International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 04 Issue: 04 | April -2020 ISSN: 2582-3930

A Smart IoT and SCADA based Architecture for Oil and Gas Industry

K.Saraswathi, Assistant Professor, Dept of EIE , SCSVMV, Enathur, Kanchipuram

***Abstract*— Anomaly detection systems deployed for monitoring in oil and gas industries are mostly WSN based systems or SCADA systems which all suffer from noteworthy limitations. WSN based systems are not homogenous or incompatible systems. They lack coordinated communication and transparency among regions and processes. On the other hand, SCADA systems are expensive, inflexible, not scalable, and provide data with long delay. In this paper, a novel IoT based architecture is proposed for Oil and gas industries to make data collection from connected objects as simple, secure, robust, reliable and quick. Moreover, it is suggested that how this architecture can be applied to any of the three categories of operations, upstream, midstream and downstream. This can be achieved by deploying a set of IoT based smart objects (devices) and cloud based technologies in order to reduce complex configurations and device programming. Our proposed IoT architecture supports the functional and business requirements of upstream, midstream and downstream oil and gas value chain of geologists, drilling contractors, operators, and other oil field services. Using our proposed IoT architecture, inefficiencies and problems can be picked and sorted out sooner ultimately saving time and money and increasing business productivity.**

Keywords—Internet of Things based Architecture, Oil & Gas Operations, Reliable Communication, Smart Objects.

I. INTRODUCTION

The oil and gas industrial process starts after the crude oil is extracted from the grounds (oilfields) and to use it as a product it must go through the refining process. Once oil is pumped from the ground, it is then travelled through pipelines to tank batteries where a separator separates oil gas and water. The crude oil is then stored in storage tanks from where it is moved to refineries, other storage tanks, tanker ships or railcar through large diameter, long distance trunk lines. To push the oil in pipelines, the pump stations are installed at regular intervals along the pipelines from start till end. In order to overcome friction, changes in elevation and other pressure decreasing factors, pumps are used to initiate and maintain pressure in the trunk lines.

The oil and gas industry supply chain is divided into three main sectors/subdivisions, Upstream, Midstream and Downstream. The Upstream sector involves the exploration drilling and production. In the first step, potential underground or underwater crude oil, natural gas fields and potential hydrocarbon reserves are searched and explored and in the second step exploratory wells are drilled and then hydrocarbons are extracted from hydrocarbon reservoirs in oil and/or gas fields that recover and bring (produce) the crude oil and/or raw natural gas to the surface. The Midstream sector involves the transportation storage and marketing of crude oil or refined products of petroleum. Pipelines, rails, trucks, tanks etc. and other numerous transport systems are used for moving crude oil and extracted hydrocarbons from production and well sites to refineries or processing stations where hydrocarbon and oil processing is performed. The various refined products are then delivered to the downstream distributors The Downstream sector involves refining of petroleum crude oil and the processing and purifying of raw natural gas. At this stage, products derived from crude oil and natural gas are marketed and distributed. The products such as gasoline or petrol, kerosene, jet fuel, diesel oil, heating, oil, lubricants, waxes, asphalt, natural gas, and liquefied petroleum gas as well as hundreds of petrochemicals are provided to the consumers through downstream operations.

There are several critical challenges in the three sectors of oil and gas industry that are described as follows:

- Detecting physical presence at oil & gas pipeline, a leak of a pipeline, or tampering with a pipeline.
- Monitoring security, integrity, configuration, condition, disposition, orientation, location, contents, or surroundings, pressure variation of the oil & gas pipelines, tanks, wells and other assets used in the supply chain of oil & gas industry.
- Optimizing pumping operations, maintaining the pipes and wells, monitoring equipment failures, corrosion, erosion in a refinery and oil & gas leakage, minimizing risks to health and safety and monitoring and improving production performance with reduced costs.
- Detecting tuberculated pipeline sections partially closed or fully closed valve gates, variations in fluid homogeneity (e.g., air pockets within a water distribution network), pipe wall structural degradation and biofilm accumulation.

Supervisory Control and Data Acquisition (SCADA) systems [1] are not scalable due to low density in time and space, expensive in terms of equipment and maintenance, not interoperable in terms of hardware and software, inflexible when there is a need for protocol change and software updating, and provides data and result with long delay. Various Internet of Things (IoT) based architectures have been proposed in the literature in different fields like IoT architecture for Social Internet of Things (SIoT) [2], Resilient IoT architecture for smart cities [3] and future internet [4]. But still yet there is no IoT based architecture for oil and gas industries. Given the critical environment of oilfields, there is a need to develop IoT architecture according to Oil & Gas industrial environment.

