Retraction Notice

The Editor-in-Chief and the publisher have retracted this article, which was submitted as part of a guest-edited special section. An investigation uncovered evidence of compromised peer review and determined the paper has little relevance to the scope of the journal. The Editor and publisher no longer have confidence in the results and conclusions of the article.

JS disagrees with the retraction. SNK, KB, FR, TY, and AJ either did not respond or could not be reached.

Inspection of unmanned aerial vehicles in oil and gas industry: critical analysis of platforms, sensors, networking architecture, and path planning

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Abstract. The rapid growth of unmanned aerial vehicles (UAVs) has huge potential in the oil and gas industry (OGI). These are especially helpful in situations in which human lives are at risk. OGI pipelines are threatened by natural and man-made disasters, which are harmful to both people and assets. Usually, oil and gas pipelines pass through extreme environments for which standard inspection, maintenance, and repairing approaches such as rope access, scaffolds, telescopic elevation platforms supported by cranes, and manned helicopters are not secure and difficult and expensive to implement. However, technological advancements like device miniaturization have boosted the performance of UAVs, offering cost-effective, efficient, and high mission flexibility. UAVs are capable of carrying sensors and cameras to perform monitoring. As pipelines span thousands of kilometers, multi-UAV systems, commonly referred to as flying ad-hoc networks (FANETs), can collaboratively complete monitoring missions more effectively and economically as compared with single UAV systems. Moreover, many issues must be resolved before the effective use of UAVs can provide stable and reliable context-specific networks. Several OGI-specific issues of UAVs such as architecture design, platform, sensors, networking architectures, and path planning models for different OGI pipeline surveillance scenarios must be resolved to use FANETs effectively for robust and sustainable networks. The prime objective of this research is a state-of-the-art review of UAVs in OGI. We first present OGI midstream challenges and parameters to give a brief overview of the challenges faced by the OGI for pipeline surveillance. Then we discuss OGI-specific scenarios for sensor readings, visual leak detection, and detection of any unusual activity that happens in the pipeline while monitoring through UAVs. We also present different OGI-specific UAV platforms, UAV networking architectures, and path planning models of FANET for efficient communication and collaboration. Finally, the challenges of UAVs and future research prospects in OGI-specific UAVs are highlighted. *© 2022 SPIE and IS&T* [DOI: 10.1117/1.JEI.32.1.011006]

Keywords: pipeline monitoring; inspection unmanned aerial vehicles; flying ad-hoc networks; architecture; routing; path planning.

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1 Introduction

The global market of the oil and gas sector is expanding continuously.[1,2] The largest products of the oil and gas industry (OGI) are fuel, oil, and gasoline. Moreover, this industry provides primary material for a multitude of chemical products that include pharmaceuticals, fertilizers, soaps, and plastics, making OGI extremely important for various industries. It is estimated that global demand for crude oil increase to 96.5 million barrels per day in 2021.[3] OGI is usually

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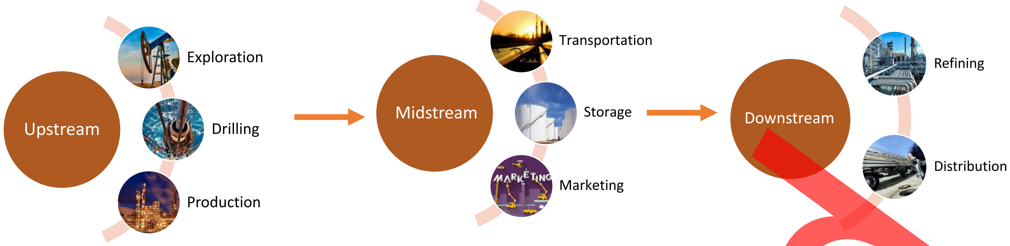

Fig. 1 Oil and gas industry subsectors.

divided into three main sectors: upstream, midstream, and downstream.[4] The discovery/production process of crude oil and natural gas is performed by the upstream sector. Processing of these materials and natural gas liquids, i.e., mostly propane, butane, and ethane, is done by the midstream sector. Storage, marketing, and transportation of these products are the responsibility of the midstream sector. This sector also provides a vital link between the distant oil and gas producing regions and populated areas (end users). The downstream industry includes petroleum chemical plants, petroleum products distributors, retailers, oil refineries, and natural gas distribution companies.[5] Figure 1 demonstrates the functions associated with these three sectors of the OGI. Transportation is one of the most critical aspects of the OGI. According to the global energy monitor, as of December 2020, there were at least 2381 operating oil and gas pipelines spread over 162 nations. These pipelines have a total length of over 1.18 million kilometers (730,000 miles), that is enough to surround the Earth 30 times. Therefore, the daily volume of oil and gas transported through pipelines has increased tremendously.[6] Hence, establishing an effective method for midstream surveillance is vital for providing safe and secure transmission of OGI assets. This study focuses on monitoring midstream scenarios in the OGI.

Inspection, maintenance, and repair (IMR) of big pipelines are key functions linked with the OGI. IMR functions experience various challenges, i.e., equipment failure, leakage, corrosion, or pipeline vandalization. This can occur due to any breakage (accidental or intentional) or because of old infrastructures,[7] resulting in the loss of oil and gas assets and environmental pollution. In the last decade, several incidents that were catastrophic to human lives and property occurred, and many people were killed due to explosions in pipelines. In Alberta, the pipeline failure rate was 1.5 failures per 1000 km in the years 2011 and 2012.[8] Similarly, in Europe, 1.2 incidents per 1000-km-long pipeline occurred in the 1970s and 0.23 in 2013.[9] As the pipeline infrastructure is distributed globally and for vital production and maintenance of oil and gas installations, a regular inspection of its equipment is extremely important.[8]

The conventional systems used for IMR operations are rope access, scaffolds, telescopic elevation platforms supported by cranes, and manned helicopters. As pipelines are huge and deployed in hazardous environments, it is difficult and costly to use these traditional methods for IMR purposes. Therefore, an efficient inspection method is required to lower the cost of IMR operations and ensure safety.[10]

The OGI is trying to benefit from various digital technologies. Supervisory control and data acquisition (SCADA) systems,[11–13] satellite remote sensing,[14,15] wireless sensors,[16] robotics,[17] and IoTs[18] are the latest technologies opted by the OGI to control, monitor, and maintain critical operations of this industry.[19] However, all of these technologies suffer from noteworthy limitations, such as mobility, latency, and cost, that need to be resolved. The OGI is still looking for feasible solutions to improve its industrial processes, enhance its safety, and offer low operating costs for IMR.

There are pros and cons of every technology, e.g., foot surveillance or monitoring through manned helicopters are costly, dependent on manpower, and have security risks. SCADA systems are efficient, but they require special hardware, and their software is also not interoperable. Satellite remote sensing provides larger area monitoring; however, it has difficulty identifying the exact location of defects. Wireless sensor networks provide zero deployments, but they are energy-constrained. Although robots give the exact location of defects, they are trained for small missions and need to operate in a highly supervised environment, which is not feasible in the hazardous environment of pipelines. Smart IoT objects provide accuracy and low human

Table 1 Comparison of digital technologies for OGI.

