Lessons learned from an IoT deployment for condition monitoring at the Port of Felixstowe

Jorge Merino * **Manu Sasidharan** * **Manuel Herrera** *
Hang Zhou * **Adolfo Crespo del Castillo** * **Ajith K. Parlikad** *
Richard Brooks ** **Karen Poulter** ***

* *Institute for Manufacturing, Dept. of Engineering, University of Cambridge, Cambridge, CB3 0FS, United Kingdom (e-mail: jm2210, mp979, amh226, hz356, ac2383, aknp2@cam.ac.uk).*
** *Blue Mesh Solutions, 51 Portland Road, Kingston on Thames, London, KT1 2SH, United Kingdom (e-mail: richard@bluemeshsolutions.com).*
*** *Port of Felixstowe, Tomline House, The Dock, Felixstowe, IP11 3SY, United Kingdom (e-mail: poulterk@fdrc.co.uk).*

Abstract: The ports sector is critical to global trade. While digitalisation of infrastructure asset management in other sectors such as manufacturing, healthcare, water supply, railway and road is rapidly growing with the possibilities of the Internet of Things (IoT) solutions, the maritime industry lags significantly behind. IoT solutions and the near real-time data they produce provide new impetus to improve fault diagnosis of assets and prevent disruptions caused due to asset breakdown. Such solutions also require reliable communication systems to support low latency and high bandwidth. To this end, we are building an IoT-based asset management solution at the Port of Felixstowe, the UK's largest container port, using 5G technology. This paper presents the steps taken, challenges faced and the lessons learned with sourcing, installation, calibration and communication of sensors in this deployment.

Keywords: IoT, Sensors, Monitoring, Data quality, Data management, 5G, Smart ports

1. INTRODUCTION

Ports play an important role in the worldwide economy as approximately 80% of global trade relies on maritime transportation (Wang and Wright, 2021). One of the main challenges that ports face today is how they become more efficient. The availability and efficiency crane operation is a key factor in the productivity of the ports (Chargui et al., 2021). However, cranes are prone to failures due to the extensive stresses and cyclic loading they experience during operations. Unexpected crane failures can lead to stoppages in loading/unloading operations and impact the turnaround times for vessels resulting in loss of revenue. Additionally, this can also result in lower customer satisfaction and and decrease in business as the shipping lines may choose another port for their operations.

IoT technologies generate data that can be used to improve the fault diagnosis and guide the predictive maintenance of crane components (Ahmed et al., 2017). Due to the real-time factor and not relying on human data collection, IoT enables data-driven inspection on demand which boosts uninterrupted port operations. IoT deployments are already being used successfully for condition monitoring of bridges (Magalhães et al., 2012; Nguyen, 2021), buildings (Park et al., 2018), road pavements (Ng et al., 2019), railway tracks (Chellaswamy et al., 2017) and drainage systems (Aarthi and Bhuvaneshwaran, 2021). RFID and GPS is used to track the movement of containers throughout freight ports for security measures and logistics efficiency (Barasti et al., 2022). Humidity, light, temperature, and CO2 detection are monitored in freight containers to ensure the quality of goods (Kaderi et al., 2019). Data from new digital technologies and applications can be used to create 'smarter decision-making', in which the more comprehensive and timely data can enable more accurate, efficient and sustainable interventions (Molavi et al., 2020); for example, monitoring vibrations of bearings to detect wear. If deployed effectively, such technologies IoT have the potential to transform the port infrastructure asset management itself (Sanchez-Gonzalez et al., 2019).

A number of challenges are commonly faced during any IoT deployment that hinder effective use of the technology. Literature has reported some known challenges, namely, security, communication, data processing, data cleansing, data management, and energy consumption (Lee and Lee, 2015; Sotres et al., 2017; Minoli et al., 2017; Sehrawat and Gill, 2018; Gorenflo et al., 2017; Pereira et al., 2020; Soni and Subhashini, 2021). This paper provides real-world examples of these challenges, approaches, and lessons learned from an IoT deployment at the Port of Felixstowe (PoF) to aid the asset management of quay cranes (QCs). The IoT deployment includes vibration sensors (magnetometer, gyroscope, and accelerometer), temperature, pressure, humidity, and strain gauges reporting at diverse intervals across 6 quay-side cranes. The sensors have collected over 6TB of data since September 2021 until February 2022, but the challenges addressed in this paper will not only focus on the obvious Big Data volume issues.

