Article Type

Intelligent IoT and UAV-Assisted Architecture for Pipeline Monitoring in OGI

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Abstract—With the advent of the Internet of Things (IoT) and Unmanned Aerial Vehicles (UAVs) in industrial application scenarios, Oil and Gas Industries (OGI) automation is undergoing a remarkable transformation. Existing monitoring methods, like IoT sensor-based surveillance, offer accuracy but struggle with transmission inefficiency. Conversely, UAV-based surveillance enables seamless communication but limited sensing capabilities. This article addresses the challenges of latency, energy efficiency, and cost in state-of-the-art leakage detection technologies for OGI pipelines. A three-tier architecture is proposed, integrating IoTs, UAVs, and Artificial Intelligence (AI)-empowered Edge Computing to enhance pipeline surveillance. We aim to propose specialized routing that addresses IoT energy and fault tolerance issues, while UAVs act as relays to transmit data efficiently to control centers, considering factors like UAV energy and data complexity. Intelligent edge services optimize data transmission, prolong UAV lifespan, and manage latency. Various use cases are explored, and open research challenges with potential solutions are presented.

The oil and gas market is expanding continuously being one of the primary needs of modern society. Oil and gas transmission and distribution network relies on pipelines, which are considered relatively safe but not entirely risk-free. Therefore, ensuring the reliability of the entire pipeline infrastructure in the oil and gas industry (OGI) is of utmost importance and has direct implications on industrial and urban security. According to CIA figures, the total length of worldwide oil and gas pipelines was around 35,50,000 km in 2017 [1]. Critical functions associated with OGI are Inspection, Maintenance, and Repairing (IMR) of large pipelines. IMR experiences various challenges that are equipment failure at pumping stations, cavitation, fire hazards, leakages caused by excavation, and corrosion [2]. Hydrocarbon leaks that occur due to pipeline damage pose a serious threat to ecological health and human safety. Therefore, detecting oil and gas leaks at an early stage could be a lifesaver [3]. Temperature, pressure, and flow values fluctuate when oil and gas are not transported smoothly from one point to another due to leaks or any other previously defined pipeline damages[4].

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Recently, cutting-edge technologies like IoT, UAVs, and robots have emerged as highly efficient and cost-effective solutions for automating and controlling OGI processes. Fiber optic solutions are indeed prevalent in the OGI for pipeline inspection due to their data accuracy and transmission capabilities but suffer from drawbacks such as high installation costs, vulnerability to external factors, and limited flexibility. UAV systems, on the other hand, provide easy access to difficult-to-reach areas but are limited in terms of sensing capabilities, lacking the ability to measure pressure, temperature, and flow within the pipelines [5]. IoT solutions collect data from various sources, but challenges exist in terms of efficient transmission, fault detection, timely transmission, and energy efficiency [6]. Hybrid systems combine IoT and other communication means, but they still face challenges related to installation costs, robustness, energy efficiency, and timely transmission [7], [8]. The majority of pipeline monitoring work focuses on giving single technology-based solutions [9], [6]. Various solutions for different domains use hybrid systems composed of IoTs and UAVs for example they are implemented in smart cities. However, OGI pipeline monitoring has its specific challenges and parameters different from other applications e.g., pipelines pass through harsh terrain where no alternate communication infrastructure is available. Therefore, these harsh scenarios considerably change the problem formulation, energy modeling, and strategies for fault-tolerance, low-latency, and energy efficiency of proposed technologies.

Design Principles for OGI Pipeline Surveillance Architecture

For a high-performance OGI pipeline surveillance architecture addressing the challenges of long pipelines, key design principles include:

Efficient communication (low latency communication): Pipelines traverse hazardous environments, lacking nearby communication infrastructure. High latency delays can lead to larger leaks, environmental harm, and safety risks.

Accuracy: Precise data is crucial for leak detection, enabling prompt and targeted responses to pinpoint leak sources with confidence.

Cost: Deploying communication infrastructure along vast, harsh terrain of OGI pipelines is expensive and high-maintenance.