In this paper we contribute to the following:

1. We are the first to propose an Internet of Things (IoT) based architecture for efficiently, reliably and accurately performing various operations of upstream, midstream and downstream sectors of oil and gas industries. The proposal of IoT architecture for the oilfield environment is the main contribution of this research that is followed by starting from the sensing infrastructure of IoT, traversing the network domains, and ending at the IoT applications.
2. The proposed architecture also considers the design aspects of each layer, suggesting the technologies that support the reliability efficiency and robustness features in each layer.
3. This proposal provides scenarios (storage tanks, pipelines, and well heads) for applying this architecture in the three sectors of oil and gas industry. The core processes are driven through automation and reduced workforce dependency.
4. This proposal also provides hierarchical methods for reliable and efficient data delivery from smart objects to the control center.

The rest of the paper is structured as follows: Section 2 provides a revision on WSN based monitoring systems for oil and gas industries. Section 3 presents our proposed modular architecture, describing its modules in detail. Section 4 describes how the architecture performs oil and gas industrial operations by monitoring the oil field environment in an efficient manner. Section 4 finally concludes the paper.

II. Wireless Sensor Network Based Monitroing Systems

In recent years various Wireless Sensor Network based solutions have been developed to handle Condition monitoring [5, 6], Refinery [7-10], Pipeline monitoring [11-18], cathodic protection [19], corrosions [20], Well head monitoring [21], pumping unit [22], Oil Drilling [23] in the oil and gas industry. But they all may suffer from noteworthy limitations as mentioned in the introduction and are also prone to many attacks [24-29]. *Radio Communication Technology* based systems include [30-32]. In [30] the authors have adopted radio communications for transmitting information sensed from the sensors for pipeline inspection. In [31], pipelines are monitored by placing sensors along the pipelines. In [32] uses radio communications for in-pipe inspection by deploying sensors at some fixed checkpoints inside the pipe but it is not feasible to perform sensing very close to a leak. Some proposals are *Acoustic Wave Technology* based systems [33, 34][37]. In [33, 34], a transmitter is placed in the pipeline and the communications with the receiver are carried out by emitting acoustic signal bursts using the pipelines as a waveguide or channel. These these systems are not suitable to monitor long pipelines with different pipe geometries. In [37], authors have adopted elasto-dynamic waves for enabling wireless communications in pipeline monitoring systems. This proposal is not suitable for in pipe inspection due to deployment challenges. Some proposals [35-36] focus on *Magnetic Induction* for wireless communications to monitor pipelines. In [35], a network of magnetic induction units is disclosed which is configured to transmit a signal or receive a signal from neighboring units by modulation of a time-varying magnetic field and sensed data is relayed in a multi-hop fashion. In [36], authors have proposed to transmit data wirelessly through magnetic induction based communications by using coils of wire wound on the pipelines. However, due to short range of communication between magnetic induction units or coils, large scale deployment or long underground pipeline monitoring is not possible.

The most recent proposal [38] involves robotic technology for pipeline inspection. It discloses wireless communication system for underground pipeline inspection including a plurality of sensor nodes carried by robots within the pipeline and each sensor node equipped with a radio transceiver. The system sends the leak detection information to aboveground relay nodes via low frequency radio transceiver which in turn send the received information to the remote monitoring center using high frequency radio transceiver via an aboveground mobile network.

III. Proposed IoT Based Architecture

Here we present an internet of things (IoT) based reliable architecture for monitoring various operations of the upstream, midstream and downstream sectors of the oil and gas industry. Figure. 1 illustrates a schematic representation of the proposed IoT based modular architectural design, comprising three modules, module of a smart object, module of a gateway and module of a control center (server). Each module is layered (including sensing, networking and application layers) and tackles specific functions to support monitoring of the interconnected oilfield environment.

The remaining section describes the three modules of the proposed IoT architecture, their functions and interactions in detail. In addition, possible technologies are suggested that can be applied to make the oilfield monitoring and other operations more reliable and efficient.

A. Smart Object

Each smart object (SO) is a physical device and a plurality of these smart objects are deployed on various oilfield assets (equipment). Smart objects enable to sense and collect data and react to specific conditions. When a group of smart objects are installed on different equipment in an oil field environment it is referred to as a Smart Oilfield.

