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Human Centric Digital Transformation and Operator 4.0 for the Oil and Gas Industry

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ABSTRACT Working at an oil and gas facility, such as a drilling rig, production facility, processing facility, or storage facility, involves various challenges, including health and safety risks. It is possible to leverage emerging digital technologies such as smart sensors, wearable or mobile devices, big data analytics, cloud computing, extended reality technologies, robotic systems, and drones to mitigate the challenges faced by oil and gas workers. While these technologies are not new to the oil and gas industry, most of its existing digital transformation initiatives follow business or process-centric approaches, in which the critical driver of the technology adoption is the enhancement of production, efficiency, and revenue. As a result, they may not address the challenges faced by the workers. As oil and gas workers are among the essential assets in the oil and gas industry, it is vital to address the challenges faced by these workers. This paper proposes a human-centric digital transformational framework for the oil and gas industry to deploy existing digital technologies to enhance their workers' health, safety, and working conditions. The paper outlines the critical challenges faced by oilfield workers, introduces a system architecture to implements a human-centric digital transformation, discusses the opportunities of the proposed framework, and summarizes the key impediment for the proposed framework.

INDEX TERMS Big-data analytics, cloud computing, digitalization, digital twin, industry 4.0, Industry Internet of Things (IIoT), oil and gas industry, operator 4.0, virtual reality, wearable technologies.

I. INTRODUCTION

Over the last few years, the oil and gas (O&G) industry has faced multiple challenges, including low oil prices for longer periods, "greater crew change",[1] inherent health, safety, and environmental (HSE) risks, remoteness of the new and future oilfields, elevated regulatory and public expectations for benefits, and geopolitical conflicts in regions that are rich in O&G reserves. These limitations challenge the O&G industry to become more innovative in order to improve revenue during low oil price periods, mitigate HSE risks, bridge the knowledge gap between the retiring and new workforce, minimize operating costs, comply with regulations, and provide benefits to public stakeholders.

With the emergence of industry 4.0, digitalization has been identified as a viable tool to be used to address many of these challenges. Therefore, almost all of the O&G players (operators, oilfield service companies, oilfield equipment manufacturers, and other stakeholders) have already developed technology road maps and started their digitalization journey [1]–[7]. Digital technologies that are at the forefront of these digital transformation initiatives include big data analytics, internet of things (IoT), mobile devices, cloud, fog and edge computing, robots and drones, artificial intelligence, wearable technologies, blockchain technology, extended reality technologies (virtual reality, augmented reality, mixed reality), digital twins, and collaborative and social tools [8]–[13]. Shell's *Smart Fields* [14], Equinor's (formerly Statoil) *Digital Centre of Excellence* [15], Chevron's *iFields* [16], BP's *Field of the Future* [17], and Petrobras' *GeDig* [18], Equinor's (formerly Hydro's) *eOperations* [19],

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[1] The "greater crew change" is also known as the "big crew change" and refers to the phenomenon that the baby boomers who have been operating the O&G facilities are now retiring, which creates a knowledge gap within the industry because the millennials who are going to fill these vacant positions have significantly less experience and expertise compared to the retiring workforce.

Halliburton's *Real Time Operations* [20], and Schlumberger's *Smart Wells* [21] programs are a few examples of current digital transformation initiatives within the O&G industry.

According to the survey results presented in [22], 87% of the participants from the O&G industry are expecting changes in the O&G value chain due to technological adoption. Additionally, 57% believe there will be modifications to the locations of operations. The report projected that the share of human-machine task hours for performing physical and manual work activities would change from 70% : 30% (human:machine) in 2018 to 62% : 38% in 2022. Changes in the value chain, the locations of operations, and the amount of human-machine task shares typically modify the existing structure of the workforce and the skill set requirements. Numerous studies have been presented to examine the impact of automation on the labour market [23]–[26]. Most of these studies concluded that the entire workforce is subject to automation but at different intensity levels. A recent study by McKinsey Global Institute showed that inclination towards automation is catalyzed by the COVID-19 global pandemic [27].

While these studies consider the potential impact of automation or digitalization purely on the capabilities of technologies to automate the physical or cognitive components of the occupation, they do not consider other modulation factors, such as the regulatory environment, corporate culture, the labour relations environment, and the expectations of the public and governments with respect to local benefits. These modulation factors typically slow down the technology adoption rate. As a result, the actual workforce predisposition for technology adoption could be considerably lower than the projected values. Additionally, advanced digital technologies allow O&G operators to extend the life of their fields and discover and delineate new O&G fields faster. As a result, the number of operating fields is gradually increasing, which potentially expands the demand for workers.

This implies that the industry 4.0 will not simply replace O&G wokers.[2] Instead, it creates an intelligent industrial ecosystem wherein human operators, the cyber (or digital) world, and the physical world coexist by complementing one another's capabilities. To gain the maximum benefit out of this coexistence, the O&G industry needs to move from a business (or process) centric digital transformation strategy to a human-centric digital transformation strategy, creating a sustainable human-cyber-physical system for the O&G industry. Thus, in this study, we propose a human-centric digital transformation framework for the O&G industry.

To propose the human-centric digital transformation framework, this study conducted a thorough literature review on the existing digital transformation frameworks, operator 4.0 frameworks, challenges faced by the O&G workers, available digital technologies, and opportunities and challenges associated with each digital technology. The finding of this literature review is then further analyzed to isolate critical challenges faced by the O&G workers and select a set of digital technologies to address these challenges. Then, a framework is proposed to integrate the selected digital technologies. Based on the opportunities and challenges associated with the selected digital technologies, this article summarizes the potential opportunities and challenges for the proposed digital transformation framework. This article presents only the theoretical design of the proposed framework. The implementation and performance evaluations are yet to be done.

The remainder of this article is organized as follows. Section 2 outlines the key challenges faced by oilfield workers. The proposed human-centric digital transformation framework is introduced in section 3. The next two sections discuss the opportunities of the proposed systems supported by literature as well as the impediments for implementing the human-centric digital transformation framework. Section 6 presents concluding remarks.

II. KEY CHALLENGES FACED BY OIL AND GAS WORKERS

The proposed human-centric digital transformation framework attempts to leverage the available digital technologies to identify and solve the challenges experienced by O&G workers. This is an iterative approach that puts workers (people) who are most affected by the said challenges at the center of the digital transformation. This is inconsistent with putting institutions (e.g., O&G field operating companies, oilfield service companies, companies connected to the supply chain, and legislators) at the center of transformation. However, by solving the challenges experienced by workers, the O&G industry will, indirectly, also benefit through solutions to significant challenges that the industry has been facing over the last few decades.

Before introducing the proposed human-centric digital transformation framework, it is essential to understand the challenges faced by O&G workers. Some of these challenges result from technological evolution, while others have existed since the early days of the O&G industry. This study focuses only on the key challenges that have been affecting the O&G workforce as a whole instead of focussing on individual employee-level challenges. The following are the five key challenges that the proposed digital transformation framework attempts to address.

Health and safety hazards: O&G exploration, drilling, production, and processing activities involve many different types of equipment, materials, and geological locations. Working with these equipment, materials, and geological locations introduces a range of health and safety hazards for field workers. Key health hazards include (1) exposure to harmful levels of diesel particulate matter released from the oilfield machinery, vehicles, and equipment; (2) fatigue due to long shifts or consecutive days; and (3) exposure to hazardous chemicals and naturally occurring radioactive materials, harmful noise levels, and extreme temperatures [28].

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[2] This article uses the term "O&G workers" to represent the O&G workforce directly involved in oilfield activities, including field workers and employees working at central command centres as well as remote operation centres.

Apart from these inherent health hazards, there is a range of safety hazards associated with oilfield activities [29]. This includes, but is not limited to, struck-by/caught-in/caught-between hazards from multiple sources such as moving vehicles or equipment, falling equipment or objects, and high-pressure lines; risk of fire and explosion caused by flammable vapour or gas ignition; risk of falling from elevated working areas such as a drilling platform, under-deck of an offshore platform, and flare stack; working in confined spaces; ergonomic-related injury hazards, such as lifting heavy objects, twisting, moving upward, pushing and pulling heavy loads, operating in awkward body postures, and undertaking the identical or equivalent activities repeatedly; risk of exposure to leaks or bursting of high-pressure lines and equipment; and risk of exposure to uncontrolled electrical, mechanical, hydraulic, or other sources of energy.

Complexities in employee training: Employment training can be divided into three major categories. The first category involves training ageing O&G workers to use modern machinery that is installed (or will be installed) in O&G drilling, production, storage, and processing facilities. The second category involves training new O&G workers to work in the O&G industry. Conventionally, both of these types of training have been offered as on-the-job training where ageing or new O&G workers observe others and get hands-on experience to operate oilfield machinery under a training manager, coworker, or outsourced professional trainer. If a trainee makes an error during the on-the-job training which the training supervisor does not spot, it may lead to a catastrophic failure. Therefore, the trainer must continually observe each trainee's action, which is somewhat challenging when there are multiple trainees per trainer. Additionally, on-the-job training methods are typically unable to fully prepare O&G workers for various real-world scenarios, potential extreme operating conditions, and a system's deviations from customary conditions without putting their health or the asset at risk [30], [31].

Emergency response and evacuation training is the third category of employment training, which is the most challenging training category. Sometimes, O&G drilling, production, storage, or processing facilities are required to shut down during an emergency response and evacuation training, causing extended facility downtime and loss of productivity. Additionally, considering the remoteness and complexity of some of these facilities, it is essential to understand the elevated risk for accidents when executing emergency response and evacuation training on an existing facility. For example, if an iceberg is on a collision course with an FPSO vessel, and if it is impossible to change the course of the iceberg, then the FPSO is required to cease operations, disconnect from the well, sail out of the area of danger, wait until the iceberg passes, sail back, reconnect to the well, follow the safety procedures and resume operations [32]. Conducting such emergency training would increase facility downtime and operational cost and may lead to unexpected accidents or health and safety-related incidents for the personnel on board.

Lack of data interpretation and decision making capabilities: At each stage of the O&G life-cycle, oilfield operators and service providers collect a large amount of data on a daily basis [33]–[35]. Typically, an offshore oil platform generates one to two terabytes of data daily [35]. A manual review of such high volume data is impossible. Transmitting one day of data from the offshore platform to a central data processing centre using a conventional 2 Mbps satellite data link takes approximately 12 days. As a result, only a small fraction of collected data, approximately 1% of the data, is available for the decision-making process [34]–[36]. Therefore, the oilfield operators are unable to make optimal decisions promptly.

When decisions are based on a small fraction of the data, a highly skilled workforce must interpret the selected portion of the data. Unfortunately, the O&G workforce is ageing. In 2016, 17% of Canada's O&G labour force was 55 or older, and 23% was between 45 to 55 years [37]. According to the American Petroleum Institute, as of 2014, 50% of the workforce was on the verge of retirement, and, on average, the next person in line was 20 years younger [38]. This sizeable demographic gap in the workforce with a "great crew change" on the horizon creates a significant talent gap. There is no well-established approach to preserving and transferring knowledge from the retiring workforce to the new (or younger) workforce. Therefore, the younger workforce struggles to interpret data or make decisions as effectively as the retiring workforce.

Unavailability of experts on-demand: As the giant oil fields are declining in their production at an approximately 8% annual depletion rate [39], the O&G industry is forced to search for new conventional and unconventional O&G reserves. Many of the new stream O&G fields are in harsh or remote locations such as the Arctic, deep water, and hot deserts [40]. Sophisticated processing techniques are required to extract O&G from these newly discovered fields. Additionally, modern machinery may be installed in these fields. Field personnel may need some assistance from the experts to operate or maintain this machinery. Transporting experts to these oilfields to assist field personnel to repair malfunctioning equipment or electromechanical components, or to train the field personnel to operate this equipment, entails a high operational cost and poses elevated health and safety risks for these experts. Although distance/remote consulting, using voice or video call, could reduce the requirement for some field visits by the experts, the effectiveness and productivity of such approaches have been relatively low.

Complexity in contract execution: Activities associated with the O&G life cycle have significant diversity, from painting accommodation quarters to operating complex machinery installed at O&G drilling/production/processing facilities. The current organizational structure of the O&G business has a hierarchical format where a single operator or multiple operators are at the top of the hierarchy, which is followed by several major oilfield service providers, major contractors, and subcontractors. Within this hierarchical structure, work done by each party, contracts between each party, and QA/QC (quality assurance and quality control) reports for the completed tasks are mainly tracked using spreadsheets. Additionally, there is a considerable conventional paper trail when establishing a contract, executing a contract, evaluating a completed task, and releasing payment. The hierarchical nature of the business, spreadsheet-based work tracking and paper-based contract executions sometimes delay the payment process. As a result, small businesses which provide oilfield services experience elevated financial risks. Trade personnel who work for these small businesses also feel financial insecurity that could affect their social and work status.

In summary, O&G workers face five significant challenges: elevated health and safety hazards, a high level of risk associated with on-the-job training programs, inability to use all available data for decision making as well as a lack of skill to interpret the data, unavailability of experts on-demand, and delays in payments for completed tasks. It is possible to utilize modern technologies such as wearables, big data analytics, artificial intelligence, and machine learning algorithms, cloud computing, internet of things, robots and drones, extended reality techniques (virtual/augmented/mixed reality), blockchain technology, and digital twins to fully or partially address these challenges. Note that the five challenges listed above existed from the early days of the O&G industry. However, the severity and the mode of these challenges has been evolving with the technological evolution. For example, at the primitive stage, the equipment used in the O&G industry were simple mechanical systems. In contrast, modern O&G production facilities are equipped with more complex and advanced equipment. Regardless of whether the equipment to be operated is a simple mechanical system or a complex advanced system, on the job training is unsafe and very challenging. Similarly, when considering the data interpretation challenge, at the primitive stage, the O&G industry had to make decisions based on limited data while the modern O&G sector is struggling to isolate essential and relevant data from dig data lakes.

III. PROPOSED HUMAN-CENTRIC DIGITAL TRANSFORMATION FRAMEWORK

An overview of the proposed human-centric digital transformation framework is illustrated in Figure 1. The framework has four main elements: O&G operator 4.0 (operator domain), oilfield assets (physical domain), analytical environment (cyber domain), and interaction between these three domains.

A. OPERATOR DOMAIN

During the last few decades, the nature of work and the type of interactions between field workers and machinery have evolved. Similar to other industries, the evolution of oilfield workers can be divided into four generations [41]–[43]. The first generation, *Operator 1.0*, performs "manual and dextrous work" with some support from mechanical tools or manually operated machines. The second generation, *Operator 2.0*, performs "assisted work" with the support of various computerized tools such as computer numerical control (CNC) systems. The third generation, *Operator 3.0*, is typically viewed as a human-robot collaboration where field workers work cooperatively with robots, machines, and other computer tools. The last generation, *Operator 4.0*, represents the "operator of the future" whose physical, sensorial and cognitive capabilities will be enhanced through human cyber-physical system integration. The concept of Operator 4.0 is widely discussed in other industries [41]–[45].

The proposed O&G Operator 4.0 consists of six components, as outlined below.

O&G worker: This is the person who is directly involved in oilfield activities and includes field workers, personnel working at central command centres and remote operation centres. The activities that the O&G workers perform can vary from conducting manual or assisted (mechanical or computer) work in a field to leveraging data analytics/artificial intelligence tools to make data-driven decisions to improve productivity and safety.