High Availability and Fault-Tolerance: Robust monitoring systems are vital across remote pipelines spanning thousands of kilometers.

Research Contributions: On the basis of the discussion above, the main contributions to the research of this work can be summarized as laid out below:

- Proposing a three-tier architecture integrating IoTs and UAVs for smart pipeline monitoring, using IoTs for accurate leakage data and UAVs as communication relays.
- Presenting an energy-efficient, fault-tolerant, low-latency communication technique for IoT nodes.
- Developing a UAV deployment and energy-management strategy for robust communication to control centers.

The rest of the paper is organized as follows. We discuss the low-tier, mid-tier, and high-tier architecture of the proposed intelligent monitoring of OGI pipelines respectively. Different use case scenarios are discussed. Next, we debate future research directions. Finally, we conclude the article.

IoTs-UAVs assisted architecture for OGI pipelines

A dedicated distributed network architecture for real-time surveillance of the OGI pipeline is designed using a fusion of multiple technologies, such as UAVs, IoTs, and Delay Tolerant Networks (DTN). We propose a 3-tier architecture comprising IoTs (Low Tier), UAVs (Mid-Tier), and Edge Computing (High Tier). The three-tier architecture is depicted in Figure 1.

LOW-TIER: IOTS

The lower tier consists of IoT devices deployed on OGI pipelines, equipped with sensors like temperature, pressure, and flow detectors to monitor and identify leaks. The main objective of this tier is to efficiently collect data and transmit it to the middle tier [10].

Functional Architecture of IoT nodes

An IoT sensing node comprises of the following units: Sensing unit, Location finding unit, Processing unit, Transceiver, Battery, and Memory. An IoT module is made up of three layers: sensing, networking, and application as shown in Table 2. The sensing layer is composed of the following sensors that are responsible for gathering data from OGI pipeline: (a) Temperature sensor, (b) Pressure sensor, (c) Ultrasonic sensor used for corrosion detection, (d) Flow sensor for accurate flow measurements. The networking layer enables communication with middle-tier components such as UAVs. A radio transceiver is used to enable short-range communication. The application layer provides the user with the appropriate interfaces to interact with the sensor modules.

Deployment Strategy

The monitoring sensors are arranged in a linear fashion along the pipelines, with each node having precisely one forward and one backward neighbor along the line. The lower tier consists of two types of nodes:

TABLE 1. OGI Monitoring Challenges & Parameters

		Important parameters			
Sr#	Recent Approaches	Cost-effective	Accuracy	Low latency	Fault-tolerance
1.	Fiber optic cable	no	yes	yes	no
2.	IoT based solutions	yes	yes	no	no
3.	UAV based solutions	no	no	yes	yes
4.	Our Proposed Hybrid Solution	yes	yes	yes	yes