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 04 Issue: 04 | April -2020 ISSN: 2582-3930

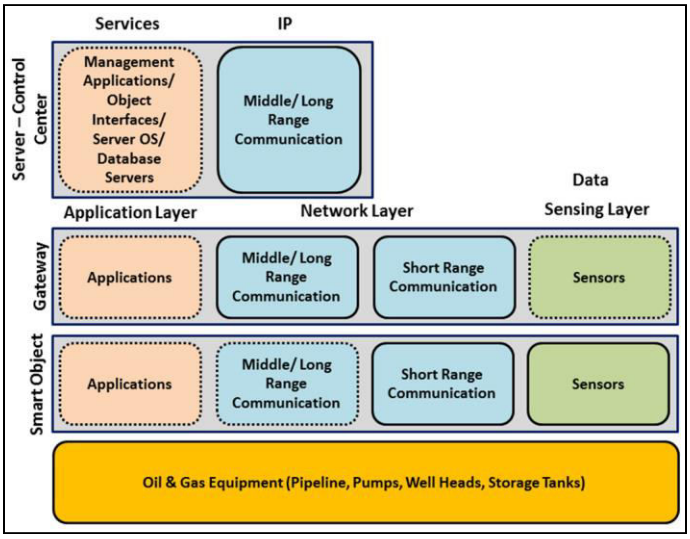

Figure 1. Proposed IoT based Architecture for Oil and Gas Industries

Thus, the data gathered by this smart oilfield has to be delivered to the server so as to process and analyze the data completely. The module of a smart object is comprised of three layers; sensing layer, network layer and application layer. The sensing layer involves data acquisition and collaboration between smart object(s) and gateway(s). Each smart object is equipped with different types of sensors, like acoustic, temperature, flow and pressure sensors to detect a leak. Networking layer is responsible for communication between smart objects, gateways and the control center. Each smart object may also include a radio transceiver at the network layer for short range communication with other smart objects and gateways.

B. *Gateway*

The gateway module is a bridge between smart objects and the control center. On the other hand, in the case when smart objects have no direct link available for direct communication with the control center through long range communication technologies; gateways will connect these smart objects to the control center. Also the gateway module will perform the responsibilities of the application layer in the absence of an application layer in the smart object module. A plurality of smart objects will be connected to the gateway module through short range communications. Sensing layer in the gateway module is optional but each gateway may also be equipped with different types of sensors, like acoustic, temperature, flow and pressure sensors. Each gateway may also include a radio transceiver at the network layer for short range communication with other gateways and smart objects. The communication between the smart objects and gateways can be achieved by employing RPL (Routing Protocol for Lossy networks) [39]. The applications running on the smart object and gateway modules will perform real time actions (fire alerts, shut down of different equipment, evacuation of the staff, and localization of faults) against anomalous events like oil and gas leakage, fire etc.

C. *Control Center*

The control center (server) module is responsible for management of applications and the analysis of the data gathered from the smart object modules, generating the information and taking important decisions against anomalous events, providing the dashboard to support the decision making process. The control center is comprised of only two layers the network and the application layer. The network layer is responsible for communication between the gateways and in some scenarios directly with the smart objects through long range communication technologies. The Application layer is basically responsible for management processes and includes the object interfaces, IoT applications, databases and service APIs, Visualization tools etc. When the collected data is analyzed using algorithms [40, 41] and problems are sorted out, actuation is performed by controlling the functions without human intervention. The control center will perform data analysis for two main purposes, first for the predictive maintenance of the equipment by analyzing the equipment condition data delivered by the smart objects to the control center and various parameters (sensed data) and detecting failure modes either before they are going to take place or when the equipment will likely to fail or need service. Thus the control center will perform preventive maintenance for maximizing production uptime and minimizing disruptions, thus to better control and maintain various assets with reduced health and safety risks. Second, the control center will analyze the data for the production performance by analyzing the daily usage and production of oil and gas.

IV. DISCUSSION

The three modules need to interact in a coordinated and harmonized manner to make this architecture successful. In this section we explain in detail how this architecture will be employed in the oil field environment, and monitor the oilfields reliably and efficiently with the combined efforts of these modules. The smart objects may vary in their characteristics and according to the possible scenarios in the oil field environment, smart objects are installed on different assets (pipelines, well heads or oil storage tanks, etc. to monitor various events like leak, corrosion etc.) in the oilfield environment.