Wearables for health and safety support: Sensors, devices and objects such as smart watches, health and activity trackers, ear-worn physiological tracking devices (typically known as 'hearables'), radio-frequency identification (RFID)-based location tracking devices, global positioning system (GPS)-based location tracking devices, environmental conditions (temperature, air quality, radiation level, etc.) and monitoring sensors, that can be employed for tracking field worker's vital signs, motions, locations, and work conditions in realtime.

Wearables and mobile devices for activity support: Smart helmets, smart glasses, smart clothes (jackets), RFID tracking devices, GPS tracking devices, smartphones, personnel digital assistants (PDAs), and computer tablets to access field data or operation, maintenance or repair manuals on-demand and get virtual assistance from remote experts.

Feedback systems: Haptic feedback systems, voice or sound commands or light-emitting diodes (LEDs), PDAs, computer tablets, and headphones or communication devices enabled with voice over internet protocol VOIP) can be used to send feedback, warnings, alarms, and other information to a field worker.

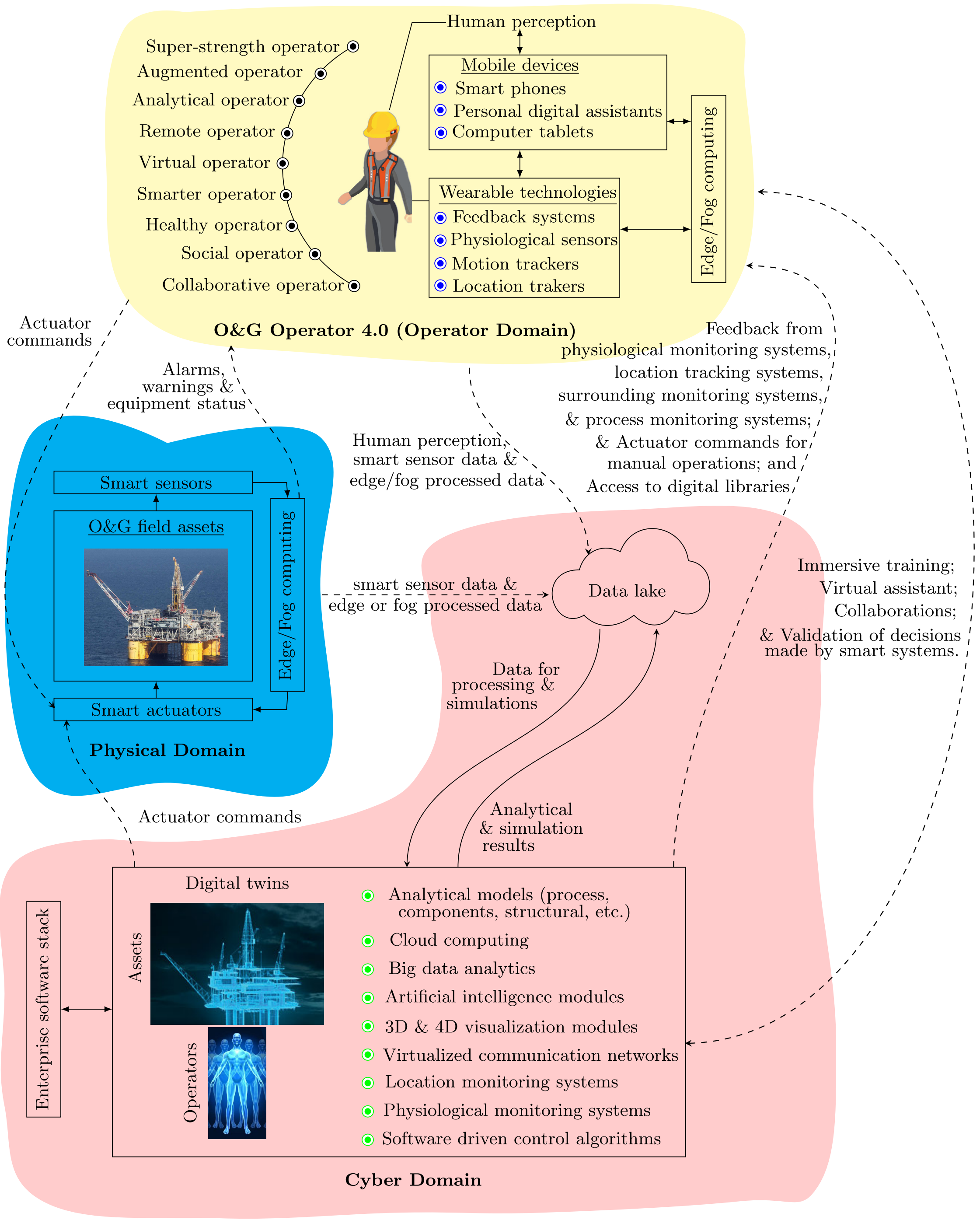

FIGURE 1. **The overview of the proposed human-centric digital transformation framework. Dashed arrows represent interactions between human, physical and cyber subsystems.**

Robotic systems: Remotely operated robotic systems or drones that allow a field worker to access hard to reach locations.

Data communication: A wireless body area network for enabling inter-device and inter-system data and information exchange. Additionally, this body area network acts as a bridge for data exchange between the O&G workers and the physical or cyber domains.

All wearables, mobile devices, and robotic systems collect data, which need to be processed, interpreted and visualized to allow O&G workers to make smart decisions promptly. When selecting a communication and processing system, it is important to ensure ubiquitous connectivity, mobility, and interoperability. Therefore, our framework proposes using wireless industrial IoT (IIoT) enabled wearables and mobile devices. These systems potentially come with edge[3] or/and fog[4] processing capabilities. IIoT edge devices typically have limited memory and processing capacities which facilitate light-weight data processing tasks, such as triggering alarms if the ambient temperature is high. In contrast, fog processors have increased memory and processing capacity, making them appropriate for heavy data processing tasks. As both edge and fog processing techniques process data locally at O&G facilities, the field workers can access the data and analytical results in realtime or near-realtime. Note that edge and fog processing conducts the data analytics in the digital domain (cyber domain). However, they are tightly coupled with the wearable and mobile devices used by the field workers; thus, they are considered integral parts of the operator domain.

When considering technology adoption, there are eight elements of Operator 4.0, namely, *super-strength operator, augmented operator, virtual operator, analytical operator, smarter operator, healthy operator, social operator, and collaborative operator* [41]–[43]. Within the context of the O&G industry, it is possible to extend this list by one element, the *remote operator*. Table 1 introduces all of these elements briefly. At all times, all O&G workers have the *healthy operator* element plus one or a multiple of other elements simultaneously. For example, future industrial instrumentation technicians and technologists consist of *healthy, augmented, analytical, and smarter operator elements* to safely and effectively execute field activities.

B. PHYSICAL DOMAIN

The physical domain represents physical assets, including the drilling, production, processing or storage facilities, equipment, and machinery installed in these facilities, O&G pipelines, oil tankers, and trucks. All existing and future oilfield assets are (will be) equipped with IIoT enabled smart sensors and actuators. These sensors collect production, asset integrity, daily operation, and environment-related data continuously. The edge processing capability of IIoT devices is exploited to process the collected data in realtime and make time-critical decisions and autonomously apply actuation commands to reduce the frequency of equipment/system failure. For example, a smart pressure sensor generates alarms if a pipeline pressure exceeds a predefined threshold and may generate actuation commands to control individual valves and motors to regulate the pipeline pressure. Data from multiple IIoT edge devices can be integrated and processed at fog processors to gain insights to run the system as optimally as possible. As mentioned earlier, edge and fog processors perform all data processing in the digital domain. However, they are closely coupled to the physical system where the IIoT sensors, actuators are installed. Therefore, edge and fog processing related to O&G physical assets are considered integral parts of the physical domain.

C. CYBER DOMAIN

The cyber domain of a future O&G facility consists of three major subsystems: digital twin, data lake, and enterprise software stack. A digital twin is an interactive multi-physics, multi-scale, probabilistic simulation of an as-built environment. It uses the best available models, sensor data, and other input data to replicate and simulate the activity, efficiency, fitness, and integrity of the corresponding physical twin throughout its operation [46]–[52]. In the proposed framework, there are two types of digital twins: asset-twin and operator-twin. Asset twins replicate the asset behaviour at either the facility, process, or equipment level, while the operator twin replicates the activities and physiology of a field operator. Digital twins receive data from the data lake, and the enterprise software stack, which include, but are not limited to:

- realtime and near-realtime raw sensor data from physical and operator domains;
- analytical results from edge and fog processing units of physical and operator domains;
- historical data related to assets and operators;
- operational, health and integrity data from similar assets;
- facility, process, and equipment blueprints, operation manuals, maintenance manuals, maintenance history, asset information management[5]-related data;
- all contracts, operation guidelines, regulatory frameworks, and asset development and benefit plans; and
- data related to market variability and trends.

Digital twins analyze data using a range of big data analytics and artificial intelligence-based tools and models. Typically, digital twins run on cloud computing systems because they process a high volume of multidimensional data using complex data analytic algorithms and tools that cannot be handled by a desktop computer or simple server system with limited memory and processing capacities. High dimensional visualization modules empowered by virtual and augmented reality visualize the data and results from the digital twin. A communication network enables seamless data and information exchange between different models and operators to optimize asset and operator utilization while minimizing health and safety risks. Software-driven control algorithms are evaluated on the digital twin to identify the most productive and safest future operating scenarios. Additionally, location and physiological tracking systems track the realtime health conditions of operators, compare them with historical

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[3] The data processed on the IIoT device or IIoT gateway which is physically adjacent to the IIoT device are called edge processing.

[4] If the data processing is taking place on a set of computers or a server which is connected to the same local area network (LAN) as the IIoT device but may be physically distant from it, this is referred to as fog processing (e.g., local computer network of a production facility).

[5] The idea of asset information management system is somewhat similar to the well-known building information management system but extended to all the assets, including buildings.

TABLE 1. Elements of the operator 4.0 [41]–[43].

Type of Operator 4.0	Description	Example application
Super-strength operator	Operators use a powered, lightweight, flexible, and mobile human-robotic exoskeleton to support limb movement and increase strength and endurance.	Drill floor crew can use this human-robot exoskeleton to lift and handle pipes and other heavy components associated with the drilling activities.
Augmented operator	Operators use wearable technologies (e.g., smart glasses, heads up displays, spatial augmented reality projectors) or use mobile devices (e.g., personal digital assistants, smartphones, computer tablets) to access all kinds of data ranging from original equipment manufacturing (OEM) data sheets to realtime operational data.	Access the most updated OEM data sheets, training videos, and maintenance guidelines quickly and reliably when performing any maintenance activity.
Virtual operator	Operators use virtual reality, which is immersive interactive multimedia and computer-simulated reality that can digitally replicate design, assembly or an entire O&G drilling/production/storage/processing facility, based applications to interact with the physical world and simulate future scenarios.	Conduct employee training in this virtual environment to eliminate the risks associated with conventional on-the-job training.
Analytical operator	Operators leverage big data analytic tools to analyze realtime data, identify trends and operational anomalies using data, predict future operation conditions, and generate future scenarios to make smart decisions promptly.	Use predictive maintenance software tools to track and project equipment health to perform maintenance activities at the right time.
Smarter operator	Operators use intelligent personal assistant (IPA)-based solutions, which are powered by artificial intelligence to interact with machines, computers, databases, and other information systems.	Based on a voice request, IPA with natural language capabilities can make activity logs, search operation/repair/maintenance manuals from digital libraries, and read the instruction to the operator while he/she performs the task.
Healthy operator	Operators wear a range of smart and connected sensors allowing a command centre to track their physiological and mental state, motion, location, temperature and air quality of the working environment to mitigate health and safety-related hazards.	Locate and medically assist field personnel during any health-related incident and schedule operators' work shifts, rest breaks, and overtime based on health-related metrics.
Collaborative operator	Operators work collaboratively with robots or automated systems to perform repetitive and non-ergonomic tasks.	Use the automated system to connect drill pipes.
Remote operator	Operators remotely operate robots and drones to perform some task at hard to reach locations or remotely operate any machines in the drilling/production/storage/processing/transportation systems.	Use drones to perform asset integrity inspection at flare stack or under the deck of offshore facilities.
Social operator	Operators connect with other operators and smart sensors, equipment, and other oilfield resources using enterprise social networking to access realtime data and to get support from others to make data-informed decisions collaboratively.	Data from smart pressure sensors and oilfield personnel location tracking system can be integrated to make selective alarms or warnings when field personnel are working on or near a high-pressure vessel.

data, identify potential health risks and notify these to O&G workers, supervisors, emergency response team, and other authorized personnel.

Data lakes are digital storage that store all the raw and processed sensor data, historical data related to assets and operators, simulation results and projections from digital twins, digital documents, enterprise data, market variability, and trends related data. The enterprise software stack includes a set of software tools that are used in the management and decision-making process of the organization. This may include software tools for automated billing systems, business process management, enterprise content management, enterprise resource planning, project management, human resource management, business process management, and IT service management.

D. INTERACTION BETWEEN OPERATOR, PHYSICAL, AND CYBER DOMAINS

Although the interactions between operator, physical, and cyber domains are complex and tightly coupled with one another, at an abstract level it is possible to summarize the key interactions as follows:

Interaction between operator and cyber domains:

Raw and locally processed data from human sensory perception, wearables, mobile devices, and robotic systems are transmitted to the operator's cyber domain for further processing. The cyber domain sends information from physiological tracking systems, location tracking systems, surrounding environment monitoring systems, and process monitoring systems to the field personnel so that they can execute field activities safely and effectively. Additionally, field personnel can request/access digital libraries such as OEM's data sheets, operating manuals, maintenance manuals, repair manuals, and equipment operating training videos from the company's cyber domain. These resources assist field personnel to effectively and safely operate field equipment and other machinery. It is possible to establish immersive training programs, virtual assistance, and inter-personnel/inter-department/inter-organization collaborations using digital twins, virtual reality, augmented reality, and wearable technologies.

In some cases, the control commands generated from the software-driven control algorithms need to be verified by field personnel or subject matter experts before applying them to smart actuators. Thus, the cyber domain may send the simulation results, predictions, and generated reports to field personnel or subject matter experts who view them using mobile devices, smart glasses or heads-up displays. When a human operator approves the control commands, the cyber domain can directly apply these commands to smart actuators installed in the physical domain to optimize production and safety.

Interaction between operator and physical domains:

Operators typically monitor the status of equipment, machines, processes, and other infrastructure in the physical domain. Their observations and measurements are entered into the mobile devices which may locally process the user entered data or relay the data to the cyber domain for processing. Operators may alter the actuation commands for oilfield equipment and machinery, manually or with the assistance of a computer system, as needed. Smart sensors in the physical domain which collect data on machine status communicate with the wearable smart feedback system of the operator. When these sensors detect any critical condition or a trend towards a critical state, they send alarms or a warning to the operator to evacuate the premises until the issue is resolved. For example, a smart pressure sensor generates alarms and warns field personnel to evacuate the premises if a pipeline pressure exceeds a pre-defined threshold.

Additionally, RFID tag readers installed at the O&G facilities continuously examine whether the O&G workers wear the required personnel protective equipment (PPEs) when entering the facility and operating any machine. This system sends warnings to O&G workers if they are not wearing the required PPEs. If the operator does not comply with the warning, the system sends a warning to the field supervisor or facility manager to take the necessary action to solve the PPE code violation occurring at the facility or field. Smart camera systems installed in the facility collect high-resolution videos and operators' images when they work at the facilities or operate machines. These videos and images are communicated to the cyber domain, where the videos and images are analyzed to determine whether the operators have the correct posture when performing field activities. Field supervisors, facility managers, and training supervisors review the analytical results of videos and images to assist their field workers to use the correct posture when conducting field activities.