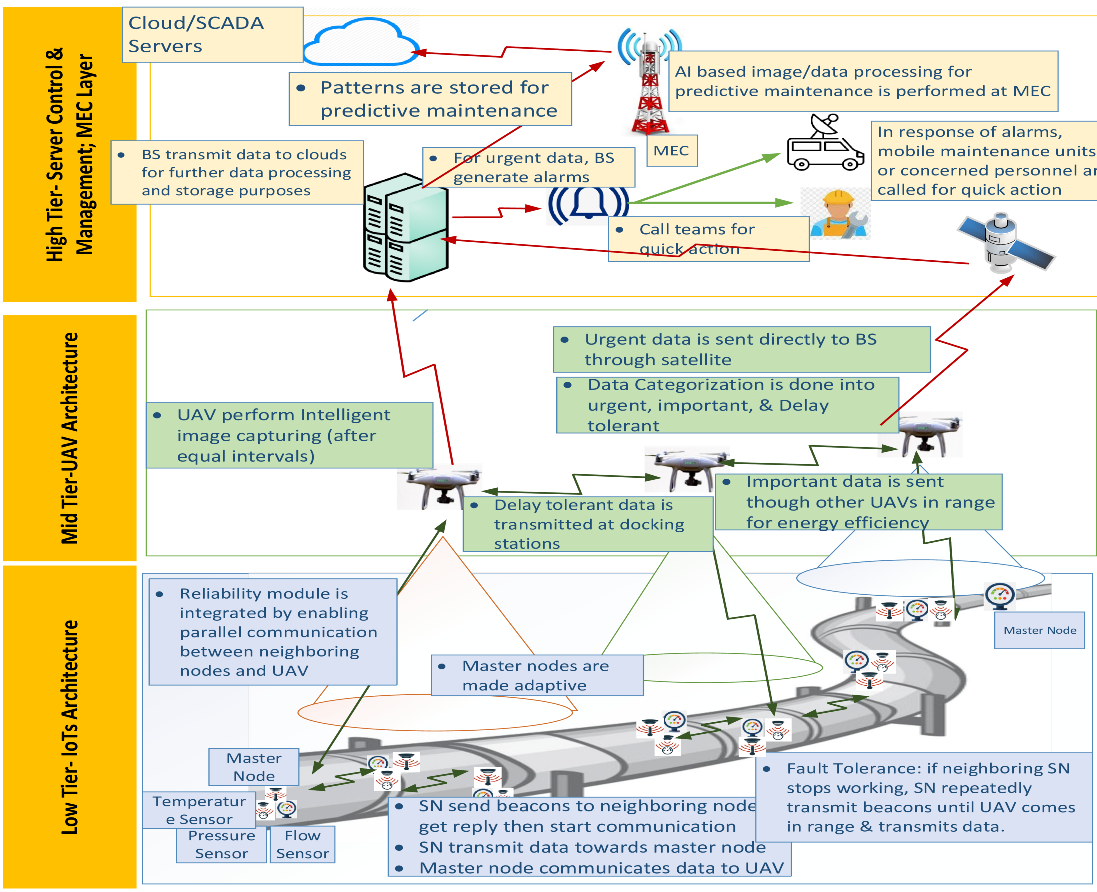

FIGURE 1. Schematic diagram of proposed 3-Tier Architecture for smart Pipeline Monitoring

Sensor Nodes (SN) and Master Nodes (MN). Pumping stations are built every 20 to 100 miles along a pipeline, based on the terrain, the pipeline, and station's capacity, and the type of commodity being transported [11].

Energy Management of IoT Nodes

OGI pipelines often traverse remote or inaccessible areas, making it logistically challenging for energy management of the IoT nodes to access and replace batteries in certain locations. This can lead to delays and increased costs. In our proposed architecture, we employ energy harvesting methods to tackle the energy requirements of IoT nodes in OGI pipeline harsh monitoring scenarios. A combination of solar energy and thermal energy harvesting techniques are implemented in IoTs to ensure these devices can operate reliably and autonomously without the need for frequent battery replacements or external power sources [12].

IoT Data Communication challenges

The installation of IoTs on thousands of kilometers-long pipelines that traverse hazardous environments presents numerous communication challenges.

Energy-Efficiency: IoTs are battery operated and managing IoTs batteries on a vast length of the pipeline

TABLE 2. IoT and UAV Module Layers

Module Layers	Purpose	Components	Examples
IoT Module Layers			
Sensing	Sense and gather data (leak, corrosion, etc.)	Sensors, Cameras	Gas, Acoustic, Temperature, Pressure, and flow sensor
Networking	Provide short-range communication with UAVs	Radio Transceiver	–
Application	Wireless Sensor Network (WSN) physical topology	Application Interface	–
UAV Module Layers			
Sensing	Sense & gather data (Computer Vision)	Cameras, Sensors	Stereo, Gas Infrared (IR) camera, Laser Fluoro sensor
Networking	Provide long-range communication	Radio Transceiver, Telemetry Link	–
Application	Provide interface to operate UAV	Application Interface	–

is a challenge. Therefore, achieving energy-efficient IoT communication becomes a challenging task.

