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# Unmanned Aerial Systems for the Oil and Gas Industry: Overview, Applications, and Challenges

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**ABSTRACT** Unmanned aerial systems (UAS) represent an evolving technology with enormous potential to revolutionize the oil and gas industry by providing a more efficient, fast, safe, and cost-effective way to perform a variety of field activities. Recently, UAS has received considerable attention from the oil and gas industry. The objective of this review article is to highlight the usability of UAS for the oil and gas industry, focussing mainly on UAS applications and the opportunities and challenges of UAS deployment in such oil and gas applications. Additionally, this paper also covers the available sensory systems for UAS and provides some recommendations to select a UAS for a given oil and gas application.

**INDEX TERMS** Asset integrity, inspection, monitoring, oil and gas industry, unmanned aerial systems (UAS).

## I. INTRODUCTION

World energy demand keeps increasing, and the oil and gas (O&G) is likely to remain the primary source to meet this ever-increasing energy demand [1]–[3]. Although demand remains high, the O&G industry currently facing several challenges, for example:

- major onshore and shallow water offshore oil fields are now mature fields, i.e. which have reached their peak production rate and have started to decline,
- new and future hydrocarbon reserves are located in extreme, hostile and hard-to-reach environments, such as deep water, ultra deep water, hot deserts, and in the arctic,
- crude oil price has been low for a longer period,
- most experienced workers are retiring soon, and the next-generation workforce is about 20 years younger, creating a significant knowledge gap, and
- the exploration, development, and production activities of oil and gas fields involves significant health, safety, and environmental (HSE) risk.

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With the fourth industrial revolution, also known as industry 4.0, the O&G industry has started to adopt digital technologies to mitigate some of the issues mentioned above [4]–[10]. Unmanned aerial systems (UAS) are at the forefront of digital adoption to address the limitations associated with a range of inspection, monitoring, and surveillance activities associated with the O&G industry [11]–[15]. Application of UAS for inspection, monitoring, and aerial surveillance is not new. UAS have been in use for decade in civil (photography [16], [17], construction [18], [19], mining [20], [21], delivery [22], [23], agriculture [24], [25], disaster management [26], [27], surveillance [28], [29]), environment (air quality monitoring [30], soil monitoring [31], crop monitoring [32], surface and groundwater monitoring [33]) and defence [34]–[36] applications.

There is a large body of literature that discusses the deployment of UAS for the O&G industry. Although these implementations demonstrate the utility of UAS for the O&G industry, there are several technological and regulatory challenges yet to be addressed before there will be industry-wide adoption. Additionally, most of these research articles include one or two applications but do not provide an overall status of UAS adoption to date for the O&G industry to date. This selective nature of current UAS adoption may not allow the O&G industry to realize the full potential of UAS adoption. Thus, the objective of this review article is to present the current status of the UAS adoption in the O&G industry, focussing mainly on UAS applications in the O&G industry and opportunities and challenges of UAS deployment in such applications. Additionally, this paper also covers the available sensory systems for UAS and provides some recommendations to select a UAS for a given O&G industry-oriented application.

The remainder of this article is organized as follows. Section II outlines the paper selection criteria for the literature survey. Section III to Section VIII gives an overview of UAS systems, applications of UAS in the O&G industries, advantages and challenges of UAS deployment for the O&G industry, available sensory systems for UAS, and factors to be considered when deploying UAS for the O&G industry-related applications, respectively. Finally, Section IX, provides a summary of the finding of this literature review.

## II. METHODOLOGY

Paper selection criteria for this literature review is outlined in TABLE 1. Initially, a keyword-based article search was conducted on four digital publication databases, namely, IEEE Xplore, OnePetro, Scopus, and Springer. These digital libraries are selected because they are the leading digital database where the researchers in digital adoption for the O&G industry publish their research findings. This keyword-based filtering identified over 700 articles. Among these articles, it was possible to obtain full access to 513 articles. As this is a keyword-based filtering, an article with the keywords does not necessarily discuss UAS-base implementation or research but may only include passing references to UAS within the article. It is essential to identify such articles and remove them from the subsequent analysis. Therefore, the abstract, introduction, and conclusion of these 513 articles were manually reviewed to isolate the most relevant articles to our study. This operation reduced the total number of articles to 95. These selected articles were reviewed in full to prepare an overview of UAS, and to identify applications, advantages, challenges, and sensory systems for UAS concerning the O&G industry.

## III. OVERVIEW OF UAS

Before presenting the findings of the literature review, this section provides an abstract level introduction to UAS and its classifications. Although this is a general introduction and does not add value to researchers in the UAS domain, it will be useful for some researchers from the O&G industry who are new to UAS.

In general, UAS is a flying platform that can be maneuvered remotely or autonomously, typically carrying a payload to assist the mission. A pilot at a ground station controls the remotely operated UAS while an onboard autopilot system is responsible for maneuvering an autonomous UAS. A hybrid approach involves the pilot at a ground station remotely controlling the takeoff and landing while the autopilot system controls the UAS during the rest of the mission. Typically for the O&G industry, the UAS payload consists of a range of sensors, and the UAS is maneuvered remotely or using semi-autonomous approaches.

**TABLE 1. Article screening criteria.**

| Searching index | Specific content |
|---|---|
| Database | IEEE Xplore, OnePetro, Scopus, Springer |
| Article types | Scientific articles published in journals, conferences, and technical reports from industry |
| Search string | ("UAV" OR "drones" OR "UAS" OR "aerial robots" OR "MAV" OR "unmanned aerial vehicles" OR "micro aerial vehicles" OR "unmanned aerial systems") AND ("oil" AND "gas"), |
| Screening procedure | The relevance with the UAS application to the O&G industry as selected based on the number of occurrences of key terms followed by the manual review of contents of abstract, introduction and conclusion. |
| Other information | Overview, applications, advantages, challenges, and regulation frameworks for UAS usage in the O&G industry are identified from the filtered articles. |

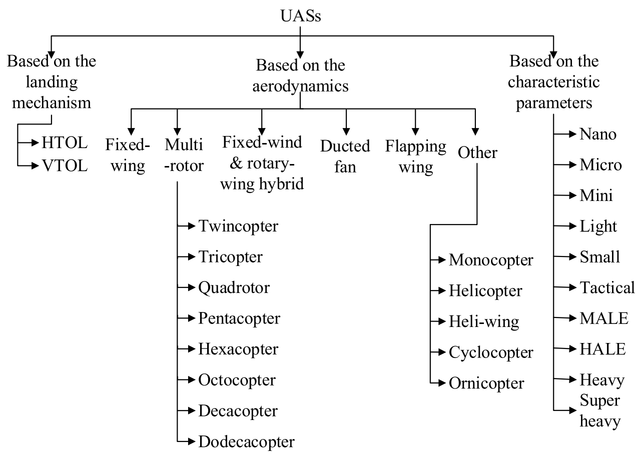


**FIGURE 1. A sample UAS classification.**

UAS can be classified based on flight dynamics, landing mechanism, and other characteristic parameters [34], [37]. A sample UAS classification is shown in FIGURE 1. A detailed classification of UAS along with general applications, a sample list of commercially available UAS and their characteristics, payload information, and a sample list of data processing software tools can be found in [34], [37].

