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IoT-Based Water Management Systems: Survey and Future Research Direction

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IoT-Based Water Management Systems: Survey and Future Research Direction

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ABSTRACT The Internet of Things (IoT) sustainable solutions are the next generation of methods for managing and monitoring valuable natural resources such as water. Research has focused on smart IoT-based water management and monitoring system designs for various types of applications, including agricultural, industrial, residential, and crude oil exploration sectors. To this end, unlike other surveys available in the literature, this work presents an all-encompassing analysis of 43 papers published between 2014 and 2022 for systems proposed to manage and monitor water in four different sectors: agricultural, industrial, residential, and oilfield sectors. In this work, we also propose a new optical water management system to address a gap in the literature, particularly for oilfield processes that require significant amounts of water to stimulate oil production. The proposed system employs an advanced optical technique for sensing and transmitting collected data. Overall, this work provides a seminal guide for future research efforts focused on integrating IoT in the field of water management and monitoring.

INDEX TERMS Water monitoring, water management, Internet of Things, residential, industrial, agricultural, oilfield scale.

I. INTRODUCTION

The vision of interrelated, internet-connected devices that collect and transfer data over a communication network without human intervention is the communications frontier of the next few decades. The technology is better known as the Internet of Things (IoT) and is considered a revolutionary paradigm shift that has the potential of substantially enabling a universe of everyday physical devices to be digitally connected. The technology collects information through wireless sensors that are self-configured into a network. This network conveys sensor measurements via a communication system to the cloud for processing and analysis as depicted in Fig. 1 [1], which includes the following key components:

- Sensors, actuators, and smart meter devices that are used for data collection of physical and chemical parameters such as pH, temperature, turbidity, and conductivity.
- Communication technology that is utilized for connecting the overall elements of the system such as ZigBee, LoWPAN, Bluetooth, and WiFi.

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- IoT cloud for data storage, processing, and analysis using emerging technologies such as Big Data, Edge Computing, Machine Learning (ML), and Artificial Intelligence (AI).
- Power sources such as chargeable/rechargeable batteries that could be equipped with energy harvesting components.

Various systems have been proposed for water management and monitoring to serve different sectors. Some of the proposed systems aimed at reducing the amount of wastewater, improving the efficiency of the water distribution systems [2], and predicting as well as alerting the community of any serious environmental issues related to water [3], which is part of the road-map for creating future sustainable IoT solutions. This impetus is driven by many reasons, one of which is the estimated amount of water lost each year, when considering the urban supply systems in the developing world [4] which could reach 32 billion cubic feet. Clearly this water waste contributes to energy waste, and, in turn, to global warming. This motivated transforming urban planning in 45 percent of cities and communities around the world to
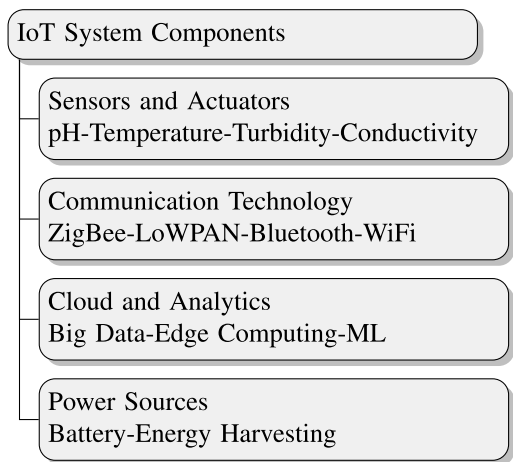
FIGURE 1. Key IoT system components.

adopt new IoT-enabled water resource monitoring and management solutions by 2024 as it is stated by the International Data Corporation (IDC) [5].