Fault-tolerance: The interruption caused by defective IoTs in the pipeline fault detection mechanism can result in OGI loss. Therefore, it is essential to detect these faulty IoTs. However, the absence of automation makes defect detection a challenging task.

Low-latency communication: Efficient transmission along pipelines is challenging therefore an IoTs routing mechanism that offers low latency is of significant importance.

Proposed Energy efficient, Fault-tolerant, and low-latency IoT communication

SN sends data to MN, capable of storing and sharing that data with a mid-tier (UAV). When an IoT node wishes to establish contact with other nodes, it sends out a beacon to other nodes in its proximity, and after receiving a reply, communication starts. The range of MN is made adaptive for energy-efficient communication with UAVs. In a linear pipeline inspection scenario, SN can only communicate with one of its best neighbors towards MN considering the shortest hop count and remaining energy of the next node. If it is unable to communicate with the designated node, it tries to communicate with an alternate neighbor. In case, no response is received from both neighbors, the node would emit beacons repeatedly until a UAV comes within range and receives data. Fault tolerance and reliability are handled by allowing parallel communication of data from nodes to relay nodes (MN) and UAVs.

The flow of the proposed 3-tier architecture is shown in Figure 2.

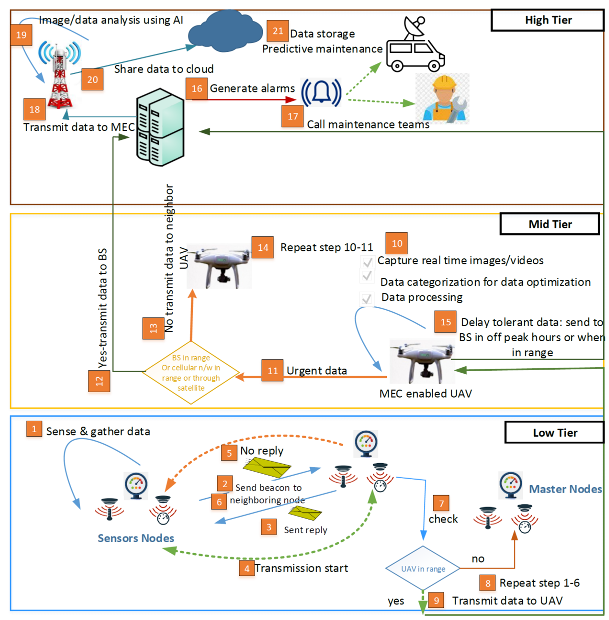

FIGURE 2. Flow diagram of Smart Pipeline Monitoring

MID-TIER: UAVS

The mid-tier is composed of UAVs that are used for detecting and localizing the IoTs in the low-tier. The basic components of UAVs are a battery, telemetry link, Arduino, and Radio Control (RC) receiver. UAVs work as a Relay Node (RN) between the IoTs and Edge computing servers. Cameras on UAVs provide real-time images/videos for response to any unusual event. It also enhances the accuracy of IoT localization and reduces reliance on satellite systems, which may not be precise enough for OGI pipeline monitoring. Autonomous UAVs capable of independently conducting surveillance operations are employed. Oil and gas infrastructure, particularly OGI pipelines, are often situated in challenging and hazardous environments where human intervention is impractical for continuous monitoring. By enabling autonomous inspection tasks, we not only expedite the inspection process but also enhance cost efficiency, reducing labor costs and minimizing the risk of human operation errors [9]. The Petroleum Institute of Abu Dhabi has developed a UAV autonomous tracking and navigation controller designed for the inspection of linear oil and gas pipelines [13].

UAV Module layers

The UAV module has three layers: Sensor, Networking, and Application layers. Table 2 shows details. Sensors sense real-time data, networking enables UAV-UAV/IoT/Tier-3 communication, and the app layer manages operations.