UAS use two primary landing mechanisms, namely horizontal takeoff and landing (HTOL) and vertical takeoff and landing (VTOL). HTOL UAS can have a very high crusing speed, but they are difficult to maneuver for landing on a specific point and its vertical movement or hovering is not possible. Most traditional aircraft comes under this category. In contrast, VTOL UAS can fly, land, and hover vertically but they are not appropriate for higher crusing speeds. Fixed-wing UAVs typically have a similar shape as the commercial

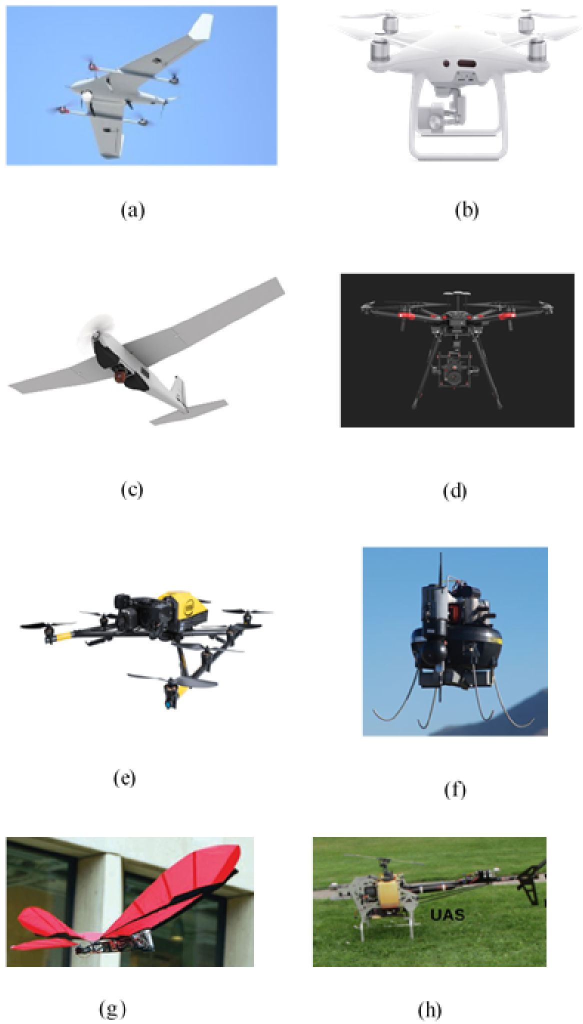


**FIGURE 2.** Sample UAS systems. (a) Fixed-wing and rotary-wing hybrid (ZT-3V [38]), (b) Quadrotor (DJI Phantom 4 Pro [39]), (c) Fixed-wing (Puma AE [40]), (d) Hexacopter (DJI Matrice 600 Pro [41]), (e) Octocopter (Intel Falcon 8+ [42]), (f) Ducted-fan UAV [43], (g) Flapping wing (MIT's Flapping UAV, Pheonix: Photo by Jason Dorfman [44]), (h) Helicopter [45].

passenger and cargo aircrafts and generally belong to HTOL category. Multi-rotor UAS belong to the VTOL category and contain multiple rotors to provide the thrust necessary to fly and control the aircraft altitude. The most attractive advantage of using multi-copters is the ability to fly at a constant altitude and also to hover at a single location while pointing its orientation to a desired target. These UAS are named based on the number of rotors that generate the thrust. For example, quadcopter has four rotors, hexacopter has six rotors, and octocopter has eight rotors. There are platforms such as tilt-wing and tilt-rotor whose hardware configurations allow them to switch from fixed-wing to rotary-wing configurations and vice-versa. These UAVs referred to as hybrid configuration for fixed and rotary wings. The ducted fan configuration is somewhat similar to multi-rotor configuration and capable of VTOL and hovers at a single location. However, the thrusters of these aerial robots are enclosed within a duct. Therefore, these thrusters are generally referred to as 'fans' instead of rotors. The flapping wing UAS mimics the flying mechanism of birds. There is a range of other rotary-wing UAVs, which include monocopters, helicopters, cyclocopters, and ornicopters.

TABLE 2 presents a sample UAS classification based on the weight and range. As outlined in [37], it is important to note that the number of categories, the range and weight specifications may slightly differ depending on the country. Out of those specified in TABLE 2, the most commonly used UAS types in the oil and gas industry are nano-, micro-, and mini-type UAS.

**TABLE 2.** UAS classification based on the weight and range [34].

| Type | Maximum weight (kg) | Maximum range (km) |
|---|---|---|
| Nano | 0.2 | 5 |
| Micro | 2 | 25 |
| Mini | 20 | 40 |
| Light | 50 | 70 |
| Small | 150 | 150 |
| Tactical | 600 | 150 |
| MALE (Medium Altitude Long Endurance) | 1000 | 200 |
| HALE (High Altitude Long Endurance) | 1000 | 250 |
| Heavy | 2000 | 1000 |
| Super heavy | 2500 | 1500 |

## IV. APPLICATION

Over the past two decades, O&G asset owners, operators, and service providers have been evaluating and leveraging UAS for a range of applications. Across the entire O&G life cycle, most popular application areas include asset integrity inspection (excluding pipelines) [13], [46]–[66], pipeline petrol [67]–[80], [80]–[84], environmental monitoring [85]–[100], geophysical/geoscience/topological surveys [45], [101]–[111], security monitoring [71], search and rescue missions [112], oilfield equipment inventory management [113], and data relay for sensor networks [114]–[116]. The following subsections discuss these applications in detail.

### A. ASSET INTEGRITY INSPECTIONS

Asset integrity management of the O&G industry generally involves conducting inspections at height, live systems, or in confined spaces. Conventional tools used to access these hard to reach areas include rope, scaffolding, or in some cases a full-size helicopter [49]. Rope access inspection is time-consuming and involves personnel working at height. Scaffolding is expensive, more time-consuming than rope access and also involves personnel working at heights. There is a possibility of damaging the asset when erecting scaffolding, especially, inside the tankers. Neither rope access nor scaffolding can be used to access and conduct the inspections of the flare stack during operations. Full-size manned-helicopters can also be used for such purposes which are referred to as "fly-by" inspections. Due to limited maneuverability in small spaces, full-size helicopters cannot be used to capture images of the radiation shield, flare boom, and the flare deck support structure [117]. Additionally, the majority of the structural parts of the offshore production and drilling facilities (e.g., underdeck) cannot be accessed using the full size helicopter, leaving rope access and scaffolding as the primary access methods to conduct inspections. Depending on the engine size and type, full-size helicopters use different fuel types ranging from aviation kerosene to aviation gasoline. Such fuels have the potential to cause a series of catastrophic incidents if the helicopter is to crash. When it comes to inspection of confined areas, both the full-size helicopter and scaffolding become unavailable, and only option left is rope access. Sending a human operator to conduct inspections in confined spaces can be associated with high risk due to chemical, gas, and radiation contaminations or lack of oxygen.

UAS are considered to be a viable option to acquire high-quality inspection data while minimizing HSE risks associated with conventional methods of access [13], [46]–[66]. Typically, UAS-based asset inspection is carried out by a two-person team that consists of a licensed pilot and an inspection engineer [117]. The pilot entirely focusses on flying the UAS while the inspection engineer operates the camera and sensor payload independently to acquire the images, videos, point-clouds, and other measurements. Based on the real-time data, the inspection engineer may request the pilot to navigate and orient the UAS to a specific pose such that the engineer can collect more data from the area of interest. There is a range of inspection activities that can be conducted using UAS, which include general visual inspection (GVI), close visual inspection (CVI), thermal inspection, data collection for three- and four-dimensional (3D and 4D) model generations. TABLE 3 lists several practical applications for UAS-based asset integrity inspection in the O&G industry.

A time and cost comparison for conventional and UAS-based asset inspection activities is reported in [56]. As given in TABLE 4, approximately 25% to 75% of cost and time-saving can be achieved using UAS in the place of conventional inspection approaches. Note that TABLE 4 presents only the inspection cost excluding the cost for preparation, transportation, and accommodation. For example, scaffolding a structural leg can require about 336 hours of setting up time and the associated cost for the scaffolding alone is about 130,000 USD [56]. Additionally, the transportation cost and accommodation cost for field workers and providing other supporting materials can be high. Alternatively, the preparation and setting up time require for UAS-based inspection can be as low as one to two hours since most of UAS are modular. Typical UAS-based inspection is carried out by a two-person team making the transportation, and accommodation costs significantly lower than that of scaffolding-base inspection. However, if any repair and replacement is necessary then scaffolding may still be required.

Besides the UAS, there are several other robotic systems under evaluation for asset integrity inspections. These systems include unmanned ground vehicles, flexible robot arms, small-scaled robotics systems for internal inspections of pipelines, wall-climbing robots, and autonomous underwater vehicles. Each of these robotic systems has its strengths and weaknesses. For example, unmanned ground vehicles have more battery power and can operate longer duration than UAS but require O&G operators to construct additional infrastructures (e.g., ramps, or access ladder) so that the robots can access multi-level O&G facility. Wall climbing robots could fell if their adhesive mechanism malfunctions during the inspection activities. Flexible robots arms are typically immobilized and located at fixed locations of the O&G facility. In addition to robotic systems, it is possible to deploy wireless sensor network to continually gather integrity data of an O&G facility. However, installation and maintenance of such sensor network increases the operation cost of the facility.

