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Methodology for Monitoring Manufacturing Environment by Using Wireless Sensor Networks (WSN) and the Internet of Things (IoT)

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Abstract

Manufacturing currently faces tremendous potentials with the rapid development of Wireless Sensor Networks (WSN) and Internet of Things (IoT). As one example, a real-time application for environment monitoring in manufacturing will offer the opportunity to improve its resource and energy efficiency. This requires a structured approach to integrating both WSN and IoT. Although established technology exists, there is a lack of methodology to construct multiple hardware and software platforms and interoperate them effectively. Thus, this paper presents a two-step framework in order to first design a system architecture and then to determine selection criteria for each component. A case study for temperature monitoring is presented for a proof-of-concept.

Keywords: Internet of Things; Wireless Sensor Networks; Environment; Manufacturing

1. Introduction

Rapid growth in emerging markets has triggered a dramatic increase in demand for resources and energy in the manufacturing industry. In fact, the industry sector accounts for over 30% of the total energy produced in the world [1]. Besides the increasing energy and commodity prices, the associated environmental impact of manufacturer's energy consumption directly contributes to the global challenges such as sustainability, climate change [2]. Manufacturers today are already feeling the pressures in their daily operations, and these challenges will persist, if not intensify.

From the life cycle engineering point of view, improving energy and resource efficiency has been identified as the key strategy to improve the sustainability in manufacturing [3]. When applying the holistic view on a manufacturing system, the technical building services (TBS) have been highlighted as a hotspot for improvement [4]. The ambient environment of a manufacturing facility (e.g. temperature, humidity, air quality) may need to be precisely regulated not only because of comforts but also due to stringent specifications and regulations, such as operation constraints, OH&S (occupational health and safety) requirements, product requirements, etc. Consequently, HVAC (heating ventilation and air-conditioning) systems often account for a significant share of the total energy consumption (over 10% at the industry level according to [1]). Thus, a continuous management and intelligent control of the ambient environment has a great potential to improve the energy and resource efficiency of a manufacturing facility.

In recent years, there has been an increasing technological shift towards a decentralised network of interconnected objects, all equipped with 'Intelligent' decision-making and data-gathering capabilities. This paradigm shift is what is currently referred to as the 'Internet of Things (IoT)', and represents tremendous opportunities for new applications across a wide range of sectors [5]. For example, applications of the IoT have seen widespread adoption in areas such as household energy metering and medical device monitoring. However, the development and application in the manufacturing domain still remain in the early stage [6-7]. A number of concepts and frameworks have been identified the

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areas for implementing IoT in manufacturing, such as smart enterprise control, asset performance management, augmented operators [7].

For the case of condition monitoring and management in manufacturing industries, the wireless connectivity and the cloud-based architectures of IoT technology can overcome previous cost barriers due to physical connectivity (the cost of cabling to the sensors) and logical connectivity (integration with existing systems) [7]. However, there is a lack of consolidated learning models to construct multiple hardware and software platforms and interoperate them effectively. Therefore, this paper presents a methodology to first design a system architecture and then to determine selection criteria for each component.

2. Background

This section reviews the recent development of technologies deemed relevant for the application of monitoring manufacturing environment.

- **Internet of Things (IoT)**

The term ‘Internet of Things’ was first used to describe Radio Frequency ID (RFID) systems developed by Procter & Gamble to more closely monitor elements of their supply chain [8]. Since then, this term has been used rather erratically with several diverging definitions. For example, The Institute of Electrical and Electronics Engineers (IEEE) define IoT as “*… a self-configuring and adaptive system consisting of networks of sensors and smart objects whose purpose is to interconnect ‘all’ things…*” [9]. Although this definition captures the underlying ideas behind the technology, the claim that the IoT is a self-configuring system has been criticised as unrealistic and inaccurate by [10]. While intelligent devices that are able to configure themselves to any application is the ultimate goal behind the IoT, the reality is that most of these devices must be configured manually and require a certain level of human input. McKinsey defines the IoT as consisting of “*objects that can both sense the environment and communicate… (becoming) tools for understanding the complexity and responding to it swiftly*”[11]. In order to further explain this high-level definition, Haller provides further description of the components for a typical IoT system: the ‘thing’ in question is the entity of interest, i.e. the object whose state we want information about; to do this, a ‘device’ or sensor can be either attached to the ‘thing’ or used to monitor the ‘thing’; ‘resources’ are the computational elements hosted by a ‘device’ in order to provide calculations or automation; finally, ‘services’ are the methods which allow users to view all this information, for example, a cloud platform that stores data from a temperature sensor, allowing viewers to view this data remotely.