Sr.#	Attributes of digital technologies for OGI	SRS	SN/IoTs	Robotics	UAVs
1.	Zero deployment	✓	×	✓	✓
2.	Cost-effective	×	✓	×	✓
3.	Accuracy	×	✓	✓	✓
4.	Low human intervention	✓	×	✓	✓
5.	Interrupted wireless communication	✓	✓	✓	×[Delay tolerant network (DTN) enabled UAVs]
6.	Energy efficient	✓	×	✓	✓(green computing)
7.	Fault tolerant	✓	×	×	✓
8.	Reliable	✓	×	✓	✓
9.	Scalability	×	✓	✓	✓
10.	Mobility support	✓	×	×	✓
11.	Minimum latency	×	Architecture	Architecture	✓

intervention, but they can suffer from interrupted wireless communication and are not prone to faults. Hence, there is a dire need to find a solution that offers zero deployments, cost-effectiveness, accuracy, scalability, support mobility, and low human intervention. UAVs, usually called drones, are a technology that provides all of these features. A brief comparison of these technologies is depicted in Table 1.

The proposed survey identifies the existing literature on inspection UAVs in the OGI. The identified research questions (RQs) and their objectives used for the systematic survey are listed in Table 2. The prime objective of this survey is to identify and explore different UAVs architecture, routing protocols, and path planning in the context of pipeline monitoring scenarios in the OGI. We also investigate the relevant trajectory models. Finally, we present OGI-specific UAV challenges and future research directions in multi-UAV systems. To the best of our knowledge, our research is the first effort of its kind to present all of the above-cited topics in a single paper specific to the OGI.

Table 2 Identified research questions.

Q. No.	Research question	Objective
RQ1	What are the challenges and issues in OGI midstream surveillance and what are the parameters for detecting these issues?	It aims to explore the OGI midstream challenges and to identify the parameters to detect these issues.
RQ2	Which UAV platforms and sensors exist to assist the surveillance of pipelines in hard areas?	It aims to explore different UAV platforms and sensors specific to OGI midstream scenarios.
RQ3	How can UAVs communicate data of any unusual activity to control centers from remote industrial areas?	It aims to list different types of UAV communication links to send data efficiently.
RQ4	What are various UAV trajectory/path planning models?	It is expected to explore and present different UAV trajectory and path planning models.
RQ5	What are the basic requirements and open perspectives of UAVs in OGI surveillance?	It aims to provide OGI requirements for an effective and efficient surveillance system and explore various challenges and future research prospects in OGI.

The remainder of the paper is organized as follows: Section 2 presents the related work section. In Sec. 3, we address RQ1 by exploring midstream challenges required to be provided digitally for the efficient and smooth flow of oil and gas assets, and we discuss the parameters of the OGI pipeline to consider for the detection of any kind of leakage or damage. In Sec. 4, RQ2 is answered; several UAV architectures with their UAV platforms and sensors in OGI are explored. Section 5 answers RQ3; we highlight the FANET networking architecture to ensure global connectivity along with the discussion on UAV networking architecture for pipeline monitoring in the OGI. Section 6 addresses RQ4; we list different types of UAV communication links to send data efficiently and in a timely manner. In Sec. 7, RQ4 is discussed; we explore and present different UAV trajectory/path planning models. In Sec. 8, RQ5 is answered based on the analysis performed in the previous parts of the paper. Finally, the conclusion is presented in Sec. 9.

2 Related Work

Small unmanned aerial vehicles (UAVs), usually called drones, provide feasible opportunities/solutions for IMR operations of oil and gas pipelines. Considering some inherent attributes of UAVs, such as zero deployments,[20] low altitude sensing,[21] flexibility,[22] mobility,[23] cost-effectiveness, and reliability, these small aerial vehicles are being heavily used in various civil applications.[24] Motivated by these features, the UAV market is expanding continuously and will reach USD 52.30 Billion by 2025.[25] The proliferation of these flying robots with their flexible sensing capacity and wireless communication potential opens new frontiers by providing more enriched surveillance approaches and cost-effective solutions for energy site monitoring. Despite continuous increases in use, UAVs still face numerous challenges that need to be addressed, such as a lack of regularity framework for UAVs, deployment challenges, architecture designs, routing challenges, and crashes due to weather conditions.

We have identified two types of surveys: those that focus on UAV-related topics, particularly in the OGI, and those that discuss multi-UAV system topics in general. In one study, the authors investigated flying ad-hoc networks (FANETs) for different OGI monitoring scenarios and discussed details for the OGI-specific UAV platform and relevant sensors.[26] In addition, the existing sensory systems for unmanned aircraft systems (UAS) and suggestions for adopting these systems for efficient inspection in the OGI were also presented. High mobility is a distinct feature of the UAV system and requires a high level of coordination and collaboration to complete tasks. Therefore, the authors of one study investigated important issues of UAVs that covered networking protocols, general architecture, and mobility models.[27] Open issues in UAV systems that need further analysis to be resolved were also highlighted. The architectural requirements and communication-related issues of FANETs, i.e., communication links, protocols, trajectory optimization, and mobility models were identified and discussed in another study.[28] The state-of-the-art methods and application examples of drone remote sensing in the OGI were highlighted in another article,[29] which also provided an overview of the typical UAV platforms and sensor systems. There were six main categories targeted in this research: environmental monitoring, pipeline monitoring, gas emission sensing, remote facility inspection, offshore oil spill detection, and petroleum exploration (including land surveying, geologic mapping, and petroleum exploration). The UAV technology improved the speed, accuracy, and effectiveness of data collection. Research gaps and opportunities for further development were also highlighted.

Another research study surveyed UAV issues in the OGI for inspection purposes.[10] Various scenarios for monitoring pipelines, open issues regarding UAVs, and further directions for research were also presented in their research. Another paper published in 2017[30] focused on different characteristics of the multi-UAV system and summarized different routing protocols from the literature in detail. The security perspective of these routing protocols wasalso discussed. Another study[31] categoried publications on networked UAVs for surveillance and monitoring and evaluated several common issues on this topic, such as the control, navigation, and deployment optimization of UAVs. Future directions, along with relevant research gaps, were also discussed.

Table 3 Year-wise comparison of UAV surveys.

	2020		2019		2018	2017		
Topics covered	Ref. 26	Ref. 27	Ref. 28	Ref. 32	Ref. 33	Ref. 10	Ref. 30	Our survey
General architecture		✓	✓	✓	✓		✓	✓
OGI specific platform	✓					✓		✓
OGI specific sensors	✓					✓		✓
UAV networking architecture for OGI								✓
Communication links			✓					✓
Routing requirements							✓	✓
UAV trajectory			✓		✓		✓	✓
OGI specific scenarios	✓					✓		✓
OGI specific UAV challenges								✓

Therefore, the OGI-specific surveys are limited to platforms and sensors relevant to OGI monitoring and lack communication and mobility management of FANETs. The other type of survey identifies general topics of multi-UAV systems, such as FANETs architecture, communication-related issues, protocols, mobility models, and so on. The year-wise comparison of these surveys and our research are summarized in Table 3. Also, the anatomical structure of the survey is depicted in Fig. 2.

