Challenges and Research Issues of Data Management in IoT for Large-Scale Petrochemical Plants

Lei Shu, *Senior Member, IEEE*, Mithun Mukherjee, *Member, IEEE*,
Michael Pecht, *Fellow, IEEE*, Noël Crespi, and Son N. Han

Abstract—The Internet of Things (IoT), which seamlessly interconnects heterogeneous devices with diverse functionalities, is an attractive choice for the large-scale petrochemical industry to develop an integrated system. With the industrial revolution, efforts have mainly been focused on factory automation, transportation security, and surveillance. The IoT plays a major role in factories with its new methods of data management and data collection. However, the IoT is still at an early stage in large-scale petrochemical plants due to the multiple coexisting heterogeneous networks in harsh and complex large-scale industrial networks. This paper presents a comprehensive survey on the IoT in large-scale petrochemical plants as well as recent activities in communication standards for the IoT in industries. This paper addresses the key enabling middleware approaches, e.g., an industrial intelligent sensing ecosystem (IISE), which allows rapid deployment and integration of heterogeneous wireless sensor networks with advancements in crowdsensing based services. In addition, this survey highlights the research issues of data management in the IoT for large-scale petrochemical plants.

Index Terms—Industrial Internet of Things (IIoT), industrial wireless sensor network (IWSN), large-scale petrochemical plants.

I. INTRODUCTION

THE Internet of Things (IoT) [1]–[11] has the potential to deliver exciting services across many sectors, from social media, business, and smart cities to industries. With the increase in research interest in the IoT, it is expected to intelligently control more than two billion devices connected to the Internet by 2020 [12]. Researchers are in pursuit of emerging technologies that enable human-centric and machine-centric networks to meet the evolving requirements in industries, e.g., factory automation systems [5], [13], [14], fault diagnosis [15]–[20], gas consumption monitoring systems [5], [21], [22], [22], surveillance [4], etc. These could take the form of an autonomous data exchange, either directly or over a network.

In this paper, we consider large-scale petrochemical plants. An example of a large-scale integrated refining and chemical enterprise is shown in Fig. 1. Apart from the manufacturing and production point of view, real-time information about the distribution area of hazardous toxic gases in large-scale industry is needed so that first-line working staff can be warned and informed about the safe paths for quick evacuation. However, the current toxic gas monitoring systems consist of static cable-connected sensor nodes and hand-held devices used by first-line workers in production and manufacturing sites with several responsibilities, such as controlling industrial equipments, robots, and handling raw materials. Only experienced first-line workers can make correct decisions and predictions about toxic gas leakage. In addition, the gathered data from these hand-held devices cannot be always used for future knowledge discovery. Moreover, it is very difficult for the first-line workers to monitor large-scale petrochemical areas because of the remote, hard-to-reach, and even prohibited areas. Last but not the least, it is extremely dangerous for workers to measure or detect toxic gas with hand-held devices.

Recently, the IoT has become an attractive choice for large-scale petrochemical plants [5], [12], [13], [21], [23]. Large-scale petrochemical plants incorporate dense wireless devices such as Radio-Frequency IDentification (RFID) tags [24] for machine identification, sensors for large-scale rotational equipment monitoring and fault diagnosis, and many more applications. This development has led to an evolutionary journey toward an industry revolution called the Factory of Things [9], [24]. In recent years, Industrial IoT (IIoT) [13], [21], [22] has drawn significant interest in the industrial environment. It allows a tight and seamless integration between lower layer components, such as sensors and actuators, to the higher level connected with the cloud platform [25].

Although hard-wired industrial communications, such as traditional field bus systems and wired hard real time switch (HART) are already installed successfully in factory automation and production management, these wired industrial communications have the following drawbacks. It is difficult and very expensive to install wiring in the harsh industrial environment, e.g., strong mechanical vibrations, high temperature, explosive gases,

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Fig. 1.   Example of large-scale petrochemical industry (©SINOPEC Maoming Petrochemical Company (Maoming Company) [Online]: http://www.sinopecgroup.com/group/en/) that consists of petrochemical materials, iron and steel pipes, a large variety of equipment, and factory buildings.

flammable liquid, and leakage of toxic chemicals. Modern manufacturing often requires frequent adjustment of process monitoring, therefore, rewiring in flexible manufacturing results huge cost. Therefore industrial wireless sensor networks (IWSNs) are good solutions to overcome these drawbacks of wired industrial communications due to the ease of deployment, low cost, flexibility, instant, and precise cyber-physical decisions to achieve Industry 4.0 [22], energy power supported by (rechargeable) battery or wireless charging. Within the IoT paradigm, IWSNs are evolving to become the global interconnection between management and factory products in large-scale industries [26]–[32]. Due to their advantages of low cost, ease of deployment, energy efficiency, and mobility compared to the traditional field bus, IWSNs have become a promising approach for manufacturers as well as plant designers. The IWSNs serve as a link between data collected on-site from heterogeneous sources [29] and the business backend. Furthermore, a crowdsensing based approach opens the door to a variety of benefits for intelligent networks with interconnected devices. It is true that other non-IoT-based solutions for petrochemical plants also handle a massive amount of data. The main difference between traditional non-IoT-based and IoT-based approaches is the nature of data for control mechanism. In a traditional approach, the monitoring systems gather predefined and structured data, afterward, structured decisions are made. However, the input data in IoT-based approaches are unstructured due to the data acquisition spread across heterogeneous sources. With the data acquisition spread across heterogeneous sources and the intelligent processing of gathered data, a sustained effort in technological innovation is needed to develop an architecture to directly control the physical world, including the machines, factories, and infrastructure that define the modern large-scale petrochemical industry.

The following summarizes our key contributions.

1) This article aims at providing a comprehensive survey on data management in the IoT for large-scale petrochemical industry that addresses the integration of heterogeneous[1]

[1]Heterogeneity in WSNs is generally caused is caused by differences in hardware and software components with different functionalities and capabilities. In addition, different storage structures and data models are also responsible for heterogeneous sources.

WSNs with the advancements in crowdsensing based services, including a brief outline of the research activities in recent years.

2) Since the current Internet technologies and protocols were not designed for constrained resources in smart devices integrated with the IoT, this paper presents the development of many extensions and adaptations of Internet technologies for the new class of networked objects and the current standardization activities for an IoT networking protocol in large-scale petrochemical plants.

3) Further, this article presents the research issues in the IoT with the advancements in middleware services. This article explains the substantial role of the IoT in harnessing the power of tight and seamless integration of heterogeneous WSNs with advancements in crowdsensing based services. This will lead to a strong and sustainable global growth, in terms of improved productivity, increased workplace safety, and reduced environmental impact.

The remainder of this paper is organized as follows. Section II discusses the recent developments of communication standards for IoT-integrated applications in the factory. The standardization activity for an IIoT networking protocol is presented in Section IV. Section III briefly overviews the data management in IoT-integrated large-scale petrochemical industries. The challenges and research issues of data management in large-scale petrochemical plants integrated with the IoT are addressed in Section VI. Finally, conclusions are drawn in Section VII.