The context of the of the project and the IoT-based monitoring strategy developed is described in the following section, including the identification of the QC components that would benefit from condition monitoring and the associated faults that are detectable (or monitor-able); identifying and calibrating the sensor candidates; and establishing communication and data management protocol. The challenges identified refer to that context and they are related to monitoring targets, sensor selection, calibration, edge communication, data management, time stamps, and data analysis. We believe that other projects in the space of IoT and data management may benefit from the insights reported within this paper.

2. CONTEXT AND CASE

The Port of Felixstowe (PoF) is the UK's largest container port, and handles more than 4 million containers from approximately 3000 ships each year. A key operational asset for the port is the quay cranes (QCs) that move the shipments between the terminal and shipping vessels. Their unavailability due to breakdowns or poor condition can not only paralyse the port operations but also cause adversely impact local and global logistics and trade-dependent industries (Kizilay and Eliiyi, 2021). Our motivation is to provide accurate and early fault detection and diagnosis to guide predictive maintenance strategies for the QC components. The QCs at PoF are prone to failures due to the extensive stresses and cyclic loading they experience during operations. The project involves an ongoing trial to monitor the condition of six of these QCs using IoT sensors communicating via 5G technology, and to employ artificial intelligence to identify pre-incident trigger conditions. If successful, the port intention is to scale the IoT deployment to the rest of the seventeen QCs.

The first stage of defining an IoT based condition monitoring programme is to identify the components and the associated failure modes that result in disruptions (BSI, 2018). Figure 1 identifies the main components of a QC. A failure mode and effect analysis (FMEA) conducted on the PoF's QCs disruption log data revealed that the spreaders and hoists contributed to most of the crane disruptions (approximately 40%). The spreader-related disruptions were associated with the extraction/retraction of the spreader, gearbox of the flippers and the twist locks. On the other hand, the disruptions caused by the hoists were due to uneven loading of containers and inspections to the rope, motor, brakes and gearboxes.

Following the FMEA, the symptoms associated with the disruptions were identified by taking cognisance of the existing literature and expert opinion gathered from the engineers and technicians at the PoF. Only detectable symptoms were considered were, i.e. there is a physical dimension that will vary from previously defined "normal" values when the disruption/failure occurs and evolves; termed as the monitoring parameters. To this end, at

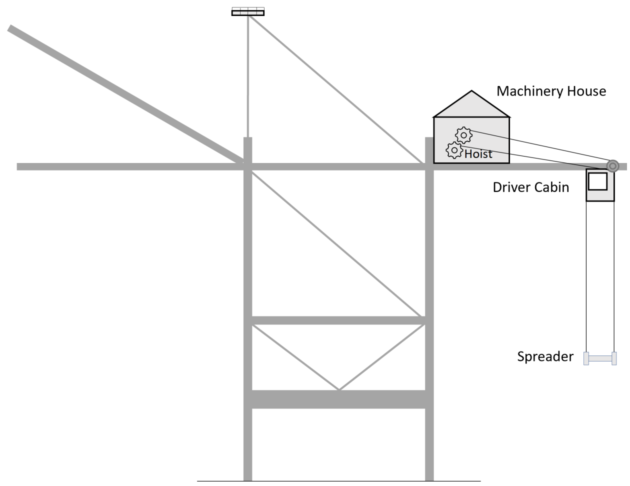

Fig. 1. Quay-side Crane schematic

the component level, it translates into monitor the (i) vibrations and temperatures of the motors, gearboxes and brake of spreaders and hoists; (ii) loading on the hoist ropes and spreader twist locks; and (iii) forces experienced by the steel structure (gantry).

Different sensors from three manufacturers were identified to monitor these components and to establish a data-driven inspection and predictive maintenance regime. Manufacturers A and C provided industry-graded battery-powered Bluetooth sensors. The former provided vibration, temperature, and humidity sensors and the latter strain gauges. Manufacturer B provided state-of-the-art sensors, including three types of vibration (magnetometer, gyroscope, and accelerometer), temperature, pressure, and humidity. Sensors deployed on the QC targets are presented in Table 1.