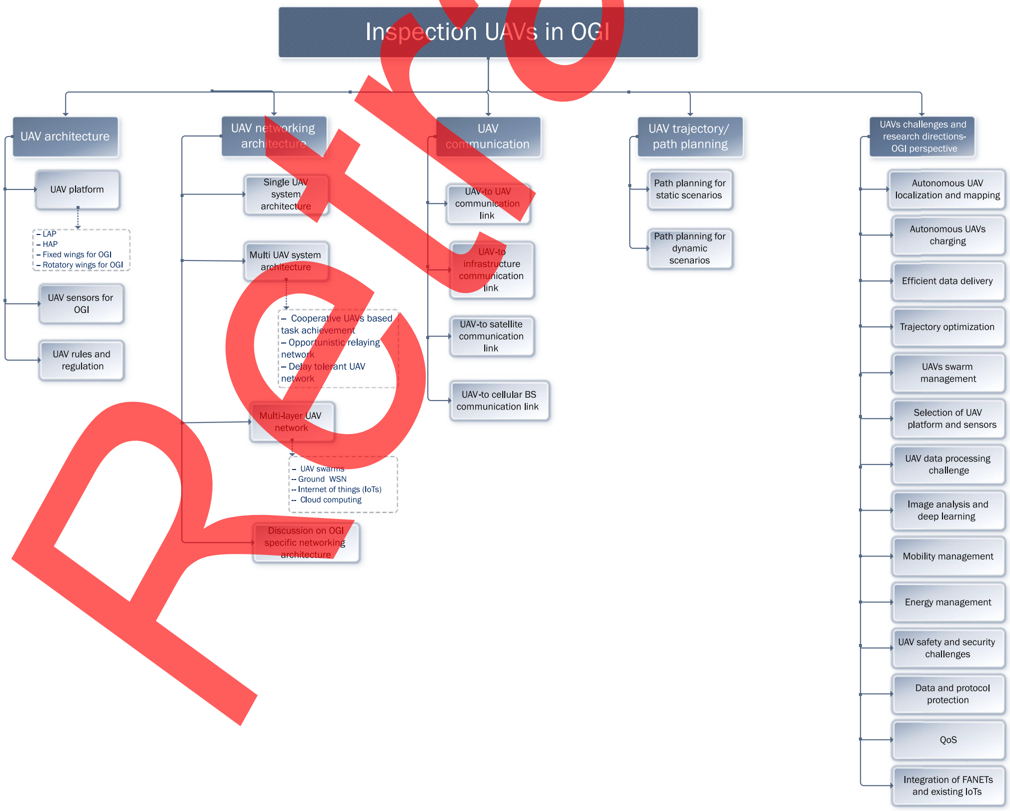

Fig. 2 Anatomical structure of survey.

3 OGI Midstream Challenges and Parameters

An OGI breakdown is usually a tragic event due to the serious consequences. Pipeline damage is caused by corrosion, material/weld failure, excavation damage, equipment failure, any inappropriate operation performed by workers, and so on. These mishaps have the potential to contaminate the environment, endanger lives, cause significant economic losses, and disrupt the agricultural activity of the local population. The health of humans and animals is also jeopardized by inhaling the gases emitted by the leaks.[34]

Temperature, pressure, and flow rate are all criteria that must be maintained by assets (oil or gas) transported through the OGI pipeline. To avoid fire dangers and crude oil freezing, the maximum and minimum temperature parameters must be maintained. Minimum and maximum pressure are also maintained to avoid cavitation and equipment breakdowns. Furthermore, delivery pressure is a consideration that is assessed throughout the transportation process to deliver the asset to the customer on time. Conclusively, the values for these parameters alter when oil and gas are not transferred smoothly from one location to another for any aforementioned reason (leak or other pipeline damage). Therefore, continuous monitoring of these parameters is vital for an efficient OGI monitoring system.

4 UAV Architecture

UAV applications demand different types of UAV platforms, sensors, and auxiliary equipment, which constitute the entire UAV system architecture. UAVs offer a variety of capabilities and qualities for different flight altitudes and payload requirements. Therefore, UAV architectural requirements for pipeline monitoring in the OGI differ for different monitoring scenarios. In this section, we delve into various classifications of UAVs and their requirements in various OGI monitoring scenarios, as well as the requisite sensors and the limitations of the rules and regulations for OGI pipeline monitoring.

4.1 *UAV Platform*

UAVs have different capabilities and properties regarding their flight altitude, payload, and so on. Generally, we classify UAV platforms based on their altitudes, such as high altitude platforms (HAPs) and low altitude platforms (LAPs).[35] Their classification can also be based on the aerodynamics or types of UAVs, i.e., fixed wing and rotatory wing UAVs. The classification of UAVs is shown in Fig. 3. In our study, we classify our midstream monitoring needs into three different scenarios.

4.1.1 *Scenario 1—sensor readings for temperature, pressure, and flow rate*

To capture values for temperature, pressure, and flow rate, there are two possibilities: UAVs themselves hold the respective sensors or UAVs collect data from ground sensors deployed

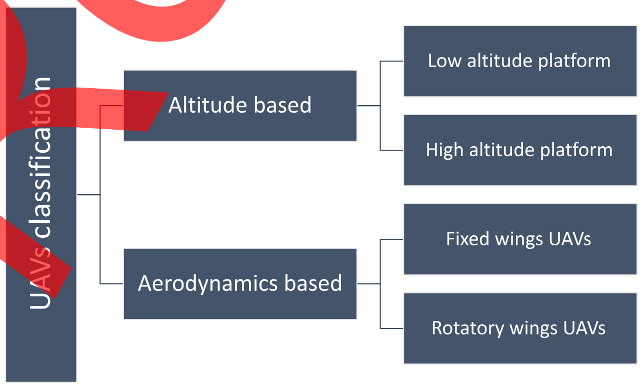

Fig. 3 Classification of UAVs.

Table 4 Comparison of HAP versus LAP.

Sr#	Characteristics	HAPs	LAPs
1.	Altitude support	Above 17 km	Tens of meters to up to a few kilometers
2.	Deployment	Time taking	Quick
3.	Geographical area	Large	Small
4.	Cost	High	Low
5.	Data collection from ground sensors	No	Yes
6.	Useful in OGI	Yes	No

on pipelines. If UAVs hold sensors by themselves in the architecture design, a compact and lightweight low-altitude UAV is the most suitable platform. Because the UAV tries to sense values from pipelines through the sensors installed on UAVs, there is a need to fly closer to the pipeline on the ground (5 to 10 m), and the required flying height is quite low (50 m). Also, if UAVs have to take values from ground sensors, a flexible and fast platform is needed. For both situations, a mini multicopter with great maneuverability and battery power for flight and sensor supply is sufficient.

LAPs offer an altitude of tens of meters up to a few kilometers. LAPs can move rapidly and are flexible.[35] Thus, their deployment is done more quickly and is usually preferred in time-sensitive applications or emergencies like OGI leak detection. Moreover, they can collect data from ground sensors, too. Therefore, for scenario 1, LAP is the most suitable platform (e.g., DJI Phantom 3, Aibotix Aibot X6). Table 4 presents the comparison between HAP and LAP.