In the industrial domain, the related concept of Industry 4.0 is another big technological shift occurring today. Industry 4.0, or the ‘Fourth Industrial Revolution’ refers to the networking of industrial components such as sensors, machines, and workpieces in order to facilitate the exchange of data enabling more efficient manufacturing processes [12]. The Industry 4.0 is considered by some to be the ‘Industrial Internet of Things’. A similar concept of a Cyber-Physical System (CPS) was first introduced by the National Science Foundation. There is widespread confusion about the differences between CPS and IoT. In an effort to set a clear distinction, Jeschke defines CPS as a closed-loop application of the IoT concept, with a strong focus on controlling the underlying physical systems [13]. Although developing control mechanisms is outside the scope of this paper, there is considerable overlap in some of the conceptualised design and components used.

As mentioned earlier, the industrial IoT remains at the concept and framework development stage. A number of barriers have been recognised at the early stage [14] which include, but are not limited to:

Existing legacy systems: Firms are often unwilling to forgo large amounts of capital expenditure to adopt a new disruptive technology when they already have significant amounts of capital invested in older technologies.

Lack of interoperability: There is a lack of integrated end-to-end solutions on the market, with firms having to utilise hardware and software from multiple platforms to create the required system.

Lack of existing learning models: Although there are a few theoretical frameworks for implementation that are well regarded, there are not many well documented practical applications for a new adopter to learn from

Correspondingly, the proposed methodology in this paper attempts to address these barriers.

- **Wireless Sensor Networks (WSN)**

Wireless Sensor Networks (WSN) can be described as the networked layer of nodes and sensors that together enable the monitoring of a specific environment. It has been increasingly recognized as a useful component for IoT and Industry 4.0 [15]. A typical WSN consists of multiple sensor nodes and base stations. Sensor nodes typically have to measure analog signals, use an Analog to Digital Converter (ADC) and transmit these values through the use of a radio frequency (RF) protocol. The base station in most applications of WSNs utilises a computer coupled with an RF transceiver to receive and decode of the inbound packets. The computer can be replaced with a microprocessor, which is a more elegant and cost-effective solution. There are different types of topology to structure a WSN, including star topology, mesh topology, and star-mesh hybrid [16]. A growing number of applications have been seen in the field of military surveillance, home healthcare, smart home, and environmental science [17].

A number of challenges have been identified when designing a WSN:

Large data quantity: WSNs typically have a very high spatial resolution, which means that any architecture developed needs to be able to handle large amounts of incoming and outgoing data. Transmission synchronization is also an issue as several packets of data transmitting at the same time can cause problems for receivers [16].

Network robustness: In order to maintain the robust communication of such a large network of devices, mechanisms for the redundancy of the network must be developed, which is a challenge due to cost requirements [18].

Power consumption: Sensor nodes are commonly battery-powered which will require maintenance efforts to replace and recharge the system regularly. The energy efficiency of the nodes is also critical for a wide industry adoption.

Higher cost: A key challenge of WSNs is their higher cost comparing to conventional legacy monitoring systems which often consist of just analog sensors linked to data logging machines.

Data security: Industrial application of WSNs often transmits sensitive firm data that can be harmful in the wrong hands. There is ongoing research into the development of better encryption standards, but at the very minimum, WSNs developed must meet industry standard 128-bit AES (Advanced Encryption Standard) encryption [19].

3. Methodology

Based on above research background, this section presents a two-step framework in order to first design a system architecture and then to determine selection criteria for each component [20].

3.1. Step One - System architecture design

The first step is developed to provide a conceptual and technology-agnostic architecture to construct a WSN incorporating the IoT for the purpose of monitoring manufacturing environment. This architecture is deemed to be generic which can be easily adopted from case to case.

There are a number of proposed architectures in literature which provides valuable experience. For instance, Zhang et al. proposed a 4-layer system architecture for a large scale application of monitoring temperature in warehouses. However, this structure is designed specifically for complex system and only allows a simple network topology for the sensing layer [21]. Texas Instruments developed the architecture based on 6LoWPAN, or ‘IPv6 over Lower-Power Wireless Personal Area Networks’ which is an emerging networking technology to utilise IPv6 data packets to connect a WSN to the internet [22]. However, there is a lack of hardware on the market that utilises this protocol. Ahmed and Gregory discussed the possibility of WSNs transitioning into modern IoT systems through the use of cloud computing technologies [23]. However, the system faces difficulties with different interfaces, which means APIs (application programming interface) do not always exist.