A. *Possible Scenarios for the Installation of Smart Objects*

When smart objects are installed on oil & gas Storage Tanks, they are equipped with pressure, temperature, flow and level sensors for remote monitoring of the oil and gas storage in the tanks. Additionally the smart objects may also include sensors for surveillance to monitor the surrounding environment. In case of any anomalous event when measurements are not within the specified limits the smart object either warn the pumping station to stop pumping more crude oil or gas, generate fire alarm or security alerts as well as inform the mobile unit /staff or nearby maintenance personnel for further action.

When the smart objects are installed on Well heads, they will contain pressure and temperature sensors that will collect temperature and pressure measurements from wellhead and level and flow sensors will provide historical and real time flow data. This wealth of information will be delivered to the control center for analysis. Smart objects on other equipment at the well site (like tanks or compressors) will collaborate with the smart objects at the well heads to avoid equipment theft, crude oil and natural gas theft and catastrophic failures as well as to ensure that wells are operating efficiently, while minimizing downtime. Also pressure relief valves are sensed continuously. If these measurements are within the specified limits then it will only deliver it to the control center as a usual process but if these measurements are not within the specified limits and some anomalous event is being occurred, the smart object will either generate fire alarms, alert the security personnel or inform the mobile unit/staff or nearby maintenance personnel as well as to the control center for further processing. The smart objects are also connected to the cathodic protection unit and high integrity pipeline protection system for predictive maintenance of well head equipment and warn earlier about the assets that require maintenance.

When a plurality of smart objects is installed on oil & gas Pipelines, they will take measurements from temperature pressure, vibration and flow sensors and if these measurements are within the specified limits the sensed data is delivered to the control center as a usual process. Otherwise the smart object will either suggest predictive maintenance or in case if an anomalous event has occurred it will generate fire alarms or security alarms as well as it will also inform the mobile unit/staff or nearby maintenance personnel for taking further action. The smart objects on pipelines are also connected to the cathodic protection unit for predictive maintenance.

When smart objects are installed on Pumps, they will take measurements from temperature, pressure and vibration sensors and if these measurements are within the specified limits the sensed data is delivered to the control center as a usual process. Otherwise the smart object will either suggest predictive maintenance or in case if an anomalous event has occurred it will generate fire alarms or security alarms as well as it will also inform the mobile unit/staff or nearby maintenance personnel for taking further action. For example in case of oil and gas leakage or spillage the smart objects will communicate the command to the closest pumping station to stop pumping more oil. In case, if any accident occurs it will also help in knowing how many people to evacuate.

The smart objects will optimize the operations like pumping activities etc. while monitoring and gathering more data and information about different business processes resulting to introduce efficiencies in all the three sectors of oil and gas industries. It will quickly locate and detect the anomalous events and not only deliver the critical information to the control center but also informs and alarms the Mobile Unit (person) to draw his/her intention towards problematic area for possible solutions. The hazardous areas can be monitored easily and remotely with fewer visits.

The smart objects will also perform Geo-fence perimeter security. The continuous monitoring ability of smart objects will help the operators to respond more quickly to any kind of security breach in the oilfield environment. The entire oilfield, authorized personnel and visitors will be assigned an active RFID tags.

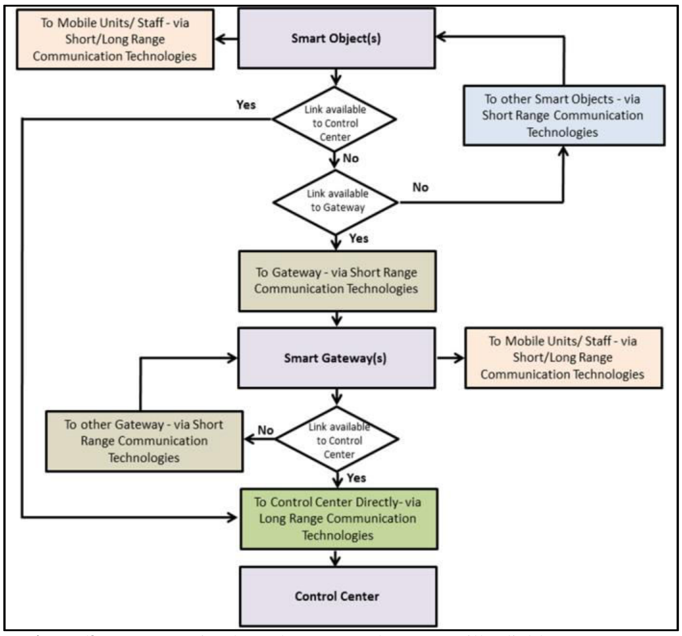

Figure 2. Chart representing how the proposed system will reliably, efficiently and accurately communicates the sensed information to the control center.