A. RELATED WORK

Many surveys in the literature describe the growing portfolio of water monitoring and management systems using IoT solutions. The authors of [6]–[8] reviewed the development of existing IoT systems for water management and quality control, including system components, communication technologies, and techniques. The authors in [9] discussed IoT applications for wastewater management and treatment in addition to the effects of human activities and their environmental impacts on the quantity and quality of water. On the other hand, the authors in [10] focused on water quality measurement (including pH, turbidity, temperature, and total dissolved solids (TDS)) and distribution based on IoT systems. In the context of domestic applications, the authors of [11] presented a review on IoT-based solutions targeting water quality monitoring, and outlined the required water-quality monitoring parameters to determine the safe-level of drinking water. Surveys similar to [12] focused only on management systems targeting water resources such as rivers and aquifers using LoRaWAN communication technology. Solutions proposed for irrigation applications were reviewed in [13], [14] by considering the parameters typically monitored in such applications such as water quantity and quality, soil characteristics, weather conditions, and fertilizer usage. Papers [15], [16] are comprehensive surveys that discussed the emerging technologies which support smart water management solutions for precision agriculture such as ML and AI, fog or edge computing, Software Defined Networks, Big Data, and Nanotechnology. A broader review of literature was conducted in [17] by outlining the research work done in smart water management systems as implemented in urban contexts (i.e., residential and industrial), emphasizing on supply and distribution networks. Also, in [2], the authors reviewed wireless communication technologies such as cellular networks,

ZigBee, LoWPAN, Bluetooth, and WiFi when employed in water distribution systems to implement a smart water grid.

The focus of the preceding surveys fall into two broad categories for IoT-based water management systems (IWMS): residential and agricultural; however, to the best of the authors' knowledge, there has been no comprehensive survey on IWMS based on applications related to agricultural, industrial, residential, and the oilfield. Thus, a principal contribution of this survey is classifying the main IWMS research directions into three major categories: agricultural, residential, and industrial. This survey also sheds light on the lack of available solutions for the oil industry based on the compiled data, especially solutions that help monitor and manage produced water for oilfield processes, such as hydraulic fracturing that injects water coupled with additional materials at high pressure to stimulate oil production. As such, building upon key research findings such as the recent advancements in optical multispectral sensors and optical communication systems, the potential for the use of optical IWMS in oilfields is explored in this paper. Therefore, the second contribution of this work is the proposing of a new IWMS system by application of recent advanced optical techniques in the fields of optical sensors and optical communications systems. It is noteworthy to mention that, the adopted selection criteria for paper collection that resulted in this survey paper is as illustrated in Fig. 2. The strategy of selecting articles included: a search using the keywords and mentioned repositories outlined in Fig. 2. Then, the latest articles from top journals and conferences were filtered based on the conditions that are detailed in the selection criteria section of Fig. 2, afterwards the selected articles were reviewed.

The remainder contents in this work is structured as follows: section II categorizes recent work published in this field into agricultural, industrial, and residential applications. section III discusses open issues by reviewing the literature presented in section II, and the section closes by presenting the proposed optical IWMS for use in oilfields and discussing the different aspects of system architecture, such as sensor technology, sensor deployment, and sensor packaging. section IV concludes the paper.

II. IWMS CLASSIFICATION

The overall system architecture for water resource monitoring and management for the different agricultural, industrial, and residential applications involves deploying different sensor types connected to the IoT cloud using Wireless Sensor Networks (WSN) as shown in Fig. 3. Indeed, IoT-based systems can be practically utilized and efficiently customized according to the application requirements such as performance, cost, reliability, and flexibility. For instance, the sensor types in use for residential applications are different from the sensors used in industrial applications and also different from the used in agricultural applications.

An efficient IWMS requires many sensors to be distributed throughout the water resources or reservoirs at each designated site to measure the desired physical and chemical

Searching Keywords: 'Water management' OR 'IoT' OR 'Water Monitoring' OR 'Smart Water System'

Search Repositories: IEEE Xplore, Google Scholar, Elsevier, ACM, ProQuest

Journals & Conferences
(between 2014 & 2022)

Technical papers
(between 2014 & 2022)

Surveys
(between 2018 & 2021)

Selection Criteria:

- The surveys
  - -- published recently.
  - -- reviewed WMS using IoT solutions.
  - -- covered all application domains.
- Technical papers
  - -- considered IoT-based WMS.
  - -- included system architecture.
  - -- covered certain application domain.

Resultant Paper:

- Review of existing survey papers (2018-2021).
- Review of existing technical papers (2014-2022).
- Classification of IWMS based on application domain.
- Identifying technical papers employing advanced technologies.
- future direction towards a proposed solution for oilfield scale.