Interaction between cyber and physical domains:

Data collected by the smart sensors installed in the facility (physical domain) and the results of edge and fog processing are transmitted to the cyber domain. All the collected data, historical data, and other related data listed in section III-C are evaluated on the digital twin to manage asset performance, risk, and utilization. Additionally, the data can be used for process automation and future scenario development. The selected and verified (if required) control commands are autonomously applied to the smart actuators to optimize the production while mitigating health and safety risks.

IV. OPPORTUNITIES

This section examines how the proposed framework solves the five key challenges (refer to section II) faced by O&G workers by leveraging digital technologies.

A. PERSONNEL HEALTH, SAFETY, AND LOCATION TRACKING

The deployment of smart sensors enables physiological tracking for each O&G worker. In support of IoT system network and cloud computing, these data are transferred to the central station for further analysis. This architecture enables realtime health monitoring and prediction for the individual field worker. Horseman *et al.* [53] developed predictive personal protective equipment (PPE) for upstream O&G, converting the traditional PPE (i.e. hard hats, belts, gloves, and safety glasses) into smart wearables using biosensors and IoT technology. The system can collect data of brain signals (i.e. alpha, beta, delta, theta, and gamma), which helps to determine the awareness states of the worker, such as concentration, boredom, sleep deprivation and tiredness. Additionally, the collected biometric data, such as heart rate, glucose level, blood pressure, and body location, are useful to track personal wellness in realtime [54]–[56]. The system can detect any slip, trip and fall, triggering an alert and an immediate incident response [57]. Essential instructions and notifications can also be produced for O&G workers through adaptive biofeedback units [53], [58].

In some initial prototypes, developers have used a micro-controller (e.g. Arduino Uno with ATmega328P) and micro-computing platform (e.g. BeagleBone Black with ARM Cortex A8) in their design. These selections reduce the size of the circuit board but show some limitations of computing capability, particularly when executing complicated computations and advanced graphical interface. This necessitates the data being transferred to a particular center for further advanced analysis using the IoT network [59]. Medical data analytics can determine whether the O&G worker has applied the proper gesture and posture when performing a task, especially in the case of repetitive actions. The ergonomic postural evaluation system can help to prevent work-related musculoskeletal disorders [60], [61]. Similarly, in the long term, aggregated biometric data are also useful for predicting the trends of health performance to avoid potential incidents in the future, such as a heart attack. The advanced healthcare functionality helps to minimize the violation of workplace health and safety codes as well as improve the safety and wellness of the field personnel.

Some environmental sensors that measure toxic gas, radiation level, noise, and temperature support asset management [58], [62]–[64]. Some measuring instruments, such as Drager X-am 2500 and Honeywell BW Ultra, can detect multi-gas, such as O_2, CO, NO_2, and H_2S. The FLIR GF77 thermal camera has the functionality for visualizing methane emissions in realtime, which improves the efficiency of gas leak surveillance [65]. These instruments are produced with a portable design for hand held use. Consequently, this reduces the number of sensors required for monitoring the entire O&G platform.

In addition, the smart sensor enables personnel location tracking in the O&G workplace [64], [66]. This could be an offshore platform with tightly-packed multi-level architecture or an onshore facility spread over a large area. This application utilizes visual computing and radio frequency identification (RFID), alone or in combination with GPS, for O&G worker localization. For example, in the case of RFID used on offshore platforms, each field worker on the rig wears an ID badge (i.e. active RFID tag) [43], [58], [64], [66]. At defined intervals, the tag transmits its ID number and essential information to the software management system. The system can then determine the worker's location accurately and send essential notifications of the safety zone.

Smart health tracking systems for personal health tracking are currently in the stage of prototyping and conceptual validation. In order to be deployed in hazardous environments and explosive areas, new designs need to use appropriate materials and encapsulate product components. These elements demand more time and effort from the developer to optimize the industrial design as well as handle the shortage of electronic component providers [67], [68].

The proposed human-centric digital transformation framework (Figure 1) employs lessons learned from these systems and concepts to enable personal health and location tracking along with the construction and maintenance of digital twins of O&G workers. Since the proposed framework connects workers' health tracking with other domains within a unified environment, it is possible to optimize the human-cyber-physical interactions. Additionally, it improves the health risk management operations and avoids any unexpected delays in organization responses (e.g. emergency evacuation, infectious disease outbreak).

B. EXTENDED REALITY TECHNOLOGIES FOR ADVANCED VISUALIZATION AND COLLABORATIONS

The development of wearables has enabled extended reality, including virtual reality (VR), augmented reality (AR) and mixed reality (MR) applications in the oil field. These applications utilize computer vision and wearable technologies to generate real-and-virtual collaborative environments with increasing human-machine interactions.

Extended reality technologies are also beneficial to visualize samples' data and models while making decisions and action plans. For example, Microsoft HoloLens has shown potential in oil exploration and production [69], [70]. This MR headset with holographic projection assists geologists in the analysis and 3D presentation of core samples of exploration drilling. The geologists can segregate and observe different layers of the core sample in a virtual 3D environment to identify the geological properties of the region. MR employment also includes merging capability between virtual and real images. For example, placing holographic projection of complex equipment on a particular surface provides a better understanding of the equipment functionality.

AR has shown potential in asset monitoring and management, and particularly for visualizing operational data of machines and processes [68], [71], [72]. Realtime data (e.g., vibration, surface temperature, pressure, and magnetic field) are collected from multiple sensors attached to the equipment. The AR hands-free headset displays these sensor readings and relevant information to its user. Additionally, AR systems connect the field worker with the subject matter expert seamlessly, allowing the field worker to get the expert's support on demand.

In O&G inspection and maintenance activities, MR technology helps to reduce the repair time of mission-critical systems (e.g., gas compressor and top drive) as well as support the collaboration among experts and field personnel [58], [68], [72]–[74]. The RealWear smart helmet, which was introduced in 2018, is an excellent example of a mobile assistance system developed for petroleum field workers. In 2019, Shell deployed this smart helmet as an AR-based remote assistance device for field operators [75]. In this deployment, the traditional helmet, networking systems, video cameras and AR displays are integrated into a single unit. The integration allows a technician on the field to connect with remote experts and a dispersed engineering team via wireless networks [68], [74], [76]. During a video call, the worker can provide views of a piece of equipment or of hard-to-reach areas around machinery. Remote experts can watch and provide immediate recommendations. Moreover, the experts can also use a telestrator to mark the components needing attention by the field worker. This procedure has usually taken several weeks, causing delays in communication, and in some cases, experts have been required to visit the field site.

A better view of the product also benefits the manufacturing of drilling and exploration equipment [69], [72]. The current approach of a product review (i.e., using typical images with a limited view) cannot deliver sufficient information and details to the end-user. This limitation results in a manufacturing gap and unnecessary delays for equipment modification. With the help of MR, the product configuration can proceed with a holographic preview with different angles. This helps the end-user to have a better feel and look at the actual product before placing an order. Also, the technology allows manufacturers to avoid misunderstanding the user's requirements when customizing the product.

The proposed human-centric digital transformation framework (Fig. 1) benefits from the successes of AR, VR, and MR technology deployments. The proposed framework attempts to connect these advanced visualization techniques with other digital technologies within a unified environment. These connections extend the use of smart helmets in the field to a new paradigm, which is not limited to displaying nearby sensory data. It involves the interaction with digital twins and predictive maintenance analytics to improve the productivity of field activities.

C. PROFESSIONAL EDUCATION AND EMERGENCY RESPONSE TRAINING

Extended reality technologies and asset twins can be integrated to create virtual training environments to train the ageing workforce to use modern technologies, orient the new workforce to navigate inside O&G facilities and operate oilfield equipment, and perform emergency response training [72], [73], [77]–[79]. Work presented in [80] outlines a general overview and procedure to follow when developing training simulators for automation control systems for the O&G industry. These virtual training environments support the training of O&G workers for various real-world scenarios, potentially extreme operating conditions, and system deviations from normal conditions without putting workers health or the asset at risk [30], [31], [81]. Virtual training reduces training time and more effectively prepares O&G workers for tasks that cannot be practically trained for in the real world. Universities and colleges can move from traditional classrooms to virtual reality enabled classrooms, allowing students to engage in the learning process actively and to get hands-on experience navigating on various types of O&G platforms and operating a range of equipment [82]. Most of the available immersive training focuses either on training drilling crews or on emergency response training.

When conducting drilling or production activities in an oilfield that poses unique challenges, advanced dynamic simulation can be run on a digital twin to conduct off-site training, prepare the drilling team and involve service personnel for the operation [83]. Recently, Eni, in collaboration with Saipem, developed a virtual training platform using field data from more than 300 wells, a dedicated computer network, 3D-rooms and virtual reality headsets [84]. It was originally used to enhance the preparation of new drilling engineers and managers, with the potential of enhancing their safety induction as well as their understanding of rigs and well-operation. The system produced an immersive experience of different drilling events, covering various drilling scenarios. A similar approach is described in [85], where a web-based video game was developed to train the O&G drilling crew. The video game exposes the O&G workers to different drilling and field scenarios in which they can develop an enhanced awareness of their work and learn what to do in challenging situations. This game-based training simulator uses artificial intelligence to generate various drilling and field scenarios and allows multiple players (employees) to interact remotely in a 3D virtual environment. It is possible to use 3D virtual reality to integrate the control room operator training with the field operator training [86]. Such integrated training improves the synergetic interactions between the two employee groups, thus preventing unwanted incidents and oilfield accidents, eliminating unplanned facility downtime, and executing robust contingency strategies to deal effectively with emergencies.

Apart from the employee training, digital technologies like digital twins, other virtual simulators, extended reality technologies and wearable technologies will play an essential role in emergency response training. Responding to emergencies is one of the most challenging tasks as they occur unannounced, are associated with unknowns during the occurrence, and allow only limited time for effective responses. It is possible to create virtual training platforms which train the asset incident management team to prioritize their responses and better understand their roles and responsibilities [87]. In safety risk management, the threat response drill (TRD) exercise has been developed with augmented reality and mixed reality technologies to provide real-world, full-scale 3D virtual scenarios of major catastrophic events [72], [88]. In each scenario, the participant needs to navigate through the 3D environment to identify the critical hazards on the job site. Any incorrect actions will result in risk escalation, severe consequences and a ''game-over'' failure outcome. These simulating features of exercise are also helpful for evaluating operational readiness before conducting real high-risk operations. Virtual training environments, such as ''VRSafety'', which has been developed for Hydro and Statoil (now Equinor) by Christian Michelsen Research, can be used to train the operators and managers on gas leak hazards response, simulate wind effects on gas leaks, demonstrate effectiveness of process safety systems, increase awareness of safety barrier philosophy and risk levels, and to convey emergency preparedness steps [89]. Additionally, underwater oil spill emergency response training has also been conducted using extended reality technologies [90].

Some emergencies require field personnel to evacuate the facilities. This is a complex task because human behaviour is typically unpredictable in actual dangerous situations. Conventional paper-based, lecture-based or video-based professional training approaches cannot evaluate human behaviour and are unable to prepare the workforce effectively for emergency evacuation, particularly for offshore facilities. This limitation can be addressed by implementing the emergency evacuation training using virtual reality [91]–[93]. When considering offshore facilities and marine transportation systems, the emergency evacuation plan typically involves deploying lifeboats and executing all emergency response activities under severe weather conditions, including high winds, high sea levels, rough sea conditions, or storms. Conducting lifeboat deployment training in calm or even moderately rough weather conditions is not practical as the emergency evacuation drill poses an unacceptable risk to the health and safety of the field workers. Therefore, virtual reality becomes the best viable option to perform emergency evacuation training for offshore facilities [94].

The proposed human-centric digital transformation framework leverages the lesson learnt from the implementations and research initiatives described above and integrates them into a unified environment that is closely coupled with digital twins. The integration of the extended reality-based training program with digital twins extends the current virtual employment training programs to a new paradigm which is not limited to drilling crew training and emergency response training, but also includes training activities related to operating production facilities, storage facilities, O&G transportation systems (pipelines, tankers, trains, etc.), and the associated mobile and stationary machinery.

D. DECISION SUPPORT THROUGH BIG DATA ANALYTICS

O&G companies have always generated extreme volumes of data at a very high daily rate. Data in the O&G industry can be generated from different resources, including sensor data from machines and processes, traditional enterprise data from operational systems, social media, web searching designs, demographic data, historical O&G exploration data, and delivery and pricing data [95]–[97]. It has been reported that the deployment of data analytics has potential to improve the O&G production by 6-8% and reduce operational costs [98]. However, as the experienced workforce is retiring and the volume of the data available for analysing is increasing exponentially, the new workforce struggles to interpret the data and utilise the entire data set for decision making. This limitation can be addressed by deploying big data analytic tools to assist O&G workers.

In exploration and development, big data analytics can help O&G workers to make strategic and operational decisions promptly. Based on realtime data, the company can deliver new insights and help operating teams optimise exploration efforts. In production, based on historical and real-time data, big data analytics can predict future performance. For equipment maintenance, based on the data collected from equipment, big data analytics can help oil and gas companies to build predictive maintenance models to prevent unplanned downtime and reduce maintenance costs [97].

Big data analytics has been using a range of tools and techniques, including 3D planes to show the relationship between data, science, technology, engineering, and mathematics (STEM) tools, and pattern recognition [99]–[101]. Machine learning tools can reveal the relationship between the recorded data more efficiently, specifically for the recent trend dealing with huge datasets [102]. A Hadoop platform, in contrast to conventional tools, can manage the massive datasets generated by micro-seismic tools, improving the success ratio by detecting potential anomalies from previous failed jobs [103].

In the last few years, drilling operations have become more complex and have been conducted in more challenging environments, including deep water and the Arctic. With realtime drilling technology, vast amounts of data can be generated and captured during operations. The data gathered from different phases of the drilling cycle can be applied to conduct various analyses, from scheduling to a drilling operation itself. The invention, improvement and application of new data recording tools (e.g., seismic acquisitions devices, channel counting, fluid front monitoring geophones, carbon capture and sequestration sites, logging while drilling), measurement and data formats have made it even more practical to employ big data analytic tools in drilling operations [99]. In this area, big data analytics can be deployed to improve the drilling performance [104], identify non-productive time [105], reduce the risks associated with drilling operations and drilling failures, and also lower drilling development costs [106], [107]. Shell uses big data analytics in near realtime to detect failures [108]. By collecting realtime data from different sensors and comparing the performance of different drilling tools, big data analytics assists the drilling flow manager to optimise the usage of all drilling equipment while minimising its idle time.

In reservoir engineering, the massive amount of data in the field of reservoir characterisation from distributed downhole sensors was used to develop a reservoir management application with four major components: visualiser, downhole data filter, model builder, and model application based on utilising big data analytics. The visualiser helped with data viewing and analysis, while the filtering component was used to eliminate outliers and unreliable data. For the model builder, machine learning tools were used to do the training, model development, and validation. The Apache Spark machine learning tool was used to conduct big data analytics. Transferring the developed model to a web-based platform was shown to facilitate user/system interactions [109]. Big data were used to improve the reservoir modelling by predicting the affective parameters using artificial intelligence, machine learning and data mining technologies [110]–[114]. To improve the modelling of hydraulically fractured reservoirs, work presented in [115] used big data analytics technologies to analyse the production data. The required data was generated by developing a dual-permeability model and trying various fracture parameters. A pattern recognition methodology was applied to the generated data to reveal the underlying trends in the data. Moreover, big data have also been used to optimise the selection and application of costly enhanced oil recovery (EOR) methods [116]. In a study done by [117], a two-step automated workflow was developed to predict the production of a thermal EOR field using machine learning methods. The first step forecasted supplementary field measurements, which then utilised these predicted field parameters to estimate production. The second step helped automate data interpretation.

