Intelligent Low-Cost Monitoring for Smart Digital Manufacturing

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Abstract

With the accelerated penetration of cloud computing and Internet-of-Things (IoTs) in contexts such as smart factories, digital manufacturing has been introduced to improve the effectiveness of manufacturing by taking advantage of massive amount of digital information. One of the digital manufacturing pathways is collecting data from IoT services and analyzing the data in a centralized manner. However, most smaller companies do not have the infrastructure and capabilities to embrace this opportunity and hence are inhibited to benefit from digital manufacturing. This paper reports on a blueprint that alleviates this problem by creating a low cost paradigm to aggregate data for Small and Medium Enterprises (SMEs) in smart digital manufacturing. This paper focuses on intelligent low-cost solutions and IoT services, aiming to identify candidate intelligent low-cost technologies and propose an affordable system to provide insights from aggregated data of SMEs. Finally, an example of real-world implementation shows the potential of integrating low-cost, off-the-shelf technologies into smart digital manufacturing.

1 Introduction

Recently, thanks to the development of digital technology, we have witnessed rapid advances in the manufacturing sector. With the help of the Internet of Things (IoTs), a wide range of edge devices send massive volumes of data to cloud-based data centers. Such edge-cloud federation can greatly facilitate the digital manufacturing paradigm because a key aspect of digital manufacturing is monitoring processes or the environment and provides novel insights for decision-making. Monitoring has become increasingly important for quality and safety control in manufacturing [1]. Digital monitoring systems have been proposed to process a large amount of data that capture the characteristics of manufacturing operations. However, these systems are generally only affordable for large companies as most SMEs lack such technology and funding [2].

Hence, we propose a different approach that adopts low-cost sensing solutions and a lightweight network protocol, sending data to remote cloud data centers with resource-constrained edge devices and limited bandwidth [3]. One of the key insights in the work is to develop reusable service modules for low-cost solutions over edge devices with limited computing and bandwidth resources [4]. This is primarily because low-cost edge devices are usually equipped with limited resource capacity and low reliability. Therefore, it is challenging to devise a lightweight, robust and simple-to-implement solution that collects data and enables connections to remote datacenters. The aim of this work is to present an architecture for low-cost monitoring in an industrial environment that contributes to digital manufacturing.

The remainder of this paper is organized as follows. We first provide an overview of related work in section 2. Section 3 presents the architecture of low-cost solutions from end-to-end. Candidate low-cost solutions are presented in section 4. Then, we demonstrate an example implementation in section 5. Finally, we conclude the paper with a discussion in section 6.

2 Related Work

2.1 Monitoring in manufacturing

There is a wide range of works focusing on monitoring in digital manufacturing. Gomaa *et al.* [5] focus on highlighting the potential of digital earth construction on an industrial scale. Many other works focus on monitoring such as temperature, air quality and vibration. These three techniques have been widely studied by a number of works [2], [6]. Jagtap *et al.* [7] adopt a specially positioned camera to identify damaged, unusable potatoes and Convolutional Neural Network to decide the potential reasons of potato waste generation. Gramegna *et al.* [8] show the applicability of data-driven digital twins for process monitoring, predicting the quality and cost of complex manufacturing. Chen *et al.* [9] adopt radio frequency identification and industrial Internet of things to monitor the real-time status of the shop floor in manufacturing. The multi-thread real-time data collection, storage technology and product tracking technology are studied. Zheng *et al.* [10] propose a hybrid sensing-based approach to monitor shared manufacturing resources. This approach adopts the sensor and customer data for cost-efficient value creation. However, most existing solutions for monitoring largely overlook the hardware and installation costs and hence fail to cope with limited resource capacities and low reliability between edge devices. Therefore, there are benefits in investigating low-cost and resource-efficient solutions for digital manufacturing with edge devices.