Table 1. Type of sensors at target locations

Sensor type	Target location	Manufacturer
Vibration, Temperature, Atm. pressure	Hoist gearbox	A
Vibration (magnetometer, gyroscope, accelerometer), Shock load, Temperature, Humidity	Hoist gear box and motors, Trolley drive	B
Strain gauge	Crane pillar base, driver cabin cable drum base	C

Figure 2 presents the flow of the data from the sensors to the applications. Ports are a tough environment for sensor communication, and thus, the IoT deployment at PoF required the use of a Bluetooth mesh with industry-ready sensors and a WiFi mesh with custom sensors in the machinery room. With a Bluetooth or WiFi mesh, sensors can transmit data between them and with the gateway. These meshes allow the sensors to transmit their data through other sensors towards the gateway in case of a sensor not being able to reach the designated gateway directly. This point-to-point communication was selected instead of alternatives like broadcast communication (e.g., LoraWan) because they do not always ensure the message delivery to the gateways, and consequently, it would have incurred cost from additional gateways to ensure the same coverage. The bandwidth of WiFi and Bluetooth meshes was considered sufficient for the volume and velocity of data generated in the edge, however, the transmission of data outside the edge network had to be ported from 4G to 5G to guarantee data delivery towards the data services. Two gateways for Bluetooth and another two for WiFi were necessary for full coverage in each QC, in the driver's cabin and in the machinery room correspondingly. All four gateways are connected to 5G modems. Data generated at the edge is submitted through Bluetooth and WiFi meshes into a 5G modem which forwards data into a Relay server in the PoF's network. The Relay server is in charge of publishing data to authorised destinations outside the PoF's network, namely a cloud bucket and a custom data server. High-precision vibration data (i.e., up to 6.7 kHz) is batched and uploaded into the cloud bucket in CSV files. Acoustic data is also uploaded in WAV format to the cloud bucket. The rest of sensors publish data in JSON files using MQTT in a custom frequency (e.g., every minute) towards the custom data server. Both a raw version and a cleansed version of data is stored in the custom data server on a daily basis (i.e., all the readings for a day in a single file). The next section explores all the challenges faced to deploy both the IoT sensors at the edge and this architecture.

3. CHALLENGES AND LESSONS LEARNED

The sensor deployment exercise for condition monitoring at the PoF highlighted some challenges similar projects might face. These are classified as identifying monitoring targets, selecting sensors, calibration of sensors, communication, data quality, and data management. The approaches taken to resolve these challenges are described as well.

3.1 Monitoring targets

Even that it seems obvious, many IoT deployments start without a real plan of what targets and parameters to monitor, specially in exploratory stages. As a result, random sensors are acquired, then not used, and finally end up in a cabinet.

Lesson 1. Know your sensing targets and measurable parameters It is key for any IoT deployment to start by identifying and prioritising the components for monitoring. These targets are identified by an analysis of failure modes which inform the engineering parameters (e.g. vibration, temperature) that needs to be monitored. In other words, identifying which assets fail more often and what are the failure types; what are the symptoms and effects of each failure. Symptoms define the parameters to be measured.

Lesson 2. Involve targets' experts The operational challenges associated with sensor targets should be considered. Experts' opinion becomes a valuable source of information to identify them. For instance, vibration monitoring on the QC hoist ropes was not practical due to the variable speed at which the hoists operate. Experts' opinion is valuable not only to identify the targets but also to advise the ideal location to place a sensor for monitoring each component. Experienced engineers and technicians are even capable of identifying any potential faults to the engines and gearboxes by sound or touch, which translates into the exact location of the housing in a component to monitor. These locations may change during sensor calibration (see 3.3), but they are always good indicators to begin the deployment.

Lesson 3. Understand targets' environment The targets and exact locations may be constrained by communication issues between the sensors and the network gateways (see 3.4). The need for power in wired sensors can also become a challenge, especially in industrial settings like a crane where cable management is not trivial. The length of cables may cause fluctuations and drop of power resulting in faults (e.g., sensors not sending data, not measuring the features correctly).

3.2 Sensor selection

Industry-ready and custom sensors are the two options for sensor selection. Customs sensors may be considered when within a budget or when available industry-ready sensors cannot measure identified parameters. In that is the case, the individual parts to monitor desired parameters must be acquired separately and assembled on a common board. It is common to start off with an industry-graded sensor and try to mirror or extend its capabilities into a custom sensor prototype. Particular sensor communication technologies may be a requirement (see 3.4) depending on the sensors' environment and amount and speed of data to be transmitted.