UAVs Deployment, Energy-management, and Fault-tolerance

UAVs Deployment: Autonomous UAVs are used to need docking stations for landing, recharging, and maintenance. However, establishing separate stations in OGI pipeline monitoring is costly. Thus, UAVs recharge at pumping stations (around 20 miles apart) where recharging and maintenance facilities exist. Fixed-wing UAVs are chosen due to their aerodynamic efficiency and endurance [14]. Each docking station hosts three UAVs for fault tolerance and recharging.

UAVs Data Communication: Pipelines pass through hazardous environments like deserts and mountains which usually lack nearby communication infrastructure. Delays in oil and gas pipeline leakage detection data communication cause high latency issues and result in OGI in larger leaks, environmental pollution, safety risks, and most importantly OGI asset loss. In our proposed architecture, UAVs operate continuously to ensure real-time, fault-tolerant, and low-latency communication. Two UAVs take off from successive docking stations, gather data from different master nodes, and return to the docking stations to transfer the collected data to control centers. Additionally, a spare UAV is available for recharging and handling any potential faults.

Intelligent Data Categorization

High bandwidth is not always available for transferring sensed data from IoTs to centralized servers. Therefore, limited data processing is done at UAVs to reduce network traffic. Data is divided into three categories: urgent, important, and delay-tolerant data. Urgent data such as leakage, fire, and corrosion are sent directly to the server for further action. For important data, such as data of faulty modules, the UAVs communicate with servers on a periodic schedule. Delay-tolerant data is transmitted during off-peak hours for energy efficiency and to reduce network traffic.

Intelligent UAV Image Capturing and Data Processing

Sensors installed on IoTs gather different kinds of data while doing pipeline inspections. UAVs periodically capture real-time videos and images. Most of this high-volume data is a repetition of patterns and there is no need to forward redundant data to the servers. Therefore, data processing at the middle tier to filter useful information is a critical challenge. However, high computational capabilities are required for image processing [15]. Therefore, we propose an intelligent image-capturing technique in which UAV captures images after adaptive intervals based on various factors such as the speed of UAVs. To attain energy efficiency, UAV transmits data in an ad-hoc manner determining the category of data. If an adverse event is detected in initial processing, the corresponding data is transmitted immediately to the edge servers. As the transmission of videos is data-intensive and energy-consuming, video data offloading is done at docking stations instead of transferring it during UAV flights [16].

HIGH-TIER: EDGE COMPUTING

Data sensed by IoTs in the low tier are collected by UAVs for further transmission toward ground control stations (GCS). To reduce network traffic and maximize efficiency, this data is further routed toward edge computing devices for analytics. The high tier uses edge nodes for data processing for predictive maintenance and then transmits optimized data for fault-tolerant storage. The high tier has two layers: The networking and application layer. The application layer offers the necessary interfaces for connecting UAVs and edge servers.

In OGI inspection scenarios, cameras are used to capture images for fault detection of pipelines. Picture orientation and surface reconstruction are the basic issues linked to OGI imagery processing. Several studies can be found that examine different methods of surface reconstruction [17]. However, to extract meaningful features and infer both qualitative and quantitative decision-making, machine learning techniques are applied. Moreover, object tracking is also a common interest in OGI applications. Although it remains difficult due to a variety of issues such as illumination, occlusion, and viewpoint variation [18]. For this purpose, deep learning approaches have shown to be the most accurate in delivering state-of-the-art results in a variety of identification and classification tasks, including image recognition, object detection, and localization. We propose to utilize the Deep Convolutional Neural Network for image analysis at the edge servers.

Comparison of Fiber optic vs Hybrid solutions

In this section, we compare the hybrid OGI pipeline surveillance solution with a fiber optic solution from the perspectives of management and maintenance. In terms of management, both fiber optic and hybrid solutions can provide real-time data. However, hybrid solutions are more versatile and scalable than fiber optics. From the maintenance point of view, both need trained personnel in their respective technology. However, the hybrid solution is more fault-tolerant and robust than fiber- optic as shown in Table 3.