4.1.2 *Scenario 2—visual leak detection*

In addition to physical sensor readings, visual images/video is mandatory for infrastructure monitoring of leak detection. A short-distance survey is necessary to monitor a small to medium-length pipeline with a length of up to several kilometers (depending on local legislation). In this circumstance, an autonomous fixed flying plan based on a sequence of way-points will assist in routine and periodic monitoring. Therefore, we need a platform that offers easy control during flight, possesses long flight durations, and is fast.

In this situation, fixed-wing UAVs (such as the Trimble® UX5) with visible and infrared cameras are viable platforms. Fixed wing UAVs offer simple structures. They are easy to control during flight, have a long flight duration, and are usually fast. They usually require space for landing and turns. Therefore, this type of platform depends upon the launcher or a runway. The launcher can be human or mechanical, which imposes restrictions on the payload that they can carry. Conventionally, fixed wing UAVs have wings spanning between 0.8 and 1.2 m. There are small fins attached on both sides of these wings. However, in-house UAVs are moderately long-winged to enable them to carry the required sensors.[10] Data should be kept for comparison with prior and future surveys and for automatic change detection using algorithms.

A system with greater endurance is required for pipelines longer than 100 km. To strengthen the monitoring ability, the rotary wing platform offers high flexibility and capacity. Rotatory wing UAVs possess complex mechanics. They usually have a short flight duration and low speed. They can fly vertically, take off, and land in small spaces.[36] As compared with fixed wing UAVs, rotatory wing UAVs are less stable. They are also more difficult to control and best suited for applications having tight spaces e.g., facility inspection.

4.1.3 *Scenario 3—detection of any unusual activity*

OGI pipelines cover thousands of kilometers throughout the globe, and a single UAV system platform is insufficient for effective monitoring. As a result, regular monitoring is essential for detecting any unexpected activity, such as a terrorist threat, theft, or damage/malfunction caused

Table 5 Comparison of fixed versus rotatory wing UAVs.

Sr#	Characteristics	Fixed wing UAVs	Rotatory wing UAVs
1.	Structures	Simple	Complex
2.	Flight duration	Long	Short
3.	Stability	High	Low
4.	Control	Easy	Difficult
5.	Capacity to take off, turn and to land	HTOL (horizontal take-off and landing)	VTOL (vertical take-off and landing)

by natural disasters. This surveillance scenario can be carried out by larger UAVs in controlled airspace, but it must be implemented in a comprehensive air traffic control framework. Engines and motors, as well as fuel and battery, can all be used to power a big UAV. A radar (SAR) sensor, which might be supplemented by an optical/IR sensor system, is ideal because the UAV is operated above 1000 m and is usually not below the clouds. This equipment, in turn, necessitates a certain payload capacity. Because radar data require more devoted and specific software, image processing and feature extraction attempts may be more difficult than in previous scenarios. Using larger and single UAV systems is quite expensive. Another approach is to use coordinated small UAV swarm technology in which each UAV is responsible for sensing/collecting data and communicating it to the control center while establishing good communication with each other. However, charging base stations needing to be at the end of each pipeline leg and autonomous decision-making capacity for recharging or returning to base in the event of severe weather are some of the challenges in this scenario. Platforms that use combined technologies of fixed and rotatory wing UAVs can be considered for this case.[36] A combination of both offers stable flights and maneuverability (e.g., Flying Wing, Songbird 1400). A comparison of fixed and rotatory wing UAVs is given in Table 5.

4.2 *Sensors*

In a UAV network, the weight of objects and the space limitation are two crucial factors to consider when deciding on the peripheral equipment (e.g., sensor and wireless networking equipment). Moreover, this weight directly affects the performance of the network. Technologies are continuously changing, resulting in miniaturization and advancements in sensors. The aim is to enhance the limited batteries of sensors. However, limitations regarding size, weight, and mechanics remain.[37]

Depending on different pipeline monitoring scenarios, we present a list of possible sensors along with suggestions for flight altitude, platform, payload, and endurance in Table 6.

4.3 *UAV Rules and Regulations*

The deployment of UAVs for various OGI midstream surveillance scenarios depends upon the rules and regulations for their deployment and routing. Various aspects must be considered when using UAVs: privacy and security, the safety of humans and other assets, collision avoidance, data protection and integrity, etc. Globally, various organizations are working together to develop rules and regulations for UAVs based on these factors.[38,39]

These authorities are responsible for defining the maximum altitude of UAVs, minimum distance from people and assets, and minimum distance from airports to avoid incidents. There are various countries where UAV registration is necessary to deploy outdoor. An online system was launched for this registration process in 2015 in Russia. UAVs weighing 0.25 to 25 kg need to be registered.[38] In the USA, users who are not registered with the FAA face civil and criminal penalties. UAVs require sufficient bandwidth to communicate with the ground control system. However, there is no specific bandwidth allocated to UAVs by the International Telecommunication Union (ITU). Therefore, countries are using different radio frequencies for UAV communication.[40]

Table 6 Sensors for inspection UAVs.[10,36]

Sr.#	Scenario	Factors details			
1.	Monitoring infrastructure	Sensors	Name	Strength	Weakness
			Visible (wavelength 0.38 – 0.76 μm)	Infrastructure inspection, spill detection, and visual interpretation	No night vision, working limited in clouds, haze, or smoke.
			Video	Enables on the fly transmission, 3D images are accessible	Useless data due to redundant info
			Stereo cameras	3D images are accessible, and provide the basis for navigation system of UAV	Augment's weight
			Lidar (active)	Background characterization (3D), enables 3D measures, and high precision	Power consumption, dependent on the inertial navigation system, limited availability commercially, size and weight issue
		Flying altitude	Very low (<50 m)		
		Payload	<7 kg		
		Endurance	<1 h		
		Platform	Multicopter with hovering capacity and high mobility		
2.	Leak detection and monitoring	Sensors	Name	Strength	Weakness
			Thermal IR $(8-14)$ μm	Night vision, vision through smoke, fog, and clouds	Reference data for comparison are required
			Gas IR camera	Leak detection, night vision	Limited by wind
			Radar	Three oil spills recognition in water, weather support	Power consumption, differential imagery needed, limited availability commercially
			Laser fluoro-sensor	Oil spills detection in snow, night support	High-energy consumption, limited availability commercially, requires a clear atmosphere (no fog), specialized processing
		Flying altitude	Low (100 m)		
		Payload	<25 kg		
		Endurance	<1 to 5 to 6 h (depend upon pipeline length)		
		Platform	Fixed wing/rotary wing		

Table 6 (*Continued*).

Sr.#	Scenario	Factors details		
3.	Some additional sensors	Name	Strength	Weakness
		Multispectral (multiple bands)	Characterization and monitoring of environmental condition clouds	Only suitable in day-light, restricted by the atmosphere, such as clouds, fog, or smoke
		SWIR [wavelength $(0.9 - 1.7)$ μm]	Thermo-electric cooler for optimal power utilization, detection of different materials/substances	Sensitive in dim light, scarce production of detector material (InGaAs)
		Near-infrared (NIR) [wavelength $(0.76 - 14)$ μm]	Characterization and monitoring of environmental condition	Reference data for comparison is required
		Hyperspectral (hundreds of bands)	Detection of different materials/substances, flexible/customizable number and resolution of spectral bands	Library needed

5 UAV Networking Architecture

Two basic networking architectures exist for UAVs: single UAV and multi-UAV system architectures. A detailed review of both and the discussion regarding their suitability in OGI monitoring scenarios are presented in the following sections.