Lesson 4. Manage custom sensors expectations Custom sensors' parts are normally cheaper, sometimes even as precise as industry-grade sensors, but require expert knowledge for assembly, configuration, and data collection. While custom sensors are flexible and can accommodate all desired parts in one board, but that makes them bulkier and less power efficient. Custom sensors must be first considered as prototypes and expectations from their performance must be managed. After testing, prototypes must be developed into final products with reliable power and communication efficiency to support sensor performance.

Lesson 5. Test your sensors Sensor candidates must be capable of measuring between and beyond the working thresholds of each parameter the targets operate in a normal situation. The failure modes inform the required precision using the sensors which will play a role while analysing changes in the operation of the monitored targets. Both, industry-ready or custom sensors must be first tested in a controlled environment to check against manufacturer specifications, not only in terms of parameters and thresholds but also in terms of communication performance. Sensor communication technologies (e.g., Bluetooth, WiFi, 5G), and protocols (e.g., MQTT, Kafka, Websockets, CoAP) must be tested in the final environment. Temperature, corrosion, and water protection may be considered at this point.

Lesson 6. Be aware of supply chains Some sensor candidates and parts might be unavailable or delayed due to supply chain issues. Additionally, some sensors could malfunction during the deployment and may need replace-

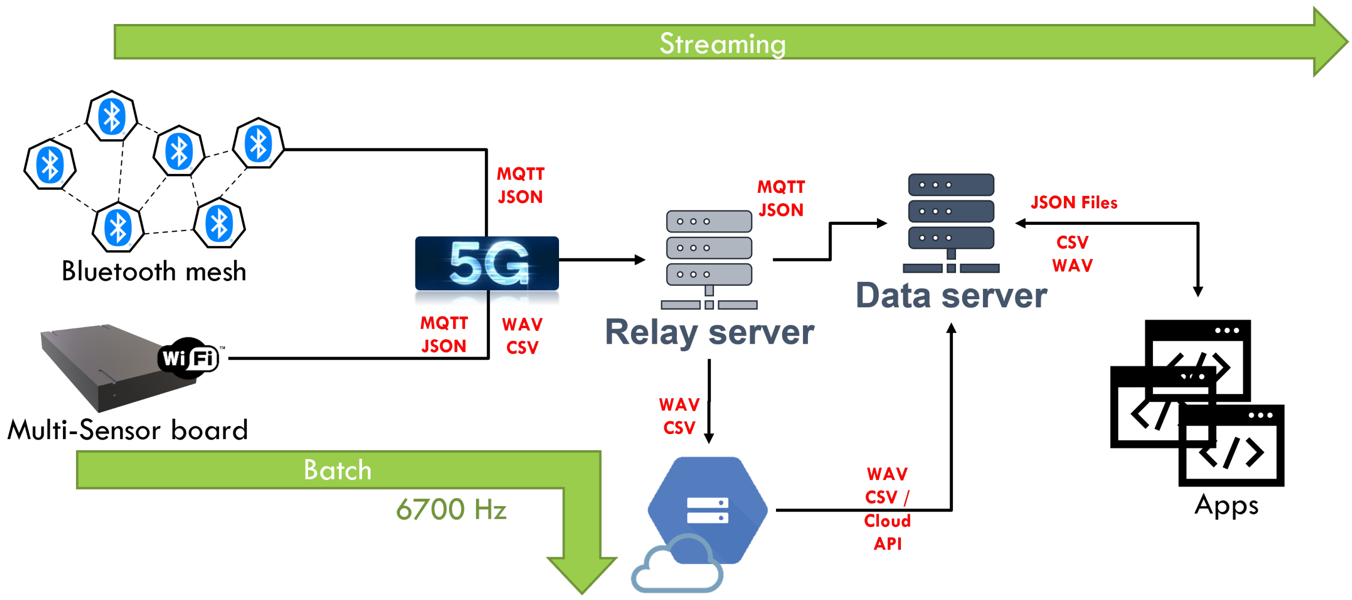

Fig. 2. Data flow

ments. Alternative suppliers should be sought beforehand to mitigate any delays.