II. Development of Communication Standards for IoT in Large-Scale Industry

Many of the existing Internet technologies and protocols were not designed for constrained resources in smart devices; therefore, IoT has fostered the development of many extensions and adaptations of Internet technologies for the new class of networked objects in the large-scale petrochemical industry. The IoT protocol stack is contributed not only by research results from academia but also by standardization bodies such as the

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TABLE I
IoT NETWORKING PROTOCOL STACK

Layers	Protocols
Application	HTTP, CoAP, DPWS, XMPP, MQTT, AMQP, CoSIP
Transport	TCP, UDP, SCTP, ICMP, DTLS
Internet	IPv6, RPL
Adaptation	6LoWPAN, 6TiSCH, IPv6-over-foo
Link	IEEE 802.15.4, BLE, DECT, ITU-T G.9959

Internet Engineering Task Force (IETF), the Institute of Electrical and Electronics Engineers (IEEE), and the European Telecommunications Standards Institute (ETSI).

IETF IoT Protocol Stack: The IETF IoT protocol stack extends four layers of the TCP/IP model (RFC 1122 [33]: link, Internet, transport, and application) with the new Adaptation layer, which is required for smart objects to adapt the small frame size of the low-power link layer to the much larger size of IPv6 packets. The adaptation layer defines mechanisms and protocols for header compression/decompression to enable the use of IPv6 on low-power links of smart objects. Table I summarizes common protocols for each of the five layers, which are elaborated more in the following sections.

A. Link and Adaptation Layers

IPv6 resides at the center of the IoT protocol stack for the interconnection between smart objects and existing services on the Internet. IPv6 with its inconceivably large address space is foreseen to be available on a wide variety of different link layer technologies meeting a wide variety of communication requirements such as wired or wireless, short or long range, and high or low data throughput. Almost all types of communication links can support IP-based communication; therefore, they are potentially operable for smart objects where the low-power requirement is the key for designing the networking models. There are several link layer technologies that are being developed for smart objects such as IEEE 802.15.4, blacktooth low energy (BLE), digital enhanced cordless telecommunications (DECT) ultra-low energy, and ITU-T G.9959. Each of these link protocols has its own corresponding adaptation layer technology; for example, IPv6 over low power wireless personal area networks (RFC 4944 [34]) for IEEE 802.15.4, IPv6 over blacktooth low energy (draft-ietf-6lo-btle) for BLE, Transmission of IPv6 Packets over DECT ultra low energy (draft-ietf-6lo-dect-ule-01) for DECT, and IPv6 packets over ITU-T G.9959 networks (draft-ietf-6lo-lowpanz) for ITU-T G.9959. The IPv6 protocol has a high overhead and restrictions that make it unsuitable for low-power or constrained networks such as IEEE 802.15.4 networks. For example, considering the limited space available for the medium access control (MAC) payload in an 802.15.4 MAC protocol data unit, the use of a 40-byte IPv6 header would be too excessive. The IETF *6LoWPAN WG*, therefore, was formed to work on the IPv6 protocol extensions required for such networks where hosts are interconnected by IEEE 802.15.4 radios. Similarly, the IETF *6lo WG* aims to connect smart objects running a number of different link layer tech-

nologies to the Internet. The results of these efforts will be a number of *IPv6-over-foo* adaptation layer specifications similar to RFC 4944 [34]. Thus far, the working group has adopted four Internet drafts that define the adaptations for IPv6 over BLE (draft-ietf-6lo-btle), DECT ultra low energy (draft-ietf-6lo-dect-ule), MS/TP (master-slave/token-passing) networks (draft-ietf-6lo-6lobac), and G.9969 networks (draft-ietf-6lo-lowpanz). IETF *6tisch WG* is another working group aiming to bring IPv6 to a specific link layer technology, IEEE 802.15.4e in this case. The IEEE 802.15.4e timeslotted channel hopping (TSCH) is a recent amendment to the MAC portion of the IEEE 802.15.4 standard. As a result the 802.15.4e timeslotted channel hopping MAC differs fundamentally from the carrier sense multiple access (CSMA) MAC found in standard 802.15.4. In short, TSCH allows for more controlled and deterministic network access as opposed to CSMA, while also offering increased resiliency to interference via channel hopping. TSCH MAC protocols are, therefore, commonly used in industrial applications.

B. Internet Layer: Routing

Due to the distinctive characteristics of 6LoWPAN (e.g., low energy availability, throughput, reliability, availability, and processing capabilities), it has specific routing requirements (RFC 5867 [35], RFC 5826 [36], RFC 5673 [37], and RFC 5548 [38]) that differ from those found in traditional IP networks. The IETF *roll WG* focuses on building routing solutions for 6LoWPANs as the result of the evaluation of existing routing protocols such as open shortest path first, intermediate system to intermediate system, *ad hoc* on-demand distance vector, and optimized link state routing, indicating that they do not satisfy all of the specific routing requirements (draft-ietf-roll-protocols-survey). The working group focuses on an IPv6 routing architectural framework while also taking into account high reliability in the presence of time-varying loss characteristics and connectivity with low-power operated smart objects with limited memory and CPU in large-scale networks. The main realization of this working group is the design of routing protocol for low-power and lossy networks (RPL), which provides a mechanism to support multipoint-to-point traffic from smart objects inside 6LoWPAN toward a central control point as well as point-to-multipoint traffic from the central control point to the smart objects inside the 6LoWPAN. Within the constrained parts of the network, the RPL offers a uniform and efficient method for realizing multi-hop networks.

C. Transport Layer

The transport layer is responsible for providing end-to-end reliability over IP-based networks. Transmission Control Protocol (TCP) sustains the traffic on the Internet and provides reliability thanks to the control overhead introduced for each transmitted packet. Reliable transport protocols over LLNs are being studied, but the amount of information for traffic control and reliability is expensive in terms of the number of transmitted packets and end-to-end packet confirmation, that directly maps to

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energy consumption. The use of user datagram protocol (UDP) and retransmission control mechanisms at the application layer are demonstrating a good tradeoff between energy cost and reliability. UDP is a datagram-oriented protocol that provides a procedure for applications to send messages to other applications with a minimum of protocol mechanism and overhead. In addition, the IETF *dice WG* focuses on supporting the use of datagram transport-layer security (DTLS) transport-layer security in constrained environments. DTLS is the UDP adaptation of TLS (hence the name Datagram TLS) that provides end-to-end security between two applications. Stream control transmission protocol (SCTP) is also used in IoT with some works focusing on constrained session initiation protocol (CoSIP) for smart objects [39].

D. Application Layer

Regardless of the specific link layer technology to deploy the IoT network, all the end-devices should make their data available to the Internet. This can be achieved by using several application layer technologies tailored for smart objects. On top of the IPv6 Internet, constrained smart objects are able to reap the benefits of a lightweight application protocol. The constrained application protocol (CoAP) (RFC 7252 [40]) is designed exclusively for smart objects to replace the hypertext transfer protocol (HTTP) and can be easily translated to HTTP for transparent integration with the Web, while meeting the smart object requirements such as multicast support, very low overhead, and publish/subscribe model. The OASIS devices profile for web services (DPWS) [41] standard is a lightweight version of W3C web service [42], providing a secure and effective mechanism for describing, discovering, messaging, and eventing services for resource-constrained smart objects. The message queue telemetry transport (MQTT) [43] is an asynchronous publish/subscribe protocol that runs on top of the TCP. Publish/subscribe protocols better meet the IoT requirements than request/response since clients do not have to request updates resulting in the decrease of the network bandwidth and in the need for using computational resources. The extensible messaging and presence protocol (XMPP, RFC 3920 [44]) was designed for chatting and message exchanging. It was standardized by the IETF over a decade ago and is a well-proven protocol that has been used widely all over the Internet. Recently, XMPP has gained attention as a suitable communication protocol for the IoT. The advanced message queuing protocol (AMQP) [45] is a protocol that arose from the financial industry. AMQP provides asynchronous publish/subscribe communication with messaging. It can utilize different transport protocols, but it assumes an underlying reliable transport protocol such as TCP. Its main advantage is its store-and-forward feature that ensures reliability even after network disruptions. CoSIP [39] is a constrained version of the session initiation protocol to allow smart objects to instantiate communication sessions in a lightweight and standard fashion. Session instantiation can include a negotiation phase of some parameters that will be used for all subsequent communication.