The smart objects will be equipped with presence sensing sensors (motion sensors) that are able to sense the movement. This movement data is shared with the gateways to check for the authorized personnel movement. If third party intruder (unauthorized personnel) movement is detected around the assets, the smart objects will generate alarms. Moreover, the smart objects will monitor the surroundings and gather data about the oil field environment to prevent pipeline theft that consequently helps in saving time and money, reducing revenue losses and protecting public safety by quickly and accurately detecting illegal taps. Our proposed system will deliver the correct information to the right person, either plant personnel or remote experts, and at the right time.

B. Reliable and Efficient Communication

The proposed system provides a method for communicating the sensed information reliably and efficiently to the control center. Figure. 2 represents a schematic view (flow chart) that illustrates how our proposed system will reliably, efficiently and accurately communicates the sensed information about the anomalous event zone (defects) within the oil field environment to the control center and taking possible measures to solve the problem. As shown in Figure. 2 when the leak or any other anomalous event is detected, the smart object first tries to send the sensed information directly to the control center through long range communication. If the direct link to the control center is not available, the smart object communicates with its connected gateway using short range communication to handover the information to the control center. But if the link to its connected gateway is not available then it will communicate with other nearby smart objects through short range communication for communicating the sensed information to the control center. When the link to the connected gateway is available to the smart object, then the gateway will hand over the information to the control center through long range communication as well as the nearby mobile units or maintenance personnel through short range communication for repairing and taking possible actions. In either case the gateway will try to communicate to nearby gateways through short range communication for communicating the sensed information to the control center. Thus in this manner the sensed information about any anomalous event will be delivered in any case to the control center reliably and efficiently. The smart objects installed on various assets (pipelines, tanks, well heads, pumps and pressure relief valves) of the oil field environment will be interconnected and will collaborate with each other intelligently and share the sensed information to achieve a common goal [42]. Their goal will be to detect or diagnose any kind of catastrophic failure or anomalous event around the whole oil field environment in timely and reliable manner to reduce revenue costs, overall downtime, increase production costs and avoid environmental or personnel damage.

V. CONCLUSION

Oil and gas industrial operations need specific skills and continuous monitoring to ensure smooth functioning of all the operations in the oilfield environment. IoT is the most potential solution for driving core processes of the three sectors of the oil and gas industrial environments in a more efficient and reliable manner. In this paper we propose an internet of things (IoT) based reliable monitoring system that involves smart objects installed on various assets of the oil and gas fields to facilitate various operations of the O&G environment. This system with minimum human intervention will provide better workplace safety and maintenance of assets. Our proposed system will perform predictive maintenance of various oil and gas industrial assets by analyzing various parameters (sensed data) and detecting failure modes either before they are going to take place or when the equipment will likely to fail or need service.

REFERENCES

[1] Boyer, Stuart A. SCADA: supervisory control and data acquisition. International Society of Automation, 2009.

[2] Atzori L, Iera A, Morabito G, Nitti M (2012) The Social Inter-net of Things (SIot)—when social networks meet the internetof things: concept, architecture and network characterization. Comput Netw 56(16):3594–3608.

[3] Abreu, David Perez, Karima Velasquez, Marilia Curado, and Edmundo Monteiro. "A resilient Internet of Things architecture for smart cities." Annals of Telecommunications (2016): 1-12.

[4] Hao Y, Linke G, Ruidong L, Asaeda H, Yuguang F (2014) Dataclouds: enabling community-based data-centric services over the Internet of Things. IEEE Internet of Things J 1(5):472–482.

[5] Mohammad Reza Akhondi, Alex Talevski, Simon Carlsen, Stig Petersen, "The role of wireless sensor networks (WSNs) in industrial oil and gas condition monitoring", IEEE DEST 2010, pp. 618-623.

[6] Minetti, G. "Wireless Sensor Networks Enable Remote Condition Monitoring." Pipeline & Gas Journal 239, no. 7 (2012): 53-54.