5.1 *Single UAV System Architecture*

In single UAV system architectures, communication between UAV and infrastructure is accomplished by a ground control center. Several UAVs can work in this system, but for each UAV, communication is done through direct contact with the infrastructure. An independent system was proposed;[41] there is no base station or control center to control the UAV, and instead all computational and sensing tasks were performed on board. An external processing unit was attached to the UAV to perform controlling and navigational tasks. It directed the vehicle to its desired location. Performance analysis of a single UAV system for monitoring different objects in a specific area was conducted in another study.[42]

5.2 *Multi-UAV System Architecture*

In a multi-UAVs system, along with UAV-to-infrastructure communication, UAV–UAV communication is also possible. All of the UAVs collaborate to improve the efficiency of the network. If any of the UAVs go beyond the range of infrastructure, it still is a useful part of the network by communicating data through other nearby UAVs. Multi-UAV systems provide cost-effectiveness,[43] scalable, flexible, and faster data access than a single UAV system.[44] Therefore, many public sector companies use the multi-UAV system for their applications.[45] A comparison of a single UAV vs. a multi-UAV system is given in Table 7.

Multi-UAV systems can work in different topologies, such as star, multistar, mesh, and hierarchical mesh topology. A brief illustration is given in Table 8.

Considering the strengths and weaknesses of these topologies, we can conclude that mesh networks are more flexible, robust, and efficient than star networks.

Table 7 Single UAV system versus multi-UAV system.

Sr.#	UAV system	UAV-GSC	UAV-UAV	Cost-effective	Scalable	Survivability	Speedy
1.	Single UAV system	✓	×	✓	×	×	×
2.	Multi-UAV system	✓	✓	✓	✓	✓	✓

Table 8 FANET topologies.

Sr.#	Topology	Working	UAV-GCS	UAV-UAV	Latency	Bandwidth	Self-organizing
1.	Star	At the center of the star, there is only one ground node.	✓	×	✓	✓	×
2.	Multistar	Multiple stars are formed and one node from each star connects to GS.	✓	×	×	✓	×
3.	Mesh	All UAVs communicate with each other and only one UAV connects to GS.	✓	✓	✓	✓	✓
4.	Hierarchical mesh	Multiple mesh networks are formed by UAVs and one node from each network connects to at least one node in the other network.	✓	✓	×	✓	✓

The multi-UAV system architecture is further classified into cooperative multi-UAV and multilayer UAV networks. The cooperative multi-UAV architecture is mostly implemented in mission-based applications in which various UAVs having different communication characteristics are used. It further incorporates cooperative UAV-based task accomplishment, opportunistic relaying network, and DTN (UAV network).

5.2.1 *Cooperative UAV-based task achievement*

- Each node works with the coordination of other nodes in the network.[46]
- It can be static or dynamic.
- For static networks, predefined functions are implemented.
- Dynamic networks have no predefined functionalities; therefore, the topology of the network is unknown and changes continuously.

5.2.2 *Opportunistic relaying network*

- Due to mobility, the UAV network suffers from frequent disconnections, so opportunistic relaying is required.[47,48]
- It improves network performance and enhances the utilization of network resources.[49]

5.2.3 *Delay tolerant UAV network*

- The links in UAV networks are not continuously available; therefore, using the DTN approach is best for UAVs.[50]
- Store and forward approach applications protect from data loss due to low connectivity.[51]

5.3 *Multilayers of UAV Networks*

The multilayer UAV network architecture incorporates other layers, such as IoT, cloud computing, or WSN networks (Fig. 4).

5.3.1 *UAV swarms*

When the mission area is large, UAVs can organize themselves in different swarms. They must protect themselves from collisions. Hence, a network of UAVs can be divided into clusters to improve their payload capacity. There should be one cluster head that is responsible for building connections within the cluster and with upper/lower layers.[52,53]

5.3.2 *Ground WSN*

It is composed of different sensors distributed in large areas to gather information and send that data to base stations. These sensors can be placed on UAVs to achieve any specific task. It could be an infrared camera or sensors for measuring temperature, wind, and so on. Two layers are structured: the UAVs layer and the ground WSN layer.[54–56]

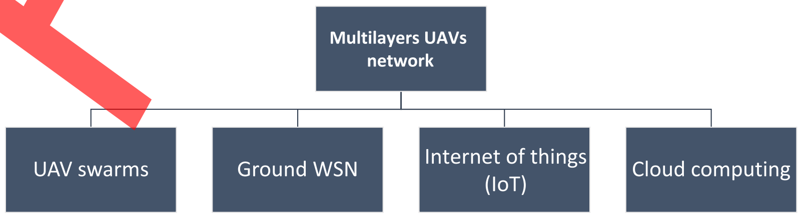

Fig. 4 Multilayer UAV.

5.3.3 *Internet of Things (IoT)*

The combination of UAVs with IoTs gives rise to the idea of the Internet of drones (IoDs). Three networks compose the architecture: the air traffic control, the internet, and the cellular network. This design can be used in a variety of applications, including surveillance, search and rescue, and so on.[57,58]

5.3.4 *Cloud computing*

UAVs are resource-constrained; therefore, intensive computational tasks can be offloaded to the cloud. This kind of architecture provides services, such as BS commands, mission organization services, image, data analysis tasks, and so on.[59,60]

5.4 *Discussion on UAV Networking Architecture for Pipeline Monitoring in OGI*

Combining multiple network topologies can help us develop a UAV-based system for efficient pipeline monitoring and in-time actions. Oil and gas pipelines are extremely large and can traverse a variety of terrains. It is possible that UAVs do not have network coverage at some spots along the pipeline. To address this problem, a store-and-forward approach can be employed, with DTN being the best choice for avoiding data loss. Moreover, one of the characteristics of UAVs is their mobility, which contributes to frequent disconnections. For that, opportunistic relaying can be beneficial. Similarly, because UAVs have limited resources, we can use cloud/edge computing technologies for data analysis. Furthermore, using various IoTs in conjunction with UAVs for sensing purposes can be a viable and scalable option for IMR operations.[61]

Finally, it is suggested that combining several network architectures for various pipeline monitoring scenarios should result in a sophisticated innovative network architecture. One of the main goals is to create a fully functional, unique network architecture that can provide the OGI with an efficient, adaptable, reliable, and cost-effective solution.

6 UAV Communication

In-time data transfer and action against any unusual activity is the key to efficient and effective OGI pipeline monitoring. However, FANET is a type of ad-hoc network that is extremely dynamic. They have frequent link formations and disruptions due to the high mobility of flying nodes. Generally, UAVs are deployed along pipelines and are responsible for data capturing and communication. Therefore, four types of communication connections exist to enable continuous connectivity and in-time information dissemination: UAV-UAV communication, UAV-control center, UAV-cellular BS, and UAV-satellite communication. To make communication possible, these types of links have different characteristics, such as antenna selection based on short- or long-range communication, access protocols, and routing protocols. Figure 5 represents these four types of links in the OGI.