III. Overview of Large-Scale Petrochemical Industry With IoT

Next-generation smart factories should be able to adopt the exchange of data information between different wireless devices, including sensors, RFID tags, and different parties in real time [46], [47]. The German Federal Ministry of Education and Research defines Industry 4.0 as "intelligent production with sustainable engineering methods and interconnected production facilities in smart factories" [23], [48]. A reference architecture for an IoT-based smart factory in Industry 4.0 that includes interaction between smart factories and consumer demands has been introduced [14]. The use of smart machines in smart factories utilizing machine-to-machine (M2M) communication with the autonomous exchange of data among devices and a server or device-to-device either directly or over a network was proposed in [12]. Fig. 2 illustrates an overview of the IoT in large-scale petrochemical industry. Major requirements in large-scale petrochemical industry with IoT are discussed as follows:

Industry is often associated with a physical process[2] that has strict requirements in terms of predictability, latency, dependability, and security. With the fourth industrial revolution, Industry 4.0 [22], [48], in smart factories [24] where "IoT, Data, and Services" play a major role, there is a transition from embedded systems to cyber-physical systems [49]. While these efforts have primarily been focused on food production, supply chain monitoring, transportation security, and surveillance [24], IoT applications are still at an early stage in large-scale industry. Since the automation efforts began to be linked to the development of RFID technologies [9], the technological advancements of sensor networks and RFIDs together have proceeded slowly but steadily [50]. RFIDs were first introduced to overcome the limitation of bar-code technology, and they have become smart identifiers with multiple applications. Nevertheless, the integration of RFIDs in WSNs as a part of machine identification, equipment monitoring, and fault diagnosis has not yet been fully investigated in large-scale petrochemical plants.

1) *Production and Manufacturing Intelligence:* According to a survey by General Electric, Global Strategy & Planning Estimates, industrial Internet can impact almost 44% of global energy consumption, and even 100% of energy production [21]. Several countries have joined together to promote and develop standardization activities in IIoT [51]. An Ethernet-based real-time architecture, the extension of HART architecture that supports real-time scheduled and unscheduled traffic and allows dynamic service management, has been introduced to make it capable of being integrated on IIoT frameworks [52]. As per the standardization activities in Europe and other organizations, coexistence in industrial automation application is introduced in [53]. The interference due to overlapping of signals between wireless automation application in time, space, and frequency, is considered in the coexistence wireless model. Cloud-based network management [54] has been

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[2]Physical process in the large-scale industry includes robots, fixtures, machine tools, workpieces, etc.
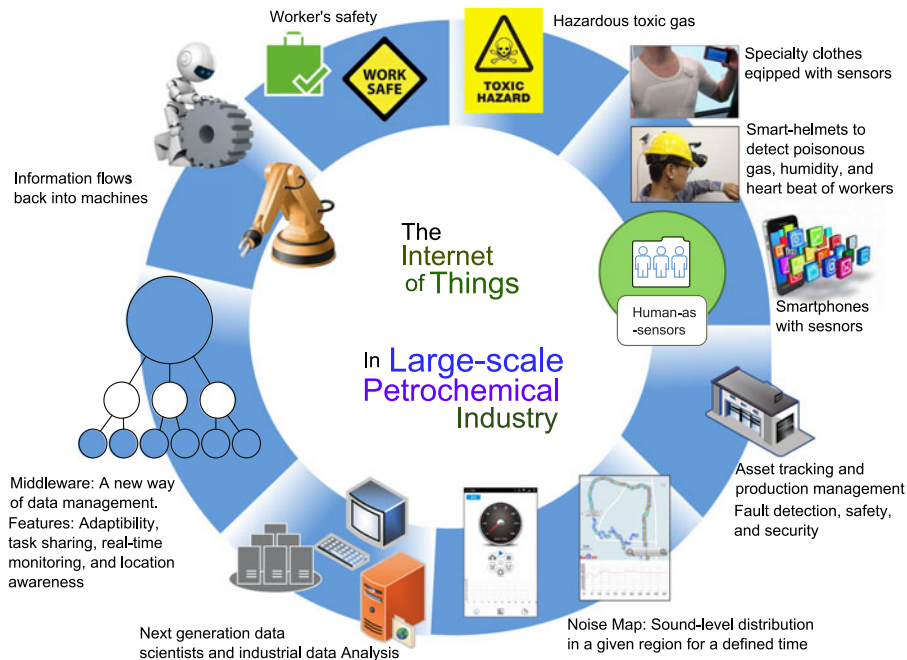
Fig. 2. Overview of IoT in the large-scale petrochemical industry.[3] This collaborative sensing would make it possible to have real-time tracking of toxic gas leakage, remote monitoring and controlling of machines and manufacturing, asset tracking, safety and security for workers, and noise map, etc. In summary, such a system would ensure vendor-independent, collaborative development, as well as offer real-time operation in large-scale petrochemical plants. (The use of some images is for nonprofit educational purpose.)

discussed in IIoT to optimize resource allocation and network load balancing. This management also supports non-IIoT applications in the same cloud data center with the advantage of centralized resource management mechanisms. Therefore, production and manufacturing intelligence in terms of energy consumption, automated architecture, overall material flow, and machine diagnosis play an significant role in large-scale petrochemical industries.

2) *Real-World Connectivity:* IoT in industry creates a new path to collaborative system development and the simultaneous operation of real and virtual components in a factory. Thus, it could be a future platform that manufacturers, application engineers, vendors, remote engineers, etc., could use to support the IoT. However, this is just the beginning of a new quasi-real-time approach for petrochemical process monitoring in industries.

3) *Safety, Security, and Impact on Environment:* A large petrochemical plant consists of petrochemical materials, iron and steel pipes, a large variety of equipment, and factory buildings. It is obvious that industrial production equipment, particularly in the petrochemical industry, is affected by long-term exposure to high temperatures and strong chemicals. These may lead to equipment faults, toxic gas leakage, and/or explosions. Therefore, safety for first-line workers as well as damage prevention for equipments are major concerns in petrochemical plants. Thus, the new methods of data management and data collection by the *advanced devices integrated with IoT* play a major role in the large-scale petrochemical factories.

[3]©Gazebo offers the ability to accurately and efficiently simulate populations of robots in complex indoor and outdoor environments. [Online]: http://gazebosim.org/

IV. STANDARDIZATION ACTIVITIES FOR THE IoT IN LARGE-SCALE INDUSTRY

A. ETSI oneM2M

The main objectives of the oneM2M partnership can be summarized as follows:
1) to develop globally agreed-upon M2M end-to-end specifications;
2) to define/focus on the common service layer and to provide a detailed service architecture including protocols, air position indicators (APIs), and standard objects;
3) to include common use cases and terminal/module aspects;
4) to consider security and privacy aspects.

This means that oneM2M develops end-to-end communication between M2M/IoT devices in wide area networks as legacy networking in the Internet, and its operation will be carried out with transparency against legacy transport protocols in application layers such as HTTP, CoAP, and MQTT. Moreover, this operation follows a method as efficient as Web communication, called RESTful.