By adopting existing frameworks, the proposed generic architecture is illustrated in Fig.1. The components are split into four layers:

Layer 1: The data acquisition comes from a traditional WSN. To keep the architecture flexible, no attempt is going to be made to define a network topology. Correspondingly, the choice of RF module will become selection criteria in Step 2.

Layer 2: The WSN interfaces with a microcontroller to deliver the data. Data processing, as well as interfacing with online systems, will be handled by this device. By utilising a microcontroller rather than a PC, the cost can be reduced significantly and direct communication with the internet can be realised.

Layer 3: A subscription cloud solution is preferred over a static server comparing to the 4-layer framework proposed by [21]. Subscription Software-as-a-Service (SaaS) and Platform-as-a-Service (PaaS) solutions are increasingly offering more than just data storage. Data analytics and notifications can be handled on the server side, simplifying and streamlining the entire architecture.

Layer 4: A mobile application is recommended in order to make the data more accessible. The data can also be accessed through a web browser on the cloud platform via a standard PC.

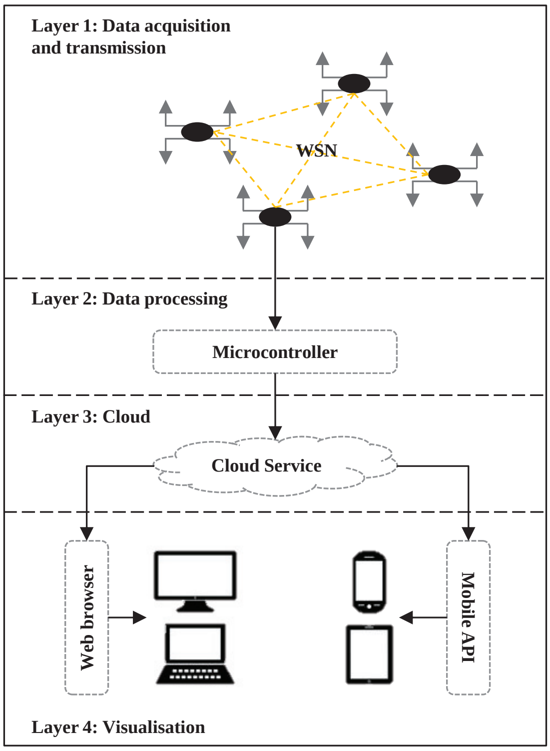


Fig. 1. Developed system architecture

3.2. Step Two – Selection criteria for components

As mentioned earlier, specific hardware and software products have not been mentioned in the architecture in Fig.1. Accordingly, the step two is to provide a qualitative guideline to select a product for each layer as summarised in table 1. It can also be used as an evaluation tool when comparing different systems.

Specifically, there are three significant design decisions to be made in Layer 1:

Network topology selection: Network topology is highly dependent on the use case and as such is difficult to standardise without knowing the specifications of potential applications. Nevertheless, RF modules that enable easy and fast switching of topologies are preferred to keep the

Table 1. Summary of selection criteria by layer

Sub-system	Design decisions	Selection criteria
Layer 1: Data acquisition and transmission	Network topology selection	• In-built ADC • Can hand multiple topologies • Minimal programming capacity • Encryption capability
	Transmitting RF module	
	Sensor selection	• Analog preferred over digital
Layer 2: Data processing	Receiving RF module	• Ability to hand transmission synchronisation
	Microprocessor selection	• Easily programmable • Ability to interface with chosen RF modules • Ability to connect to the internet
Layer 3: Cloud	Subscription cloud platform	• Provided API for interfacing • Server side computing
Layer 4: Visualisation	Selection of a mobile OS for development	• Easy to use graphing/ analytics libraries • Real-time notifications support

RF = Radio Frequency; ADC = Analog to Digital Converter;
API = Application Programming Interface; OS = Operating System

design adaptable. Topology can widely differ depending on the scale of the application, redundancy requirements, and available sensor power.

RF module selection: Unlike other systems, a microprocessor is considered unnecessary for this purpose in this framework as it increases the cost and energy consumption significantly. Alternatively, the recommendation is to stipulate an integrated RF module with limited built-in processing functionality. At the minimum, the module must be able to convert analog to digital signals (for sensor measurements), handle multiple topologies and have limited ability to be programmed. By selecting a programmable sensor, factors such as sample rates, sleep times and packetisation of data can be controlled easily without having to build complex circuitry. In addition, an RF module with modern encryption standards is mandatory.

Sensor selection: Sensors are selected for the specific task that the network is set up to measure and as such is hard to provide specific selection criteria. As a general recommendation, analog sensors are suggested over digital sensor due to the cost reasons. Also, the presence of an onboard ADC on the RF module would make a digital sensor redundant.