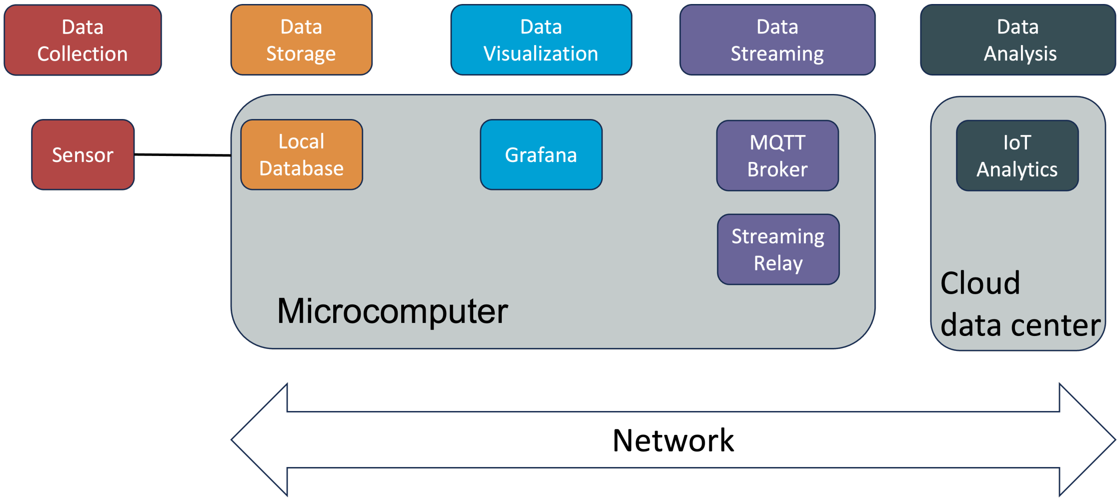

Figure 1: Blueprint for a stand-alone solution

2.2 Low-cost monitoring in manufacturing

There is a number of works investigating low-cost solutions for manufacturing from the state-of-the-art.

Some works adopt microcontrollers such as Arduino Uno to execute computation. Fuentes *et al.* [11] use Arduino to devise a new data logger for monitoring photovoltaic systems at low cost in remote areas. The data logger comes with a resolution of 18-bits, including 8 analog inputs for measuring up to 8 PV modules and/or weather sensors, 3 inputs for low-cost analog temperature sensors and virtually unlimited inputs for digital temperature sensors. Abraham *et al.* [12] propose a low-cost indoor air quality monitoring system by adopting wireless sensor networks. A linear least square estimation-based method is used to calibrate the sensor and the measurement data. Oberloier *et al.* [13] provide a low-cost, open-source power monitoring system. Digital Universal Energy Logger (DUEL) nodes are adopted to read and scale the voltage and current which is connected and logged to Arduino Unos through Inter-Integrated Circuit (I2C) on a bus.

Many other works resort to Raspberry Pis, obtaining signals from sensors, conducting computation and eventually visualizing the data. Perumal *et al.* [14] propose a cost-efficient energy building system for the building environment, aiming to take automatic adaptive decisions for better Energy consumption in the upcoming future. Lewis *et al.* [15] propose a solution for air temperature, pressure and humidity for environmentally-controlled calibration laboratories. Raspberry Pi is chosen over Arduino because it has sufficient computing and storage capacities for sensor operation, web interfaces and email alerting. Hawkridge *et al.* [16] report an approach for small and medium sized enterprises (SMEs) in terms of digitalization. The approach uses low-cost, off-the-shelf technologies to enable simple configuration changes and provide suitable low-cost candidate technologies. Nevertheless, most existing works do not consider the data aggregation between multiple edge devices and hence fail to fully unleash the potential of large-scale IoT services.

2.3 Network protocol for low-cost monitoring

There are mainly two kinds of communication protocols in ditigal manufacturing. One is short distance communication protocols and the other is long distance communication protocols. These protocols include but not limited to Zig bee, Bluetooth, WIFI, Radio Frequency and LTE Networks. Mudaliar *et al.* [17] present an IoT based power monitoring system in the switchgear industry. Raspberry Pis are used to collect data from existing energy meters. The historical data is stored locally on the Raspberry Pi and displayed through Grafana. The system has an IC to convert Modus RTU protocol to WiFi signal. Ilchev *et al.* [18] propose a new communication protocol for low-cost IoT sensor data. Several important protocol features are defined such as data encryption, integrity checking, sender authentication and data retransmission in light of packet delivery failures. Magadan *et al.* [19] report an electric motor monitoring system based on industrial IoT. The system is implemented to detect operational anomalies and predict maintenance needs. The data is delivered to IoT analytics service in the cloud and vibration analysis is carried out in the temporal and frequency domains.

However, none of the existing works aggregate data and conduct big data analysis on a large scale. This impairs the benefits of adopting IoT services because an enterprise may have several production lines or several shop floors. The data generated from different locations may be potentially correlated and hence it is beneficial to jointly analyze those data.

3 Blueprint for low cost monitoring with data aggregation

In this section, we propose a blueprint for low-cost digital manufacturing. Conventional monitoring systems include those that collect data and display the data to operators or those that store historical data and conduct analysis to provide add-value services such as anomaly detection and predictive maintenance.