Cost of installation and reliability are important factors in selecting the option for monitoring long OGI pipelines. In summary, utilizing IoTs (for sensing purposes) and UAVs (as communication nodes) in an OGI pipeline monitoring scenario is more suitable than using fiber optics. Table 1 shows a brief comparison of fiber optics, UAV, and IoT-based solutions.

USE CASES

Use Case 1: Energy-Efficient Data Transmission

In this scenario, there are five sensor nodes (SNs) deployed on a pipeline for monitoring purposes, with two of them being master nodes (MNs) with higher energy and processing capabilities (nodes A and E). When node B has data to send, it selects the route with the shortest hop count and more energy towards a MN. As a result, it sends the data to node A. If node C needs to transmit data, it chooses either node D or E as its destination. Similarly, node D selects node E for data transmission.

Use Case 2: Fault-Tolerant Mechanism

Consider the scenario in which only one route is available due to the failure of other node. For instance, if node C has data to send and node B is no longer functioning, it selects the alternative route C -> D -> E, using short-range communication to ensure energy efficiency. Additionally, node C informs all other nodes and the control center about the failed node B.

Use Case 3: Fault-Tolerant and Low-Latency Mechanism

This use case involves both routes being unavailable because of node failures. In such a scenario, if node C has data to send, and nodes B and D are non-operational, it employs a mechanism to reach out repeatedly with beacon messages using long-range communication until a UAV (Unmanned Aerial Vehicle) comes within range. Once the UAV is in range, it can retrieve the data from node C and act as a relay for transmitting the data. Furthermore, node C communicates the information about the unavailable routes, enabling necessary actions to be taken. All these use cases are depicted in Figure. 3

Open Challenges & Future Research Directions

There are several research directions for an integrated OGI pipeline monitoring architecture comprising intelligent IoTs, UAV, and edge computing. Foremost, most of the sensor and UAV devices are resource-constrained, limiting their participation in artificial intelligence techniques and smart communication. Federated learning utilization in OGI and UAVs is required to enable resource-constrained devices to perform AI-based critical tasks. There is scope for applying low-accuracy learning techniques at the low and middle tier while deep learning-based high-accuracy techniques can be initiated at the edge and cloud servers. UAVs are battery constrained in the scenario of flying over large pipelines. Multipoint wireless power transfer techniques and innovative energy delivery mechanisms are required to be investigated for UAVs and IoTs along with edge offloading techniques [19]. Moreover, energy-efficient routing and swarm coordination techniques are required for UAVs. Controlling and managing many devices on board for mission-critical surveillance can lead to synchronization, connectivity, and latency concerns. Smart dynamic path planning is necessary to enable a fully coordinated and stable multi-UAV network that covers a long OGI pipeline optimally. Docking station planning for UAV charging, maintenance, and communication are also among the key tasks [9].

Image analysis techniques are called upon for surface reconstruction, segmentation, land-cover map-

TABLE 3. Comparison of Hybrid solution vs Fiber optic: Management & Maintenance Perspective

	Aspect	Hybrid Solution	Fiber Optic
Manag.	Versatility	High	Low
	Real-time Data	High	High
	Scalability	High	Low
	Complexity	High	Low
Maint.	Fault-tolerance	High	Low
	Maintenance Efficiency	High (node failure)	low (central failure)
	Redundancy	High	Low
	Training	same	same