[7] Adejo, A.O., Onumanyi, A.J., Anyanya, J.M. and Oyewobi, S.O., 2013. Oil And Gas Process Monitoring Throughwireless Sensor Networks: A Survey. Ozean Journal of Applied Science, 6(2).

[8] Savazzi, S., Guardiano, S. and Spagnolini, U., 2013. Wireless sensor network modeling and deployment challenges in oil and gas refinery plants. International Journal of Distributed Sensor Networks, 2013.

[9] Talevski, A., Carlsen, S. and Petersen, S., 2009, June. Research challenges in applying intelligent wireless sensors in the oil, gas and resources industries. In 2009 7th IEEE International Conference on Industrial Informatics (pp. 464-469). IEEE.

[10] Brent E. McAdams, "Wireless Sensor Networks Applications in Oil & Gas", AN-1105-001, ENTELEC, Conference & Expo, April 28-28, 2016, Houston, TX, USA. [online available]

http://www.automation.com/pdf_articles/oleumtech/AN_Wireless_Sensor_Networks_Applications_in_Oil_Gas.pdf.

[11] Jin, Y. and Eydgahi, A., Monitoring of distributed pipeline systems by wireless sensor networks. In Proceedings of The. 2008, November.

[12] Cegla, Frederic, and Jon Allin. "Ultrasonic Monitoring of Pipeline Wall Thickness with Autonomous, Wireless Sensor Networks." Oil and Gas Pipelines: Integrity and Safety Handbook (2015): 571-578.

[13] Nwalozie, G C; Azubogu, A C O; Okafor, A C; Alagbu, "Pipeline Monitoring System Using Acceleration-Based Wireless Sensor Network",E E. IUP Journal of Telecommunications7.2 (May 2015): 42-58.

[14] Henry, Nweke F., and Ogbu N. Henry. "Wireless sensor networks based pipeline vandalisation and oil spillage monitoring and detection: main benefits for nigeria oil and gas sectors." The SIJ Transactions on Computer Science Engineering & its Applications (CSEA) 3, no. 1 (2015): 1-6.

[15] Yoon, Sunhee, Wei Ye, John Heidemann, Brian Littlefield, and Cyrus Shahabi. "SWATS: Wireless sensor networks for steamflood and waterflood pipeline monitoring." IEEE network 25, no. 1 (2011): 50-56.

[16] Kim, Jong-Hoon, Gokarna Sharma, Noureddine Boudriga, and S. Sitharama Iyengar. "SPAMMS: A sensor-based pipeline autonomous monitoring and maintenance system." COMSNETS 10 (2010): 118-127.

[17] Jawhar, Imad, Nader Mohamed, and Khaled Shuaib. "A framework for pipeline infrastructure monitoring using wireless sensor networks." In Wireless Telecommunications Symposium, 2007. WTS 2007, pp. 1-7. IEEE, 2007.

[18] Mohamed, Nader, Imad Jawhar, Jameela Al-Jaroodi, and Liren Zhang. "Monitoring underwater pipelines using sensor networks." In High Performance Computing and Communications (HPCC), 2010 12th IEEE International Conference on, pp. 346-353. IEEE, 2010.

[19] Al-Faiz, Mohammed Zeki, and Liqaa Saadi Mezher. "Cathodic protection remote monitoring based on wireless sensor network." Wireless Sensor Network 4, no. 9 (2012): 226.

[20] Hozoi, Adrian, Zoltan Papp, and Peter van der Mark. "Sensor Network for Corrosion Monitoring." Wireless Sensor Network: 28.

[21] Yi, Pan, Lizhi Xiao, and Yuanzhong Zhang. "Remote real-time monitoring system for oil and gas well based on wireless sensor networks." In Mechanic Automation and Control Engineering (MACE), 2010 International Conference on, pp. 2427-2429. IEEE, 2010.

[22] Gao, Meijuan, Jin Xu, and Jingwen Tian. "Remote monitoring system of pumping unit based on wireless sensor networks." In Industrial Technology, 2008. ICIT 2008. IEEE International Conference on, pp. 1-4. IEEE, 2008.

[23] Xu, Qinghua, Jinyu Jiang, and Xianbiao Wang. "Research and Development of Oil Drilling Monitoring System Based on Wireless Sensor Network Technology." In Networks Security, Wireless Communications and Trusted Computing, 2009. NSWCTC'09. International Conference on, vol. 2, pp. 326-329. IEEE, 2009.