**TABLE 3. Pragmatic UAS application to O&G asset integrity management [117].**

| Location & System | Components |
|---|---|
| Flare system | Tower/boom members and joints, pipework, support structure, access latter, flare deck, ignition system, pilot burners, flare tips, and nozzle |
| Drilling derrick | Structural nodes, missing or damaged cladding, loose, |
| Exhaust | Supporting structure for exhaust, ducts |
| Underdeck | Drains pipework and support, cellar deck primary steelwork, spider deck primary steel work, pipework connections |
| Splash zone | Jacket, legs, GBS, riser clamps and supports, riser guides and weld tie-back to jacket structure, caisson, J-tubes, and dead weight support |
| Overboard structures | Communication dishes, antennas and supports, helideck supporting structure, escape ladders, walkways/bridges, crane booms |
| Floating units (e.g. FPSOs) | Hull (internal and external), mooring chains |
| Chimneys | The height and circumference of the chimney structure, lighting conductor, supports and fixings, gantries |
| Confined areas | Vessels and pipework |

**TABLE 4. Inspection time and cost [56].**

| Inspection work | Conventional | | With UAS | | Saving percentages |
|---|---|---|---|---|---|
| | Time (hr) | Cost (USD) | Time (hr) | Cost (USD) | |
| Ballast tanks | 12 | 4800 | 9 | 3600 | 25% |
| Void space | 6 | 2400 | 3 | 1200 | 50% |
| Legs | 24 | 9600 | 18 | 7200 | 25% |
| Helideck | 3 | 1200 | 1 | 400 | 66% |
| Crane boom | 1 | 400 | 0.5 | 200 | 50% |
| Hull bottom | 16 | 6400 | 4 | 1600 | 75% |

### B. PIPELINE PATROL

O&G transmission pipeline network comprises over 3 million kilometers of piping and is the primary infrastructure of the midstream of the O&G lifecycle [118]. This network continues to grow. For example, by 2022, it has forecasted that Asia will extend its pipeline network by 71,000 km by investing about USD 99 billion, while North America will extend its pipeline network by 55,000 km by investing about USD 160 billion [119]. Vehicles and heavy digging equipment, in particular, pose a threat to the O&G pipeline network [81]. Human activities around the pipelines also may damage the pipeline causing catastrophic failures. Additionally, there is a possibility for vandalism and sabotage from people who are against the pipeline and who may want to steal oil. If there is an equipment failure in this pipeline network, such as breakages and leaks, it will lead to several issues, as listed below.

- Fatalities and series medical conditions: In 2004, high-pressure natural gas pipeline explosion occurred in Ghislenghies (Belgium) resulted in 24 fatalities and over 120 injuries [120].
- Environmental damage and subsequent health issues: In 2010, a crack has occurred due to the corrosion and fatigue, spilling over 3800 $m^3$ of heavy crude oil into the Kalamazoo River (Michigan, USA). This resulted in significant environmental damage and caused health issues for hundreds of Michigan residents due to toxic exposure from the oil [120], [121].
- Loss revenue and increase of OPEX: When there is an oil or gas leakage, the amount has spilled a waste, and the owner/operator must invest millions of dollars in cleaning up the environmental damage. For example, the clean-up cost of the Kalamazoo River was around USD 1.21 billion [121].
- Damage to company public image and threaten the security of the energy source: Environmental activists and the general public are very critical about accidents associated with O&G pipelines. In the event of a major accident, the pushback coming from these groups can cause a severe damage to the public image of the operator, which can potentially affect financial condition of the industry due to a drop in share prices. Additionally, a damaged pipeline can give rise to an energy shortage locally or globally; for example, in 2014, one of the TransCanada Corporation's gas transmission pipelines was exploded and burned, resulting in a natural gas shortage in some parts of Canada and UAS [122].

Since an attack or damage to a pipeline network or equipment failures can lead to enormous ecological impact, health issues, loss of revenue, and international oil market disruption, it is crucial to perform a periodic assessment on the physical state and functionality of the pipeline network. General approaches to evaluate pipeline integrity include visual inspections and mass balance measurements. In the past, this was performed by a foot patrol team or an aerial surveillance team using manned light aircraft or manned helicopter. Both approaches are costly as compared to UAS-based approach. Foot patrols may not be a viable option to inspect a longer pipeline, which extends hundreds and thousands of kilometers. Real-time monitoring systems based on networks of small sensors are also considered (piloted and implemented) for evaluating the physical state and functionalities of pipeline networks [123]. These sensor networks consist of a range of small sensors, including pressure, acoustic, flowrate, and temperature sensors to measure real-time flowrate and wall thickness and to identify and localize leaks. Sensor networks can provide information to a central computer to assess real-time pipeline state. However, there are some other logistical issues may exist when with such implementation. These concern reliability, standardization, energy consumption, and general operational and physical security issues, especially for long-distance pipeline and in areas susceptible to vandalism and sabotage [124], [125]. Satellite-based remote sensing seems a viable option to fulfill the ever-increasing demand for the near real-time pipeline monitoring. However, the configurations of spatial and temporal data resolution of operational satellites are still not enough for O&G pipeline monitoring [72]. Airborne pipeline monitoring using either a manned aircraft (small) or a helicopter may still require flying very close to the terrain, which in turn raises a series of safety concerns and involves high noise levels. The patrolling frequency is generally decided by the cost.

Most of the challenges associated with conventional pipeline monitoring can be addressed by deploying UAS to conduct pipeline patrols, [67]–[84]. The type of UAS to perform pipeline patrolling and the type and resolution of the sensors that are attached to the selected UAS depends on the survey type (GVI, CVI, spectral survey), duration (in minutes or hours), and length (in km) of the pipeline. These deployments can help to detect and monitor leaks and spills, detect and monitor unauthorized access and trespassing, and conduct surveys in remote and hard to access regions.

There are several techniques available for detecting and tracking O&G leakages and spills [72]. UAS can be equipped with optical cameras to acquire high-resolution stills (images) and videos of the pipeline and its surroundings. Subject matter experts (SME) can review those stills and videos to identify the leaks of the pipelines. As compared to the ground substrate, defective areas will produce warmer regions in case of oil leaks and colder regions in case of gas leaks. This temperature difference can be captured using thermal infrared (TIR) sensors. Standalone TIR images captured on different days of the same area can be used to identify temperature variations and isolate the potential oil or gas leaks. It is important to note that there are several other factors, such as water content, can affect the soil temperature. Therefore, the finding from TIR should be validated with other auxiliary methods such as soil impedance measurements.

Hydrocarbon contamination reduces the vegetation vigour and lowers the vegetation index. Additionally, it leaves spectral marks on the plant. Therefore, monitoring of the plant health around the pipeline can indicate the potential hydrocarbon leaks. This can be achieved by acquiring and comparing repetitive multi-spectral measurements of vegetation using the sensors operate in the visible and near-infrared (NIR) wavelengths.

Note that the density and the frequency of data acquisition are rapidly increasing with the adoption of UAS for pipeline monitoring. Therefore, it is challenging to manually review and analyze this multitude of data to detect the anomalies in the pipeline itself, the surrounding soil and the vegetation. Therefore, automation of data interpretation using specialized computer software tools supported by artificial intelligence is required to achieve the maximum benefits from the collected data.

### C. ENVIRONMENT MONITORING

Environmental monitoring related to the O&G industry consists of several activities, which include, but not limited to, environmental impact assessment, wildlife monitoring, gas emission monitoring, spill detection, spill clean-up activity monitoring, reclamation activity monitoring, detecting and tracking icebergs, and ice reconnaissance. The environmental impact assessment activities commence at the early exploration stage and continues until site abandonment. At the early environmental impact assessment, UAS can replace low altitude manned aircraft and collect high-resolution aerial images, videos, and point-cloud data to generate dense topological maps and 3D models of the area of interest [101]–[103]. These maps and models can then be leveraged for planning the exploration activities and construction activities so that environmental impact is minimized. Additionally, these initial maps and models serve as a reference for reconnaissance activities at the abandonment stage.