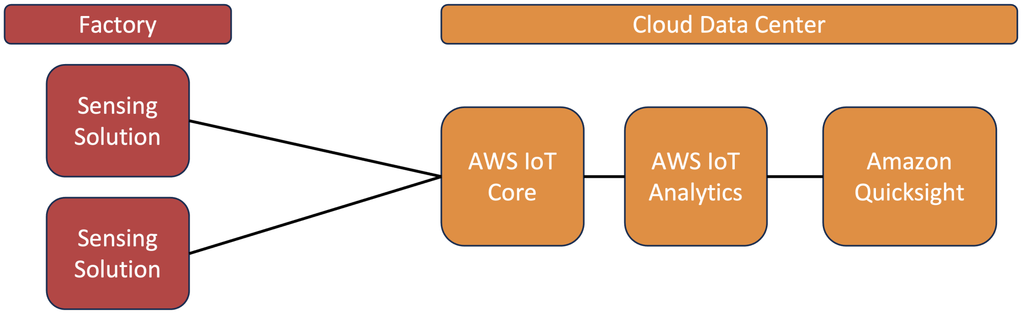

Figure 2: Blueprint for a low-cost system

3.1 Scope of low-cost monitoring

In this paper, we propose a blueprint for digital manufacturing including 5 service modules: data collection, data storage, data visualization, data streaming and data analysis.

The data collection service module is responsible for acquiring data from sensors attached to machines or environments. Then, we attach context and meaning to the raw data. Eventually, if necessary, the data is calculated based on configuration parameters.

After that, the processed data is stored in the data storage service module which is an InfluxDB database.

The data visualization service module fetches the contextualized data from the database. Operators can access the data and information through a web application or the database API.

After that, the contextualized data is formatted in Json. A timestamp and a machine ID are also included in the message and sent to a local MQTT message broker. The message broker stores the data in customized topics. Then, a streaming relay component is adopted to read messages from the local MQTT message broker and streams the message to remote an IoT Analytic service in the cloud.

Eventually, the data analysis module processes the data, displays the final results and provides overall insights of the aggregated data from different machines or locations.

3.2 Low-cost in digital manufacturing

In the context of digital manufacturing, low-cost refers to monitoring systems in which the capital investment is low, the cost of development is low and the operational cost is low [16]. In this work, we consider the overall cost of a digital monitoring solution, including sensors, computation devices, communication technologies, data storage, data visualization and data analysis. We also consider other costs, i.e., development, installation and operation costs.

The term low-cost is relatively dependent on the circumstances of a company. For example, low-cost for a medium company could be too expensive for a micro company. In this paper, we consider a monitoring solution as low cost if each hardware component is less than £100 and the total cost of a solution is less than £1000. Low-cost solutions may not be the best value. Nevertheless, many SMEs face the choice between a low-cost solution and nothing because they may not afford anything more expensive.

3.3 Blueprints for low-cost monitoring

We describe blueprints for a low-cost monitoring solution and the architecture of the system. As illustrated in Figure 1, the data collection module senses the raw data and transfers the data to a microcomputer which is the computational device for the solution. A microcomputer is usually equipped with multiple CPUs which enables task execution in parallel. Consequently, a microcomputer can perform data storage, data visualization and data streaming simultaneously. Moreover, a microcomputer can be directly connected to a monitor which allows the visualization of data and information.

Figure 2 illustrates a blueprint for the overall system. Several sensing solutions are connected to the local WiFi in a factory. The raw data is streamed to AWS IoT core through MQTT protocol in a remote cloud data center. The data is aggregated to the AWS IoT Analytics service. A number of Lambda functions are triggered by the data. Eventually, the results are displayed via Amazon Quicksight and can be accessed through web applications. It is beneficial to aggregate data from different solutions because the data of those solutions are potentially correlated and hence we can obtain useful information by jointly analyzing those data.

4 Technologies for low-cost monitoring

4.1 Low-cost data collection

In this section, we present a number of candidate sensors for data collection in manufacturing such as ambient temperature, for temperature changes, process temperature, for heat generation and air quality, for generic air quality in shopfloor.

Table 1 shows some popular sensing technologies. Temperature can be achieved by thermocouples and thermistors, air quality can be achieved by metal oxide (MOX) technology, and vibration can be achieved by MEMS accelerometers,.

When considering those low-cost sensors, there is a tradeoff between performance and price. Nevertheless, the range and sensitivity by many non-industrial sensors are sufficient for most use cases.