FIGURE 2. Paper collection criteria flowchart.
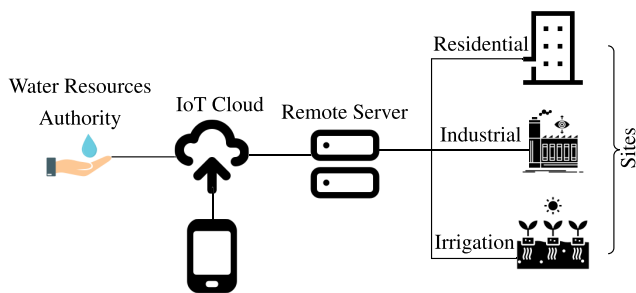
FIGURE 3. Illustration of an IoT-based water management system.

parameters of the water, such as water level and flow rate, temperature, pH, turbidity, conductivity, dissolved oxygen, water salinity, and ions concentration [18]. The IWMS then transmits the collected data from these installed sensors and stores them on the cloud for further processing and analysis. Smart water meters are also installed to monitor and record consumers usage. These meters upload the water consumption readings automatically and periodically,

or inquiry-based, to the IoT cloud and on to the applicable water centralized repository responsible for managing water data. A mobile APP or web dashboard, is usually implemented as part of such a system to interface with end-users. End users will be able to view water information related to their sites, create water accounts, and get billing information, among other functionalities. Each of the reviewed systems targets at least one of the following goals based on the current survey:

- Remote water resources monitoring and management.
- Infrastructure and equipment conditions monitoring to predict any upcoming failures, leakage, tampering, or maintenance needs.
- Predicting serious environmental issues related to water management and water quality through physical and chemical characteristic measurements and analysis.
- Monitoring consumed quantities for each resource and ensuring fair distribution by examining usage purpose.
- Using collected data for decision-making, water allocation, and billing services.

This review examines many references and categorizes them into agricultural, industrial, and residential applications, which have been proposed in the development of smart real-time IWMS. We discuss the appropriateness of system architectures, examining employed wireless communication and sensor technologies.

A. AGRICULTURAL (IRRIGATION)

Approximately 85% of the global freshwater resources are consumed for irrigation use [19], more than 60% of which is wasted, as reported by the Food and Agriculture Organization of the United Nations [20], [21]. The rise in IoT technologies has stimulated interest among researchers, who have proposed using advanced IWMS instead of manually operated systems to achieve better water resource utilization. This advancement was discussed in [13], which provided a comprehensive survey of the published IWMS solutions between 2014 and 2019. The systems were categorized according to the first author's origin, water distribution method, sensor utilization, and water amount estimation. The work in [13] revealed that India has the highest interest in developing IWMS. This country's interest in developing a low-cost and efficient IWMS has significantly increased over the past few years. For instance, in [22], a low cost system was proposed to monitor irrigation for Indian farmers. In [23], the authors presented a simple precision agriculture system for greenhouse monitoring connected through a web-based application. Another automated precision agriculture monitoring system was presented in [24], but considered a different application that is monitoring the process of crop fertilization. In [25], they also proposed a remote automated irrigation system, which provides notifications via mobile SMS using fog and IoT cloud technologies. A mathematical model to predict water amounts needed for irrigation was proposed in [26], in addition to, a real-time monitoring of agricultural parameters including water. For more reliable and intelligible operation, the authors in [27] demonstrated a simple and low-cost IoT control system with multiple control capabilities. The proposed system in [27] comprises three different controllers: electro-pumps, water reservoirs, and pump stations in conjunction with restricted user access for security purposes. Another perspective was offered in [28] and [29], which proposed the integration of Blockchain with constrained IoT devices to measure water consumption. The authors of [28] indicated that the increase in power consumption due to the integration of the proposed Blockchain architecture required additional 6% of energy as compared to classical systems that operate without the Blockchain inclusion; however such a system provides trusted sensing devices over public Blockchain networks. A smart irrigation system was proposed in [30] to be suitable for drip, sprinkler, surface, and lateral irrigation models.

B. RESIDENTIAL (DOMESTIC)

IoT-based advanced techniques have been adopted in real-time for residential IWMS applications to monitor water quality and residential water consumption [31]. Measuring the water level at water tanks has been a major research focus as it allows for the development of sustainable and controlled residential water systems [32]–[40]. The authors in [32] proposed a system that continuously monitors the water level to control the flow into the tank by switching a motor on or off according to the level and storing the collected data in the cloud, which homeowners can access using an Android application. The work in [33] reported another tank sensor system installed and tested on a university campus to generate data reports, which can be later accessed by end-users via the web or sent by SMS or email alerts. A system that operates on a larger scale, such as for a village or urban area, was proposed in [37], [40]. The main goal of this system is to control water distribution and storage so that water pumping and distribution can be automated wirelessly and effectively to minimize losses. The use of a laser sensor to continuously monitor the water level in a tank was proposed in [41] to simplify the design of a real-time IWMS, where the controller automatically turned a water pump on or off to maintain a certain level. Another method to measure the water consumption and feed data to a central unit for further analysis was discussed in [34], [35] where the end-users could access the generated reports through a web visualization in addition to SMS or email alert systems. These methods rely on the amount of water flow in the supply pipes, which are distributed through the community, where a network of water flow sensors is installed and connected to a controller that feeds data to a central node.