At the layer 2, there are two main design decisions to be made:

Receiving RF module: the same RF module characteristics described in Layer 1 are desirable for receiving modules. In addition, the ability to handle transmission synchronisation is desired.

Microprocessor selection: The microprocessor selected should be easily programmable while also being low-cost and able to run off a battery power. It is crucial that the microprocessor has off the shelf components for interfacing with the selected RF modules, saving operator time and enabling easier operation. The microprocessor should also have a networking capability to interact with internet systems.

At the layer 3, the subscription could platform should be able to easily handle the inflow and outflow of large amounts of data. A cloud platform with an API is essential, as the authentication procedures involved are time-consuming without an API. As an additional requirement, the ability to handle data analysis and provide server-side notifications will also be valuable. This means that development can take place independent of which platform the user is using.

At the layer 4, the selection of a mobile OS for development is more of the than not a question of what the customer's requirements or preferences are. The aim of the developed application is to be able to view the data in real time as well as the visualisation of historical data. The ability to easily handle notifications is also preferable.

4. Case study

In this section, a case for metering and monitoring of temperature in an office environment was selected for the purpose of demonstration and proof-of-concept, which was used as a test bed before the large scale and costly implementation in other parts of the manufacturing facility.

The office is approximately 60 m^2, equipping with 14 working stations. There are 3 HVAC ducts at the ceiling towards the southern end of the room and large windows on the northern elevation. In addition, the HVAC system is centrally controlled and the temperature cannot be adjusted locally in the room. As a result, the temperature disparity and irregularity were the main complaints from the office residents. Thus, the temperature system was designed to quantify the temperature change in the room. Following the proposed design methodology, the implemented monitoring system consists of four layers as shown in Fig.1. Owing to a generic architecture, there was no adjustment to the step one in 3.1. The following section demonstrates the selection of key components according to the guideline presented in 3.2.

- **Layer 1**

According to Table 1, two RF modules are compared as summarised in table 2. Consequently, the Digi Xbee® series was chosen after the assessment.

Table 2. Selection of RF modules

	Ciseco® XRF RF	Digi Xbee® Series
ADC capability	Yes, up to 4 inputs	Yes, up to 6 inputs
Ability to hand multiple topologies	Yes, but have to be manually programmed	Yes, almost any topology can be configured with firmware updates
Programmable	Yes, no software exists so not user-friendly	Yes, through the use of X-CTU software
Encryption	AES 128-bit standard	AES 128-bit standard

Facility Management of the building confirmed the air-conditioning set point was 22℃. A simple analog sensor was required with a suitable operating range and error rating of not more than a few degrees. Since analog temperature sensors are almost homogenous, the easiest one to source for this case study (due to shipping time) was chosen. The selected TMP36 is a low voltage, precision temperature sensor (±1℃), which is also suitable to operate with microprocessors and the selected RF module XBee.

As this was a small-scale proof-of-concept, only 3 modules were used in the network. A simple star topology was utilised due to the small scale of the application. Utilising a mesh network for a complex application on XBee devices only requires a different firmware installation. In other words, the framework and selection remain largely valid even with more modules added or a different WSN topology.

- **Layer 2**

Since the RF module has been defined, the layer 2 selection was mainly focused on selecting microprocessors as shown in table 3. Both options can effectively fulfil the design requirements, where Raspberry Pi® seems over-engineered for the tested case. In addition, the authors favoured Ardurino® mainly due to the presence of the Xbee® APIs. In other words, programming for these devices was significantly easier.

Table 3. Selection of microprocessors

	Arduino®	Raspberry Pi ®
Description	Small, open source microprocessor	Small, miniature System-on-a-chip Computer (SoC)
Easy to program	Yes, programmed through a serial interface on a PC; utilises a C-based programming language; available learning resources on the internet.	Yes, capable of running a full OS such as Windows 10; but slightly over-complex for design requirements
Ability to interface with Xbee modules	Yes, interfacing hardware and APIs exist	Yes, interfacing hardware but no specific APIs exist
Internet connectivity	Yes, but an external adaptor has to be purchased	Inbuilt Ethernet and Wi-fi

- **Layer 3**

Three cloud platforms were compared according to the proposed framework as listed in Table 4.