In production engineering, big data analytics was used to forecast the production performance [118], develop a production allocation technique [119], and optimise the performance of electric submersible pumps by identifying emergencies such as overheating and unsuccessful start-ups [120], [121]. In a study done by [122], big data was utilised to optimise the performance of rod pump wells based on a three-step workflow: data acquisition, data calculations, and data visualisation. At the data acquisition step, well test data and well equipment data were collected. The data calculation step automatically developed the modes based on the acquired data. Finally, the developed model and insights derived were visualised using a user-friendly graphical interface. Moreover, big data was integrated into development planning optimisation, where the production type curves were generated via machine learning and the results coupled with integrated economic analyses to guide field development [123].

Downstream, big data analytics was used to develop a workflow to investigate the effects of completion parameters on well productivity by using a statistical approach to analyse the data gathered from 4500 wells that were under slickwater treatment [124]. The work presented in [125] employed big data analytic tools to reduce the downtime and maintenance cost of a cracked gas compressor (CGC) by analysing current and historical operating data, end-of-life criteria, and failure conditions. Big data analytics also has been used to improve shipping performance. The work presented in [126] collected data from a large car truck carrier (LCTC) for three months. Collected data was analysed using eXtreme Gradient Boosting (XGBoost) and Multi-Layer Perceptron (MLP) neural networks to identify the potential operational gains. A range of studies analysed realtime data, historical data, maintenance reports, and operator data to improve O&G occupational safety and identify the underlying hidden trends [127]–[130].

Big data analytics also has emerged as an essential tool for supporting managerial decision making. Big data discovery efforts can reveal previously unknown findings, resulting in insights that are helpful for managerial decision-making [131]. In the past, people were limited in their ability to store and process data while some experts used to make decisions based on their intuitions, this was not always accurate as large-scale data collection was not possible [132]. Currently, big data have led to increased volume, velocity and variety of data. This has made it easier to analyse the data in terms of statistical reliability and improvement of models [133]. Big data analytics has a significant effect on business value and firm performance, leading to savings, reduction of operating and communication costs, increased returns, improved customer relations, and new business plans.

All the examples listed above demonstrate application of big data analytics to support oilfield operations. While it is not possible to tap all the knowledge and experience from the retiring workforce for big data analytics tools, these tools can analyse a multitude of data, which were left aside earlier, and propose sound action plans for the current and future workforce. With the advancement of industry 4.0 and rapid deployment of IoT [134], big data [33], [135], and artificial intelligence and machine learning algorithms [136], [137] in the O&G industry, current and future workers can collect more data from their operating assets, feed them into a digital twin system, analyse the data using a range of data analytic tools, and make more informed decisions promptly.

E. ACCESS INACCESSIBLE SAFELY AND COMFORTABLY

As a part of asset integrity management activities, O&G field workers are required to conduct a series of actions, including general visual inspections, closed visual inspections, thermal inspections, and data collection for constructing or updating 3D or 4D models. These data collection or inspections tasks sometimes taken place at great heights (e.g., flare stack, drilling derrick, overboard structures, under-deck, splash zone), in confined or enclosed spaces (e.g., inside the pressure vessels and hydrocarbon storage tanks), and around live systems (e.g., around the pipelines at high pressure or temperature, or around the live flare stack). These hard to reach areas are conventionally accessed with the aid of ropes, scaffoldings, or helicopters [138].

Working at height increases the risk of falling. Deploying human operators to inspect confined or enclosed spaces such as storage tanks or pressure vessels may expose the operator to harmful chemicals, gases, and radiation levels. Additionally, these places typically lack oxygen, causing severe health hazards. Working around high pressure or high-temperature pipelines, valves, or live flare stacks also introduces a range of health and safety hazards for field personnel. Apart from the inherent health and safety hazards, it is essential to note that ropes, scaffolding, and helicopters are not comfortable workstations.

The human-centric digital transformation framework leverages mobile robots to perform asset inspection and asset integrity-related data collection tasks, removing human operators from hazardous environments. The human operator can be safely and comfortably located at a stationary (e.g., office) or mobile (e.g., van or ship) remote-control station, or a safe place on the O&G platform that allows the operator to maintain a visual-line-of-sight (VLOS) with the robots.

There are four types of robotic systems that can be used for asset inspection purposes: (i) unmanned ground robots for top-side facility inspections [139], [140], (ii) flexible robot arms and small-scaled robots for confined area and tanker inspection [141]–[147], (iii) underwater robots for underwater asset inspection [147]–[149], and (iv) remotely operated aerial vehicles (drones) to perform inspections conventionally performed by rope access, scaffolding, or helicopter based inspection teams [138], [150]–[170].

These mobile robot platforms host a range of active and passive sensors, including high-resolution pan, tilt, and zoom cameras, multi-spectral sensors, infrared sensors (short, near, thermal or gas-IR sensors), contact and non-contact vibration sensors, non-contact temperature sensors, hyperspectral sensors, laser scanners, synthetic aperture radars, laser gas detectors, laser or radar altimeters, and microphones [39], [139], [147], [148], [170]–[172]. Operators located at a stationary or mobile remote control station use realtime high definition video feed from the robot as the feedback to perform control, navigation, and inspection activities. Additionally, a stereo camera system, laser scanner data, and sonar scan data (if available) can be utilized to eliminate collisions.

F. UNPARALLEL VISIBILITY AND FAST PAYMENT

The O&G industry is highly fragmented, scattered, and consists of a diverse group of personnel. Accountability, traceability, collaboration, and transparency of oilfield activities and oilfield personnel are of utmost importance. Typically, it is challenging to follow a trail of documentation to verify contractors', employees' and experts' credentials, access their proof of identity and perform background checks. This creates an industrial ecosystem where fewer employees directly work for the O&G operator while the majority of the field workers are employed at oilfield service companies, major contractors, or sub-contractors. Hierarchically connected multiple business entities involve a high level of bureaucracy, demand enormous effort and resources, and necessitate numerous legal and financial intermediaries in contractual agreements. When a company at the bottom of the hierarchy completes a task at an oilfield, it usually takes a more extended period to acquire various sign-offs, certifications, and warranties before handing the completed work to the O&G operator. Unfortunately, this adds a delay in payment for the completed task, making it challenging for the small companies to survive in the long run.

The proposed human-centric digital transformation framework proposes to utilize blockchain technology to address this issue, enable direct employment, and release the payment as soon as the work is done. Blockchain is an immutable distributed ledger technology (DLT) that establishes trust and security in peer-to-peer transactions or information exchanges. Instead of having a central authority or intermediaries to record and coordinate transactions between two (or multiple) parties, each participant of the blockchain network can interact and transact with one another in a peer-to-peer manner. The available blockchain implementations can be categorized into three groups. While the first group contains only cryptocurrency (e.g., Bitcoin), the second group contains only the business logics (e.g., Linux foundation's Hyperledger), and the third group includes both cryptocurrency and business logics (e.g., Ethereum). There are four major uses of blockchain: (i) recording value exchange, (ii) administrating smart contracts, (iii) combining smart contracts to form a decentralized autonomous organization (DAO), and (iv) certifying proof of existence for certain data. More information on blockchain technology, its current status, classification, applications, and open issues are discussed in [173]–[184].

A smart contract is the key feature of blockchain technology that can assist the O&G industry to reduce the delay in contract execution and payments. The O&G company may work collaboratively with major oilfield service companies to define business logic, i.e., a set of if-then rules and timelines for each oilfield activity. The smart contract automatically executes its terms when predefined business logic is met. On behalf of the operator, DAO advertises jobs or calls tenders for each oilfield activity. A person, company, or vendor with appropriate qualifications as backed up by digital ID can apply for the job or place bids on projects. DAO and the selected oilfield employee, service provider, or equipment manufacturer enter a smart contract. Each aspect of oilfield projects, including labour operation, working hours, health and safety accidents, outcomes of quality inspection, and working conditions, are collected, registered, and exchanged on a distributed ledger allowed by blockchain. The smart contract continuously evaluates the agreed terms between the two parties and releases the payment immediately to the tradesperson or company once the agreed terms are fulfilled. This removes the need for extra paperwork that requires time and resources to track oilfield activities and a set of signatures to issue payments. Most notably, if any error occurs, a reverse transaction can be performed easily using blockchain technology as a clause in the smart contract with the consent of all the parties involved. This is virtually impossible when using a traditional project management system. These use of blockchain could encourage direct hiring of trade personnel, and small-scale service companies become more financially secure and stable than the existing hierarchical business model.

The success of blockchain technology deployment in the O&G industry is tightly coupled with the deployment of IIoT systems since the system needs specific data to execute business logics. For example, assume that a smart contract has an hourly rate for a tradesperson. The smart contract must know the number of hours that the tradesperson worked in order to execute the business logic and automatically release the payment for the tradesperson. If the working hours are still recorded on papers, it can take days to digitize the data, delaying the payment process. This can be eliminated by integrating the blockchain system with IIoT location tracking systems. All the working hour data can be accurately tracked and stored in the blockchain, enabling real-time salary calculation and on-time payment release. In the proposed digital transformation framework, blockchain system implementation integrates the digital twin, enterprise software stack, and smart devices to access the data and execute smart contracts in a timely way.

V. CHALLENGES

Despite the opportunities discussed earlier, several challenges need to be addressed when implementing the proposed human-centric digital transformation framework.

A. HUMAN-MACHINE INTERACTION

Although the ergonomics and user interface have been accounted for in the design of wearable devices, the field deployment still raises concerns about the operator-device interaction [185], [186]. The working conditions in the O&G industry are different from other industries, as petroleum environments include extreme noise, weather, and hazards [67]. For example, introduction of any electronic device in an explosive area needs to satisfy strict examinations of the inherent health, safety and environmental risks. These safety requirements make the device larger and heavier with appropriate materials, environmentally sealed compartments and a bulky protective casing. To work in these hazardous environments, the field worker also needs to wear protective clothing, safety glasses and other equipment. This requirement partly limits the motion, vision and wearable-device use of the worker. Given these difficulties, the deployment of new interacting technologies such as touchscreen [187], virtual reality keyboards [188] and fingerprint [189] records is questionable. The small screens in industrial tablets (e.g., Tab Ex 01 with 8″ screen [190]) also limits text presentations and visual content for information display [67], [191]. These challenges have been motivating researchers and developers to improve the human-computer interaction for industrial wearable devices.

These applications are associated with advanced computing algorithms, with which the users are often not familiar [76], [192]. The internal operations of the AI/ML systems are likely not understand by the operators who will decide whether to trust experience or the machined-based supporting aids for decision making. The lack of operator knowledge of the supporting systems can affect wearable devices' effective use and trust, especially during unpredictable and emergent events [193]. The classroom organization for training end users can take considerable time and effort because of the complicated content and number of subjects. In some cases, many AI/ML systems are usually assumed to be a black box deployed with little training [193], [194]. This temporary solution is cost-saving but likely fails to capture the benefits of the automated supporting system completely. Consequently, the employment of new technologies cannot achieve the desired return on investment. This issue has motivated many researchers to upgrade the GUI design in terms of transparency and explainable of automated system computation [67], [195]. This research attempts to determine optimal GUI design and formulate design recommendations, which affect the effective deployment of wearable devices [193].

B. DATA PRIVACY

In the last few decades, the increasing popularity of wearable devices has also resulted in increasing privacy lawsuits in different industries. These cases provide lessons for the O&G industry.

Wearable devices enable location and physiological tracking of the field operators. These new kinds of information have raised many legal concerns about privacy implications in the workplace [196]–[198]. A lawsuit against Intermex Wire Transfer company in 2015 is an excellent example of privacy invasion and unfair business practices associated with this new technology. In this case, employment was terminated because an employee had uninstalled a smart-phone application required the employee's job. The application has the ability to track location even when the employee was off-duty, which made the employee feel uncomfortable. To this end, this lawsuit was settled, but it highlights new grounds to sue employers using personal tracking data [199]. A similar case can happen with the O&G industry when deploying personal tracking devices for field workers. The tracking data is useful not only for surveillance, but also for analyzing employee performance (i.e., health and behaviour patterns). In contrast, the data can reveal sensitive ergonomic information associated with the hazardous working conditions [196]. These elements help explain the hesitation of both employer and employee to adapt digitalization.

M3SH Technology, a manufacturer of health and safety electronic mining equipment in New Brunswick, Canada, has addressed some of the privacy violation concerns through the device's configurations [200]. The wearable tracking is implemented using a specific number assigned for each wearable rather than individual identification. The tracking functionality is also automatically switched off in specific areas such as washrooms and when the employee is off-duty. This kind of configuration helps to protect privacy when deploying wearable devices at the mine site. Automatic disabling of the tracking unit still needs more empirical studies to confirm the effectiveness, especially in the case of health monitoring devices, which are expected to collect medical data all the time, even when the employee is off-duty. Mitigating an infectious disease outbreak is a good example of the need for healthcare risk management. Disabling the device off-duty may result in misinterpretation and faulty reports of the health status.

Cross-border data flow is another concern of privacy protection. For example, there is a legal gap between US and EU legislations of general data privacy protection [201]. Here, the analysis focused on the case of fitness trackers and smart watches (e.g., Fitbit and Jawbone). As most of the products originate from the US, the collected data are usually transferred back to the US for further processing. Notably, the customer has limited information about the data-processing processes as well as involvement of third-parties. Also, the EU has developed a comprehensive regulatory framework for data protection, which is not available in the US. When data is stored in other countries, a similar level of privacy protection is difficult to achieve. This legal gap between countries give rise to many uncertainties. Digitalization necessitates the implementation of cloud technologies and advanced analytic tools. When the data is transferred to another country, an effective management model for privacy protection is required to comply with the legislation system [196].

The issues mentioned highlights weaknesses in the existing legislation and governance systems for digitalization. Guidance from governments and international collaborations between governments are also necessary to support petroleum companies in the digitalization process as well as manage cross-border data [201]–[203]. Initial government efforts have been implemented to address privacy issues. New comprehensive regulations for data privacy have been published, such as the General Data Protection Regulation (GDPR) by Europe, Personal Information Protection and Electronic Documents (PIPEDA) by Canada, National Information Security Standardization Technical Committee (TC260) by China, etc.

Despite the data privacy issues, Richardson and Mackinnon recommend considering digitalization as an excellent opportunity to upgrade the existing systems and mitigate the management gaps [196]. For example, following the publication of GDPR, the European Commission also identified which non-EU countries provide adequate protection for international trade negotiations [204], [205]. The identification process and negotiation may be time-consuming and become significant barriers for international collaboration, especially with many Middle East countries having high records of cyber incidents. Therefore, regulation requires non-EU companies to address the concerns of data privacy and protection, for qualification before expanding their business in Europe.

C. CYBER SECURITY

The performance of the proposed human-centric digital transformation framework creates real-time human-cyber-physical connectivity, which is more vulnerable to cyber-attacks than the traditional disconnected framework. According to data presented in [206], the energy sector was the second-largest target of cyber-attack in 2016, and 75% of US O&G companies reported a minimum of one cyber-attack during that year. The severity of cyber-attack and vulnerability to cyber-attack varies with the different phases of the O&G life cycle [206]. For example, geophysical surveys are less vulnerable to cyber-attacks and the severity of the cyber-attack is low. In contrast, production and development drilling are highly vulnerable to cyber-attacks, and the severity of the cyber-attack on these activities is extremely high.