Identification of wildlife corridors and sanctuaries is also vital when planning for exploration, construction, and operation of O&G extraction facilities. This serves two purposes. First, it will not disrupt the natural harmony of the surrounding ecosystem, and second, it avoids the potential threats and attacks that can come from the wildlife [99], [100]. As reported in [100], wildlife encounter is the second-highest HSE incident for Total E&P Uganda (refer to FIGURE 3).

High-resolution aerial images and videos taken from UAS can be analyzed to identify natural habitats and wildlife corridors. O&G industry can leverage this knowledge when planning activities in these regions to avoid wildlife conflicts and subsequent pushback from environmental activists and local regulations.

Oil spills and leaks typically generate visible marks on the soil, vegetation, and even on the water (ocean, river, lake) surfaces. Therefore, they can easily be detected. However, gas leakages do not create a visible mark. While such leaks may create an odor sensitive to human, this is not an appropriate way to detect a gas leak. It is not safe to deploy foot patrols and it is expensive to deploy manned aircraft (helicopters) frequently to survey, identify, and locate gas leaks. These limitations can be mitigated by deploying UAS equipped with the appropriate sensor payloads, which may include highly sensitive optical, multi-spectral, and gas detection sensors to detect and locate gas leaks effectively.

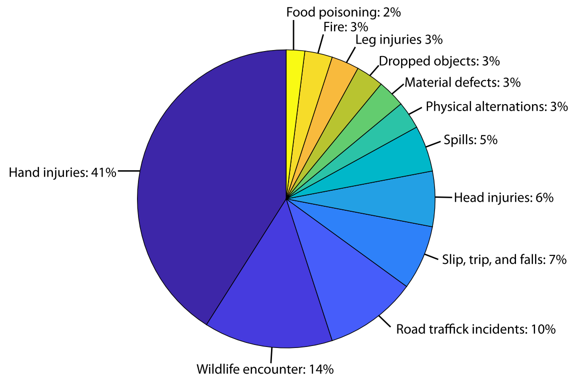


**FIGURE 3.** **HSE incidents of Total E&P Uganda [100].**

When considering offshore O&G exploration, drilling, production, and transportation, asset owners and operators have extensive experience respecting to influences of current, waves, and wind on offshore installation and vessels. However, this knowledge is still limited for the ice-infested regions, such as offshore Newfoundland. Ice management plans in these regions require offshore asset owners/operators to detect, track and forecast sea-ice, ice ridge and iceberg movements, and accumulation in their operation regions [85], [126]–[128]. Sensor platforms for monitoring ice infested areas can be categorized into three groups: airborne (satellites, manned aircraft/helicopters, UAS), surface-based (shipboard, buoys, unmanned surface vessels (USVs), offshore platform), and subsea (moored, unmanned underwater vehicles (UUVs)). Overview and comparison of these sensor platforms are given in TABLE 5 and TABLE 6, respectively [85].

**TABLE 5.** **Sensor platform overview for ice management [85].**

| Sensor Type | Platform | | | | |
|---|---|---|---|---|---|
| | Satellite | UAS | Shipboard | Buoy | UUV |
| Optical (visible to near IR, TIR) | ✓ | ✓ | ✓ | | ✓ |
| Laser altimeter/scanner | ✓ | ✓ | | | ✓ |
| Radiometer | ✓ | ✓ | ✓ | | |
| SAR (Synthetic-aperture radar) | ✓ | ✓ | | | |
| Marine radar | | | ✓ | | |
| Scatterometer | ✓ | ✓ | | | |
| Radar altimeter | ✓ | ✓ | | | |
| Acoustic techniques | | | ✓ | | ✓ |
| Meteorological suite | | ✓ | ✓ | ✓ | |
| Oceanographic suite | | | ✓ | | ✓ |

From TABLE 6, it can be seen that each of the sensor platforms has its own strengths and weaknesses. When considering all the characteristics together, deployment of UAS seems have more benefits than other systems. Limited sensor payload is the critical disadvantage of UAS. For practical implementation, it is recommended to employ a combination of the above sensor platforms rather relying on a single standalone system. Recently, research was conducted to tag

**TABLE 6. Sensor platform comparison (E:Excellent, VG:Very Good, G:Good, H:High, L:Low, I:Intermediate, S:Sparse, D:Distant, C:Close) [85].**

| Sensor Type | Platform | | | | | | |
|---|---|---|---|---|---|---|---|
| | Satellite | UAS | Manned aircraft | Shipboard | Buoy | USA | UUV |
| Coverage | E | VG | | L | H | I | G |
| Spatial resolution | I | H | | I | S | | E |
| Temporal resolution | L | I | | H | I | L | I |
| Cost per area | I | | H | L | H | | I |
| Degree of availability | L | H | I | | | | L |
| Payload capacity | E | L | H | | L | I | |
| Suggested regions of operation | D | D/I/C | | C | D/I | I | C/I |

icebergs with GPS trackers, where UAS were used as the transportation platform to deliver a GPS tracking device onto iceberg [95]. This enables accurate tracking of the iceberg movements.

## D. OIL AND GAS EXPLORATION SURVEYS

At the early stage of hydrocarbon (or mineral) exploration, local regulators and resource industries conduct aerial geophysical and topographical surveys to identify targets for exploration drilling activities, and to plan subsequent exploration, construction, and production activities. In general, these aerial surveys are conducted using fixed-wing manned aircraft, helicopters, or satellite systems. The most commonly conducted airborne surveys include radiometric, magnetic, and gravity surveys. Additionally, fixed-wing aircraft and helicopters may host light detection and ranging (LiDAR) sensors to map the topology of the area under investigation. This is referred to as airborne laser terrain mapping (ALTM). Critical limitations of these aerial surveys include high cost and poor data resolution. These limitations can be addressed by deploying UAS for conducting these initial aerial survey and reconnaissance activities.

There are several light-weighted magnetometers, high-resolution cameras, and custom data processing tools available for drone-based geophysical surveys [45], [101], [105]–[107], [129]. UAS can fly at an elevation of 250 feet while the conventional manned aircraft are required to fly at an elevation of 2000-5000 feet. Combining the lower elevation with closer survey grid-patterns, UAS can acquire the geophysical measurements at high-resolution. Some researchers have developed algorithms to generate digital terrain maps (DTMs), leveraging the aerial images acquired using UAS [103]. 2D/3D image processing and point-cloud processing approaches have been proposed for fracture analysis, outcrop modeling, and to identify mechanical stratigraphic for large-scale fracture corrido and fault damage zones [101]. UAS-based geophysical surveys are not only limited to traditional airborne surveys but also to extend into high-density seismic surveys in most inaccessible environments on the earth and onshore regions with high vegetation [102], [109], [109]–[111]. Additionally, UAS have evaluated as a viable solution for dense sensor deployments to conduct geophysical surveys [111].

## E. OTHER APPLICATIONS

Apart from the four essential applications discussed above, several other applications can benefit from the deployment of UAS. These applications are summarized below.

### 1) OILFIELD EQUIPMENT INVENTORY [113]

Oilfield equipment is typically stockpiled in outdoor areas. Accurately tracking and managing of this bulk equipment and components is challenging and requires considerable labor and cost. Therefore, O&G asset owners, operators, and oilfield service providers avoid managing precise inventory systems while keeping a sufficient stock of those equipment. Ultra-high frequency (UHF) RFID tag-based solutions can be implemented to accurately manage oilfield equipment inventory. Since passive UHF-RFID tags do not require batteries to operate, they can be attached to any oilfield equipment. UAS host the corresponding UHF-RFID reader and flies over the equipment stockpile. Passive UHF-RFID tags are energized using the power provided by the RFID reader's radio link so that the tag can communicate its serial number to the reader. The received serial numbers are recorded along with the date, time, and geolocation stamps. The UAS may wirelessly connect with and update a cloud-enabled oilfield equipment inventory database. If the real-time connectivity with the oilfield equipment inventory database is not allowed or viable, UAS can save the acquired inventory data locally and retrieves once the UAS lands.