Developing smart water quality monitoring systems to eliminate the need and cost of water analysis in a laboratory is another current significant research focus. The authors in [42] discussed a pilot project that implements a smart water grid management system in a village near the Bay of Bengal. The project deployed different sensors, generating real-time data, at various strategically chosen locations to measure water quality. These sensors were then connected to a microcontroller in a long-range (LoRa) module that communicates with the cloud through a LoRa gateway. The system notifies the authorities through email, SMS, and a web interface accessible to the end-user if there is a decline in water quality below acceptable measures. It is also capable of switching off the water flow to the village promptly. Another advanced smart automated water purification system was proposed in [38] that first measured the water's turbidity level, and when it reached an alarming threshold level, it triggered the water purifying process.

Systems that can jointly monitor water quantity and quality were proposed in [36], [39]. The authors of [36] proposed a system that utilized ultrasonic water level and water turbidity sensors operating via a Raspberry Pi, directly connected to the IoT cloud. This system also has a user-friendly web-based monitoring and controlling smartphone application that allows residents to easily monitor and control their water system remotely. The proposed system in [39] combined water quality sensors such as pH and temperature, turbidity,

water distribution sensors such as ultrasonic water level and flow, and microcontrollers through an IoT system, providing residents with the ability to control the incoming water quality level via an installed home-based water filter.

A different approach that classifies the water level into three categories, Safe, Not Safe, and Danger, was proposed in [43]. The purpose of this classification was to help the end-user identify a threat in case of a potentially catastrophic flood situation by collecting the data via WiFi, and then storing the collected data in the cloud for water data analytics, which becomes accessible to end-users through the web. The authors in [44] proposed a smart water system for managing rain water to be stored or to be further processed so that it can be used for other purposes. In [45], the authors proposed a smart water management project which connects sensor modules to a system running the LabVIEW software that is capable of sending the data to the IoT cloud. The proposed project used trusted IoT cloud services such as Amazon's Web Services or Microsoft's AZURE for statistical analysis and control purposes the whole system. In [46], the authors proposed a framework to monitor water consumption based on number of consumers in the house. In [47], the authors proposed a framework for real-time water monitoring with the integration of a ML model for water consumption pattern prediction. The system is interfaced with an Android mobile APP to display real-time data for end-users. In [48], the authors presented a household scenario for a smart IoT-based water management system to limit the over usage of water.

C. INDUSTRIAL

Industrial facilities are one of the primary water pollution sources; however, monitoring and controlling water quality using IWMS for large-scale applications is a challenging task. These applications require complex IoT systems with many different sensor types and the vast amounts of collected data require efficient monitoring and managing algorithms [49]. The authors in [50] targeted large-scale industrial wastewater monitoring by proposing a WSN that interconnects various sensors, such as turbidity, density, temperature, and pH, by using IoT for long-term real-time monitoring and water quality reporting. A prototype created to minimize water contamination due to industrial activities was proposed in [51]. The system involves pH, conductivity, temperature, and turbidity sensors that are interconnected using Zigbee and WiFi modules controlled through the IoT. The IWMS of [52] was designed for water quality monitoring of surface waters such as rivers, lakes, transitional or coastal waters, and artificial or substantially modified water bodies.

Another industrial application, that motivated considerable research efforts, involves the need to develop efficient water distribution systems (WDSs) [53]. For example, an efficient WDS should detect any leakage in the water supply system similar to what proposed in [54]. The authors of [54] employed an intelligent STUF-280T water meter based on a low-cost ultrasonic flow measurement technology that reads

water flow. The water meter then transmits data to the cloud using RESTful-based web services.