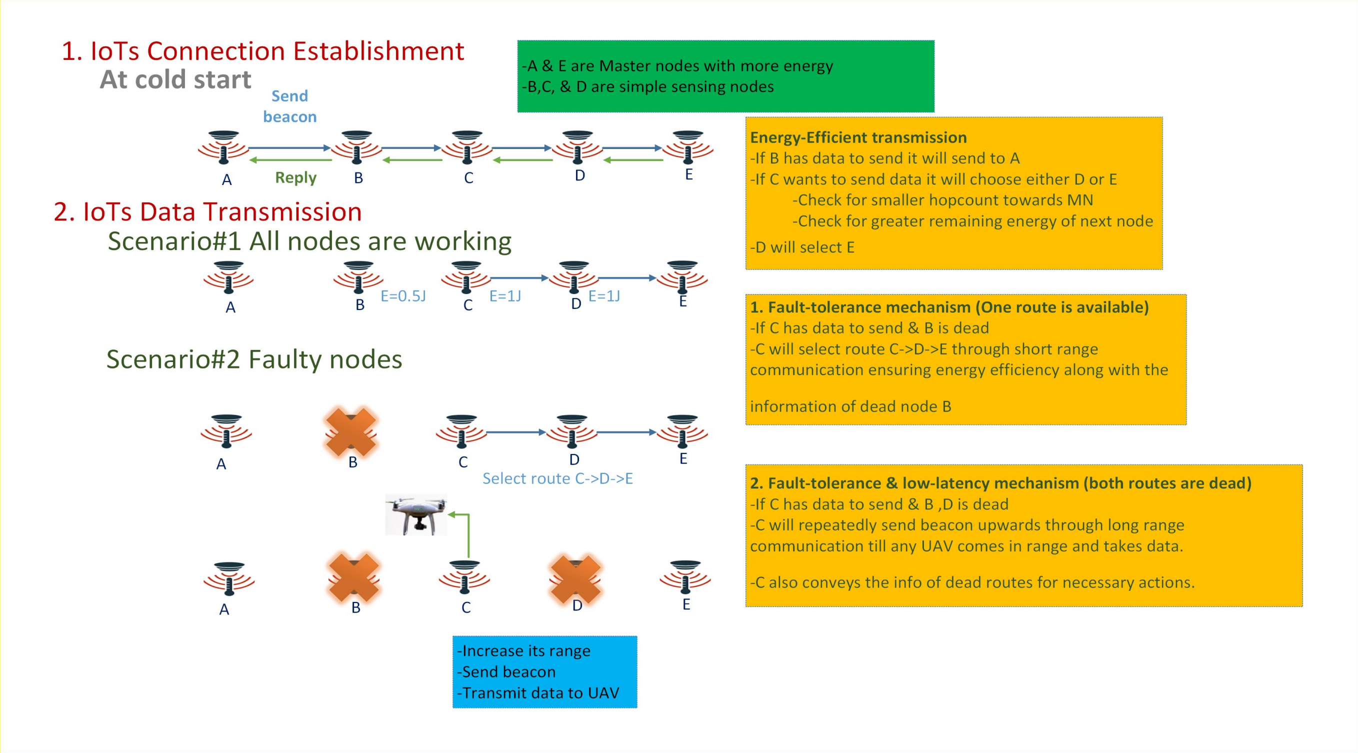

FIGURE 3. Use cases of IoTs assisted UAVs for energy-efficient, fault-tolerant, and low-latency communication

ping, and object tracking. Although deep learning techniques provide higher accuracy, their computational requirements are high. This fact necessitates a three-way trade-off based on time sensitivity, resource requirement, and accuracy of the image analysis task. High mobility is one of the distinct features of UAVs and IoT sensors in un-assisted terrains. Research work can be carried out to investigate the UAV's mobility and their reaction to different emergency events such as a fire in the OGI pipeline. Lastly, due to the unique characteristics of UAVs and IoTs, such as the lack of a fixed infrastructure, dynamic communication mechanisms, and unmanned terrain, cyber and physical security is at high risk. Data security protocols that consider the inherent requirements of energy efficiency, reliability, fault-tolerance need to be investigated for OGI pipeline monitoring [4].

Conclusion

The global network of OGI pipelines demands the safe transfer of this crucial asset. It is crucial to continuously monitor these pipelines for maintenance, safety, and security purposes.Most of the proposed solutions rely on a single technology that leads to various energy, reliability, communication, and optimization challenges. An amalgamation of IoTs, UAVs, and Edge intelligence-based 3-tier architecture for large-scale pipeline surveillance was proposed. The architecture incorporates energy-efficient and fault-tolerant communication between sensor nodes and UAVs. Edge computing-assisted UAVs also perform data optimization for real-time images and sensor data.

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