### 2) SEARCH, RESCUE AND DISASTER MANAGEMENT [12], [15], [112], [130]

The O&G industry is committed to providing a safer working environment with a lower probability of an accident. Despite these efforts and standards, it is still necessary to reduce the threats to human life and property, which may occur due to inadequate emergency response. If an accident occurs, locating the field personnel as fast as possible is crucial to ensure their safety. For example, during an accident in the Gulf of Mexico, the emergency responders failed to locate 11 offshore field workers which resulted in 11 deaths [112]. Wireless sensor network-based or RFID tag-based personnel tracking systems can be implemented to locate the field personnel [112]. Most of the existing implementations rely on the Wi-Fi network or RFID reader network integrated to the drilling, production, refining, or any other facility. Unfortunately, relying on the local infrastructure is not a viable option during accidents because the local Wi-Fi network or RFID reader network may also be damaged or not functioning in case of an accident. This limitation can be addressed using UAS wherein the RFID reader is hosted in the UAS, which fly over the facility to locate the field personnel. Onboard sensors of the UAS can map and 3D reconstruct the damaged facility enabling the emergency response team to identify safe entry and exit points and routes to rescue the located field personnel. Additionally, real-time video (visual and thermal) feedback from the UAS would assist the emergency responder in assessing field personnel conditions and situations around them to prioritize rescue attempts.

#### 3) DATA RELAY FOR LINEAR WIRELESS SENSOR NETWORK [114]–[116]

Wireless sensor networks (WSNs) are used for pipeline monitoring, where the sensors are connected linearly. This type of WSN is referred to as a linear sensor network (LSN), which employs the sequential information-hopping capability of each node to communicate the collected data to the data processing center. Failure or attack (physical or cyber) occurring at a single node may isolate several nodes from the network affecting the reliability of the network. The isolated (disconnected) sensor node would not be able to communicate the sensed data to the central data processing center leading to suboptimal pipeline management. The impact coming from the failed node can be mitigated, and the reliability of the network can be improved using UAS to relay the data at the defected sensor node.

In addition to the above failure problem, there are few more limitations that can be found in pure multi-hop communication method used in LSN. As an example, an O&G pipeline can extend hundreds or even thousands of kilometers, making LSN less economically viable. Additionally, the number of relay nodes used in LSN may need to be increased to ensure the continuous connectivity and the reliability of LSN. To address these limitations, a new LSN architecture called UAS-based LSN (ULSN) has been introduced [115]. The ULSN architecture consists of four types of nodes: sensor nodes (SN), relay nodes (RN), UAS, and sink. Similar to conventional LSN, SN collect data and use traditional multi-hop routing approach to transmit their data to the nearest RN. RNs act as a head node for surrounding SN. UAS moves backward and forward along a linear structure such as O&G pipeline, and collects data from RN. Therefore, RN uses a one-hop routing approach instead of multi-hop, reducing the requirement of high-power allocation for the RN. It is possible to place redundant RN to ensure continuous connectivity and reliability of the network. Two sink nodes are located at either end of the pipeline to download the data from UAS. ULSNs are more reliable and offer a high level of flexibility when deploying a sensor network for monitoring linear structures (pipelines). It has been demonstrated that ULSNs increase data capacity [131], [132], assist with failure detection and sensor calibration [133], and provide added security support [134]. Note that the use of UAS to collect data from RN and bring it to the sink node introduces extra end-to-end time delay compared with conventional LSN.

#### 4) SECURITY SURVEILLANCE AND FLEET MANAGEMENT [12], [71]

In general, once the drilling, production, and refinery facilities are in place, it is possible to place a permanent surveillance system to conduct security surveillance and fleet management. However, during the exploration and construction phases, placing a permeant surveillance system is impractical and challenging. This can be eliminated by deploying UAS attached with optical and thermal camera systems to capture high-resolution stills and/or real-time videos. If RFID tags are attached to field workers and equipment, UAS-based RFID readers can be deployed for real-time tracking of the equipment and field workers. Knowing the location of field workers and equipment allows field supervisors to effectively manage the fleet, improve occupational health and safety, and allocate the available resource to optimize the field activities. Additionally, images and videos can be used to identify unauthorized access and theft as well as to assess whether the field workers follow standard safety procedures when performing the tasks assigned to them.

#### 5) FINDING ABANDONED WELLS [104]

O&G drilling and production activities have over 150 years of history. At the very early stages of this business, the industry was not properly structured and regulated. Thus, documentation of drilling activities related to the early age of the O&G industry is typically unavailable. As a result, still there exists a large number of undocumented wells. Regulators now request O&G operators to identify existing wells within a buffer zone,[1] surrounding the unconventional wells that will be hydraulically fractured. This requirement is placed to avoid the hydrocarbon communicating from the hydraulically fractured well to an undocumented and possibly unplugged well, which can potentially cause HSE hazards. Operators can generally consult local regulator's well database, company records, historical maps, and photos to identify active wells, inactive wells, orphan wells, and abandoned wells (both plugged and unpugged). Additionally, the operator has to survey the buffer zone to locate undocumented wells and attempt to properly plug these wells to avoid any potential accidents. UAS can be used as a sensor platform to conduct this survey rapidly and at a lower cost. Magnetic survey tools can be employed to detect and locate wells with a magnetic casing, and high-resolution LiDAR can be attached to the UAS to detect and locate the wells with nonmagnetic casing (wood or cast iron).

## V. ADVANTAGES

There are several advantages of deploying UAS in the O&G industry. As drawn from the literature and our own research experiences, some of these advantages are summarized below.

### A. IMPROVED SAFETY FOR WORKERS

Using UAS, it is possible to eliminate working at heights, and in contaminated environments, confined spaces, remote regions, and any regions with geopolitical conflicts.

[1] For example, The Commonwealth of Pennsylvania, 1000-feet around the unconventional well is defined as the buffer zone [104].

Additionally, the possibility to deploy UAVs to conduct remote sensing around offshore facilities allows facility owners and operators to effectively plan and execute ice-management plan. Use of UAS to detect and track wildlife safeguards the field personnel, especially exploration and construction team, from potential wildlife threats. Most of the micro- and mini-UAS (which are the most popular for asset inspection activities) are battery-powered. As result, they involve considerably lower threat compared to aviation fuel-powered manned helicopters in the event of a crash or emergency landing. Almost all the UAS used in O&G inspections usually come with multiple redundant autopilots to eliminate the possibility of crash landing onto a facility [135].

### B. REDUCED COST AND TIME

As there is no requirement for scaffolding or support infrastructure for rope access, a considerable cost and time saving can be achieved with UAS-based inspection and monitoring activities. UAS-based asset inspection is carried out by the two-person team, which is considerably smaller than the conventional rope-access or scaffolding inspection team and reduces the operation cost of the inspection. This becomes a great advantage when conducting offshore asset inspection as it reduces the number of beds (accommodation) and helicopter seats (transportation) requirements.

### C. MINIMIZED DISRUPTION

UAS-based flare stack inspection does not require shutting down the operation and it is capable of acquiring high-resolution stills, videos, and thermal images on demand even when the flare is live. Additionally, when a defect is detected, UAS can perform more frequent inspections (and monitoring) of the detected defect of the flare stack to evaluate the rate of propagation of the defect and the fitness for service. With this data asset, owners/operators can make informed decisions to continue the operation until the spare parts become available on-site, to delay the repair and replacement until the next turnaround, or to shut down the operation immediately to avoid catastrophic failure.

### D. BETTER INFORMATION

UAS-based inspections can easily and quickly access almost all the places within the onshore/offshore facilities and pipelines to acquire high-resolution stills, videos, thermal images, spectral images, and point-clouds. These high-resolution images contain more information about the integrity of the asset compared to the satellite and manned-aircraft-based images. Artificial intelligence-enabled cloud-based inspection data processing tools can provide real-time or near real-time feedback to the inspection engineers allowing them to effectively identify the potential issues of the assets and then collect more data from these regions for further defining the issue. This selective data acquisition is realizable using UAS because they have exceptional hovering capability and ability to work in high wind.

### E. FREQUENT INSPECTIONS

Due to the low cost and no additional infrastructure requirements, UAS-based inspections can be performed on-demand and frequently. Therefore, the asset owner/operator can have more updated data about an asset's fitness for service and timely advice on the continuation of operations and mitigation of potential integrity issues.