An efficient WDS should also reduce water contamination by monitoring quality over the entire distribution system [55]. In this regard, an advanced ML algorithm was proposed in [56] as a later stage in an IoT-based smart water quality monitoring system that consists of four sensors: pH, temperature, conductivity, and turbidity, which would enable water quality predictions for large-scale applications. In addition to reducing water contamination, WDSs must also optimize water supply and consumption. This has been tackled in the work presented in [57], which aimed at developing a meticulous water management system at the city level. In [57], the authors used a wireless IoT-enabled meters to propose a system that sends data to the cloud, then to a centralized control room for real-time monitoring. The system of [57] also integrated an IoT-enabled mobile-friendly web portal for accessing various water usage statistics along with the ability to pay water bills online. The work of [58] discussed the different available sensors that can be deployed using WSN in large-scale facilities; such as big organizations and communities, to monitor water availability based on the level in the storage system. The authors of [59] employed capacitive level and water flow sensors to develop a simple, low-cost IoT system for water level detection. In [60], the authors targeted monitoring water quality in water bodies through proposing a low-cost real-time system with the integration of deep learning model for prediction for water suitability for human consumption. In [61], the authors proposed a model for optimized water distribution in smart cities with the integration of ML for prediction and data analysis. In [62], a simple monitoring system for water usage was proposed that is integrated with a mobile APP to target isolated areas.

III. OPEN ISSUES AND FUTURE RESEARCH DIRECTION

IWMS research efforts focus on agricultural, industrial, and residential applications, as discussed in section II. Research activities in oil field applications are still limited to developing groundwater monitoring systems that aim to determine the effects of oil and gas production on groundwater quality using surrogate multiparameter probes [63]; however, IWMS can also assist with the prediction and guided prevention of oilfield scale in applications such as hydraulic fracturing. Hydraulic fracturing, or fracking, involves the use of high salinity, high temperature, and high pressure water containing 240,000+ ppm TDS, that have the potential to form mineral scale, which in turn represents a serious problem that accounts for most maintenance issues. Scale is so problematic that it can lead to total production loss caused by flow conduit choking [64]. Costs related to scale deposition were estimated at approximately $800 million in the United Kingdom, $9 billion in the USA, and $3 billion in Japan, compared to $2.5 trillion globally. The classic discrete water scale monitoring method involves water quality sample collection and laboratory analysis, which is impractical [65] since sample collection should be as close to the production site as possible
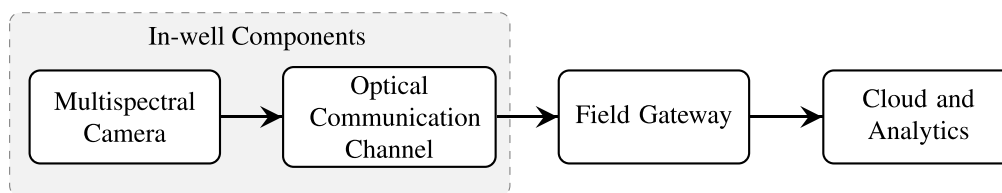
FIGURE 4. Block diagram of the proposed in-well IWMS infrastructure.

and procured from different parts of the well. This sample collection and analysis is impractical for at least two reasons: (1) scale formation may occur in inaccessible parts of the well, such as the internal pipeline surface, underground pumps, and different parts of system equipment [66], and (2) the collected samples could be mixed or physically or chemically altered during transportation. These limitations have many implications, motivating the need to develop advanced real-time IWMS techniques for predicting and preventing oilfield scale. This technology can be beneficial in obtaining information, valuable for making business decisions, while a real-time history record can assist in monitoring changes in key physical reservoir parameters [67].

A. PROPOSED SYSTEM INFRASTRUCTURE

An extrinsic optical IWMS solution is proposed based on advanced optical sensing and transmission techniques, as it is presented in the block diagram of Fig. 4. The proposed in-well IWMS infrastructure consists of advanced optical cameras that employ efficient multispectral imaging technology. These cameras are connected through optical data transmission systems to the field gateway (i.e., ground base station), which, in turn, receives the water characteristics collected from the underground to be communicated through the IoT cloud for further analysis and investigation. The cameras as well as the communication lines are installed inside a ruggedized carrier as shown in Fig. 5 to protect the system from the expected harsh conditions. This solution can assist in providing the crucial flexibility and the adaptability needed for permanent in-well deployment solutions.