4.2 Low-cost computation

The proposed blueprints mostly use microcomputer as computational device. Microcomputers are hence used as edge devices and will be discussed in this section. Since we aim at

Variable	Sensor type	Range	Sensitivity	Price
Temperature	Thermocouple	-200 to 1750°C	1 to 5°C	£2 to £80
Air quality	Metal oxide	0 to 65000ppb	1ppb	£10 to £100
Vibration	MEMS	0 to 32kHZ a	400 to 2.2mV/g	£0.7 to £60

Table 1: Low-cost sensing technologies

low-cost solutions in manufacturing, only single board microcomputers are conisdered in this work.

Raspberry Pi 4B is equipped with Quad core Cortex-A72 (ARM v8) 64-bit SoC @ 1.8GHz CPU, 1 to 8 GB memory, 2.4 GHz and 5.0 GHz IEEE 802.11ac wireless, Bluetooth 5.0 and BLE Gigabit Ethernet. The price ranges from £35 to 75£.

Another candidate microcomputer is Okdo ROCK 4 C+ that is equipped with a six core ARM processor, 64bit dual channel 3200Mb/s LPDDR4, up to 4K@60 HDMI, MIPI DSI, MIPI CSI, 3.5mm jack with mic, 802.11 ac WIFI, BT 5.0, USB Port, GbE LAN and 40-pin color expansion header. The price of Rock 4 C+ is £58.5.

ODROID-C4 features Amlogic S905X3 quad-core with2.0 GHz Cortex-A55processor. The board has 4 GB of DDR4 RAM memory, on the board there are Ethernet Gigabit port, HDMI 2.0 4K/60Hz port, four USB 3.0 ports and one microUSB 2.0, 40-pin GPIO, connectors for microSD card and eMMC and IR receiver. It works with Ubuntu20.04 or Android Pie 9.0 systems.

Apart from the hardware, we also need to consider the cost of software development and installation. Thanks to the large community of Raspberry Pi, customers can benefit from a wide range of libraries and tutorials that the community provides.

4.3 Low-cost communication technologies

A variety of communication networks are available for consideration in the design of a connected digital manufacturing solution. These networks utilize a series of protocols, which are essentially sets of regulations that enable electronic devices to engage in communication. The aspect of portability holds significant weight in numerous digital manufacturing applications, often serving as the primary determinant for opting for one communication method over another. This is particularly evident in Internet-of-Things (IoT) scenarios, where the preference leans towards compact and portable hardware. An alternative avenue for achieving portability involves the use of wireless communication, a strategy that allows data collection to be portable while maintaining stationary computing devices.

Bluetooth Low Energy (BLE) and Wi-Fi wireless networks boast the highest data transmission rates and fall within the cost-effective category. Notably, these technologies are already integrated into the Raspberry Pi microcomputer, eliminating the need for supplementary hardware. Additionally, external communication networks like USB and Ethernet also enjoy widespread adoption in portable systems due to their rapid installation process and compatibility with a wide array of devices. In industrial contexts, the selection of an appropriate communication network is a pivotal consideration.

In the realm of industrial applications, the demand often centers around real-time communication and a heightened level of durability, qualities that are more effectively achieved through wired communication as opposed to wireless alternatives. Several prominent wired communication protocols cater to these specific requirements. Noteworthy among these are EtherNet/IP, PROFINET IRT, EtherCAT, Powerlink, and SERCOS III. EtherCAT, in particular, distinguishes itself by offering a unique combination of top-tier performance and cost-effectiveness. It delivers deterministic communication within a solution at a notably lower expense compared to its protocol counterparts.

EtherCAT boasts impressive data rates exceeding 100MBps, and shields for both Raspberry Pi and Arduino are available for a modest cost of £35 and £44, respectively. This underscores the feasibility of implementing this industrial-grade technology within a budget-friendly solution, aligning its price range with some of the more economical wireless networks.

4.4 Low-cost data storage, data analysis and visualization

Data storage presents two primary avenues: local processing and cloud-based solutions. For localized data management, an array of open-source software options are at one's disposal, including influxDB, MySQL, CouchDB, Redis, and others. On the other hand, the cloud offers an alternative, with major Database-as-a-Service (DBaaS) providers like Amazon DynamoDB and Microsoft Azure SQL Database offering cloud-based data storage solutions. However, the cost-effectiveness of cloud storage might not be readily apparent unless substantial data quantities necessitate such an approach.

Analyzing sensor data finds support in diverse open-source analysis tools like Pandas, PyBrain, Tensor Flow, among others. Incorporating alerts typically involves integration into existing management systems. Nevertheless, a rudimentary alerting mechanism can be established using an SMTP library, thereby triggering email notifications when the analysis software detects specific conditions.