### F. FLEXIBILITY AND AVAILABILITY

UAS come in different sizes, payload capacities, and endurance. Additionally, there is a wide variety of plug-and-play type sensors available for UAS. Therefore, the inspection team has more flexibility (choices) when selecting a UAS and sensor payload depending on the client's requirements, location of the inspection, and in complying with the local regulatory frameworks.

### G. MINIMIZE THE ENVIRONMENTAL IMPACT

Micro and mini UAVs, which are applicable for facility inspection, are typically powered by a battery pack. Therefore, during the data acquisition time, these systems have a zero-carbon footprint. The inspection team generally consists of two field personnel. When considering offshore facility inspection, transporting two persons involves a considerably lower carbon footprint than transporting a larger inspection team, and the materials for scaffoldings and rope access. The noise level (sound pollution) of the UAS is significantly lower compared to the manned-aircrafts and helicopters.

## VI. CHALLENGES

Although adaption of UAS for the O&G industry can minimize the HSE risks, CAPEX and OPEX, some challenges are yet to be addressed before industry-wide adaption. As drawn from the literature and our own research experiences, key challenges for the adoption of UAS in the O&G-related operations are summarized below.

### A. LIMITED SENSOR PAYLOAD

Nano-, micro- and mini-UAS are the widely used in the O&G industry. These UAS offer great flexibility and maneuverability around and within the confined spaces and complex structures. Unfortunately, the sensor payload of these UAS is limited. For example, Intel Falcon 8+ V-shape octocopter, which is used by Cyberhawk for oilfield asset integrity inspections, has a maximum payload capacity of 0.8 kg [135]. This implies that the inspection team cannot host a large number of sensors together in a single run. They need to carefully evaluate and plan the inspection tasks and select the sensor payload to optimize the information captured in a single run while reducing the cost and time for data acquisition. The inspection team may have to execute multiple data acquisition runs by hosting different sensors to gather all the types of data (optical, thermal, IR, LiDAR, etc.) they need.

### B. SHORTER BATTERY LIFE

Flight time of most of the commercially available nano-, micro- and mini-UAS varies from 5 minutes to 30 minutes

[34]. This may further be reduced depending on the level of power consumption of the sensor payload. This implies that any UAS has to pause its inspection activities and land at a home position for recharging. To reduce the time taken for recharging, the inspection team typically carries several fully charged spare batteries with them. Once the UAS lands at the home position, the inspection team swap the batteries and may connect the discharged battery to a charging port. As soon as the battery swap is completed, UAS continues its inspection activities. Although carrying a set of spare batteries can reduce the time spent on inspection activities, it raises a safety concern. To avoid this limitation, several research activities are continuing on wireless charging of the UAS batteries [136].

### C. BIG DATA CHALLENGE

During only a single day of operation, a UAS may produce terabytes (TB) of data (high-resolution stills and videos). Manual review of this multitude of data requires a significant amount of time and may require multiple SMEs to simultaneously review the different parts of the survey or inspection data increasing the cost for data interpretations. Typical cost and time-saving methods involve selectively processing part of the collected data to identify and assess the integrity or safety of the infrastructure. As a result, a massive amount of useful data stays behind without contributing to the decision-making process. Another reason for selective data processing is that infield desktop computers may not possess the required processing and visualization capability to handle the multitude of data collected by UAS. These limitations can be addressed by deploying artificial intelligence (AI) enabled systems to analyze the collected data and using a cloud-based processing technique to process the data [63]. AI systems can analyze all the collected data, identify and assess asset integrity, security, or any other issues, and generate recommendations for repair and replacements. SMEs may review and validate these recommendations.

### D. RF AND MAGNETIC INTERFERENCE

Current regulations require all UAS deployed for civil application to be remotely piloted systems, not fully autonomous systems. The pilot maintains visual line-of-sight with the aerial vehicle and controls it via an RF link. The RF interference that is generated within a facility can lead to for dropping the communication link between the drone and the pilot's control unit. To address this limitation, there are multiple redundant autopilot systems included in the UAS so that UAS can maintain its pose and perform less aggressive maneuvers until the RF communication link is re-established. When large steel structures are in proximity to each other, they create magnetic interference. This magnetic interference alters the earth's magnetic field causing onboard compass readings to deviate from the actual value, resulting in the UAS to lose stability or even lead to a loss of control and crash land on the facility. Therefore, the magnetic interference effect is always included in the pre-flight risk assessment with appropriate actions to minimize the interference. Again, multiple redundant autopilot systems installed in the UAS help to avoid crash landing and to stabilize the UAS in the area saturated with magnetic interference.

### E. NOT USEFUL FOR CONTACT TESTING

In the context of asset integrity inspection, it is common to carry out contact non-destructive testing, examination, or inspection (NDE/NDT/NDI) to accurately define the health of an asset. For example, thickness gauging, ultrasonic testing, electromagnetic testing, eddy current testing, or magnetic particle inspection involve physical contact with assets under testing. Unfortunately, current UAS technology does not currently support this type of contact testing.

### F. SATELLITE AVAILABILITY

The majority of autopilot systems, which stabilize the UAS pose, rely on the GPS-based localization. These autopilot systems become unusable for the locations where satellite signals are unavailable or not reliable (e.g., underdeck and congested areas). This may affect the local stability of the UAS. There are a number of research activities ongoing to accurately localize nano-, micro- and mini-UAS in a GPS denied environment [137]. However, an industry-wide accepted general framework for localizing UAS in a GPS denied environment has yet to be established.

### G. VARIABLE WIND CONDITIONS

For both onshore and offshore applications, variable wind conditions are common. When an exterior inspection is conducted in any onshore or offshore facility, it is crucial to consider the local wind condition, as well as near-term weather forecasts before selecting a UAS for the inspection task. Each type of UAS has a maximum wind speed resistance. This value is defined by UAS manufacture through a series of mathematical models, simulations, and experiments. When a UAS operates under high wind speed, the local controllers for the UAS may not be able to stabilize the robot. This may cause the UAS to lose its controllability and crash land. When the wind speed increases, the local controller allocates more power to the propellers to overcome the wind resistance, increasing battery consumption. As a result, the inspection activity gets interrupted more frequently to swap batteries. In some cases, the inspection team may have to abandon the inspection until the wind speed reduces to a level that is safe for flying their UAS.

### H. LIGHT CONDITIONS AND SHADOWS

Regardless of the type of sensor (HD-Camera, thermal camera, laser, and other sensors), the pilot needs to maintain a visual line-of-sight with the UAS all the time when conducting any inspection or monitoring. This can be achieved only when there exists an adequate level of light. Additionally, a darker environment, such as inside tankers and underdeck, could affect the quality of the data captured by the cameras during GVI and CVI. Due to these factors, some UAS have onboard controllable lighting systems to artificially illuminate the area of interest. When there is not enough power or space on the UAS, artificial lighting can be attached to the facility to illuminate the area of interest. Intense sunlight and artificial illumination can create shadow effects on the camera, which could cause reduced visibility. This challenge can be minimized by scheduling the external inspection when the sunlight is not strong (in the evenings) or by adding filters on the camera lens. Additionally, the high-resolution stills and videos can be pre-processed to identify and correct the shadowing effect before employing them for GVI or CVI.

### I. DUSTS AND UNCLEANED SURFACES

The dusty environment creates two significant issues. First, UAS circuitry may start to malfunction due to the deposition of wet/dry dust particles on the circuit. This issue can be mitigated by manufacturing a dust-proof housing for all the UAS power and control units. The second challenge is that the turbulent airflow created by the rotary-wings of the UAS may easily raise the dust deposited on the asset, obstructing the camera view. In addition to dust, layers of marine growth, rust, or soft coating may cover the asset. Since current UAS technologies are not capable of removing these layers, rope access or scaffolding is still required to remove these obstructions before launching the UAS to conduct GVI or CVI.

### J. HIGH AMBIENT TEMPERATURE

During exterior inspection, UAS are exposed to direct sunlight. In certain regions, direct sunlight creates high ambient temperature, which may cause overheating of the UAS equipment, and a deviation from its nominal operating conditions. Additionally, high ambient temperature, together with the temperature generated by onboard systems, may cause the batteries to explode, shutting down the onboard systems (navigation, control, etc.). As a result, the UAS could crash, increasing HSE risk. Therefore, it is essential to consider the ambient temperature level during the pre-flight risk assessment and conduct inspections only during the safe ambient temperature levels.