1) ADVANCED OPTICAL SENSORS

Various sensors have been used in IWMSs for water quantity and quality measurements as it is outlined in table 1. These sensors can be categorized into four types: physical sensors, chemical sensors, optical sensors, and biosensors [68]. Optical sensors are the only viable solution that allow for real-time measurements without the need for chemical reagents. These sensors are highly accurate, yielding values that are typically within 3–5% of laboratory data. Optical sensors are used to measure water quality parameters such as dissolved oxygen, pH, turbidity, bacteria, hydrocarbons, and nitrates; however, the only optical sensor type, which decompose the spectral absorption properties of the sensed material such that the characteristics of interest can be estimated, are the optical nitrate and multispectral sensors. The operational principle of the former is basic since it measures the absorbed nitrate
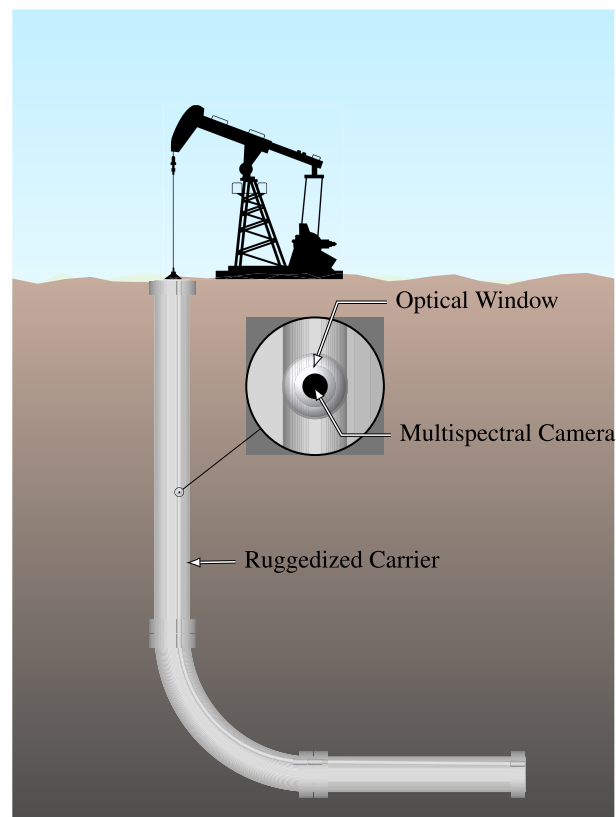
FIGURE 5. Illustration of the proposed in-well IWMS infrastructure.

ultraviolet (UV) light using a photometer, then the measured spectral absorption used to determine the nitrate concentration. The latter technique (;i.e., multispectral sensors) employs advanced methods in multispectral imaging to analyze material compositions due to their advantages in terms of efficiency and accuracy; however, the currently proposed systems utilize expensive multispectral imaging cameras, such as those used by the authors of [69].

Sensors based on multispectral images have not yet been investigated in the context of IWMSs for oilfield applications, to the best of this authors' knowledge [69]. Multispectral imaging research, where different images are used to capture material data within individual spectral bands, has been a significant focus of academic and industrial interest since 1970 due to the concept of 'spectral fingerprint' of each material. The collected data are analyzed to acquire specific chemical characteristics. Multispectral imaging is an efficient technique for sensing material composition in a non-invasive way; however, its deployment has been limited due to the

TABLE 1. List of presented smart IWMS and their associated system components.