For visualization purposes, leveraging a web interface emerges as the optimal choice. Such an interface enables both local and network-based data display. Numerous web-based visualization packages are accessible, including options like Grafana and Dash.

4.5 Discussion

The progression of creating cost-effective monitoring solutions encounters limitations stemming from the constrained capabilities of budget-friendly hardware and software, the inadequate durability of non-industrial components, potential challenges in merging with existing systems, and the heightened development workload. Nonetheless, with technological advancements, formerly expensive hardware and software transition into an accessible and reasonably priced domain, catering to a broader spectrum of users. Simplifying the development process and addressing integration complexities necessitates tapping into the expansive communities associated with various low-cost platforms, benefiting from the plethora of libraries and tutorials they offer.

This section introduces initial insights into technologies that hold the potential for contributing to economical industrial monitoring solutions. These findings are a facet of ongoing endeavors focused on crafting integrated solutions aimed at enhancing digital capabilities for small and medium enterprises (SMEs).

5 Case study

The objective of this case study is to demonstrate the practical application and effectiveness of the blueprints presented in Section 3 in the development of affordable monitoring solutions that can make a valuable contribution to the realm of digital manufacturing. Within this case study, specific low-cost technologies have been pinpointed as candidates and essential low-cost components have been constructed using reusable service modules, aligning with the foundational concepts outlined earlier.

5.1 Solution description

As part of the Smart Manufacturing Data Hub project, we develop a low-cost monitoring prototype for ambient temperature as illustrated in Figure 3.

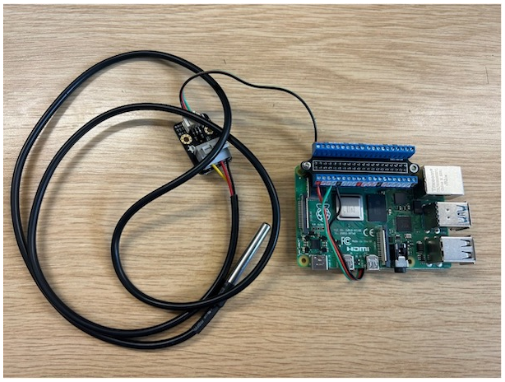

Figure 3: Low-cost monitoring demonstrator

The system is implemented using the blueprint as described in Figure 1. The ambient temperature monitoring solution adopts a DS18B20 temperature sensor connected with a Raspberry Pi model 4B through a Mini breakout board. The Raspberry Pi performs computation for Local Data Storage, Local Data Visualization and Data Streaming. All service modules are run in Docker containers. The communication between Data Storage and Data Visualization is realized by HTTP requests. The communication between Data Storage and Data streaming is realized by MQTT messages. Also, we use MQTT messages to stream data to Data Analysis module. The data analysis module is located in AWS cloud and adopts AWS IoT Analytics pipelines.

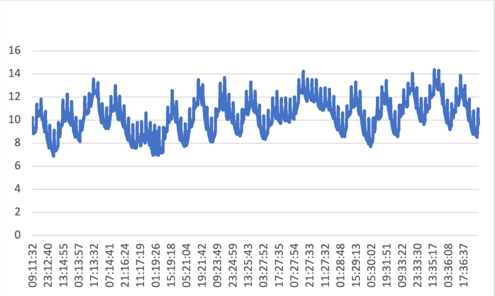

Figure 4: Sensor data from the temperature solution

Figure 4 shows that the temperature monitoring system collects data from the environment, stores the data and visualizes the data at the cost of less than £150. This case study demonstrates that the blueprint proposed in Section 3 can be efficiently adopted to develop low-cost monitoring solutions for digital manufacturing.

6 Conclusion

The aim of this work is to provide strategies for achieving cost-effective monitoring in digital manufacturing while also pinpointing feasible economical technologies that can be employed in conjunction with these strategies. This work has successfully outlined suitable approaches for building monitoring solutions for digital manufacturing. It is implied by this research that budget-friendly, readily available components have the potential to be employed in the subsequent non-critical industrial monitoring scenarios. Firstly, in cases involving valuable yet budget-conscious assets where the cost of conventional monitoring systems cannot be rationalized. Secondly, in situations necessitating the swift establishment of preliminary, experimental systems when the potential return on investment has yet to be ascertained. Furthermore, careful consideration must be given to the data aggregation aspects of these cost-effective monitoring technologies. How to efficiently use massive data from different solutions is still an open question.

7 Acknowledgement

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