As the proposed framework has acquired data from millions of sensors attached to the O&G assets, including operators, the data rate of the system is high and very difficult to monitor in realtime as data get streamed into storage [207]. The variety of data sources and non-standard data formats for data streams facilitate botnet attacks on the data source, destination, and the connectivity by capitalising on their vulnerabilities. Therefore, data security and privacy policies must be enforced within a real-time processing environment of big data during the data acquisition stage itself. It is also essential to verify and validate the origin of data using sophisticated authentication, encryption, and privacy policies.

Performing analytics is a crucial phase in the life cycle of the proposed digital transformation framework. The purpose collecting and maintaining big data with good data storage systems is to process and analyse big data to gain data insights and to make timely, as well as, accurate decisions. Companies collect a plethora of contextual and sensitive data about customers to analyse their interactions in order to arrive at a more meaningful marketing strategy to provide them with personalised products and enhanced services. Analysing such data in the cloud from various sources could lead to unexpected privacy leakages [208].

How to present the analysis results to a user is another essential work of big data analytics. If the user cannot easily understand the meaning of the results, the results will be useless. Business intelligence and network monitoring are two common approaches because their user interface plays a vital role in making them workable. Zhang *et al.* [209] pointed out that the visual analytics tasks for commercial systems can be divided into four categories: exploration, dashboards, reporting, and alerting. The study presented in [210] showed that the interface for electroencephalography (EEG) interpretation is another noticeable research issue in big data analytics. User interfaces for the cloud system is the recent trend for big data analytics [211], [212]. This usually plays vital roles in a big data analytics system, one of which is to simplify explaining the needed knowledge to the users, while another is to make it easier for the users to handle the data analytics system to work with their options. There are typically three main steps in data analytics: data preparation to identify, clean and format the data according to the requirements of the analytics model; adoption of the analytic model; and communication of the output to provide data insights. Each of these steps include security and privacy challenges due to inherent vulnerabilities.

Since most big data analytics systems are designed for parallel computing, and they typically work on other systems (e.g., cloud platform) or work with other systems (e.g., search engine or knowledge base), the communication between big data analytics and other systems strongly affects the performance of the whole process of knowledge discovery in databases (KDD). Because of these latent problems, security has become one of the open issues of big data analytics [213], hence the proposed human-centric digital transformation.

D. LACK OF TECHNOLOGICAL READINESS

Almost all the O&G facilities and work environments belong to hazard Zone-0[6] or Zone-1.[7] The former is the area where an explosive atmosphere is continuously present or frequently occurring for long periods, while the latter represents the area where, under regular operation, an explosive situation is likely to occur periodically. All the smart sensors and actuators, mobile devices, wearable technologies, robotic systems, and drones focussing on hazard Zone-0 and Zone-1 applications are subjected to a range of regulations [214]–[216]. These regulations introduce some challenges when designing and deploying smart, portable, or wearable devices in the oilfield. Some of these challenges are listed below [217], [218].

- It typically takes months, if not years, for the product development process of inherently secure smart, portable and wearable devices to be deployed at the O&G workplace.
- The longer life cycle of product development and the rapid pace of technological evolution may cause new smart, portable or wearable devices to become obsolete once launched.

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[6] Zone-0 is an area where an explosive atmosphere is continuously present or frequently occurring for long periods of time.

[7] Zone-1 is an area where, under normal operation, an explosive situation is likely to occur periodically.

- Typical product development cost can surpass US$ 250,000.
- It is impossible to carry out field trials or test products at high-risk O&G facilities; and
- there is a scarcity of cheap, long-lasting, intrinsically safe, lightweight, and Zone-0 and Zone-1 certified batteries to power the portable and wearable devices.

In addition to hazard Zone-0 and Zone-1 regulatory requirements, the instrumentation designers must consider the effective space available for sensor and electronics deployment. In most cases, this space is exceptionally limited, requiring a more compact and miniature design for the sensors and the associated electronics [219]. When the sensor is more compact, one sensor component may produce RF interference on other components, causing erroneous sensor data. Additionally, a high level of RF interference created by the operating machines and electric power lines may also affect the quality, accuracy, and precision of the collected and communicated data [220]. Smart sensors and actuators, portable devices, wearables, and communication infrastructure must, therefore, be designed in such a way that they can function under a wide range of environmental and industrial conditions and produce and transmit reliable quality data to the control centres.

VI. SUMMARY AND DISCUSSION

This paper proposes a human-centric digital transformation framework for the O&G industry. The proposed framework leverages emerging digital technologies such as IIoT, wearables, mobile devices, big data analytics, digital twins, extended reality technologies (virtual-reality, augmented-reality, and mixed-reality), blockchain technology, robotics systems, and drones to solve critical challenges faced by the O&G field workers. These key challenges include elevated health and safety hazards, high levels of risk associated with on-the-job training programs, inability to use all the available data for decision making, lack of skill to interpret the data, unavailability of experts on demand, and delays in payments for completed tasks.

The proposed human-centric digital transformation framework contains three major domains; operator domain, physical domain, and cyber domain. The operator domain consists of human operators, wearables for health and safety support, wearables and mobile devices for activity support, feedback systems, robotic systems, and a body area network to enable seamless data communication between each subsystem of operator domain, and physical and cyber domains. The technology deployment introduces nine elements to the future field workers (operator 4.0), namely, super strength-, augmented-, virtual-, analytical-, smarter-, healthy-, social-, collaborative-, and remote-operators. Future field operators must possess the health-operator element. Depending on the task on hand, and the technologies that have been deployed to assist the field workers, they may possess one or multiple elements of Operator 4.0. The physical domain consists of all the oilfield asserts, and IIoT enabled smart sensors and actuators. The cyber domain consists of three major subsystems: digital twins (both the asset and operator twins), data lake, and enterprise software stack.

Smart sensors, wearables, and mobile devices with edge and fog processing capabilities process the collected data in real-time and make time-sensitive decisions, such as identifying any health-related incidents and sending alarms to the emergency response team. All the collected data and edge or fog processed data are transmitted to the cyber domain for further analysis. The cyber domain leverages advanced data processing and visualization techniques to process and visualize incoming data, perform history mapping, identify anomalies, create future scenarios, enable virtual training, track the asset and field workers' locations, monitor the field personnel health conditions, and make data-driven decisions. Field personnel can use the simulation results coming from the cyber domain to perform the field activities safely.

The proposed human-centric digital transformation framework offers a range of opportunities. It (i) enables personnel health, safety, and location tracking to enhance field personnel safety, (ii) improves collaborations and data visualization through extended reality technologies, (iii) provides an immersive training platform to conduct professional education and emergency response training without putting anyone's life or an O&G facility at a risk, (iv) provides data-driven decision support to make critical decisions in a timely manner, (v) offers safe and comfortable ways to access and perform inspections at hard to reach locations, and (vi) enables direct employments and fast payments for the completed field works, using blockchain technology.

There are several impediments to the proposed human-centric digital transformation framework. These impediments include cybersecurity, data privacy, challenges associated with human-machine interaction, regulation, and technological constraints for deploying any product in hazard Zone-0 and Zone-1. These challenges are not unique for the proposed framework but for any digital transformation initiatives within and outside the O&G industry. Researchers, product developers, policymakers, and subject matter experts with O&G operating and service companies and other technology/regulatory sectors must work collaboratively to address these limitations.

Note that this paper focuses on how to deploy digital technologies to assist O&G field workers. However, the applications of digital adoption are not restricted to assisting field workers but offer numerous opportunities for the O&G industry as a whole. For example, from the process or business point of view, digital twins offer several other opportunities, including asset performance management, asset risk assessment, process automation, future scenario developments, collaborative decisions support, avoidance of information wastage and misinterpretation, which shorten the time from plan to production. Similarly, the deployment of IIoT systems, blockchain technologies, drones, other robotic platforms, extended reality technologies, big data analytics, artificial intelligence, machine learning, and other digital technologies has numerous applications for the O&G industry. These opportunities are widely discussed in academic and industrial literature. The proposed human-centric digital transformation framework can be extended to cater to these business objectives without compromising the core value of the proposed framework in empowering the O&G field workers digitally.

REFERENCES

[1] Equinor. (2019). *Digitalisation is Changing our Company*. Accessed: Dec. 3, 2019. [Online]. Available: https://www.equinor.com/en/how-and-why/digitalisation-in-our-dna.html%

[2] Equinor. (2019). *Establishing a Digital Centre of Excellence—Equinor Towards 2030*. Accessed: Dec. 3, 2019. [Online]. Available: https://www.equinor.com/en/magazine/statoil-2030—putting-on-digital-%bionic-boots.html

[3] Shell Global. (2019). *Digital Innovation*. Accessed: Dec. 3, 2019. [Online]. Available: https://www.shell.com/energy-and-innovation/overcoming-technology-chal%lenges/digital-innovation.html

[4] Saudi Aramco. (2019). *Saudi Aramco Explains its Digital Transformation*. Accessed: Dec. 3, 2019. [Online]. Available: https://www.chemicalprocessing.com/articles/2019/saudi-aramco-explains%-its-digital-transformation/

[5] Suncor. (2019). *Suncor Accelerates Digital Transformation Journey Through Strategic Alliance With Microsoft*. Accessed: Dec. 3, 2019. [Online]. Available: https://www.suncor.com/en-CA/newsroom/news-releases/1945172

[6] British Petroleum. (2019). *Digital Innovation*. Accessed: Dec. 3, 2019. [Online]. Available: https://www.bp.com/en/global/corporate/what-we-do/technology-at-bp/dig%ital-innovation.html

[7] Chevron. (2019). *Chevron Partners With Microsoft to Fuel Digital Transformation From the Reservoir to the Retail Pump*. Accessed: Dec. 3, 2019. [Online]. Available: https://www.chevron.com/stories/chevron-partners-with-microsoft

[8] Accenture. (2016). *The 2016 Upstream Oil and Gas Digital Trends Survey*. Accessed: Dec. 3, 2019. [Online]. Available: https://www.accenture.com/_acnmedia/PDF-9/Accenture-Upstream-Oil-Gas-%Digital-Energy-Trends-Survey-Infographic-Final.pdfla=en#zoom=50

[9] B. Dudley, B. Weinelt, M. Spelman, P. Gomez, R. Heusden, R. Siyam, M. Ashraf, J. Collins, A. Khan, and W. Popp, *Digital transformation Initiative: Oil and Gas Industry*. Cologny, Switzerland: World Economic Forum, 2017.

[10] A. Winsor and S. Sanderson, "2018 tech trends for the oil and gas industry," Deloitte, London, U.K., Tech. Rep., 2018.

[11] PwC Canada. (2019). *Digital in Oil and Gas—Facing a Digital Revolution*. Accessed: Dec. 3, 2019. [Online]. Available: https://www.pwc.com/ca/en/industries/energy/digital-services.htmlOnl%ine

[12] R. Mishra. (2019). *Top Tech Trends in oil and Gas for 2019*. Accessed: Dec. 3, 2019. [Online]. Available: https://www.accenture.com/us-en/blogs/accenture-energy/top-tech-trends%-in-oil-and-gas-for-2019

[13] F. D. Silva, S. Dutta, A. Jaitly, G. Choudhary, S. Banerjee, and R. Kumar, "Building the digital spine of oil & gas enterprises," TATA Construct. Services, Kolkata, India, Tech. Rep., 2019.

[14] L. de Best and F. G. Van Den Berg, "Shell's smart fields-sustaining and accelerating benefits from intelligent fields," in *SPE Intelligent Energy International*. London, U.K.: Society of Petroleum Engineers, 2012.

[15] Equinor. (2017). *Digitalisation Driving Value Creation*. Accessed: Jan. 14, 2020. [Online]. Available: https://www.equinor.com/en/news/digitalisation-driving-value-creation.%html

[16] M. Green. (2012). *Innovation: Chevoron's 'Ifield' Links Performance, Savings*. Accessed: Jan. 14, 2020. [Online]. Available: https://www.api.org/news-policy-and-issues/blog/2012/06/13/innovation-%chevrons-i-field-links-perfor

[17] C. E. Reddick, "Field of the future: Making BPs vision a reality," in *Proc. Intell. Energy Conf. Exhib.* London, U.K.: Society of Petroleum Engineers, 2006, pp. 1–6.

[18] G. V. L. Moises, T. A. Rolim, and J. M. Formigli, "GeDIg: Petrobras corporate program for digital integrated field management," in *Proc. Intell. Energy Conf. Exhib.* London, U.K.: Society of Petroleum Engineers, Feb. 2008, pp. 1–7.

[19] F. Rydzak, L. S. Breistrand, F. O. Sveen, Y. Qian, and J. J. Gonzalez, "Exploring resilience towards risks in eoperations in the oil and gas industry," in *Proc. Int. Conf. Comput. Saf., Rel., Secur.* Berlin, Germany: Springer, 2006, pp. 57–70.

[20] A. J. Garcia Irausquin, S. Sankaran, G. Mijares, J. A. Rodriguez, and L. A. Saputelli, "Real time operations in asset performance workflows," in *Proc. Intell. Energy Conf. Exhib.* London, U.K.: Society of Petroleum Engineers, Feb. 2008, pp. 1–5.

[21] A. Hussain, J. C. Vega, M. A. Hassane, S. A. Yusaf, and A. A. Abdul-Halim, "Enhancing smart completion capabilities by integration with digital oil field real time monitoring system in a green field of ADMA-OPCO," in *Proc. Abu Dhabi Int. Petroleum Exhib. Conf.*, Nov. 2016, pp. 1–16.

[22] T. A. Leopold, V. Ratcheva, and S. Zahidi, "The future of jobs report," World Economic Forum, Cologny, Switzerland, Tech. Rep., 2018.

[23] C. B. Frey and M. A. Osborne, "The future of employment: How susceptible are jobs to computerisation," Oxford Univ., Oxford, U.K., Tech. Rep., 2013.

[24] C. B. Frey and M. A. Osborne, "The future of employment: How susceptible are jobs to computerisation?" *Technol. Forecasting Social Change*, vol. 114, pp. 254–280, Jan. 2017.

[25] J. Manyika, M. Chui, M. Miremadi, J. Bughin, K. George, P. Willmott, and M. Dewhurst, "A future that works: Automation, employment, and productivity," McKinsey Global Inst., New York, NY, USA, Tech. Rep., 2017.

[26] C. Lamb, "The talented Mr. Robot: The impact of automation on Canada's workforce," Brookfield Inst., Toronto, ON, Canada, Tech. Rep., 2016.

[27] S. Lund, A. Madgavkar, J. Manyika, S. Smit, K. Ellingrud, M. Meaney, and O. Robinson, "The future of work after COVID-19," McKinsey Global Inst., New York, NY, USA, Tech. Rep., 2021.

[28] Occupational Safety and Health Administration United States of Department of Labor. (2019). *Health Hazards Associated With Oil and Gas Extraction Activities*. Accessed: Feb. 6, 2020. [Online]. Available: https://www.osha.gov/SLTC/oilgaswelldrilling/healthhazards.html

[29] Occupational Safety and Health Administration United States of Department of Labor. (2019). *Safety Hazards Associated With Oil and Gas Extraction Activities*. Accessed: Feb. 6, 2020. [Online]. Available: https://www.osha.gov/SLTC/oilgaswelldrilling/safetyhazards.html

[30] R. Holm and M. Priglinger, "Virtual reality training as a method for interactive and experience-based learning," in *Proc. Intell. Energy Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2008, pp. 1–7.

[31] S. Colombo, S. Nazir, and D. Manca, "Immersive virtual reality for training and decision making: Preliminary results of experiments performed with a plant simulator," *SPE Econ. Manage.*, vol. 6, no. 4, pp. 165–172, Oct. 2014.