Application	Year	Ref	Sensors	Wireless System	Remarks
Agriculture	2014	[23]	temperature, humidity and moisture sensors	GSM	Precision irrigation
	2017	[22]	Soil moisture, pH, and temperature sensor	GSM	Automated irrigation
	2018	[27]	Temperature and electrical conductivity sensors	ZigBee/LoRaWAN	Precision agriculture
	2018	[24]	Soil humidity , temperature, and moisture sensors	N/A	Precision agriculture and fertilization monitoring
	2019	[87]	Water level, soil moisture, temperature, humidity, and rain sensors	LoRa	Water consumption optimization
	2019	[88]	Drones, multiparametric sensor	LoRaWAN	Precision irrigation
	2020	[89]	Flow sensor	GSM	Saving water and cost
	2021	[28]	Flow sensor	LoRaWAN	Blockchain integration
	2021	[90]	Ultrasonic sensor	LoRaWAN	Rain water harvesting management for irrigation purposes
	2021	[30]	Soil moisture, temperature, and level sensors	2G or 3G	Suitable for drip, sprinkler , surface , and lateral move irrigation models
	2021	[29]	Soil humidity , water level, and temperature sensors	RFID and WiFi	Blockchain integration
	2022	[26]	soil sensor and weather station	LoRa, WiFi, and ZigBee	real-time monitoring and control of water irrigation
	2022	[25]	Moisture, level, temperature, and humidity sensors	GSM / GPRS	Low-cost intelligent irrigation
Residential	2015	[43]	Ultrasonic, water level sensors	WiFi	Introduction of three water levels indicators (Safe,Not Safe, and Danger)
	2016	[33]	Water level sensor	WiFi	Predictive analysis to detect water consumption and leakage in smart homes
	2017	[42]	ORP, pH, salinity, level, turbidity, temperature, and flow sensors	LoRa	Control water flow in a timely manner and measure water quality in rural areas
	2017	[31]	Sensors and Remote Telemetry Units (RTU)	WSN	Water distribution and leak detection
	2016	[32]	Water level sensor	WiFi	Managing water usage
	2017	[35]	Water flow sensor	GSM	Monitoring water use
	2017	[37]	Pressure sensor, ultrasonic sensor, and flow meter	WiFi	Groundwater resource management
	2018	[36]	Water level sensor and turbidity sensor	WiFi	Focus on Software Engineering Design
	2018	[41]	Laser sensor	WiFi	Managing and planning water usage
	2018	[38]	Turbidity sensor	WiFi	Low-cost water quality
	2019	[34]	Water Flow sensor	WSN	Improving the Quality of Service (QoS) of water services, consumer satisfaction
	2020	[39]	Ultrasonic water level, flow, pH, temperature, and turbidity sensors	WiFi	Monitoring water quality
	2020	[40]	Water flow sensor	WiFi	Water consumption monitoring and leakage detection
	2021	[44]	Ultrasonic water level	N/A	Rain water utilization
	2021	[45]	Pressure, temperature, turbidity, conductivity, flow, pH, and soil moisture	N/A	Water conservation and water quality analysis
	2021	[46]	Proximity sensor	N/A	Monitoring water consumption based on number of persons in house
	2021	[47]	Water level, vibration, and temperature sensor	GPRS	ML integration to predict water consumption
	2021	[48]	Water flow and level sensors	LoRaWAN	Household scenario.
Industrial	2015	[53]	Strain, temperature, pressure, flow, and corrosion sensors	WiFi/GSM	Optimizing water supply and consumption
	2017	[91]	Water valve	WiFi	Water distribution system
	2017	[63]	PH, electrical conductivity, TDS, oxidation reduction potential (ORP), and dissolved oxygen (DO) sensors	GPRS	Monitoring groundwater quality
	2018	[92]	Water flow meter, ultrasonic sensor	WiFi	Measuring water flow in pipes and water level in reservoirs
	2019	[93]	Pressure sensor, pulse sensor	LoRa	Smart measuring system
	2020	[94]	Water flow sensor	WiFi	Smart water metering
	2020	[95]	Water flow sensor	WiFi	Extension to [94]
	2020	[59]	Capacitive level sensor, temperature sensor flow meter	WiFi	Management of water usage and temperature for cooling
	2020	[96]	Temperature, leakage, and pressure sensors	WiFi	Focusing on Software solution (SCADA control system)
	2020	[60]	pH, humidity, temperature, CO_2 sensors	WiFi	IoT cloud for data storage, deep learning for water quality prediction
	2021	[61]	Ultrasonic, flow, and rain sensors	WiFi	Smart city water distribution
	2021	[62]	Ultrasonic and flow sensors	WiFi	Water consumption recording with mobile APP

size and cost of the multispectral cameras. A research group at the Nanophotonics Research Group in the Harvard John A has recently implemented a novel multispectral camera prototype that utilizes nanowire sensors, creating a cheap multispectral camera that is similar in size to conventional digital cameras, such as those in portable mobile phones [69]. We propose using such multispectral cameras to sense the chemical properties of the water inside the well as part of a promising IWMS setup.

This sensing technique would provide the crucial adaptable functionality needed for acquiring data from underground wells and pores within a harsh environment. Another significant advantage of multispectral remote sensing is that the extracted collected spectrophotometry information can be improved as ML and image processing techniques advance [70], potentially eliminating the need for the implementation of various sensor types to attain the different physical and chemical water properties of interest [71].