6.1 *UAV-to-UAV Communication Link*

OGI pipelines cover large areas and pass through hazardous environments. In such cases, using a single UAV system for surveillance is insufficient; hence we must deploy multi-UAV systems. Therefore, UAV-to-UAV communication is a critical component of this system. The U2U link is established between UAVs to support ad-hoc communication. This link is usually enabled via the Mesh method. Pipelines in the OGI, on the other hand, are linear. Hence, UAVs are deployed linearly. The route for data dissemination is established through the intermittent UAV nodes, and one node from the network is designated as a gateway node. The gateway node is in charge of collecting data from all nodes and transmitting it to the ground control station. For U2U communication, short-range communication antennas are utilized, and depending on the routing protocol, a long-range antenna may be used for the gateway node.[62]

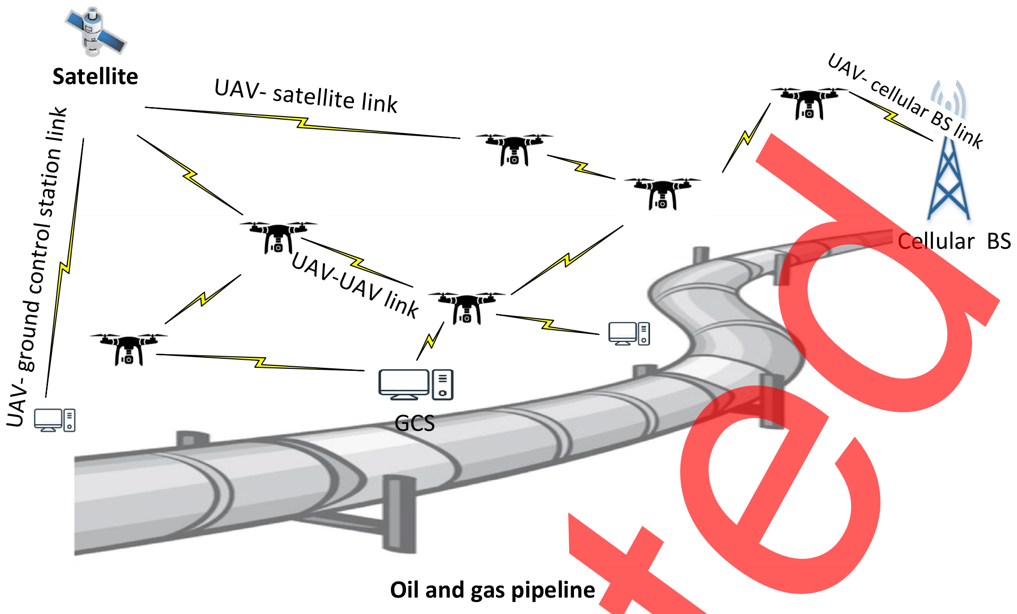

Fig. 5 UAV communication links.

6.2 *UAV-to-Infrastructure Communication Link*

Pumping stations can have control stations installed for recharging UAVs, receiving data, and taking appropriate measures or actions against any unusual activity. These control stations serve as data communication gateways. Therefore, UAV-to-infrastructure communication is a key element of this architecture. It is the simplest model of communication, and all UAVs and the ground control station can establish a direct relationship.[52,63] However, for extremely dynamic settings, this architecture is not suitable. Because each UAV in the network relies on GCS for communication, if GCS fails for any reason, the entire network collapses and suffers.

6.3 *UAV-to-Satellite Communication Link*

UAVs may connect with their GCS as well as other UAVs through satellites along the pipeline. Star topology can be established between UAVs and satellites.[52] However, this strategy has several drawbacks, such as high latency and the expensive cost of satellite leasing for services. Moreover, transmitting data by satellite demands a significant level of transmission power and energy consumption. Therefore, mini or micro-UAVs, which are often equipped with limited batteries, find it challenging.[64]

6.4 *UAV-to-Cellular Base Station Communication Link*

Cellular networks are becoming one of the most widely used modes of communication. It is a centralized approach. The entire targeted pipeline is divided into zones, commonly referred to as cells. Each cell is served by a cellular base station, that is in charge of determining routes to destinations. Because the UAV-cellular link requires low power transmission, it consumes less energy. As a result, it improves the network coverage by leveraging the existing cellular infrastructure. It also supports mobility. However, taking services from any cellular network is an overhead cost. For this connectivity, global system for mobile communication, universal mobile telecommunications system, general packet radio services, long term evolution, and wireless data transmission technologies like Wi-Fi and worldwide interoperability for microwave access can be used.[65]

7 UAV Trajectory/Path Planning

The environment has a major effect on UAV-oriented missions. Any environmental change might cause UAV nodes to malfunction or relocate themselves from their existing locations. One of the distinguishing aspects of UAVs is their ability to relocate, which allows them to adapt to the ever-changing needs of their surroundings. Therefore, to fulfill OGI pipeline surveillance requirements, the UAV path needs to be planned carefully. Two types of data must be provided to the ground station for oil and gas pipeline monitoring operations. A mission trajectory should maintain a continuous connection with the ground control station in the event of an emergency, such as a leak or a fire. Another data type records regular patterns for predictive maintenance and it can be sent whenever connectivity is possible. Nowadays, commercial UAVs primarily communicate with ground control stations using point-to-point transmissions. They use an unlicensed spectrum with restricted performance. Therefore, path planning is critical for achieving the optimal performance of the network. There are two scenarios for which deployment has been studied: static deployment and dynamic deployment. In the literature, several strategies have been presented to handle the issues of planning each path. We will go through each of them in depth in the next section.

7.1 *Path Planning for Static Scenarios*

In static deployment scenarios as in OGI pipelines, the ground control stations are predefined and fixed. Choosing the best UAV landing spot is a nonconvex optimization issue. Its dimensionality grows as the number of UAVs grows.[66] Numerous algorithms have been proposed for the optimal placement of UAVs.[67,68] The authors in these investigations assume that UAV and GCS are within a certain range. They aimed to provide a maximum coverage area. In another study,[58] the authors consolidated the constraint of possible hovering time of the UAV in the placement decision. They considered the average throughput to be their objective function. In the fronthaul capacity challenge, an idea of cache-enabled UAVs was introduced.[69,70] Contents were proactively downloaded and cached at off-peak hours of the UAVs or when they were docked for recharging. By decreasing the fronthaul traffic strain, content was thus directly transferred to the desired user.

7.2 *Path Planning for Dynamic Scenarios*

In dynamic scenarios, an optimal path is planned for UAVs along with the dynamic ground control stations. In the absence of any fixed control stations for pipelines, the optimization problem gets more complicated. A mechanism for optimal UAV trajectory, aiming to have high throughput and low energy consumption, was proposed.[71,72] Artificial intelligence is being utilized to cope with and rebuild UAV networks after natural disasters. A genetic algorithm was used to discover the best path for UAVs.[72] A single UAV used the space division multiple access methods to provide services to multiple mobile ground terminals. Furthermore, the Kalman filter was used to predict the location of the next ground terminal. In this way, the trajectory of the UAV was planned.[72] The concept of time-varying UAV speed was utilized.[73] It helped in reducing the data collection time. Another algorithm that considered minimal energy consumed by UAVs when moving from one point to another was proposed.[58] A brief comparison of both categories of path planning is given in Table 9.