[32] V. Warren, J. Pennell, and D. Gover, "Enquiry report ice incursion incident searose FPSO," Canada-Newfoundland & Labrador Offshore Petroleum Board, Barrington, IL, USA, Tech. Rep., 2018.

[33] M. Mohammadpoor and F. Torabi, "Big data analytics in oil and gas industry: An emerging trend," *Petroleum*, vol. 6, no. 4, pp. 321–328, Dec. 2020.

[34] A. Brun, M. Trench, and T. Vermaat, "Why oil and gas companies must act on analytics," McKinsey & Company, New York, NY, USA, Tech. Rep., 2017.

[35] B. Bechtold. (2018). *Beyond the Barrel: How Data and Analytics Will Become the New Currency in Oil and Gas*. Accessed: Feb. 7, 2020. [Online]. Available: https://gblogs.cisco.com/ca/2018/06/07/beyond-the-barrel-how-data-and-% analytics-will-become-the-new-currency-in-oil-and-gas/

[36] M. Spelman, B. Weinelt, R. van Heusden, R. Siyam, M. Ashraf, V. Chidambaram, J. Collins, A. Khan, W. Popp, A. Shah, P. Agrawal, and S. Shroff, "Digital transformation initiative oil and gas industry," World Econ. Forum Accenture, Cologny, Switzerland, White Paper REF 060117, 2017.

[37] "Diversifying Canada's oil and gas workforce—A decade in review," Petroleum Labour Market Inf., PetroLMI, Calgary, AB, Canada, Tech. Rep., 2018.

[38] C. Tomlinson. (2018). *Energy Companies are Forgetting the Lesson of Great Crew Change*. Accessed: Feb. 10, 2020. [Online]. Available: https://www.houstonchronicle.com/business/columnists/tomlinson/article%/Energy-companies-are-forgetting-the-lesson-of-13271735.php

[39] A. Shukla and H. Karki, "Application of robotics in onshore oil and gas industry—A review—Part I," *Robot. Auto. Syst.*, vol. 75, pp. 490–507, Jan. 2016.

[40] ROGTEC. (2011). *Andrew Gould Delivers Keynote Speech at Howard Weil Energy Conference 2011 in New Orleans*. Accessed: Feb. 7, 2020. [Online]. Available: https://www.osha.gov/SLTC/oilgaswelldrilling/safetyhazards.html

[41] D. Romero, P. Bernus, O. Noran, J. Stahre, and Å. Fast-Berglund, "The operator 4.0: Human cyber-physical systems & adaptive automation towards human-automation symbiosis work systems," in *Proc. IFIP Int. Conf. Adv. Prod. Manage. Syst.* Cham, Switzerland: Springer, 2016, pp. 677–686.

[42] D. Romero, J. Stahre, T. Wuest, O. Noran, P. Bernus, Å. Fast-Berglund, and D. Gorecky, "Towards an operator 4.0 typology: A human-centric perspective on the fourth industrial revolution technologies," in *Proc. Int. Conf. Comput. Ind. Eng. (CIE)*, Tianjin, China, 2016, pp. 29–31.

[43] T. Ruppert, S. Jaskó, T. Holczinger, and J. Abonyi, "Enabling technologies for operator 4.0: A survey," *Appl. Sci.*, vol. 8, no. 9, p. 1650, Sep. 2018.

[44] E. Kaasinen, F. Schmalfuß, C. Özturk, S. Aromaa, M. Boubekeur, J. Heilala, P. Heikkilä, T. Kuula, M. Liinasuo, S. Mach, R. Mehta, E. Petäjä, and T. Walter, "Empowering and engaging industrial workers with operator 4.0 solutions," *Comput. Ind. Eng.*, vol. 139, Jan. 2020, Art. no. 105678.

[45] R. J. Rabelo, D. Romero, and S. P. Zambiasi, "Softbots supporting the operator 4.0 at smart factory environments," in *Proc. IFIP Int. Conf. Adv. Prod. Manage. Syst.* Cham, Switzerland: Springer, 2018, pp. 456–464.

[46] G. S. Saini, P. Ashok, E. van Oort, and M. R. Isbell, "Accelerating well construction using a digital twin demonstrated on unconventional well data in North America," in *Proc. 6th Unconventional Resour. Technol. Conf.*, 2018, pp. 3264–3276.

[47] P. Sharma, D. Knezevic, P. Huynh, and G. Malinowski, "RB-FEA based digital twin for structural integrity assessment of offshore structures," in *Proc. Offshore Technol. Conf.*, Apr. 2018, pp. 1–6.

[48] M. G. Mayani, M. Svendsen, and S. Oedegaard, "Drilling digital twin success stories the last 10 years," in *SPE Norway One Day Seminar*. Bergen, Norway: Society of Petroleum Engineers, 2018.

[49] D. Nadhan, M. G. Mayani, and R. Rommetveit, "Drilling with digital twins," in *Proc. IADC/SPE Asia Pacific Drilling Technol. Conf. Exhib.*, 2018, pp. 1–18.

[50] J. Van Os, "The digital twin throughout the lifecycle," in *SNAME Maritime Convention*. Providence, RI, USA: The Society of Naval Architects and Marine Engineers, 2018.

[51] T. Poddar, "Digital twin bridging intelligence among man, machine and environment," in *Proc. Offshore Technol. Conf. Asia*, Mar. 2018, pp. 1–4.

[52] J.-P. Mohr, "Digital twins for the oil and gas industry," Hashplay, Inc., Tech. Rep., 2018.

[53] S. J. Horseman, C. M. Sloman, S. A. Seay, M. A. Al Abdrabbuh, and Y. Alem, "Adding the Predictive P into personal protective equipment," in *Proc. SPE Int. Conf. Exhib. Health, Saf., Secur., Environ., Social Responsibility*, 2018, pp. 1–17.

[54] F. Sanfilippo and K. Y. Pettersen, "A sensor fusion wearable health-monitoring system with haptic feedback," in *Proc. 11th Int. Conf. Innov. Inf. Technol. (IIT)*, Nov. 2015, pp. 262–266.

[55] M. M. Baig, H. GholamHosseini, and M. J. Connolly, "Mobile healthcare applications: System design review, critical issues and challenges," *Australas. Phys. Eng. Sci. Med.*, vol. 38, pp. 23–38, Mar. 2015.

[56] M. Heinz and C. Rocker, "Feedback presentation for workers in industrial environments—Challenges and opportunities," in *Proc. Int. Cross-Domain Conf. Mach. Learn. Knowl. Extraction*, 2018, pp. 248–261.

[57] C. R. Baudoin, "Deploying the industrial internet in oil & gas: Challenges and opportunities," in *Proc. SPE Intell. Energy Int. Conf. Exhib.*, Sep. 2016, pp. 1–11.

[58] M. Mardonova and Y. Choi, "Review of wearable device technology and its applications to the mining industry," *Energies*, vol. 11, no. 3, p. 547, Mar. 2018.

[59] D. Singh and C. K. Reddy, "A survey on platforms for big data analytics," *J. Big Data*, vol. 2, no. 1, pp. 1–20, 2014.

[60] R. Krakau, S. Trzcielinski, and W. Karwowski, "Advances in the ergonomics in manufacturing managing the enterprise of the futurer," in *Proc. 5th Appl. Hum. Factors Ergonom. Conf.*, Jul. 2014, pp. 94–105.

[61] C. Marino and J. Vargas, "Ergonomic postural evaluation system through non-invasive sensors," in *Proc. Int. Conf. Comput. Sci., Electron. Ind. Eng.*, 2019, pp. 274–286.

[62] P.-S. Murvay and I. Silea, "A survey on gas leak detection and localization techniques," *J. Loss Prevention Process Industries*, vol. 25, no. 6, pp. 966–973, Nov. 2012.

[63] F. Arduini, S. Cinti, V. Scognamiglio, D. Moscone, and G. Palleschi, "How cutting-edge technologies impact the design of electrochemical (bio)sensors for environmental analysis. A review," *Analytica Chim. Acta*, vol. 959, pp. 15–42, Mar. 2017.

[64] L. Klein, M. Ramachandran, T. van Kessel, D. Nair, N. Hinds, H. Hamann, and N. Sosa, "Wireless sensor networks for fugitive methane emissions monitoring in oil and gas industry," in *Proc. IEEE Int. Congr. Internet Things (ICIOT)*, Jul. 2018, pp. 41–48.

[65] FLIR. (2019). *FLIR Launches its First Uncooled Methane Gas Detection Camera*. Accessed: May 25, 2021. [Online]. Available: https://www.flir.ca/news-center/press-releases/flir-launches-its-first%-uncooled-methane-gas-detection-camera/

[66] S. Bauk and A. Schmeink, "Port workers' safety monitoring by RFID technology: A review of some solutions," *J. Maritime Res.*, vol. 13, no. 2, pp. 63–68, 2016.

[67] D. Blauhut and K. L. Seip, "An empirical study of mobile-device use at Norwegian oil and gas processing plants," *Cognition, Technol. Work*, vol. 20, no. 2, pp. 325–336, May 2018.

[68] T. Jacobs, "AR headsets give oil and gas sector the quicker fix," *J. Petroleum Technol.*, vol. 70, no. 7, pp. 32–34, Jul. 2018.

[69] R. Savijani. (2017). *4 Ways Hololens Will Revolutionize the Oil Drilling and Exploration Industry*. [Online]. Available: https://www.softwebsolutions.com/resources/hololens-app-for-oil-and-na%tural-gas-industry.html

[70] J. Bourne. (2019). *How BP is Using Mixed Reality and HoloLens in Particular for its Upstream Operations*. Accessed: May 25, 2021. [Online]. Available: https://www.virtualreality-news.net/news/2019/dec/05/how-bp-using-mixe%d-reality-and-hololens-its-upstream-operations/

[71] A. Ranganathan. (2017). *How Augmented and Virtual Reality is Helping Oil & Gas Companies*. Accessed: May 25, 2021. [Online]. Available: https://energy.economictimes.indiatimes.com/energy-speak/how-augmented%-and-virtual-reality-is-helping-oil-gas-companies/2514

[72] J. Potts, T. Sookdeo, J. Westerheide, and D. Sharber, "Enhanced augmented/mixed reality and process safety applications," in *Proc. SPE Middle East Oil Gas Show Conf.*, Mar. 2019, pp. 1–9.

[73] M. Grabowski, A. Rowen, and J.-P. Rancy, "Evaluation of wearable immersive augmented reality technology in safety-critical systems," *Saf. Sci.*, vol. 103, pp. 23–32, Mar. 2018.

[74] F. Saxen, O. Rashid, A. Al-Hamadi, S. Adler, A. Kernchen, and R. Mecke, "Image-based methods for interaction with head-worn worker-assistance systems," *J. Intell. Learn. Syst. Appl.*, vol. 6, no. 3, pp. 141–152, 2014.

[75] S. Ochanji. (2019). *Shell Launches Augmented Reality Remote Assistance Device*. [Online]. Available: https://virtualrealitytimes.com/2019/04/10/shell-launches-augmented-re%ality-remote-assistance/

[76] J. Posada, C. Toro, I. Barandiaran, D. Oyarzun, D. Stricker, R. De Amicis, E. B. Pinto, P. Eisert, J. Döllner, and I. Vallarino, "Visual computing as a key enabling technology for industrie 4.0 and Industrial internet," *IEEE Comput. Graph. Appl.*, vol. 35, no. 2, pp. 26–40, Apr. 2015.

[77] P. Wang, P. Wu, J. Wang, H.-L. Chi, and X. Wang, "A critical review of the use of virtual reality in construction engineering education and training," *Int. J. Environ. Res. Public Health*, vol. 15, no. 6, p. 1204, Jun. 2018.

[78] I. Juricic, L. Malaguti, and M. Poggi, "Virtual reality of a typical eni platform to anticipate and train for start-up, maintenance and emercency operations," in *Proc. Offshore Medit. Conf. Exhib.*, Mar. 2015, pp. 1–9.

[79] L. C. Da Cruz and J. C. De Oliveira, "A CAVE/Desktop collaborative virtual environment for offshore oil platform training," in *Proc. 18th Symp. Virtual Augmented Reality (SVR)*, Jun. 2016, pp. 178–182.

[80] S. V. Susarev, E. A. Bulkaeva, Y. V. Sarbitova, and D. S. Dolmatov, "Training simulators development technique for oil and gas industry automation control systems," in *Proc. IEEE 2nd Int. Conf. Control Tech. Syst. (CTS)*, Oct. 2017, pp. 207–210.

[81] B. J. Veitch, R. J. Billard, and A. Patterson, "Emergency response training using simulators," in *Proc. Offshore Technol. Conf.*, May 2008, pp. 1–7.

[82] A. Retnanto, M. Fadlelmula, N. Alyafei, and A. Sheharyar, "Active student engagement in learning-using virtual reality technology to develop professional skills for petroleum engineering education," in *SPE Annu. Tech. Conf. Exhib.* London, U.K.: Society of Petroleum Engineers, 2019, pp. 1–9.

[83] S. Oedegaard, L. Hollman, G. Smaaskjaer, E. Claudey, O. Mehus, T. Andreassen, and J. Nabavi, "Using simulator to prepare for total loss risk scenarios utilizing controlled mud cap drilling in the Barents-Sea," in *Proc. IADC/SPE Drilling Conf. Exhib.* London, U.K.: Society of Petroleum Engineers, 2018, pp. 1–16.

[84] A. Maliardi, P. Ferrara, R. Poloni, S. Spagnolo, E. De Marchi, T. Grasso, and P. Allara, "Virtual reality in D&C: A new way for immersion training and operation simulation," in *Abu Dhabi Int. Petroleum Exhib. Conf.*, London, U.K.: Society of Petroleum Engineers, 2018, pp. 1–13.

[85] I. S. Brasil, F. M. M. Neto, J. F. S. Chagas, R. Monteiro, D. F. L. Souza, M. F. Bonates, and A. Dantas, "An intelligent and persistent browser-based game for oil drilling operators training," in *Proc. IEEE 1st Int. Conf. Serious Games Appl. for Health (SeGAH)*, Nov. 2011, pp. 1–9.

[86] J. M. Gilmore, "Benefits of using dynamic simulation and 3-D virtual reality for safety," in *Proc. Offshore Medit. Conf. Exhib.*, Mar. 2013, pp. 1–6.

[87] A. Abu Haleeqa, S. McIntyre, S. Al Afifi, F. Taqi, B. Butt, R. Simmons, and C. Rodrigues, "Incident command virtual reality icvr immersive training system," in *Proc. Abu Dhabi Int. Petroleum Exhib. & Conf.* London, U.K.: Society of Petroleum Engineers, 2018, pp. 1–14.

[88] P. Ugoji, A. Ibhadode, and A. Amadi, "Building the next generation of petrotechnical professionals through gamification," in *Proc. SPE Abu Dhabi Int. Petroleum Exhib. Conf.*, Nov. 2017, pp. 1–13.

[89] S. Hoiset and E. Glittum, "Risk and safety training using virtual reality (VRSafety)," in *SPE Int. Conf. Health, Saf., Environ. Oil Gas Exploration Prod.*, London, U.K.: Society of Petroleum Engineers, Apr. 2008, pp. 1–13.

[90] Y. Yu, D. Mao, H. Yin, X. Zhang, C. Sun, and G. Chu, "Simulated training system for undersea oil spill emergency response," *Aquatic Procedia*, vol. 3, pp. 173–179, Mar. 2015.