The oneM2M functional architecture in Fig. 3 comprises the following functions: application entity (AE), common services entity (CSE), and underlying network services entity (NSE). An AE is an entity in the application layer that implements an M2M/IoT application service logic. Each application service logic can be resident in a number of M2M/IoT nodes and/or more than once on a single M2M/IoT node. Each execution instance of an application service logic is termed an AE. Examples of the AEs include production and machine monitoring, remote controlling, machine diagnosis, etc. A CSE represents an instantiation of a set of *common service functions* of the

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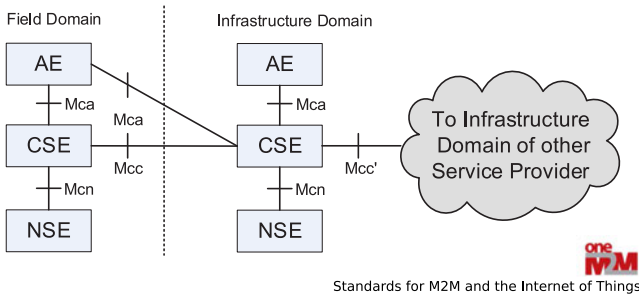

Fig. 3. oneM2M architecture and interworking scenario. The functional architecture consists of AE, CSE, and NSE. The AE may include production and machine monitoring, remote controlling, machine diagnosis, etc.
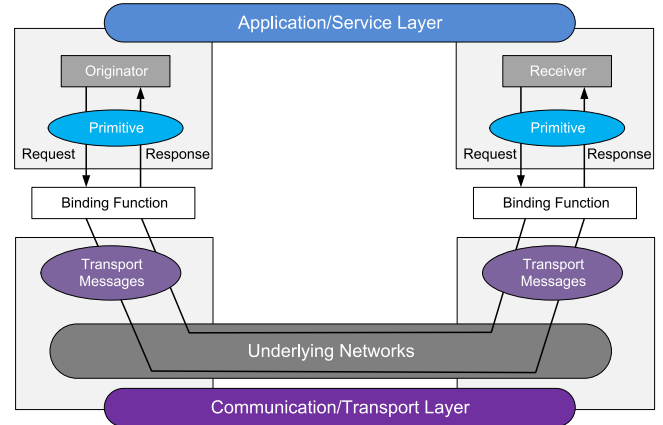

Fig. 4. oneM2M layers. This layered model comprises three layers: Application layer, common services layer and the underlying network services layer.

M2M/IoT environments. Such service functions are exposed to other entities through the reference points.

Reference Points: The functional architecture in oneM2M Release 2 specifications [55] discusses all the reference points in details. We briefly overview these reference points with their purposes. A reference point that consists of one or more interface of any kind, is supported by the CSE. The *M2M Communication* is abbreviated as *"Mc(-)."* The transport and connectivity services of the Underlying Network supports the information exchange between two M2M entities.

1) Reference point for M2M communication with AE (Mca): This reference point exists in the communication flow between an AE and a CSE. The AE uses the service supported by the CSE and the CSE communicates with AE through this reference point.

2) Reference point for M2M communication with CSE (Mcc): Two CSEs connect each other through Mcc reference point. A CSE uses the service supported by another CSE with Mcc reference point.

3) Reference point for M2M communication with CSE of different M2M service provider (Mcc$'$): This flows enable a CSE of an infrastructure domain (IN) residing in the infrastructure domain of an M2M service provider to communicate with a CSE of another IN residing in the infrastructure domain of another M2M service provider.

4) Reference point for M2M communication with NSE (Mcn): Reference point Mcn is used for accessing underlying NSEs.

Each CSE is identified with a unique CSE-ID. An NSE provides services from the underlying network to the CSEs. Examples of such services include device management, location services, and device triggering. No particular organization of the NSEs is assumed.

The oneM2M architecture is resource-based, and the functionality of the system is exposed by means of APIs over the reference points. Operations upon resources hosted by a CSE are carried out via an established channel that constitutes the communication on the reference points Mca and Mcc.

As shown in Fig. 4, each resource operation comprises a pair of primitives: Request and response. In order to provide a well-defined interface for the reference points in the architecture, the following aspects need to be provided: 1) the collection of primitives carried over a specific reference point and 2) the de-

scription and applicability of security methods in relation to the underlying protocols and reference points involved. In accordance with the oneM2M architecture, each reference point is applicable to a wide range of underlying network technologies and transport protocols. oneM2M only defines a set of bindings for specific underlying network technologies and transport protocols. These bindings are not limiting the applicability of the interfaces when used in other underlying networks and transport protocols.

B. IEEE P2413 WG

IEEE has launched a new working group, named P2413 WG, in terms of a standard for an architectural framework for IoT. This standard defines an architectural framework for the IoT, including descriptions of various IoT domains, definitions of IoT domain abstractions, and identification of commonalities between different IoT domains. The architectural framework for IoT provides a reference model that defines relationships among various IoT verticals (e.g., transportation, healthcare, etc.) and common architecture elements. It also provides a blackprint for data abstraction and the quality "quadruple" trust, which includes protection, security, privacy, and safety. Furthermore, this standard provides a reference architecture covering the definition of basic architectural building blocks and their ability to be integrated into multi-tiered systems. The reference architecture also addresses how to document and, if strived for, mitigate architecture divergence. Currently, 25 members have been involved in this standard: Cisco Systems, Emerson, General Electric, Intel, etc.

The P2413 WG aims to accelerate the growth of the IoT market by enabling cross-domain interaction and platform unification through increased system compatibility, interoperability, and functional exchangeability. So, P2413 WG defines an IoT architecture framework that covers the architectural needs of the various IoT application domains. That is, to increase the transparency of system architectures to support system benchmarking, safety, and security assessments, the P2413 WG's work involves reducing industry fragmentation to create a critical

TABLE II
COMPARISON ON VARIOUS DEVELOPMENTS IN IIoT AND THEIR REQUIREMENTS

	Main focus	Production and manufacturing intelligence	Dynamic collaboration collaboration	Connectivity	Safety and security security
Smart factories [24], [56]	Mass customization, new planning methods for factories, flexibility, and best maintenance services.	Autonomous data exchange and strong relationship with customers.	Improved machine efficiency.	Real-time energy assessment.	Not properly discussed.
VirCA [57], [58]	Integrates numerous existing hardware and software components, including sensors, actuators, control algorithms.	Strong relationship between virtual and real entities.	Close relationship between sensing-decision-actuation.	Provide a VR environment.	Interface to improve service, security, and reliability.
Connectivity and layout design [59], [60]	Cloud-based layout design and connectivity issue.	Useful for plant designers during wireless coverage prediction.	Virtual network deployment, post-layout verification.	Short-range machine-type wireless connectivity.	Not well discussed.
Remote monitoring and diagnosis of machines [61]	Aims to monitor production process and machine condition in a more flexible and efficient way.	Machine maintenance and flow management.	An Android APP and a web-based application running on a remote server.	Remotely connected.	Not well discussed.
Remote controlling and monitoring of processes [62], [63]	Timely monitoring, control and optimizations in manufacturing unit.	Energy optimization process.	Integrates sensor, devices to the web services	Gather real-time data of manufacturing process.	Not well discussed.
Industrial intelligent sensing ecosystem (IISE)	Combines the benefits of crowdsensing and middleware services.	Remote production monitoring	*Humans-as-sensors* with multifunctional sensors upload, and share data.	A new way of *crowdsensing* based collaborative data collection.	Aims at improving productivity and workplace safety.

mass of multistakeholder activities around the world and leveraging the existing body of work. To achieve their goal, P2413 WG interacts with external groups. For a unified IoT architectural framework, it is essential to interact with standardization activities for IoT-based vertical applications to cover the various applications, their requirements, and specific IoT functionalities in the IoT architectural framework. Also, the applications ensure that the framework can be referenced by these standardization activities. Besides interactions with standardization activities within IEEE, P2413 WG working group will strive to establish liaisons with other standardization bodies. Discussions are underway with IEEE 802.24, IEC SG8, oneM2M, and IIC.

