
   7. Road traffic statistics from the Department of Transport
      Available at: https://roadtraffic.dft.gov.uk/downloads
   8. National Underground Asset Register (NUAR)
      Available at: https://www.gov.uk/guidance/national-underground-asset-register-nuar
   9. Crop Map of England (CROME)
      Available at: https://www.data.gov.uk/dataset/be5d88c9-acfb-4052-bf6b-ee9a416cfe60/crop-map-of-england-crome-2020

The complexity of implementing this system can vary depending on the trade-offs between accuracy, computing capacity, and carbon footprint. This system potentially could include API calls to pull information related to planning and permissions. The sources of information could be text results, pdf files, images, etc. We may need to use Large Language Models (LLMs) to parse and extract relevant information from multiple sources. If there are more reliable sources that could provide us information in the expected format from APIs, this component could be as simple as some simple rules.

6. **AI-based analysis:** Multi-modal analytics detect and classify suspicious activity. A fusion layer combines evidence from helicopter, satellite, UAV, ground sensors, and works intelligence. Rule-based or ML scoring produces TPI risk ratings based on proximity to the pipeline, type of activity, absence of authorisation, asset criticality, and depth of cover. The detections are then compared against permits, planning applications, or Line search before U dig (LSBUD) notifications.

   Overall, this unit is responsible for intelligently combining different types of information from all the above-mentioned sources. Monitoring could be feasible for excavations, any heavy machinery, encroachment recognition for driveways, sheds, or walls, and traffic load risk estimation from vehicle patterns, etc which depends on the availability of data.

7. **GIS dashboard integration:** All the detections can be integrated into an existing or new dashboard with detailed map-based visualisations and drill down ability to detailed information with proofs (like images indicating activities)
8. **Condition-based monitoring feedback loop:** This help to improve or train the AI models and to improve the decision rules. Once confidence builds, continuous feeds (permits, planning, satellite, sensors, and fixed cameras) can be used to drive proactive monitoring. UAVs and/or helicopters would then serve primarily as verification and response tools, reducing reliance on routine visual patrols alone.

Note: Additionally, there could be an Agentic AI based chat interface that could ease the interaction with the monitoring system. The features could include;

- Conversational querying - natural language questions instead of SQL/GIS filters.
- Context aware retrieval - links into GIS layers, permits, planning feeds, UAV imagery, CCTV, sensor logs.
- Chain of thought style reasoning - agent explains why an incident was flagged.
- Integration hooks - can trigger downstream workflows and access other tools for triggering or taking relevant actions.

5. Concluding Remarks

National Gas aims to develop a robust multi-layer asset surveillance system embedded with AI to create a more efficient surveillance regime. The primary objective of implementing this AI-based surveillance system is to fundamentally transform how National Gas monitors its infrastructure. This transformation is driven by three core design goals: automation for operational efficiency, enhanced accuracy in event and threat detection, and continuous long-term monitoring capabilities that extend far beyond the temporal and spatial limitations of traditional snapshot methods such as helicopter and line walking inspections.

This project has explored opportunities to integrate innovative technologies into National Gas surveillance methods for data collection, processing, and alert deployment. The study looked at satellite monitoring, drone-based platforms, classical sensing technologies, and emerging quantum sensing capabilities as potential updates or additions to traditional surveillance methods. The technical assessment provided an evaluation of these key enabling technologies that can form the foundation of the proposed multi-layer surveillance architecture. Each technology was evaluated across multiple dimensions to inform decision-making and system design, covering fundamental principles and operational characteristics, commercially available market solutions and vendors, data output formats and resolution capabilities, service costs where available, and technology readiness levels with particular focus on quantum sensing applications.

Building upon this technological foundation, we proposed a data pipeline and architecture designed to integrate diverse data sources into a unified surveillance system. This integration framework incorporates enabling technologies and services necessary for seamless data flow and processing, coupled with an intelligent AI model for autonomous surveillance. The proposed AI model is designed to monitor assets using both real-time and historical data streams, incorporating existing surveillance infrastructure alongside new data sources including satellite monitoring, classical and quantum sensing, drones, condition monitoring sensors, and other relevant operational data sources.

Two specialized AI models have been presented; each tailored for distinct operational use cases: vegetation growth detection and third-party interference monitoring.

Throughout this report, detailed recommendations have been provided within each specific technical section to guide implementation strategies and technology adoption pathways. These recommendations form the basis for the strategic proposals that follow.

Next, we will present our consolidated recommendations and the proposal for Alpha development and testing. This will be conducted through a collaborative workshop organized with different stakeholders at National Gas to ensure alignment with operational requirements, validate technical approaches, and establish clear pathways for system development and deployment.

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Annexes

Annex 1: Powerful DJJ Payload/Sensors List [3,4]