### K. AVIATION INTERFERENCE

When considering exterior inspections, UAS might breach commercial and restricted airspace. This is a significant concern because the sense and avoidance capabilities of UAS is still at the early stage. There is a danger that a UAS can unintentionally collide with another commercial or passenger aircraft. To minimize such risks, specific rules and regulations related to air-field operations are now available. These include minimum lateral clearance to the nearest airport, clearance to commercial airspace, required certification, license, and insurance to fly a UAS. Additionally, a number of research projects are underway toward establishing industry-wide standards for sense and avoidance systems.

### L. REGULATORY CONSTRAINTS

With the increased use of UAS in none-military applications, airworthiness, malicious practices, and interference to public properties and privacy raise significant concerns [138], [139]. This led to a series of rules and regulations to govern the use of UAS for none-military applications [139]–[146]. The current regulatory frameworks focus on three key aspects, including targeting the regulated use of airspace by UAS, imposing operational limitations, and tackling the administrative procedures of flight permission, pilot licenses, and data collection authorities to address the safety and privacy concerns associated with the UASs usage in non-military applications. Unfortunately, there exists a distinct heterogeneity among the national regulations regardless of the common goal of ensuring the safety and protect the privacy of citizens and properties. As a result, the UAS service providers to the O&G industry my have to take special pilot licenses and operation permits when deploying their UAs in different countries [146], [147]. This could add extra administrative burden to the UAS service providers and may delay UAS deployments in the O&G industry.

## VII. AVAILABLE SENSORS

There is a range of sensors that can be attached with UAS to conduct inspecting, monitoring, and surveillance tasks. These sensors can be divided into two major categories, namely active sensors and passive sensors. Note that some of the sensors listed below can be employed for localization and navigation of UAS. However, this article does not focus on the UAS localization or navigation but focus on application and challenges of deploying UAS in the O&G industry.

### A. PASSIVE SENSORS

Passive sensors rely on natural energy sources like sunlight to illuminate the target. Key passive sensor types that can be used for UAS-based inspecting, monitoring, and surveillance tasks are summarized below [34], [72], [85], [148].

#### 1) VISIBLE SENSORS

Optical sensors operate within the visible part of the electromagnetic spectrum belongs to this category. These sensors are applicable for GVI and CVI of the O&G infrastructure as well as for spill detection. The performance of the visible sensors is affected by the atmospheric effects, such as clouds, haze, or smoke. Depending on the capabilities, visible sensors can be categorized into multiple classes, including sensors for high-resolution stills, video cameras, and stereo cameras.

#### 2) VIDEO CAMERAS

Modern cameras include a dedicated sensor to record high-resolution video, along with a dedicated sensor to capture high-resolution stills. Alternatively, a single optical sensor may perform both tasks simultaneously or with some form of switching mechanism between the two formats. Recorded videos generally supplement high-resolution stills and enable

3D reconstruction of an asset. A real-time video feed at lower spatial resolution (which is defined by the uplink bandwidth of the sensor) aids the inspection engineer and remote pilot to effectively carry out the inspection task. Additionally, real-time video can be used for monitoring leaks, spills, and security threats.

#### 3) STEREO CAMERA

While a single optical sensor cannot provide depth information,[2] this limitation can be mitigated by using a stereo camera system. The operational principle of extracting depth information from the stereo camera is similar to the human visual system. As the stereo camera enables the generation of 3D imagery, it can also be applied for asset integrity inspection activities.

#### 4) MULTISPECTRAL SENSORS (MS)

These sensors use multiple spectral wavelengths simultaneously. They are mainly applicable for characterizing and monitoring the environmental conditions. These sensors utilize the algebraic combinations of measurements in various spectral wavebands to detect environmental features and to identify plant stress, disease, and nutrient or water status. Knowing the environmental conditions allows SMEs to detect potential O&G leaks and spills. Similar to visible sensors, MS sensors are also suitable under daylight conditions and are affected by the atmospheric effects, such as clouds, haze, or smoke.

#### 5) SHORT-WAVE INFRARED (SWIR) SENSORS

SWIR is highly sensitive in low-light conditions. As a result, they are applicable for night time characterizing and monitoring of environmental conditions. The power consumption of this type of sensor is comparatively low. SWIR is not visible to the human eye but can be detected using indium gallium arsenide (InGaAs) sensors. The limited production of InGaAs may introduce some challenges for SWIR-based sensor manufacturing.

#### 6) THERMAL-INFRARED (TIR) SENSORS

These sensors detect the temperature variation, with typical applications including leak detecting, leak monitoring, and infrastructure monitoring. The sensor can operate day and night, and its operation is not affected by atmospheric effects such as cloud, haze, and smoke. In almost all cases, a reference data set is needed to interpret the TIR images.

#### 7) NEAR-INFRARED (NIR) SENSORS

The measurements of these sensors are sensitive to vegetation conditions. Therefore, they mainly applicable for the characterization and monitoring of vegetation. Similar to TIR images, NIR images also rely on a reference data set to interpret new measurements.

#### 8) HYPER-SPECTRAL SENSORS

These types of sensors sample hundreds of frequency bands from the electromagnetic spectrum. In general, the resolution and number of bands are customizable, which offers a high level of flexibility when configuring the sensor for different applications. Due to the hyper-spectral capability, it is possible to use these sensors to identify materials and substances. Therefore, it can be used to characterize and monitor environmental conditions and to conduct asset integrity inspections.

#### 9) GAS IR CAMERA

These sensors are capable of detecting gas fumes/clouds, which may or may not be visible to the human eye. Therefore, they can be used for the detection and monitoring of gas leaks. Although they can operate at night, the performance of the sensor is highly dependant on winds.

Note that optical sensors generally belong to the passive sensor category and are designed for working under natural light. However, activities like CVI and GVI can be conducted under artificial light illumination. The sensor is considered to be a passive sensor because the sensor does not project the light onto the target. Rather, the target is illuminated by an independent light source that may or may not be a part of the optical sensor.

### *B. ACTIVE SENSORS*

These sensors emit some form of radiation onto the target and measure the fraction reflected by the target or the time duration from emission to the reception. This implies that the sensor has two major components: an emitter and a detector. Extra power is needed to operate the emitter unit, requiring a relatively larger power source to energize an active sensor compared to a passive sensor. Due to the bulk power source and extra hardware required to emit radiation onto the target, the typical weight of active sensor systems is higher than passive sensor systems. Therefore, active sensors are less versatile for use in UAS than passive sensors. Key active sensor types that can be used for UAS-based inspecting, monitoring, and surveillance tasks are summarized below [34], [72], [85], [148].

#### 1) LASER SCANNERS (LiDAR)

Laser scanners emit laser light and measure the round-trip-time (or time-of-flight) to generate a point cloud representing objects within the field of view of the sensor. This point-cloud can be leveraged to generate very high resolution surface models and accurate 3D models of the infrastructure. This provides an effective way to identify small-scale changes and irregularities so that asset owners/operators can effectively plan and execute repair and replacement operations to avoid catastrophic failures. Note that the position of each point in the point cloud is given with respect to the body coordinate frame of the sensor. The gap between the sensor

[2] Although the single image does not capture the depth information, a sequence of images can be processed using advanced image processing approaches such as structure from motion (SFM) and photogrammetry to construct 3D objects using images captured from a general camera.

(alternatively, UAS) and the asset does not remain constant throughout the inspection. Therefore, the information in the sensor body frame must be converted into the world frame.

#### 2) SYNTHETIC APERTURE RADAR (SAR)

Typical applications of SAR include detecting and monitoring of oil spills, leaks, monitoring of all weather conditions and characterizing and monitoring of other environmental conditions such as ocean currents and ice conditions. Additionally, by processing SAR data, it is possible to map land subsidence to the millimeter-scale enabling the identification of subsidence patterns long before a landslide or other disaster occurs. Periodic SAR surveys can help to identify security threats for O&G infrastructure.