V. DISCUSSION ON VARIOUS APPROACHES FOR IoT IN LARGE-SCALE INDUSTRY

A. Smart Factories

The potential characteristics of smart factories in Industry 4.0 include mass customization [56], new planning methods for factories, flexibility [24], best maintenance services, improved machine efficiency, and overall strong relationships with customers [64]. In addition to offering a new way to provide services to customers, energy consumption issues can be monitored with the help of big data collected by the IoT in large-scale industry. Table II compares the various developments in IIoT and their requirements. An approach for improving IoT-based energy management in smart factories has been introduced [14]. The data are collected by using smart meters and sensors; management experts can then conduct real-time energy assessments by analyzing the data stored on the cloud. This integration of energy consumption data will lead to sustainable smart factories. According to a survey by the American Society for Quality (ASQ) in 2014, industries equipped with smart factories have experienced an almost 49% increase in customer satisfaction

[65]. At the same time, 96% of respondents expect that their industry will be integrated with the IoT, and most believe that the IoT will make industries more environmentally friendly in the near future [66].

B. Mixed Physical and Virtual Components

Along with developments in different application fields, mixed virtual and physical realities [58], [67], systems of systems [68], cyber-physical systems [49], remote laboratories, cloud technology in robotics [69], and the virtual collaboration arena (VirCA) [58] have offered a new vision. There is significant interest in the development of multivendor solutions for industrial manufacturers. Some open platforms, such as the robot operating system-industrial consortium [70], robotic technology (RT)-middleware (RTM) [71], [71], and its open implementation openRTM-aist version 1.1.1 [72], which was developed and distributed by Japan's National Institute of Advanced Industrial Science and Technology, have been established to support or create an interface to improve service, security, and reliability.

The central idea of VirCA[4] is the adoption of a sharable and fully customizable virtual workspace. It offers the opportunity to design, implement, and evaluate approaches and build strong relationships between virtual and real entities. The main modules of VirCA include a virtual reality (VR) engine to provide a VR environment and a Web edition to equip users with various interactive applications as plug-in modules. VirCA integrates numerous existing hardware and software components, including sensors, actuators, control algorithms, etc., using RTM-based component interfaces. Compared to other recently discussed

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[4] ©VirCA is freeware developed by MTA SZTAKI, Institute for Computer Science and Control, Hungarian Academy of Sciences [57]. [Online]: http://www.virca.hu/

platforms,[3] the VirCA multiuser facilities integrated with multiple end points are a class apart. This platform offers a truly novel approach with its close relationship between sensing-decision-actuation triplets, which is key to its importance in industrial applications [58].

C. Wireless Connectivity and Layout Design in Industrial Networks

Pre- and postlayout verification are the important issues in layout and connectivity design in industrial networks. Predeployment information about the radio links would be useful for postlayout verification. Different wireless solutions, such as WiFi, have been proposed to meet the application-specific requirements of customers. However, there is still a lack of development in industry standard design for cloud-network architecture due to the limitations of social networking optimization [73], which may not be applicable to industrial applications because of multiple coexisting heterogeneous networks in harsh and complex industrial environments. Thus, a consistent design approach for industrial networks that will support every phase of the IoT in industry, such as virtual coverage, layout design, and overall integration of cloud computing, is mandatory in current industrial wireless networks.

A case study in an oil refinery site has been carried out to verify the cloud-based layout and connectivity issues [59]. In addition, to verify the model in an arbitrary field, a random geometric graph-based approach was used to connect each cloud node. Experimental verification confirms the effectiveness of the radio model for plant designers during wireless coverage prediction, virtual network deployment, and postlayout verification in industrial scenarios with co-existing heterogeneous radio access as a part of the IoT in industry.

D. Radio-Access in IoT-Enabled Large-Scale Industries

A novel stochastic model [60] has been proposed for short-range machine-type wireless connectivity in high-density wireless industrial networks. It uses a three-dimensional computer-aided design tool to predict obstructions in different scenarios; afterwards, the reliability of the radio links can be established using propagation theory. Also, it is expected that there may be coexistence difficulty between WiFi and the IEEE 802.15.4 physical layer. This architecture [60] also handles the coexistence and overlapping problems in cloud-based IoT.

Bandwidth allocated to sensor nodes becomes a scare resource in IoT-enabled networks. In addition, the transmission medium is generally under-utilized [74] in multihop topology-based WSNs [75]. To improve the channel utilization, spectrum sharing is a promising approach under a condition that there is no harmful interference to the existing primary users. To handle the spectrum congestion problem, cognitive radio (CR)-based networks are widely applied in many wireless applications [76]. Further, carrier aggregation [77] allows to transmit data over multiple noncontiguous carrier in licensed and nonlicensed bands. Recently, IEEE 802.11ac standards [78] provides a flexible channel assignment for both adjacent and non adja-

cent channels. There has been a significant interest on channel bonding (CB) [79], [80] that aims to combine a set of under-utilized noncontiguous bands to avail large bandwidth for packet transmission within a short duration. A detailed study on CB is discussed in [81] for CR sensor networks [82]. The CB offers an flexible way to meet the various requirements (e.g., energy consumption, delay minimization, throughput maximization) of a network.

E. Remote Configuration, Monitoring, and Diagnosis of Machines

Remote monitoring and diagnosis of machines play an important role in large-scale industries [83]. Recently, a project called Touchplant [61], regional Italian project funded by Lombardia, aims to monitor production process and machine condition in a more flexible and efficient way. The maintenance in terms of adopting efficient energy-flow and production-flow is always one of the important aspects in any industries [84]. An overall architecture [85] is presented to monitor real-time machine data with an Android APP and a web-based application running on a remote server. It is expected that remote access is one of the next-level machine maintenance and flow management in the large scale, particularly, large-scale petrochemical plants.

F. Monitoring and Optimization for Production Process:

Various techniques are proposed to collect and analyze data from production process, to overall schedule material flow in the plants. Manufacturing environment becomes more flexible with factory automation integrated with IoT [86]. In addition, energy management is also an important aspect in intelligent manufacturing and production process [62], [87], [88]. It is suggested that energy consumption in a manufacturing line can be greatly reduced with a particular process's performance improvement. Zhang *et al.* [89] presented an overall architecture that extends the techniques of IoT to manufacturing field. In a production process, timely monitoring, control and optimizations are main challenges in manufacturing unit.

Recently, few work presented the way to manage entire energy optimization process including monitoring, analysis, and management [63]. An automated architecture is proposed that collects and correlates the different events and uses complex event processing. To improve the energy optimization, a service-oriented architecture (SoA) was suggested. This architecture extends the capabilities of enabling business-based IoT and services [90] that aims to gather real-time data of manufacturing process, which seamlessly enables intelligent production management [91]. It also integrates the physical industrial components such as sensor, devices, to the web services.