Employing in-the-well multispectral remote sensing can be helpful in scale prediction and guided prevention since scale deposition in an oilfield is formed when incompatible types of water, specifically injection and formation water, are mixed under specific thermodynamic conditions [72]. The type and severity of the scale formed depends on the metal ions present and their concentrations in both the injection and formation water in addition to other factors, such as contaminants from corrosion products. Using multispectral imaging to measure water characteristics such as pH, conductivity, water flow, metal ions concentration, water salinity, and TDS in conjunction with proper ML methods may predict scale formation. The collected data is necessary for efficiently training ML algorithms that will accurately predict the amounts and types of scale formed and how soon flow conduit choking may occur. The data can also be used to train ML algorithms to detect early flow influx, which will improve well-control safety, and to measure the drilling fluid's rheological properties, which is essential for proper hydraulic management and the development of an automated kick detection system, resulting in safer and more efficient operations [73]–[75]. The collected data can also help monitor wellhead pressure to prevent screen out, optimize fluid and proppant amounts, and reduce cost [76]. Wellhead pressure monitoring is part of a drilling risk evaluation, essential for risk assessment and response. One of the risks that must be monitored is oil leakage, the biggest threat to drilling operations [77]. Oil leakage causes damage to drilling tools, high drilling fluid consumption, hole pressure imbalance, and can lead to well wall collapse; therefore, it is vital to acquire real-time drilling data, which can be analyzed to estimate the risk so that problems can be detected early, and catastrophic accidents can be avoided. The data can also be used to build an intelligent system as a replacement for the standard torque and drag modeling programs, which will provide a reliable continuous surface drilling profile that is essential for early operational problem detection.

2) DATA TRANSMISSION TECHNIQUES

The harsh environment, the need to acquire data from underground wells, the elevated pressures and temperatures, and the corrosive media in the downhole pipes makes data collection and transformation using wireless communications techniques, [27] such as Bluetooth [6] WiFi [41] LoRa/LoWPAN [42] GSM [53] and GPRS [31] impractical. Implying that the only feasible solution for data transmission that can withstand the heat, pressure, moisture, corrosion, and vibration expected is optical communication technology: either wireless or wired techniques such as wired optical fiber or directed laser light. Wireless laser-based photonic systems have not yet been considered for oilfield applications, although free-space visible laser light communication (VLLC) technology is promising for compact and high-speed wireless communication links. These systems are ideal alternatives for in-well ultra-fast wireless data links as compared to conventional techniques. It is noteworthy to mention that VLLC technology has also been considered for underwater wireless optical communications (UWOC) for many important applications [78].

3) ARCHITECTURAL DESIGN

The optical transceiver and sensors must be protected by a compact and ruggedized carrier that can fit within the annular spaces of the well, either between the casing and the wellbore or the production tubing and casing, this concept is presented in Fig. 5 and is similar to the optic gyroscope system of [79].

The entire system; i.e, the sensors and the transceiver, all packed into the ruggedized carrier, can be preassembled at a factory before in-well installation. Another possible alternative would be to install the carrier during drilling operations since the remote sensing parts, including the transceivers and the sensors, can be installed by utilizing an underground in-pipe robot. The robot would need to be lightweight, mobile, suitable for the diameter of the in-line pipeline, suitable for a long-distance pipeline, and high temperature and pressure resistant. Robots are efficient and used in many similar applications [80]–[84]: and the design of a small mobile robot for underground applications and robotic crawlers, which can go through various small diameter piping sections such as U-bends, have been discussed in [81], [82].

Optical windows should be integrated within the ruggedized carrier so that the light signal can penetrate the carrier to the desired sensed liquid. The optical window should also have high optical performance to avoid affecting the utilized multispectral camera. The optical sensor should be protected from harsh conditions, such as high pressure, high temperature, corrosivity, and vibration, so it can operate without damaging the sensing elements that must be protected with a robust sensor capsule. It is noteworthy also to mention that suitable capsules have been designed using 316L Stainless Steel due to its resistance to oxidation and anti-corrosion properties, along with its ability to withstand high pressure up to 15,000 psi and temperatures up to 150°C [85], [86].

IV. CONCLUSION

This work presents a comprehensive review of a wide range of research work for proposed and designed IoT-based water management systems. It describes a general architecture of smart water monitoring systems, followed by a breakdown of the different applications associated with IoT-based water management systems by classifying those systems into residential, industrial, and agricultural. This work surveys state-of-the-art research proposed for IoT-based water management systems design as it applies to each application. This discussion concludes by introducing a novel optical IoT-based water management system designed for use in oilfields via exploring possible solutions and discussing what could be practically achievable for each element of the system. This work aims to serve as a motivation for further research concerning IoT-based water management systems designated for oilfield applications.

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