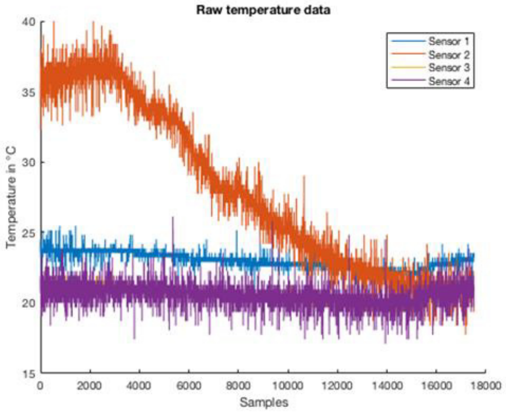
Table 4. Selection of microprocessors

	IBM BlueMix®	Data.Sparkfun®	AWS Cloud Services®
Ease of use	Not easy, requires developer experience	Easy to use, with multiple tutorials	Intermediate, with multiple tutorials
API	APIs provided, but not many user documentations exist	APIs with beginner functions, tutorials to gain access with Arduino®	Extensive range of APIs
Server side computing	Extensive suite of server-side capabilities, including notifications, analytics, and artificial intelligence	Basic, can only see data pipelines	Extensive suite of server-side capabilities, including machine learning and analytics

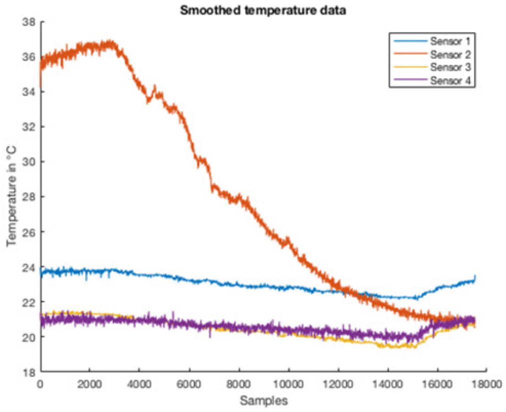
Due to the relatively simple requirements of this case, the Data.Sparkfun® was selected for its simplicity and extensive range of learning resources. Nevertheless in more complex applications of WSNs, with larger amounts of data, services such as machine learning and artificial intelligence can provide a great value.

- **Layer 4**

The visualisation was simplified for this case. By using a live serial connection, real-time data was able to be observed on a PC as shown in Fig.2. The initial data collected is extremely noisy (see Fig.2.a), with many fluctuations of up to a few degrees. This was expected of analog components with transient components of the circuitry planning a part. Instantaneous readings can vary and an average of a few points should be used. Thus, a moving average filter was used to smooth the data and the results are shown in Fig.2.b. The results were further validated by comparing to the reading from a thermometer.



a) Data as recorded



b) Data after applying a moving average filter

Fig. 2. Example of temperature monitoring

The results presented in Fig.2 were collected between 1:30pm to 7:00pm in May. The sensor 2 was located on the windowsill and was directly exposed to sunlight which reflects the temperature change in the outside environment. However, there was a clear temperature difference among other sensors. The sensor 1 was located in the middle of the office which was constantly 1-2 ℃ above the HVAC set-point. In comparison, the sensor 3 and 4's readings were continuously under the set temperature. Thus, the temperature disparity and irregularity have been confirmed.

After the successful testing of the concept, the same design methodology and the developed system are being tested for monitoring the temperature for a pharmaceutical warehouse. The enforced regulations require manufacturers to closely monitor and precisely control the environment where the products are stored [24]. The warehouse application faces further challenges including largely non-controllable events such as doors opening, large amounts of inventory causing an increase in specific heat capacity [20]. The signal interference and data loss in a WSN are also observed due to the structure of the warehouse and large amounts of stored liquid products. The findings and lessons learnt from the warehousing application will be presented in the future.

5. Conclusions and Outlooks

This paper has developed a generic methodology for designing a Wireless Sensor Networks for the aim of monitoring manufacturing environment. Furthermore, this method has laid the platform for a more seamless integration of WSN and the Internet of Things. Through following the 2-step framework, any adapter can aim to achieve a monitoring solution specific to their needs.

A case study of temperature monitoring in an office environment was presented for demonstrating and proving the proposed methodology. Although there is a clear difference between offices and manufacturing facilities, the observed temperature disparity and irregularity in the case study will be only intensified in manufacturing industries. In other words, there is a much greater improvement opportunity for manufacturers through a close monitoring of their facilities. The use of WSN and IoT can overcome existing barriers such as large capital investment, physical and logical connectivity. The benefits of such practices will not only benefits manufacturers with a reduced cost and ensured quality from the economic perspective, but also a reduction in energy consumption and the associated environmental impact.

To realise these benefits, industrial IoT requires further research to address challenges such as big data, data security, etc. In addition to the technology issues, a life cycle perspective of deploying such complex system is also necessary to guarantee a feasible and positive outcome. Thus, another future work is recommended to conduct life cycle assessment of increased use of information and communication technologies (ICT) with the advent of IoT and WSN.

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