8 Requirements, UAVs Challenges, and Research Directions—OGI Perspective

In this section, we examine the fundamental requirements of the OGI in existing solutions before moving on to UAV challenges and future research prospects in the OGI.

8.1 *OGI Requirements*

In the existing solutions, the following are the basic needs of the OGI that must be filled for an efficient and effective monitoring system:

1. **Cost-effectiveness:** Transportation of oil and gas assets from remotely located industrial areas to users is a critical task. A thousand kilometers pipeline passes through hazardous

Table 9 Dynamic versus static path planning algorithms.

Category	Ref.	Findings	Shortcomings
Static scenarios	58	Consider average throughput to be objective function. Hovering time constraint is considered in the path planning decisions.	No universal analytical framework for optimal location gathering.
	69, 70	Cache enabled UAVs. Reduces fronthaul capacity challenge.	
Dynamic scenarios	71	High throughput, low-energy consumption.	Refs. 71–74 propose mechanisms for one UAV.
	72	Genetic algorithm is used to find the optimal path after a natural disaster.	
	74	Space division multiple access methods are implemented by a single UAV to give services to multiple mobile ground terminals. Prediction of the next ground terminal location is done through the Kalman filter.	
	73	Time-varying UAV speed. It helps in reducing the data collection time.	
	58	Minimal energy consumption of UAVs is considered when moving from one position to another.	Considers only the energy factor and does not consider the cost of mobility.

environments to complete this task. Therefore, a cost-effective solution is the basic requirement of the OGI for performing efficient pipeline inspection.

2. **Low human intervention:** The OGI also demands a solution that is not dependent on humans to allow for faster leakage/explosion detection and avoid risk to human life.
3. **Security:** Oil and gas assets are a precious resource of any country. Therefore, the secure transportation of the asset is one of the basic demands of the OGI.
4. **Timely detection of an unusual event:** Any unusual event can occur due to equipment failure, leakage, corrosion, or pipeline vandalization, resulting in loss of oil and gas assets and environmental pollution. Therefore, timely detection of any catastrophic event is required to minimize losses.
5. **Fast data transmission:** Both crucial and typical data can come from pipelines. Critial data is information that indicates a pipeline issue and needs to reach the control station as quickly as feasible. Normal data is utilized for maintenance, though. To prevent losses, a mechanism for faster communication of crucial data should exist.
6. **Accuracy:** To repair pipeline damage or leaks quickly and effectively, it is crucial to know the exact location of the damaged pipeline. Therefore, the accuracy of the inspection mechanism is also one of the requirements of the OGI.
7. **Scalability:** There is a possibility that OGI pipelines extend to more areas, so the inspection system must be easily scalable.
8. **Fault tolerant:** An extensive inspection system is constructed as pipelines span thousands of kilometers. It should be fault tolerant for alerting the control center to fix an issue if some of the inspection system's components stop functioning.

Traditional monitoring methods, such as foot surveillance or manned helicopter monitoring, are expensive because they are human-dependent and time-consuming, and they expose both humans and infrastructure to security hazards. Moreover, alternative digital technologies, such as SCADA systems, WSN/IoT-based technologies, and robots, require little human intervention and can detect anomalous events quickly. However, communication, accuracy, fast data acquisition and transmission, scalability, and fault tolerance are still some of the issues to be addressed. However, UAVs can be deployed and controlled remotely,[29] requiring minimal human participation. They are also equipped with cameras that give real-time surveillance, allowing for fast detection and recovery of any unexpected events. They can also make use of technology such as edge computing and DTNs.[75] UAVs will be able to handle nearby data owing to edge computing, which reduces latency and network traffic. The concept of DTNs can be used to efficiently use bandwidth. As pipelines are deployed in hazardous environments for which communication infrastructure may not available, UAVs can communicate with satellite in the event of an emergency and can store data if it is not essential and send it later when the communication infrastructure becomes accessible.[76]

8.2 *UAVs Challenges and Research Directions—OGI Perspective*

The North Sea E&P company stated that employing UAVs to inspect assets can be twenty times faster and half the cost of traditional inspection methods.[77] From this survey, it can be concluded that autonomous UAV inspection systems play an important role in OGI inspection and have become the primary development direction for the energy sector. Although FANETs differ in certain respects from typical ad-hoc networks such as MANETs and VANETs, the underlying premise is the same: a network of mobile nodes that are established on the fly. Traditional MANETS and VANETS hold various challenges that still need to be addressed. However, FANETs are different from MANETs and VANETs; therefore, various additional challenges specifically related to FANETs must be solved. Several studies have examined the performance and efficiency of multi-UAV networks, but there is still room to investigate some more critical aspects linked to FANETs in various dimensions, such as autonomous UAV localization mapping, autonomous UAVs charging, efficient data delivery, trajectory optimization, UAVs swarm management, selection of UAV platforms sensors, UAVs data processing challenges, UAVs image analysis, mobility management, energy management, UAVs safety security, data protocol protection, QoS, and FANETs integration with IoTs. Some of the challenges mentioned above have been addressed for specific domains. However, the OGI sector has its specific challenges that will be presented in the ensuing sections. Figure 6 depicts various open issues.

Fig. 6 UAV challenges and research directions—OGI perspective.

8.2.1 *Autonomous UAV localization and mapping*

Autonomous localization is a very important aspect of UAVs. It is an essential need for navigation that is used to locate and assure the coverage of onsite key targets. The GPS localization technique is mainly used in UAVs.[78] However, the localization accuracy of any GPS depends heavily on the technique to compute the locations and measurement conditions of its environment (i.e., open sky environment or buildings.). An application, such as pipeline inspection, needs a few centimeters of accuracy to work properly. Hence, we cannot rely only on GPS as a localization system. Moreover, vision-based localization and navigation technologies are very prevalent nowadays. They are based on images collected by the onboard camera, and visual simultaneous localization and mapping (VSLAM) algorithms are used. A VSLAM algorithm is suitable for visual-guided systems as it can identify robots, assess their condition, and generate a picture of the external environment simultaneously. The previously described strategies have unquestionably improved the intelligence and autonomy of UAVs localization and mapping, but these approaches are still in their infancy. UAVs must fly and gather photographs for pipeline inspection activities, causing the scenery to change rapidly. Therefore, recognizing the dynamic environment is a critical issue that must be addressed. Tolerance for image blur, object occlusions, and lighting variations should all be considered.[79]

8.2.2 *Autonomous UAV charging*

In UAV communication scenarios, battery constraint is a big challenge. For OGI, the UAVs must fly in a line for long distances, and there might be times and situations when no nearby communication infrastructure is in range for charging and replacement purposes as pipelines run through hostile environments. It is also critical to disconnect the UAV from the relay network regularly without losing data. This, however, is both costly and complex. In another study, the authors created macro base stations to manage battery recharge and replacement difficulties.[80] Solar energy harvesting strategies were developed in a recent study, but they are less efficient than fuel and stored energy batteries because solar techniques are dependent on the intensity of light. To improve the performance of energy, introducing distributed multipoint wireless power approaches and innovative energy delivery mechanisms for UAVs is required.