[91] G. B. Zampronio, A. B. Raposo, and M. Gattass, "A 3D simulation system for emergency evacuation in offshore platforms," in *Proc. 17th Symp. Virtual Augmented Reality*, May 2015, pp. 99–106.

[92] Focus Design. (2014). *Offshore Rig Fire Evacuation Simulation—Online Demo HD*. Accessed: Feb. 19, 2020. [Online]. Available: https://www.youtube.com/watch?v=WR_gN474csQ

[93] M.-W. Koo, S. Ha, J.-H. Cha, and D.-Y. Cho, "Fire incident training for offshore worker using virtual reality," in *Proc. 27th Int. Ocean Polar Eng. Conf.*, Jun. 2017, pp. 886–890.

[94] B. Veitch, R. Billard, and A. Patterson, "Evacuation training using immersive simulators," in *Proc. 18th Int. Offshore Polar Eng. Conf.*, Jul. 2008, pp. 223–227.

[95] S. Singh, S. Pandey, R. Shankar, and A. Dumka, "Application of big data analytics to optimize the operations in the upstream petroleum industry," in *Proc. 2nd Int. Conf. Comput. Sustain. Global Develop. (INDIACom)*, 2015, pp. 1074–1079.

[96] H. Patel, D. Prajapati, D. Mahida, and M. Shah, "Transforming petroleum downstream sector through big data: A holistic review," *J. Petroleum Explor. Prod. Technol.*, vol. 10, no. 6, pp. 2601–2611, Aug. 2020.

[97] M. Brule, "Tapping the power of big data for the oil and gas industry," IBM Corporation, New York, NY, USA, White Paper IMW14680-USEN-01, 2013.

[98] H. Hamzeh, "Application of big data in petroleum industry," Dept. Electron. Comput. Eng. Istanbul Sehir Univ., Istanbul, Turkey, White Paper, 2016.

[99] J. Spath, "Big data," *J. Petroleum Technol.*, Dec. 2013.

[100] P. Anand, "Big data is a big deal," *J. Petroleum Technol.*, vol. 65, no. 4, pp. 18–21, Apr. 2013.

[101] A. Alfaleh, Y. Wang, B. Yan, J. Killough, H. Song, and C. Wei, "Topological data analysis to solve big data problem in reservoir engineering: Application to inverted 4D seismic data," in *Proc. SPE Annu. Tech. Conf. Exhib.* London, U.K.: Society of Petroleum Engineers, 2015, pp. 1–17.

[102] R. Roden, "Seismic interpretation in the age of big data," in *Proc. SEG Tech. Program Expanded Abstr.*, Sep. 2016, pp. 4911–4915.

[103] P. Joshi, R. Thapliyal, A. Chittambakkam, R. Ghosh, S. Bhowmick, and S. Khan, "Big data analytics for micro-seismic monitoring," in *Proc. Offshore Technol. Conf. Asia*, 2018, pp. 1–5.

[104] E. Maidla, W. Maidla, J. Rigg, M. Crumrine, and P. Wolf-Zoellner, "Drilling analysis using big data has been misused and abused," in *Proc. IADC/SPE Drilling Conf. Exhib.*, Richardson, TX, USA: OnePetro, 2018, pp. 1–25.

[105] Q. Yin, J. Yang, B. Zhou, M. Jiang, X. Chen, C. Fu, L. Yan, L. Li, Y. Li, and Z. Liu, "Improve the drilling operations efficiency by the big data mining of real-time logging," in *Proc. SPE/IADC Middle East Drilling Technol. Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2018, pp. 1–12.

[106] J. Johnston and A. Guichard, "New findings in drilling and wells using big data analytics," in *Proc. Offshore Technol. Conf.*, 2015, pp. 1–8.

[107] M. Hutchinson, B. Thornton, P. Theys, and H. Bolt, "Optimizing drilling by simulation and automation with big data," in *Proc. SPE Annu. Tech. Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2018, pp. 1–16.

[108] B. Marr. (2015). *Big Data in Big Oil: The Amazing Ways SHell Uses Analytics to Drive Business Success*. [Online]. Available: https://www.smartdatacollective.com/big-data-big-oil-amazing-ways-shel%l-uses-analytics-drive-business-success/

[109] O. Bello, D. Yang, S. Lazarus, X. S. Wang, and T. Denney, "Next generation downhole big data platform for dynamic data-driven well and reservoir management," in *Proc. SPE Reservoir Characterisation Simulation Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2017, pp. 1–38.

[110] M. R. Brule, "Big data in exploration and production: Real-time adaptive analytics and data-flow architecture," in *Proc. SPE Digital Energy Conf.*, London, U.K.: Society of Petroleum Engineers, 2013, pp. 1–7.

[111] S. A. Haghighat, S. D. Mohaghegh, V. Gholami, A. Shahkarami, and D. A. Moreno, "Using big data and smart field technology for detecting leakage in a CO_2 storage project," in *Proc. SPE Annu. Tech. Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2013, pp. 1–7.

[112] A. S. Popa, E. Grijalva, S. Cassidy, J. Medel, and A. Cover, "Intelligent use of big data for heavy oil reservoir management," in *Proc. SPE Annu. Tech. Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2015, pp. 1–14.

[113] A. Lin, "Principles of big data algorithms and application for unconventional oil and gas resources," in *Proc. SPE Large Scale Comput. Big Data Challenges Reservoir Simulation Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2014, pp. 1–9.

[114] C. Chelmis, J. Zhao, V. S. Sorathia, S. Agarwal, and V. Prasanna, "Semi-automatic, semantic assistance to manual curation of data in smart oil fields," in *Proc. SPE Western Regional Meeting*. London, U.K.: Society of Petroleum Engineers, 2012, pp. 1–18.

[115] E. Udegbe, E. Morgan, and S. Srinivasan, "From face detection to fractured reservoir characterization: Big data analytics for restimulation candidate selection," in *Proc. SPE Annu. Tech. Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2017, pp. 1–20.

[116] J. Xiao and X. Sun, "Big data analytics drive eor projects," in *SPE Offshore Eur. Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2017, pp. 1–9.

[117] E. Martin, P. Wills, D. Hohl, and J. L. Lopez, "Using machine learning to predict production at a peace river thermal eor site," in *Proc. SPE Reservoir Simul. Conf.*, London, U.K.: Society of Petroleum Engineers, 2017, pp. 1–8.

[118] D. Seemann, M. Williamson, and S. Hasan, "Improving resevoir management through big data technologies," in *Proc. SPE Middle East Intell. Energy Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2013, pp. 1–11.

[119] B. T. Rollins, A. Broussard, B. Cummins, A. Smiley, and T. Eason, "Continental production allocation and analysis through big data," in *Proc. 5th Unconventional Resour. Technol. Conf.*, 2017, pp. 2053–2060.

[120] N. Sarapulov and R. Khabibullin, "Application of big data tools for unstructured data analysis to improve esp operation efficiency," in *Proc. SPE Russian Petroleum Technol. Conf.*, London, U.K.: Society of Petroleum Engineers, 2017, pp. 1–11.

[121] S. Gupta, L. Saputelli, and M. Nikolaou, "Big data analytics workflow to safeguard esp operations in real-time," in *Proc. SPE North Amer. Artif. Lift Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2016, pp. 1–14.

[122] T. Palmer and M. Turland, "Proactive rod pump optimization: Leveraging big data to accelerate and improve operations," in *Proc. SPE North Amer. Artif. Lift Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2016, pp. 1–15.

[123] M. Ockree, K. G. Brown, J. Frantz, M. Deasy, and R. John, "Integrating big data analytics into development planning optimization," in *Proc. SPE/AAPG Eastern Regional Meeting*. London, U.K.: Society of Petroleum Engineers, 2018, pp. 1–16.

[124] D. Khvostichenko and S. Makarychev-Mikhailov, "Effect of fracturing chemicals on well productivity: Avoiding pitfalls in big data analysis," in *Proc. SPE Int. Conf. Exhib. Formation Damage Control*. London, U.K.: Society of Petroleum Engineers, 2018, pp. 1–13.

[125] M. von Plate, "Big data analytics for prognostic foresight," in *Proc. SPE Intell. Energy Int. Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2016, pp. 1–6.

[126] A. Anagnostopoulos, "Big data techniques for ship performance study," in *Proc. 28th Int. Ocean Polar Eng. Conf.*, 2018, pp. 887–893.

[127] M. Tarrahi and A. Shadravan, "Advanced big data analytics improves hse management," in *Proc. SPE Bergen One Day Seminar*. London, U.K.: Society of Petroleum Engineers, 2016, pp. 1–7.

[128] M. Tarrahi and A. Shadravan, "Intelligent hse big data analytics platform promotes occupational safety," in *Proc. SPE Annu. Tech. Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2016, pp. 1–21.
[129] C. Pettinger, "Leading indicators, culture and big data: Using your data to eliminate death," in *Proc. Amer. Soc. Saf. Eng. (ASSE) Prof. Develop. Conf. Expo.*, Jun. 2014, pp. 1–8.
[130] L. Cadei, M. Montini, F. Landi, F. Porcelli, V. Michetti, M. Origgi, M. Tonegutti, and S. Duranton, "Big data advanced anlytics to forecast operational upsets in upstream production system," in *Proc. Abu Dhabi Int. Petroleum Exhib. Conf.*, London, U.K.: Society of Petroleum Engineers, 2018, pp. 1–14.
[131] J. Dyche. (2014). *Big Data and Discovery*. [Online]. Available: https://jilldyche.com/home/big-data-and-discovery
[132] L. Duan and Y. Xiong, "Big data analytics and business analytics," *J. Manage. Anal.*, vol. 2, no. 1, pp. 1–21, 2015.
[133] H. Chen, R. H. Chiang, and V. C. Storey, "Business intelligence and analytics: From big data to big impact," *MIS Quart.*, vol. 36, pp. 1165–1188, Dec. 2012.
[134] T. R. Wanasinghe, R. G. Gosine, L. A. James, G. K. I. Mann, O. de Silva, and P. J. Warrian, "The Internet of Things in the oil and gas industry: A systematic review," *IEEE Internet Things J.*, vol. 7, no. 9, pp. 8654–8673, Sep. 2020.
[135] T. Nguyen, R. G. Gosine, and P. Warrian, "A systematic review of big data analytics for oil and gas industry 4.0," *IEEE Access*, vol. 8, pp. 61183–61201, 2020.
[136] K. M. Hanga and Y. Kovalchuk, "Machine learning and multi-agent systems in oil and gas industry applications: A survey," *Comput. Sci. Rev.*, vol. 34, Nov. 2019, Art. no. 100191.
[137] Y. N. Pandey, A. Rastogi, S. Kainkaryam, S. Bhattacharya, and L. Saputelli, *Machine Learning in the Oil and Gas Industry*. Berkeley, CA, USA: Apress, 2020.
[138] M. T. Connolly, "The use of multi rotor remotely operated aerial vehicles (ROAVs) as a method of close visually inspecting (CVI) live and difficult to access assets on offshore platforms," in *Proc. Abu Dhabi Int. Petroleum Exhib. Conf.*, London, U.K.: Society of Petroleum Engineers, 2014.
[139] I. Peerless, A. Serblowski, and B. Mulder, "A robot that removes operators from extreme environments," in *Proc. SPE Annu. Tech. Conf. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2016.
[140] A. Wilson, "Robot removes operators from extreme environments," *J. Petroleum Technol.*, vol. 69, no. 8, pp. 72–74, Aug. 2017.
[141] T. Black, "Report on petrobot application guidelines," Petrobot Project, Jaipur, India, Tech. Rep., 2016, pp. 1–175.
[142] S. Terpstra, "Opening up the oil, gas, and petrochemical markets for robotics," Petrobot Project, Jaipur, India, Tech. Rep., 2016.
[143] R. Brown, "Petrobot tank field trials," Petrobot Project, Jaipur, India, Tech. Rep., 2016.
[144] "Petrobot—Wp3—Field testing of pressure vessel robots," WP3 Members-Dekra, Innospection, GE Inspection Robot., OC Robot., Gassco, Chevron, Quasset, Shell, Petrobot Project, Jaipur, India, Tech. Rep., 2016.
[145] Petrobot. (2016). *Welcome to Petrobot—Petrobot Project*. Accessed: Jan. 16, 2019. [Online]. Available: http://petrobotproject.eu/
[146] IPU Group. (2016). *Atex Zone 0 Classification*. Accessed: Jan. 15, 2019. [Online]. Available: https://www.ipu.co.uk/what-is-atex-directive/atex-zone-0/
[147] "Shell robotics, sensing and process control capabilities," Shell Global Solutions Int., Amsterdam, The Netherlands, Tech. Rep., 2015.
[148] A. Shukla and H. Karki, "Application of robotics in offshore oil and gas industry—A review—Part II," *Robot. Auto. Syst.*, vol. 75, pp. 508–524, Jan. 2016.
[149] F. D. Ledezma, A. Amer, F. Abdellatif, A. Outa, H. Trigui, S. Patel, and R. Binyahib, "A market survey of offshore underwater robotic inspection technologies for the oil and gas industry," in *Proc. SPE Saudi Arabia Sect. Annu. Tech. Symp. Exhib.*, London, U.K.: Society of Petroleum Engineers, 2015, pp. 1–9.
[150] V. Sudevan, A. Shukla, and H. Karki, "Current and future research focus on inspection of vertical structures in oil and gas industry," in *Proc. 18th Int. Conf. Control, Autom. Syst. (ICCAS)*, Oct. 2018, pp. 144–149.
[151] S. Whitfield. (2017). *Case Study: Drone Technology Inspection of Uk North Sea Facility*. Accessed: Aug. 12, 2019. [Online]. Available: https://pubs.spe.org/en/jpt/jpt-article-detail/?art=3632
[152] T. Jacobs, "Data from above: The advantages of unmanned aircraft," *J. Petroleum Technol.*, vol. 65, no. 10, pp. 36–43, Oct. 2013.
[153] H. Sabry, "Optimisation of shutdown inspection activities in the lng industry," in *Proc. Abu Dhabi Int. Petroleum Exhib. Conf.*, 2015, pp. 1–3.
[154] D. English, "Improving asset management at process plants through uav (unmanned aerial vehicle) inspections," in *Proc. Abu Dhabi Int. Petroleum Exhib. Conf.*, 2015, pp. 1–7.
[155] I. Asiodu-Otughwor, O. Akhibi, and U. Aja-Onu, "Deployment of remotely operated aerial vehicles: Managing asset integrity in the 21st century," in *Proc. SPE Nigeria Annu. Int. Conf. Exhib.*, Aug. 2015, pp. 1–10.
[156] R. Caldwell, "Hull inspection techniques and strategy-remote inspection developments," in *Proc. SPE Offshore Eur. Conf. Exhib.*, 2017, pp. 1–11.
[157] R. Brown, T. Bouma, D. Drenth, W. van Hoorn, and E. Sjerve, "Accelerated adoption of disruptive robotic inspection technologies through targeted roadmapping and communities of practice," in *Proc. SPE Offshore Eur. Conf. Exhib.*, 2017, pp. 1–11.
[158] H. Sabry, "Integrity of LNG flare systems," in *Proc. Abu Dhabi Int. Petroleum Exhib. Conf.*, Nov. 2017, pp. 1–13.
[159] V. S. Kumar, "Innovative use of drones improves safety on asset integrity," in *Proc. Abu Dhabi Int. Petroleum Exhib. Conf.*, 2017, pp. 1–6.
[160] B. Hedges, S. Papavinasam, T. Knox, and K. Sprague, "Monitoring and inspection techniques for corrosion in oil and gas production," in *Corrosion*. Dallas, TX, USA: NACE International, 2015.
[161] A. G. Bruzzone, M. Massei, R. Di Matteo, and L. Kutej, "Introducing intelligence and autonomy into industrial robots to address operations into dangerous area," in *Proc. Int. Conf. Modeling Simulation Auto. Systesm*, 2018, pp. 433–444.
[162] M. Faria, I. Maza, and A. Viguria, "Applying frontier cells based exploration and lazy Theta* path planning over single grid-based world representation for autonomous inspection of large 3D structures with an UAS," *J. Intell. Robotic Syst.*, vol. 93, nos. 1–2, pp. 113–133, Feb. 2019.
[163] R. Piancaldini, U. Chiarotti, L. Piedimonte, A. Belloni, J. Kremeyer, M. Thelen, J. Polzer, C. Clees, L. Bancallari, and U. Barbieri, "Dromosplan—An innovative platform of autonomous uavs for monitoring and inspecting infrastructures and industrial sites," in *Proc. Offshore Medit. Conf. Exhib.*, 2019, pp. 1–14.
[164] L. Kridsada, L. Chatchai, C. Manop, and S. Thana, "Sustainability through the use of unmanned aerial vehicle for aerial plant inspection," in *Proc. Offshore Technol. Conf. Asia*, 2016, pp. 1–9.
[165] F. Wen, J. Wolling, K. McSweeney, and H. Gu, "Unmanned aerial vehicles for survey of marine and offshore structures: A classification organization's viewpoint and experience," in *Proc. Offshore Technol. Conf.*, 2018, pp. 1–9.
[166] F. Wen, J. Pray, K. McSweeney, and H. Gu, "Emerging inspection technologies–enabling remote surveys/inspections," in *Proc. Offshore Technol. Conf.*, 2019, pp. 1–16.
[167] J. Lou, A. Hoor, W. Zeng, M. Hull, J. Wei, C. Walton, D. Truch, S. Silva, and B. Broman, "Field implementation of above water riser robotic inspection tools-reducing safety risk while improving efficiency and effectiveness," in *Proc. Offshore Technol. Conf.*, 2019, pp. 1–11.
[168] V. Sudevan, A. Shukla, and H. Karki, "Inspection of vertical structures in oil and gas industry: A review of current scenario and future trends," in *Proc. RDPETRO Res. Develop. Petroleum Conf. Exhib., Abu Dhabi, UAE, 9-10 May*, Jun. 2018, pp. 65–68.
[169] C. Dunn, B. W. Horton, P. White, T. Rothbloom, J. Turley, and C. Chang, "State-of-the-art 3D visualization and data acquisition techniques," in *Proc. SNAME Maritime Conv.*, 2017, pp. 1–19.
[170] T. R. Wanasinghe, R. G. Gosine, O. De Silva, G. K. I. Mann, L. A. James, and P. Warrian, "Unmanned aerial systems for the oil and gas industry: Overview, applications, and challenges," *IEEE Access*, vol. 8, pp. 166980–166997, 2020.
[171] G. Singhal, B. Bansod, and L. Mathew, "Unmanned aerial vehicle classification, applications and challenges: A review," Preprints.org, Basel, Switzerland, Tech. Rep. 2018110601, 2018.
[172] Y. Ham, K. K. Han, J. J. Lin, and M. Golparvar-Fard, "Visual monitoring of civil infrastructure systems via camera-equipped unmanned aerial vehicles (UAVs): A review of related works," *Visualizat. Eng.*, vol. 4, no. 1, pp. 1–8, Dec. 2016.
[173] J. Li, D. Greenwood, and M. Kassem, "Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases," *Autom. Construct.*, vol. 102, pp. 288–307, Jun. 2019.
[174] J. Yli-Huumo, D. Ko, S. Choi, S. Park, and K. Smolander, "Where is current research on blockchain technology?—A systematic review," *PLoS ONE*, vol. 11, no. 10, Oct. 2016, Art. no. e0163477.
[175] F. Casino, T. Dasaklis, and C. Patsakis, "A systematic literature review of blockchain-based applications: Current status, classification and open issues," *Telematics Inform.*, vol. 36, pp. 55–81, Mar. 2018.