#### 3) LASER ALTIMETERS

These sensors operate at lower frequencies than the laser scanner and emit short flashes of laser lights and measure the time taken for reflected signal to return to the sensor [85]. This round-trip-time information is then used to compute the distance traveled. This distance measurement can then be used to generate the topography or shape of the surface under inspection. Therefore, these sensors can be used for asset integrity inspection and topological map generation at the exploration, construction, and reclamation phases of the upstream O&G life-cycle.

#### 4) RADAR ALTIMETER

The operation principles and applications of the radar altimeter are somewhat similar to a laser altimeter. The key difference is that the laser altimeter employs a laser light while the radar altimeter employs radio waves in their measurement system.

#### 5) LASER GAS DETECTOR

These sensors emit radiation at a gas specific wavelength into the area of interest. For example, a specific wavelength to detect methane is 1.65 nm. If the gas corresponding to the emitted wavelength is present, it will absorb the part of the emitted radiation, and the sensor will measure the backscattered radiation after the absorption. Differential absorption laser gas detector uses pulses of two different wavelengths to detect the presence of specific gases. One wavelength of the light pulse serves as a reference while the second wavelength is absorbed by the gas (if present). These sensors can be employed for gas leak detecting and monitoring, can operate both the day and night conditions, and do not generate false detections. Apart from high power consumption, there are a few other limitations of these sensors, which include a limited range of detection ($\sim$100 m), imprecision in windy conditions, and a limited sampling area.

#### 6) LASER FLUOROSENSOR

This is the most reliable and useful instrument that detects hydrocarbon against various backgrounds such as water, soil, weeds, ice, and snow. The main application of the laser fluorosensor is to detect and monitor hydrocarbon leaks and spills. Although this sensor group can work during day and night, it requires specialized processing and requires a clear atmosphere.

#### 7) RGB-D CAMERA

An RGB-D (red, green, blue, and depth) camera captures RGB image and the corresponding depth image. Thus, the RGB-D image contains four channels. Although capturing RGB images can be viewed as a passive sensing mechanism, a typical RGB-D camera (e.g., the Microsoft Kinect) emits a structured light onto the area of interest to estimate the depth information associated with each pixel of the RGB image. Thus, it should be considered as an active sensor. The captured depth information can be employed for 3D reconstruction of the object under inspection. By overlaying RGB information onto the 3D reconstructed object, it is possible to identify the defects, cracks, and corrosion on the object under examination.

## VIII. SELECTION OF UAS FOR O&G INDUSTRY APPLICATIONS

By analyzing the applications, advantages, challenges, and available sensory systems found in the selected articles, we have prepared the following guidelines to deploy UAV the O&G industry related applications.

**Step 1** **- Define the scope of the project:** From the outset, it is essential to thoroughly analyze the task at hand and define the project scope, including the type of data (e.g., temperature, high-resolution stills, multi-spectral images, laser scans), quality of data, timeline, and budget.

**Step 2** **- Evaluate the terrain conditions:** Terrain conditions must be evaluated to determine the best landing mechanism.

**Step 3** **- Estimate the flight distance or volume:** In the case of pipeline monitoring, the distance to be traveled provides the general idea of the total flight duration. For all other applications, such as asset integrity inspections, the volume needed to be covered governs the total flight duration. Since UAS have limited battery life, overall knowledge of the flight distance and volume is important as the inspection team plans their spare battery supply and to select appropriate battery charging mechanism.

**Step 4** **- Review international and national legislation:** Prior to commencing any UAS-based activities in the region of interest, it is essential to identify the licensing and certification requirements, restricted air spaces, restricted UAS, restricted sensory systems, maximum weight limitation at takeoff, maximum lateral clearance for people, structures, commercial airspaces, airports, etc., and maximum and minimum elevations. This allows the UAS operator to select the right UAS, sensor payload, and mission plan to comply with all the regulations applicable to the region of interest.

**Step 5 - Select the platform and sensor payload:** Based on the project scope, terrain condition, flight distance and volume, and related local and international regulations, the project team can select the UAS (also known as a platform) and sensors for their project.

**Step 6 - Select data processing tools:** Depending on the project scope and sensor payload, the most useful data processing software tools need to be selected.

**Step 7 - Apply for operating permission:** Depending on the operational region, the UAS service provider, together with the O&G operator, may have to apply to the local regulator to get permission to deploy UAS for inspection, monitoring, or surveillance tasks.

In general, it is not recommended that the O&G asset owner or operator to conduct UAS-based inspection, monitoring, or surveillance activities by themselves. Rather they should hire a UAS service company to conduct these activities. This recommendation is in the place because UAS service companies have more expertise in flying UAS. They also have knowledge on local and international regulations, and the required certification and training compared to O&G asset owners and operators.

## IX. DISCUSSION

This study conducted a literature review to produce a general overview of recent research in the field of UAS for the O&G industry. This overview consists of the classifications of UAS, applications of UAS for the O&G industry, opportunities and challenges of UAS deployment, available sensory systems for UAS, and the guidelines for selecting UAS for a given O&G industry application.

Available UAS classify based on landing mechanism, flight-dynamics, or characteristic parameters, i.e., weight and range. The landing mechanism of a UAS can either be VTOL, HTOL, or a hybrid of these two approaches. Fundamental aerodynamic mechanisms include fixed-wing, multi-rotor, a hybrid of fixed-wing and multi-rotor, ducted-fan, flapping-wing, and other rotary-wing. The most popular multi-rotor configurations are quadrotor, hexacopter, and octocopter. Based on the weight and range, UAS can be categorized either as nano, micro, mini, light, small, tactical, MALE, HALE, heavy, or super heavy. It was also found that the classification based on the weight and range may differ from country to country.

Key UAS applications related to the O&G industry include asset integrity inspection, O&G pipeline patrol, environmental monitoring, O&G exploration surveys, oilfield equipment inventories, search and rescue missions, disaster management, data relay for LSN, security surveillance, fleet management, and identifying undocumented abandoned wells. By deploying the UAS for these applications, it is possible eliminate the requirement of working at heights, in confined spaces, hazardous environments, and other hard to reach areas. Inspection time and cost can significantly be reduced as there are no requirements for additional infrastructure, such as scaffolding, and no requirement for site preparation. Additionally, disruption of operations is minimized as UAS-based flare stack inspection can perform without shutting down operations. Due to the low cost and fast data collection capabilities of UAS-based inspection programs, it is possible to conduct asset inspection more frequently. Additionally, UAS provides better information because it can fly very close to the asset and get high-definition stills and videos. The stability and maneuverability of the UAS provides for more selective collecting of more data from areas that are suspected of having some defects. UAS-based inspection, surveillance, and monitoring activities have lower environmental impact compared to conventional approaches. Finally, the UAS industry is rapidly growing, and new types of UAS, sensors, autopilot systems, and other supportive electromechanical systems are becoming available rapidly. Therefore, UAS service companies have great flexibility when selecting UAS and associated sensory systems for civilian applications.

Despite a large number of applications and numerous advantages, there are several limitations yet to be addressed before there will be industry-wide adaption of UAS. These challenges can be categorized into two groups, namely regulatory challenges and technological challenges. Limited sensor payload and shorter battery life (flight time) dominates the technology challenges. Other technological challenges include, processing high-resolution big data in real-time, RF and magnetic interference with controller and onboard electronics, autopilot systems performing poorly in GPS denied environments, unable to conduct contact tests, weather conditions (wind, light, ambient temperature) impact on the quality of the acquired data, limited capability for sense and avoidance, and conducting inspections at a dusty environments and unclear surfaces.

With the rapid adaption and deployment of UAS for civilian applications, issues such as airworthiness, malicious practices, and interference with public property and privacy breaches raise significant concerns. International and national regulators are developing new rules and regulations for the use of airspace by UAS, imposing operational limitations, pilot license, and data collection authority.

When selecting a UAS for an O&G industry-related application, there are several factors that the operator must consider. These factors include the type and quality of the data, terrain conditions, flight distance and volume, and international and national regulatory frameworks. Based on these factors, the UAS service company can select the most suitable UAS and sensor payload for the applications. In general, it is not recommended that the O&G company conduct UAS-based inspection, surveillance, and monitoring activities by themselves. Instead, it is recommended that a UAS service provider be hired which has more knowledge, expertise, hands-on experience, as well as the required pilot certificates, license and insurance.

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