8.2.3 *Efficient data delivery*

In-time data dissemination of critical data of natural or man-made disasters is a key to successful inspection in the OGI. Therefore, efficient data delivery and routing is a challenging task. As pipelines pass through different terrains, there can be areas where no communication infrastructure is possible. Therefore, studies can be undertaken to examine the adoption of recent technologies, such as Wi-Fi, WIMAX, LTE, antenna, or satellite transmission, to establish the continuous connection of UAVs to base stations in different scenarios.

8.2.4 *Trajectory optimization*

In the OGI, pipelines pass through different terrains, i.e., mountainous regions, desert areas, and plains. Therefore, the trajectory optimization of UAVs in OGI surveillance scenarios is critical. To perform the OGI surveillance missions successfully and efficiently, there should be optimal coordination between UAVs. Different algorithms are proposed in the literature to give optimal paths for UAVs by sharing different information, such as locations, links, etc. Due to the high mobility of UAVs, effective dynamic path planning is necessary to enable a fully coordinated and stable multi-UAV network.[81,82]

8.2.5 *UAV swarm management*

In OGI scenarios, multiple UAVs are tasked with traveling along pipelines for inspection. There should be optimal coordination between UAVs to perform inspection missions successfully and efficiently. However, controlling and managing many devices on board simultaneously can lead to synchronization, connectivity, and latency concerns. Therefore, UAV swarm management requires special attention. These challenges can be solved using game theory, contract theory, optimal transport theory, machine learning, and optimization theory algorithms.

8.2.6 *Selection of UAV platform and sensors*

The choice of suitable platforms and relevant sensors for efficient and effective OGI inspection missions is very important in FANETs. UAVs have different flight dynamics, orientation, and positioning mechanisms that may greatly influence the efficiency of inspection UAVs. The payload is influenced by the sensors chosen. Because UAVs are battery-powered, the height at which they fly and the weight they carry have an impact on their endurance. Therefore, further research can be done in this area to suggest relevant sensors and platform solutions for various OGI inspection scenarios.

8.2.7 *UAV data processing challenge*

Different sensors installed on UAVs gather different kinds of data when doing pipeline inspections, e.g., the camera captures snaps; thermal IR captures vision through smoke, haze, or clouds; and the temperature sensor records the temperature. Processing this data to get any useful information is a critical challenge. High computational capabilities are required for processing that might be not possible onboard UAVs. The optimal solution for this problem might be cloud or edge computing.[83]

8.2.8 *Image analysis and deep learning*

In OGI inspection scenarios, cameras are used to capture images of several events in pipelines. Therefore, image analysis is the most critical challenge in UAVs. Picture orientation and surface reconstruction are the basic issues linked to UAV imagery processing. Several studies have examined different methods of surface reconstruction.[84] However, to extract meaningful features and infer both qualitative and quantitative decision-making, certain machine learning and recognition approaches are required. Image identification and categorization is a commonly used remote sensing method. For example, for land-cover mapping, segmentation, and classification, many classification algorithms have been used.[85] Object tracking is a natural area of interest in UAV applications, although it remains difficult due to a variety of issues such as illumination, occlusion, and viewpoint variation.[86] Deep learning approaches have beem shown to be the most effective, delivering state-of-the-art results in a variety of identification and classification tasks, including image recognition, object detection, and localization. A specific sort of deep learning model, the deep convolutional neural network (DCNN), has been proven to reach state-of-the-art performance in a variety of image-related tasks.[87] Stochastic gradient descent (SGD) is used to update weights after scanning a small number of data (mini-batch) to efficiently train the DCNN model.[88] With image raw pixels as inputs and given the target outputs in the training dataset, SGD is used to update weights after scanning a small number of data (mini-batch).

8.2.9 *Mobility management*

High mobility is one of the distinct features of UAVs. So, dealing efficiently with the mobility patterns of UAVs in the OGI is a challenging task.[89] Several mobility models for FANETs have been introduced. Yet further work might be carried out to deeply study the UAV’s motion and their reaction to different situations. Another option is to examine and combine the best movement features of several mobility models to develop a more efficient mobility model.

8.2.10 *Energy management*

Energy is the backbone of a multi-UAVs network. Whenever data is sensed or transmitted, energy is utilized by the UAV. Patrolling of UAVs also consumes energy. Therefore, energy-efficient deployment to long-distance pipelines is very important. There should be a mechanism to efficiently place UAVs throughout the pipeline to decrease energy consumption. Moreover, the recharging schedule for UAVs should also be considered for future research.

8.2.11 *UAV safety and security challenges*

Safety and security are critical features for UAV-based systems. In fact, due to their low-cost and wireless communications, UAVs are prone to faults. As a result, they may lose control of the central server and crash into the OGI site or land in an undesirable area. To overcome this issue, algorithmic solutions for UAV networks should provide autonomous and self-configuring mechanisms. Therefore, there is a dire need to identify the best security measures that guarantee the detection of failures, abnormal UAV behavior, or compromised UAVs, which may cause the UAVs to lose control from the central servers, fly outside the monitored site, or crash in an undesirable area. Furthermore, power consumption rises because advanced security and privacy methods often require a significant amount of processing power and memory. Combining privacy and security with interoperability is hard, yet the need to find a balance between energy usage and security is necessary. Designing a safe and controlled landing method is critical from a safety standpoint. Hence there is a need to offer several techniques that promise a safe landing of the gadget in an emergency, avoiding communication connection failures, crashes, and engine breakdowns.[90]

8.2.12 *Data and protocol protection*

Security is a critical concern in FANETs. Because of the unique characteristics of FANETs, such as the lack of a fixed infrastructure, dynamic communication mechanisms, and uncontrollable natural conditions at energy sites, it is difficult to ensure data and protocol safety. More studies should be conducted to determine procedures for a reliable and secure UAV network.[91]

8.2.13 *QoS*

Currently, one of the major open concerns in FANETs is the quality of service provisioning. Because FANETs are responsible for transmitting a variety of data types, such as videos, snaps, and time-sensitive data, there should be mechanisms to ensure adequate QoS in terms of bandwidth, delay, packet loss, etc.

8.2.14 *Integration of FANETs and existing IoTs*

A combination of FANETs and other technologies, such as existing IoTs, could be a good idea for a pipeline monitoring inspection solution that is efficient, reliable, and cost-effective. Mechanisms for integrating FANETs and IoTs should be established.

9 Conclusion

This research has provided a thorough review of the OGI-specific UAV architectural design, as well as networking and communication link models for multiple pipeline surveillance scenarios. We have categorized pipeline surveillance through UAVs in three different scenarios: getting sensor readings for temperature, pressure, and flow rates; visual leak detection; and detection of any unusual activity. Low-cost, reliable, and fault-tolerant different networking architectures were examined for the above-mentioned scenarios. Finally, there are some open issues and challenges with using UAVs networks in the OGI. We expect that many researchers and professionals who are interested in designing a FANET network for effective IMR operations in OGI will find this paper valuable.

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