[176] M. Andoni, V. Robu, D. Flynn, S. Abram, D. Geach, D. Jenkins, P. McCallum, and A. Peacock, "Blockchain technology in the energy sector: A systematic review of challenges and opportunities," *Renew. Sustain Energy Rev.*, vol. 100, pp. 143–174, Feb. 2019.

[177] S. Seebacher and R. Schüritz, "Blockchain technology as an enabler of service systems: A structured literature review," in *Proc. Int. Conf. Exploring Services Sci.* Cham, Switzerland: Springer, 2017, pp. 12–23.

[178] E. Karafiloski and A. Mishev, "Blockchain solutions for big data challenges: A literature review," in *Proc. IEEE EUROCON 17th Int. Conf. Smart Technol.*, Jul. 2017, pp. 763–768.

[179] W. Meng, E. W. Tischhauser, Q. Wang, Y. Wang, and J. Han, "When intrusion detection meets blockchain technology: A review," *IEEE Access*, vol. 6, pp. 10179–10188, 2018.

[180] D. Mingxiao, M. Xiaofeng, Z. Zhe, W. Xiangwei, and C. Qijun, "A review on consensus algorithm of blockchain," in *Proc. IEEE Int. Conf. Syst., Man, Cybern. (SMC)*, Oct. 2017, pp. 2567–2572.

[181] M. A. Khan and K. Salah, "IoT security: Review, blockchain solutions, and open challenges," *Future Gener. Comput. Syst.*, vol. 82, pp. 395–411, May 2018.

[182] M. Conoscenti, A. Vetro, and J. C. De Martin, "Blockchain for the Internet of Things: A systematic literature review," in *IEEE/ACS 13th Int. Conf. Comput. Syst. Appl. (AICCSA)*, 2016, pp. 1–6.

[183] T. M. Fernández-Caramés and P. Fraga-Lamas, "A review on the use of blockchain for the Internet of Things," *IEEE Access*, vol. 6, pp. 32979–33001, 2018.

[184] T. B. da Silva, E. S. de Morais, L. F. F. de Almeida, R. da Rosa Righi, and A. M. Alberti, "Blockchain and industry 4.0: Overview, convergence, and analysis," in *Blockchain Technology for Industry 4.0*. Amsterdam, The Netherlands: Elsevier, 2020, pp. 27–58.

[185] Y. Hao and P. Helo, "The role of wearable devices in meeting the needs of cloud manufacturing: A case study," *Robot. Comput.-Integr. Manuf.*, vol. 45, pp. 168–179, Jun. 2017.

[186] M. Peruzzini, F. Grandi, and M. Pellicciari, "Exploring the potential of operator 4.0 interface and monitoring," *Comput. Ind. Eng.*, vol. 139, Jan. 2020, Art. no. 105600.

[187] D. Medeiros, L. Teixeira, F. Carvalho, I. Santos, and A. Raposo, "A tablet-based 3D interaction tool for virtual engineering environments," in *Proc. 12th ACM SIGGRAPH Int. Conf. Virtual-Reality Continuum Appl. Ind. (VRCAI)*, 2013, pp. 211–218.

[188] C.-M. Wu, C.-W. Hsu, T.-K. Lee, and S. Smith, "A virtual reality keyboard with realistic haptic feedback in a fully immersive virtual environment," *Virtual Reality*, vol. 21, no. 1, pp. 19–29, Mar. 2017.

[189] C. Camara, P. Peris-Lopez, and J. E. Tapiador, "Security and privacy issues in implantable medical devices: A comprehensive survey," *J. Biomed. Informat.*, vol. 55, pp. 272–289, Jun. 2015.

[190] *Tablets for Hazardous Areas (Android)*, ECOM Instrum. GmbH, USA, 2021.

[191] H. Torvatn, P. Kamsvag, and B. Klove, "Industry 4.0 visions and reality–status in Norway," in *Proc. IFIP Int. Conf. Adv. Prod. Manage. Syst.*, 2019, pp. 347–354.

[192] J. Posada, M. Zorrilla, A. Dominguez, B. Simoes, P. Eisert, D. Stricker, J. Rambach, J. Döllner, and M. Guevara, "Graphics and media technologies for operators in industry 4.0," *IEEE Comput. Graph. Appl.*, vol. 38, no. 5, pp. 119–132, Sep./Oct. 2018.

[193] A. Adadi and M. Berrada, "Peeking inside the black-box: A survey on explainable artificial intelligence (XAI)," *IEEE Access*, vol. 6, pp. 52138–52160, 2018.

[194] R. Guidotti, A. Monreale, S. Ruggieri, F. Turini, F. Giannotti, and D. Pedreschi, "A survey of methods for explaining black box models," *ACM Comput. Surv.*, vol. 51, no. 5, pp. 1–42, Jan. 2019.

[195] D. Kammer, M. Keck, T. Gründer, and R. Groh, "Big data landscapes: Improving the visualization of machine learning-based clustering algorithms," in *Proc. Int. Conf. Adv. Vis. Interface*, May 2018, pp. 1–3.

[196] S. Richardson and D. Mackinnon, "Left to their own devices? Privacy implications of wearable technology in Canadian workplaces," Surveill. Stud. Centre, Queen's Univ., Kingston, ON, Canada, Tech. Rep., 2017.

[197] BBC News. *Privacy Complaint for Fitness Wristband Makers*. Accessed: May 25, 2019. [Online]. Available: https://www.bbc.com/news/technology-37859676

[198] B. Martínez-Pérez, I. de la Torre-Díez, and M. López-Coronado, "Privacy and security in mobile health apps: A review and recommendations," *J. Med. Syst.*, vol. 39, no. 1, pp. 1–8, Jan. 2015.

[199] K. S. Shaw. (2017). *GPS Tracking of Employee Devices : How Much is Too Much*. Accessed: 2019. [Online]. Available: https://onlabor.org/gps-tracking-of-employee-devices-how-much-is-too-m%uch/

[200] *Future of Mining With Wearables: Harnessing the Hype to Improve Safety*, Deloitte, London, U.K., 2019.

[201] M. Chen, T. Zhao, H. Zhang, and S. Luo, "Privacy protecting fitness trackers: An oxymoron or soon to be reality," in *Social Computing and Social Media. User Experience and Behavior*. Cham, Switzerland: Springer, 2018, pp. 3–18.

[202] M. Chibba and A. Cavoukian, "Privacy, consumer trust and big data: Privacy by design and the 3 C'S," in *Proc. ITU Kaleidoscope, Trust Inf. Soc.*, Geneva, Switzerland: International Telecommunication Union, 2016, pp. 1–5.

[203] J. Srinivas, A. K. Das, and N. Kumar, "Government regulations in cyber security: Framework, standards and recommendations," *Future Gener. Comput. Syst.*, vol. 92, pp. 178–188, Mar. 2019.

[204] European Union. *Adequacy Decisions*. Accessed: May 25, 2021. [Online]. Available: https://ec.europa.eu/info/law/law-topic/data-protection/international-%dimension-data-protection/adequacy-decisions_en

[205] I. R. Sanchez, *GDPR and Canadian Organizations: Addressing Key Challenges*. London, U.K.: Deloitte, 2018.

[206] A. Mittal, A. Slaughter, and P. Zonneveld, "Protecting the connected barrels—Cybersecurity for upstream oil and gas," Deloitte Develop. LLC, London, U.K., Tech. Rep., 2017.

[207] A. K. Bhardwaj and M. Singh, "Data mining-based integrated network traffic visualization framework for threat detection," *Neural Comput. Appl.*, vol. 26, no. 1, pp. 117–130, Aug. 2014.

[208] N. Rastogi, M. J. K. Gloria, and J. Hendler, "Security and privacy of performing data analytics in the cloud: A three-way handshake of technology, policy, and management," *J. Inf. Policy*, vol. 5, pp. 129–154, Mar. 2015.

[209] L. Zhang, A. Stoffel, M. Behrisch, S. Mittelstadt, T. Schreck, R. Pompl, S. Weber, H. Last, and D. Keim, "Visual analytics for the big data era—A comparative review of state-of-the-art commercial systems," in *Proc. IEEE Conf. Vis. Anal. Sci. Technol. (VAST)*, Oct. 2012, pp. 173–182.

[210] A. Harati, S. Lopez, I. Obeid, J. Picone, M. Jacobson, and S. Tobochnik, "The TUH EEG CORPUS: A big data resource for automated eeg interpretation," in *Proc. IEEE Signal Process. Med. Biol. Symp. (SPMB)*, Dec. 2014, pp. 1–5.

[211] A. Thusoo, J. S. Sarma, N. Jain, Z. Shao, P. Chakka, S. Anthony, H. Liu, P. Wyckoff, and R. Murthy, "Hive: A warehousing solution over a map-reduce framework," *VLDB Endowment*, vol. 2, no. 2, pp. 1626–1629, 2009.

[212] M. Beckmann, N. Ebecken, M. Beckmann, and F. Nelson, *A User Interface for Big Data With RapidMiner*. Boston, MA, USA: RapidMiner, 2014.

[213] B. Furht and F. Villanustre, *Big Data Technologies and Applications*. Cham, Switzerland: Springer, 2016.

[214] M. Anderson, D. Pilon, R. Pack, S. McCorriston, K. Blanchard, J. Fauth, K. Hood, A. Ohrt, D. Jesen, and J. Morin, "Code for electrical installations at oil and gas facilities," SackPower, Regina, SK, Canada, Tech. Rep. 4, 2015.

[215] HSE. (2004). *Hazardous Area Classification and Control of Ignition Sources*. Accessed: Mar. 1, 2020. [Online]. Available: https://www.hse.gov.uk/comah/sragtech/techmeasareaclas.htm

[216] "Guide to explosive atmospheres & hazardous locations," Intertek, London, U.K., Tech. Rep., 2012.

[217] A. Nelson and M. Konopczynski, "Challenges in implementing the digital oil field a real-world look at data retrieval, storage and efficient utilization," in *Proc. Offshore Medit. Conf. Exhib.*, 2019, pp. 1–13.

[218] T. P. Ventulett and L. M. Villegas, "Enabling the best by preparing for the worst: Lessons from disaster response for industrial iot in oil and gas," in *Proc. Abu Dhabi Int. Petroleum Exhib. Conf.*, London, U.K.: Society of Petroleum Engineers, 2018, pp. 1–21.

[219] R. R. Hillis, D. Giles, S. E. van der Wielen, A. Baensch, J. S. Cleverley, A. Fabris, S. W. Halley, B. D. Harris, S. M. Hill, P. A. Kanck, A. Kepic, S. P. Soe, G. Stewart, and Y. Uvarova, *Building Exploration Capability for 21st Century*, vol. 18. Littleton, CO, USA: Society of Economic Geologists, 2014, ch. 12: Coiled Tubing Drilling and Real-Time Sensing-Enabling Prospecting Drilling in the 21st Century, pp. 243–259.

[220] W. Gharibi, M. Aalsalem, W. Z. Khan, N. Armi, and W. Ghribi, "Monitoring gas and oil fields with reliable wireless sensing and Internet of Things," in *Proc. Int. Conf. Radar, Antenna, Microw., Electron., Telecommun. (ICRAMET)*, Oct. 2017, pp. 188–191.

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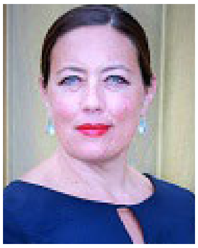

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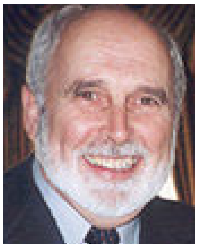

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