G. Industrial Intelligent Sensing Ecosystem (IISE)

Collaborative data collection in large-scale petrochemical plants: Apart from wired sensor nodes, wireless sensors nodes (either static or mobile) are widely deployed in large-scale petro-

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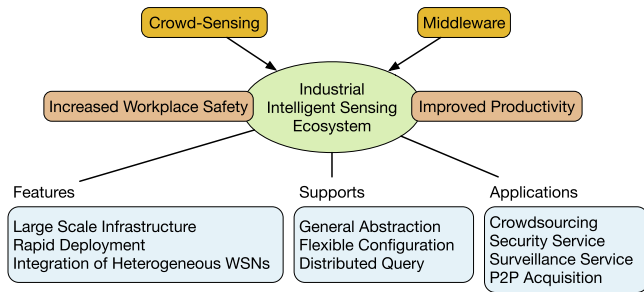

Fig. 5. Crowdsensing based IISE (CIISE) as a collaborative approach in modern industrial plants, aimed at improving productivity and increasing workplace safety.

chemical plants to enable efficient and reliable sensing for harmful areas. In addition, smart phones have global positioning system (GPS) and high computational resources, and cars with GPS are used as mobile and static sensors. With the advantages of easy deployment and with the mobile connectivity of WSNs and low-price multifunctional sensors, *humans-as-sensors* [113] can sense, upload, and share data to contribute to industrial sensing systems. Thus, the *crowdsensing* based approach leads to a new way of collaborative data collection in large-scale petrochemical plants.

The IISE aims to provide an industrial environment integrated with the IoT. IISE provides middleware communication models to support production monitoring, pollution analyzing, leakage detection [114], and asset tracking. The main features of IISE include collaboration, multiple sources, and knowledge discovery helped by information sharing among co-workers, portable devices as sensors transported by workers, and exploiting data with domain knowledge. Fig. 5 presents the features of a crowdsensing based IISE (CIISE). CIISE [104] combines the benefits of crowdsensing and middleware services [114] aimed at improving productivity and workplace safety. However, due to the harsh industrial environment, network connectivity, which creates monitoring gaps, is one of the main issues in IISE.

The proposed architecture follows global sensor networks, assuming a rapid deployment and integration of heterogeneous WSNs. This architecture supports flexible configuration, general abstraction, and distributed query. The middleware architecture follows the classical principles of layered middleware with advancements in crowdsensing based services. The detailed configuration settings are discussed in [104]. The core functionality components consist of the communication interface, data aggregation, exception handler, query manager, and device control.

In addition, CIISE also participates in crowdsensing services. Sensors for information such as gravity, GPS, proximity, and accelerometer are used in smartphones, and wearable devices such as smart helmets [104] are used to measure work environments and monitor workers' personalized activities. Afterward, the quality assessment of data is processed to obtain the information from crowd-sourced data. In an industrial network, signal reconstruction must be performed to recover the sample data crowdsensing, including mobile sensors integrated with

humans-as-sensors, and the coverage can be extended. [23], [114]. Although humans not necessarily go to measure toxic level in gas leakage areas, however, the real-time location of human and toxic gas level are useful to provide safe route and evacuation after toxic gas leakage. This provides worker safety with improved productivity, particularly in oil and gas plants [23], [114].

Factory Noise Effect: Factory noise level above 90 dB creates hearing impairment[5] to the human ear [115]. There are several ways to protect workers from noise damage in a large industrial area. Noise-protective materials can be wrapped around noise-generating pipes. Noise-absorbent materials can be used in transmission media, particularly in walls to reduce the noise effects. Another proven solution is the use of special earphones mounted on helmets to reduce noise at recipients' ears [116]. However, it is equally important to have information about the noise-level distribution and the infrastructure or networks to measure noise in a factory. A noise map in an industrial area can be very helpful at providing this information [116]–[118]. A noise map[6] is a geographic representation of the sound-level distribution in a given region for a defined time. As CIISE includes the benefits of crowdsensing, large number of people with smartphone and professional noise-sensing devices contribute to the noise information to visualize noise distribution. However, lack of timely update and accurate geo-location are major research challenges for noise maps in large-scale industrial areas.

VI. CHALLENGES AND RESEARCH ISSUES OF DATA MANAGEMENT IN THE IoT-INTEGRATED LARGE-SCALE PETROCHEMICAL PLANTS

A. Middleware Service

The middleware service in IoT-integrated factories can be viewed as a novel approach that helps to bridge the gap between high-level requirements and applications in petrochemical factories. It provides the interoperability to support distributed applications. The middleware platform that reuses the software and hardware platforms, benefits the IoT in industrial applications in terms of cost, distributed architecture, and global adaptability. The research activities on WSNs have focused on data gathering and forwarding dedicated to a single application for the entire network to detect or monitor physical changes and activities. However, due to the transition from typical WSN applications to industrial applications with the IoT paradigm, IWSNs, it has become imperative to design a cross-platform method for sophisticated routing and energy-saving strategies.

Middleware Requirements: Some of the requirements for middleware in industrial applications do not particularly relate to traditional WSNs, but they may apply to a high-level distributed computing system. The middleware system for IWSNs [15]

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[5]U.S. National Institute for Occupational Safety and Health, certify workplace standards in terms of maximum working hours under high levels of factory noise, e.g., it is advisable to work less than 8 h and less than 4 h under noise levels of 90 dB and 95 dB, respectively.

[6]DBSENSE is an online Android client that allows a citizen to contribute to noise information and facilitates the visualization of noise distribution. [Online]: http://www.dbmap.cn/

TABLE III
COMPARISON OF INDUSTRY-GRADE MIDDLEWARE SYSTEMS

Middleware Systems	Surveillance	Context Discovery	Data Evaluation	Signal Reconstruction	Scalability
CARISMA [92]	No	Yes	Yes	No	Yes
Mires [93]	No	No	No	No	Yes
GREEN [94]	No	No	No	Yes	Yes
Tinycubus [95]	No	Yes	Yes	No	Yes
TinyLIME [96]	No	No	No	No	No
Detmold *et al.* [97]	Yes	No	No	Yes	Yes
SOA [98]	No	No	No	No	Yes
Prometheus [99]	No	Yes	Yes	No	–
Device-independent [100]	No	No	No	No	Yes
Ella [101]	Yes	No	–	No	Yes
MILS [102]	Yes	Yes	Yes	No	–
CAMEO [103]	No	Yes	Yes	No	Yes
CISI [104]	Yes	Yes	Yes	Yes	Yes
General purpose SoA [105]	No	Yes	Yes	–	Yes
Publish/subscribe SoA [106]	No	No	Yes	No	Yes
Unified SoA [107]	–	No	–	No	Yes
PRISMA [108]	–	Yes	–	No	Yes
ubiSOAP [109]	–	Yes	Yes	Yes	Yes
KASoM [110]	–	Yes	Yes	Yes	No
MidSHM [111], [112]	Yes	No	–	Yes	Yes

must be generic. It should aim to meet all the industrial requirements. In this context, we summarize the comparison between industry-grade middleware services in Table III. A comprehensive survey on middleware for IoT has been presented in [112]. Some of the main requirements of middleware in large-scale industry are listed below.

1) Adaptability: This is one of the major requirements for middleware services in IoT applications. Hardware-independent [100] applications and user requirements or changes within the network must be facilitated by the services designed for industrial applications.