[24] C. Karlof, D. Wagner, "Secure Routing in Wireless sensor networks: attacks and countermeasures", In: Proc. of first IEEE international workshop on sensor network protocols and applications, May 2003.

[25] A. Wood, J. A. Stankovic, "Denial of service in sensor networks," IEEE Computer, 3 (10):54-62, October 2002.

[26] Khan, W. Z., Aalsalem, M. Y., Saad, N. M., Xaing, Y., & Luan, T. H. (2014, April). Detecting replicated nodes in wireless sensor networks using random walks and network division. In Wireless Communications and Networking Conference (WCNC), IEEE , pp. 2623-2628, 2014.

[27] Zeng, Y., Cao, J., Zhang, S., Guo, S., & Xie, L. (2010). Random-walk based approach to detect clone attacks in wireless sensor networks. Selected Areas in Communications, IEEE Journal on, 28(5), 677-691, 2010.

[28] Khan, W. Z., Aalsalem, M. Y., & Saad, N. M. (2015). Distributed clone detection in static wireless sensor networks: random walk with network division. PloS one, 10(5), e0123069, 2015.

[29] Aalsalem M Y, Khan W Z, Saad N M, et al. A New Random Walk for Replica Detection in WSNs[J]. PloS one, 2016, 11(7): e0158072.

[30] Sabata, Ashok, and Sean Brossia. "Remote monitoring of pipelines using wireless sensor network." U.S. Patent 7,526,944, issued May 5, 2009.

[31] Allison, Peter S., Charles E. Chassaing, and Bryan Lethcoe. "Acoustic impact detection and monitoring system." U.S. Patent 7,607,351, issued October 27, 2009.

[32] Ivan Stoianov, Lama Nachman, Sam Madden, and TimurTokmouline, "PIPENET: Wireless Sensor Network for Pipeline Monitoring," IPSN'07, April 25-27, 2007, Cambridge, Massachusetts, U.S.A.

[33] Louis, P.M.I. and Cooper, J.F., Lawrence Livermore National Security, Llc, 2008. Acoustic system for communication in pipelines. U.S. Patent 7,423,931.

[34] George Kokossalalus, Acoustic Data Communication System for In-pipe Wireless Sensor Networks, Ph.D. Thesis, 2006.

[35] Jack, Nathan, and Krishna Shenai. "Methods and systems for wireless communication by magnetic induction." U.S. Patent 7,831,205, issued November 9, 2010.

[36] Zhi Sun, Pu Wang, Mehmet C. Vuran, Mznah A. Al-Rodhaan, Abdullah M. Al- Dhelaanjan F. Akyildiz, "MISE-PIPE: Magnetic induction-based wireless sensor networksfor underground pipeline monitoring," Ad Hoc Networks 9 (2011) 218-227.

[37] Liang, Kenneth Kin-nam, Jacques Jundt, and Philippe Salamitou. "Downhole sensor networks using wireless communication." U.S. Patent 7,602,668, issued October 13, 2009.

[38] Wu, Dalei, Kamal Youcef-Toumi, Samir Mekid, and Rached Ben-Mansour. "Wireless Communication Systems for Underground Pipe Inspection." U.S. Patent Application 14/569,889, filed December 15, 2014.

[39] Winter T, Thubert P, Brandt A, Hui J, Kelsey R, Levis P, Pister K, Struik R, Vasseur J, Alexander R (2012) RPL: IPv6 routing protocol for low-power and lossy networks, IETF, IETF, RFC 6550, March 2012, [Online]. Available: https://tools.ietf.org/html/rfc6550.

[40] Akusok A, Bjork KM, Miche Y, Lendasse A (2015) High-performance extreme learning machines: a complete toolbox for big data applications. Access, IEEE 3:1011–1025.

[41] Palattella MR, Accettura N, Vilajosana X, Watteyne T, Grieco LA, Boggia G, Dohler M (2013) Standardized protocol stack for the Internet of (important) Things. IEEE Commun Surv Tutorials 15(3):1389–1406.

[42] Wazir Zada Khan, Mohammed Y Aalsalem, Muhammad Khurram Khan, Quratulain Arshad, When social objects collaborate: Concepts, processing elements, attacks and challenges, Computers & Electrical Engineering, November 2016, http://dx.doi.org/10.1016/j.compeleceng.2016.11.014