2) Task-Sharing: Unlike typical single-application-oriented WSNs, a middleware service should not allow nodes to be used for more than one application. There must be a task-sharing ability for performing collaborative sensing and for running different applications from other parts of the network.

3) Real-Time Monitoring: A middleware service must be designed to monitor and detect any physical changes or events in real time. In large-scale industrial applications, the monitoring process should allow the operation of a network as a whole to be considered.

4) Location Awareness: Some recent studies on geographical location-based routing protocols suggest that middleware service should enable a topological or geographical location-based approach. The location of any sensor nodes along with their 1- and 2-hop neighbors can be determined based on the GPS or smart location-based applications.

Middleware Classification: According to their functionalities, middleware services are classified into low-level, virtual machines, and service-oriented approaches [119]–[121]. Tasks such as energy-saving based routing protocols and data aggregation are the main features of a low-level middleware system. However, these services are hardware-specific, making them less suitable for IoT-based industrial applications. Meanwhile, many research activities are underway to support hardware-independent middleware services.

The virtual machine-based approach [122] takes advantage of the ability to overcome hardware-dependent services. Another type of approach is the message-based approach. Middleware acts as an interface between the underlying system and the message structure. However, a large amount of messages are required for a highly distributed system, leading to overloaded and, therefore, blocked communication. For a heterogeneous network model, service-oriented middleware [123] is one of the solutions for industrial applications integrated with IoT. Any sensor node can be used for a particular service related to sensor reading, data storage, and aggregation. This approach is highly collaborative and can be easily integrated with service-oriented IoT applications in the industry.

B. Crowdsensing

The growth of online social media networks with geo-location-based mobile crowdsensing applications [124]–[127] has resulted in an explosion of user-generated content on the Web, from mobile devices to social media platforms. These real-time crowd-sourced data can be used for social awareness and crisis management [127]. Fig. 6 illustrates the main factors involved in crowdsensing integrated with the IoT. This figure also shows that crowdsensing consists of data sharing, personalized individual data sensing, and data visualization. Crowdsensing integrated with humans-as-sensors in industrial regions is also used to monitor environmental changes, toxic gas leakage, and many other events. Individuals can also personalize their service preferences and define how to monitor their daily activities. This enables personalized service for workers, and, subsequently, their contributions to addressing problems such as carbon emissions and toxic gas leakage in industrial areas. The basic concept

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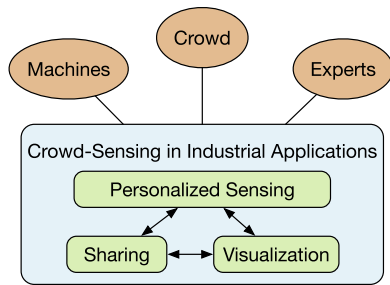
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Fig. 6. Main factors involved in crowdsensing in large-scale petrochemical industrial applications. Here machines represent all types of sensors, processing units, smartphones, and specially designed clothes and equipment. Experts make decisions to handle industrial surveillance and crisis management integrated with IoT. Data sharing, personalized sensing of individuals, and data visualization are the major parts of crowdsensing.
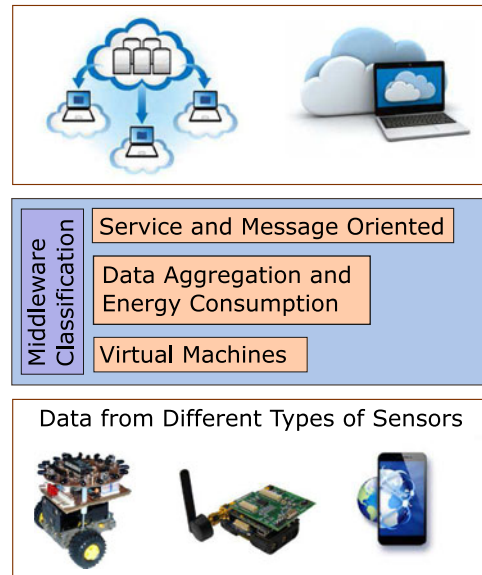

Fig. 7. Heterogeneity, standardization, geo-awareness, and open access are the main research challenges in IoT-based large-scale industry. A cloud is viewed as computing infrastructure to facilitate the management of IoT resources and to fully utilize the valuable data.

of the human-as-sensor comprises many aspects. It reduces the initial deployment cost for sensor networks. Moreover, first-line workers are highly mobile; hence, integrated sensors can easily get more accurate real-time data while making decisions about critical issues.

Recently, Huo *et al.* [104] proposed a middleware-based data system from mobile sensors that are typically distributed in space and time. A testbed has been built to validate the middleware, which can successfully support crowdsensing in CISI applications. Along with static sensors, new smart helmets [104], [128] based on existing wireless technologies and embedded sensing technologies are used to monitor CO_2, SO_2, SH_4, wind speed, humidity, and temperature in industrial areas. It has been suggested that the proposed middleware for CISI can be further extended to different applications scenarios with a flexible framework.

Crowdsensing allows public and professional users to collect, analyze, and share local information. Therefore, building up a crowdsensing network benefits the information-sharing and decision-making processes of the whole industrial society. Crowdsensing has already had a strong impact on social networking, environmental monitoring, and industrial applications. In addition to the online-data gathered from sensor nodes, humans can also act as sensors with smartphones, smartbands, specially designed clothes, and equipment [128], [129]. *Humans-as-sensors* [113], [127], [130] share the observation and views with each other with the help of smart wireless transmission [124]. Although the data collected from a crowd is useful, there are still some concerns about the information gathered by the large number of sensors integrated with the IoT in the large-scale industry.

1) Standardization: While humans-as-sensors can share observations and help to monitor environmental changes and toxic gas leakage in factories, there may be some misleading information flow that can negatively affect decision making. For example, due to a large number of users in a social networking service, any public opinion may spread very quickly. Sometimes, these public opinions do not contain any credible data and users are often very prone to add their personal comments or views to these less-than-credible data [131]. Therefore, proper filtering of crowd-sourced data and of the information gathered for decision making are important aspects to be discussed in the distributed industrial zone.

2) Real-Time Update: The aggregated data from crowdsensing should be processed quickly so it can be used to make real-time decisions for any event, such as toxic gas detection, explosions, etc. This step would make it possible to ensure the safest immediate evacuation process during a crisis. Human safety can, thus, be established in large-scale industry with the help of IoT.

3) Heterogeneity: The multisourced sensor data leads to the heterogeneity in customized sensing systems due to different communication protocols and expressions of targeted sensor data streaming. Fig. 7 illustrates the following issues. Thus, the heterogeneity issues should be addressed for integrating wireless networks and managing semi- or unstructured data to support crowdsensing in CISI applications.

4) Geo-Awareness: Collecting geographic data from a crowd is required in order to precisely predict a toxic gas leakage area or other damage [132]. Processing geographic-aware data are also very useful to enable collaborative decision making in an industry integrated with the IoT.

5) Open Access: The benefits of a crowdsensing service must be accessible to people involved in the industry, particularly to first-line workers. The service must be as simple as possible, as the coverage and connectivity issues in a network are difficult to maintain. Also, the services and applications related to critical services should be accessible by means of simple SMS instead of smartphones.

6) Cloud Computing Based Framework: Since traditional computing approaches are not capable of handling the increasing demand of massive data processing due to the large numbers

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of sensors connected to the networks, cloud computing is an effective approach to extend system capabilities with massive storage, computing, and software services in a scalable manner. To this end, a promising research area is to develop a computing framework that facilitates the processing of mass sensor data.

VII. CONCLUSION

The IoT in large-scale industry has the potential to address the fundamental needs of petrochemical plants. As a part of an industrial intelligent sensing ecosystem that allows participating in crowdsensing, a middleware system integrated with the IoT will emerge to manage several issues associated with data management in large-scale petrochemical plants. Along with current middleware research in large-scale industry, it has been observed that petrochemical industries integrated with the IoT will drive the new growth paradigm.

Unlike typical single-application-oriented IWSNs, a middleware system should be able to meet evolving industrial requirements including adaptability, task sharing, real-time update, and location awareness. A considerable part of this paper elaborated how crowdsensing should benefit information-sharing and decision-making processes. Humans and sensors will be as *humans-as-sensors*, yielding both higher overall productivity and worker safety, particularly in oil and gas plants. Standardization, real-time update, geo-awareness, and open access are the main issues to be addressed in the future. As the IoT continues to be integrated with large-scale petrochemical plants, both standardization activities and an architectural framework for data management issues have been discussed to mitigate architecture divergence. The reference architecture should cover the definition of basic architectural building blocks with the ability to be integrated into multi-tiered systems. Driven by constantly changing digital technologies with their ability, industrial standards in the IoT are in an early stage; hence, a future research avenue would be to study the applicability of the IoT to the requirements and markets of large-scale petrochemical plants.

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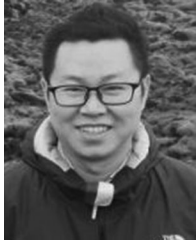
Lei Shu (M'07–SM'15) received the B.Sc. degree in computer science from South Central University for Nationalities, Hubei Sheng, China, in 2002, the M.Sc. degree in computer engineering from Kyung Hee University, Seoul, Korea, in 2005, and the Ph.D. degree from the Digital Enterprise Research Institute, from the National University of Ireland, Galway, Ireland, in 2010.

Until March 2012, he was a Specially Assigned Researcher with the Department of Multimedia Engineering, Graduate School of Information Science and Technology, Osaka University, Japan.

Prof. Shu was the recipient of the Globecom 2010 and ICC 2013 Best Paper Award. He is currently an Editor-in-Chief for *EAI Endorsed Transactions on Industrial Networks and Intelligent Systems*, and Associate Editor for IEEE SYSTEMS JOURNAL, IEEE ACCESS, etc. He has served as Co-Chair for international conferences/workshops over 50 times, e.g., IWCMC, ICC, ISCC, ICNC, Chinacom, especially the Symposium Co-Chair for IWCMC 2012, ICC 2012, the General Co-Chair for Chinacom 2014, Qshine 2015, Collaboratecom 2017, Mobiquitous2018, Steering and TPC Chair for InisCom 2015; he has been a TPC member of more than 150 conferences, e.g., ICDCS, DCOSS, MASS, ICC, Globecom, ICCCN, WCNC, and ISCC.

Mithun Mukherjee (S'10–M'16) received the B.E. degree in electronics and communication engineering from the University Institute of Technology, Burdwan University, Burdwan, India, in 2007, the M.E. degree in information and communication engineering from the Indian Institute of Science and Technology, Shibpur, India, in 2009, and the Ph.D. degree in electrical engineering from the Indian Institute of Technology, Patna, India, in 2015.

He is currently a Specially Assigned Researcher with the Guangdong Provincial Key Laboratory of Petrochemical Equipment Fault Diagnosis, Guangdong University of Petrochemical Technology, Maoming, China. He has authored approximately 35 publications accepted or published by refereed international journals/magazines/letters. His research interests include wireless sensor networks, wireless communications, energy harvesting, and cloud computing.

Dr. Mukherjee was the recipient of the EAI WICON 2016 and IEEE SigTelCom 2017 Best Paper Award. He has served on more than 10 TPCs, Publicity, Posters, and the Ph.D. Track Chair/Co-Chair for international conferences/workshops; he has been a TPC member of more than 20 conferences. He was the Guest Editor of the ACM/Springer *Mobile Networks & Applications (MONET)* and a Guest Editor of IEEE ACCESS. He has been serving as the Special Issue Editor of the EAI endorsed *Transactions on Industrial Networks and Intelligent Systems*.

Michael Pecht (S'78–M'83–SM'90–F'92) received the B.S. degree in physics, M.S. degree in electrical engineering, and M.S. and Ph.D. degrees in engineering mechanics from the University of Wisconsin, Madison, WI, USA.

He is a world-renowned expert in strategic planning, design, test, and risk assessment of electronics and information systems.

Dr. Pecht is a Professional Engineer, an ASME Fellow, an SAE Fellow, and an IMAPS Fellow. He is the Editor-in-Chief of IEEE ACCESS and was a Chief Editor of the IEEE TRANSACTIONS ON RELIABILITY for nine years, and the Chief Editor for *Microelectronics Reliability* for 16 years. In 2015, was the recipient of the IEEE Components, Packaging, and Manufacturing Award for visionary leadership in the development of physics-of-failure-based and prognostics-based approaches to electronic packaging reliability. He was also the recipient of the Chinese Academy of Sciences President's International Fellowship. In 2010, he was the recipient of the IEEE Exceptional Technical Achievement Award for his innovations in the area of prognostics and systems health management. In 2008, he was the recipient of the highest reliability honor, the IEEE Reliability Society's Lifetime Achievement Award. He was also the recipient of the European Micro and Nano-Reliability Award for outstanding contributions to reliability research, the 3M Research Award for electronics reliability analysis, and the IMAPS William D. Ashman Memorial Achievement Award for his contributions in reliability assessment methods for electronics products and systems.

Noël Crespi received the Master's degrees from the University of Paris-Sud (Paris 11), Orsay, France, and University of Kent, Canterbury, U.K., the Diplome dingénieur from Telecom ParisTech, Paris, France, and the Ph.D. degree and an Habilitation from Paris VI University, Paris, France (Paris-Sorbonne).

In 1993, he was with CLIP, Bouygues Telecom, and then at Orange Labs in 1995. He took leading roles in the creation of new services with the successful conception and launch of Orange prepaid service and in standardization (from rapporteurship of the IN standard to coordination of all mobile standards activities for Orange). In 1999, he joined Nortel Networks, as Telephony Program Manager, architecting core network products for the EMEA region. He joined the Institut Mines-Telecom in 2002, and is currently a Professor and the Program Director, leading the Service Architecture Laboratory. He coordinates the standardization activities for the Institut Mines-Telecom at ITU-T, ETSI, and 3GPP. He is also an Adjunct Professor at KAIST, Daejeon, South Korea, an Affiliate Professor at Concordia University, Montreal, QC, Canada, and is on the four-person Scientific Advisory Board of FTW (Austria). He is the Scientific Director of the French-Korean Laboratory ILLUMINE. His research interests include service architectures, services webification, social networks, and Internet of Things/services.

Son N. Han received the Dipl.Ing. degree in applied mathematics from the Hanoi University of Technology, Hanoi, Vietnam, in 2006, the M.S. degree in computer science from the University of Seoul, Seoul, South Korea, in 2009, and the Ph.D. degree in computer networks from the Institut Mines-Télécom, Télécom SudParis, Evry, France, in 2015.

He is currently a cofounder and COO of the Mevry Company, Paris, France. His research interests include Internet of Things and Web-based communication.