3.3 Sensor calibration

Calibration is necessary to ensure precision, consistency of measured parameters and minimise uncertainty. Sensor location plays a major role in the precision of the sensor which must be attached as close as possible to the real source of the parameter generation in the monitored target. For example, a gearbox dissipates energy in the form of temperature which will be higher than normal if the couplings are not well lubricated and need maintenance; the temperature sensor should be attached as close as safely possible to the couplings, and if it must be in the gearbox housing, gearbox ventilation intake must be avoided. Knowledge from inspectors and maintenance engineers can also be valuable while calibrating the sensors since they can identify the best location in each monitored target for most sensors. Sensor locations must be identical across all similar monitored targets.

Lesson 7. Consistent sensors' position Sensor consistency is affected by how the sensor is positioned on the monitoring target. This can be easily overlooked while attaching the sensors to the selected location. Sensor position impacts how sensed parameters are interpreted. For instance, some sensors measure vibration across 3-axes and the readings depend on the orientation in which the sensors are positioned. The readings must be pre-processed for analysis if the sensors are positioned inconsistently. This increases the complexity of the data pipelines. Consistent positioning shall be addressed even more carefully when assembling custom sensors, where each part should be assembled identically. Most sensors have some reference to this in their specification/documentation, but visible marks on the sensor itself support consistent deployment.

Lesson 8. Mirror sensor configuration Some sensor parameters can be fine-tuned through configuration, sometimes in terms of sampling frequency (i.e., how often a measurement is taken), or granularity (i.e., how precise each measurement is). It is vital to keep the exact same configuration for similar monitored targets to ensure consistency.

Lesson 9. Document deployment Sensors' location, position, and configuration must be documented thoroughly to minimise uncertainty while using generated data during analysis. It is vital to understand where do the readings generated from the sensors actually belong within the monitored targets and locations. Therefore, it is important to create and document sensible and understandable sensors identifiers that enable the association with monitored targets and locations while collecting and analysing the data (see 3.6).

3.4 Edge communication

Guaranteeing good communications is one of the most important challenges to address during an IoT deployment. WiFi, Bluetooth, Zigbee, RFID, cellular (i.e., 4G/5G), LoraWan, Sigfox, NB-IoT are amongst the most popular technologies in IoT, and most IoT projects use a combination of them to achieve effective and efficient communication. The selection of the technologies must be mainly based on two factors: range and bandwidth.

- Range is affected by the environment where the sensors are deployed. In QCs, some sensors are in a machinery room surrounded by steel walls, whereas others are in the driver's cabin which moves along the crane (see Figure 1). Thick steel walls and movable parts like the driver's cabin impact the range of the sensors. Thus, most IoT deployments avoid the direct connection of sensors to a central data service by using gateways to improve the range of the sensors. This also adds a layer of security to constraint the access from the internet directly to the sensors. Gateways'

locations must be planned to ensure good coverage for all the connected sensors.
- Bandwidth efficiency is affected by range, and it is another reason why it is important to ensure good coverage. The bandwidth of the communication technology selected must be able to cope with the data transmission volume and speed.

Lesson 10. Do not underestimate Volume and Velocity It is easy to underestimate the amount of data and the rate that an IoT deployment can generate. Vibration sensors are a good example of this problem, as they can generate data in the range of kHz (i.e. 1000s of data points/second). Reliable communication technology selection supports the scalability of IoT projects. The low latency technologies (e.g., WiFi/5G) offer real-time interactivity for services which is key to the success of near-real time condition monitoring and predictive maintenance of critical assets like QCs. Large-bandwidth technologies supports more sensors to be connected. Edge computing can be employed to reduce the communication burden.

Lesson 11. Do not forget sensor maintenance It is also important to consider the maintenance of the sensors themselves, as it is almost impossible to avoid communication losses during their lifetime. Even with good coverage, sensors and gateways misbehaviour will create communication issues. Power losses are the usual reason for loss of communication. Most sensors work on batteries, but even if the sensors are wired, power fluctuations or source power losses must be considered. This power and communication losses reflect in timestamps drifts (see 3.5) and data loss. Battery and power connectors corrosion in tough environments (like in a port environment) must be taken into account as well. Asset management procedures apply to the sensors similarly to any other monitored target, with the advantage of sensors reporting self-monitoring data themselves.

3.5 Data Quality

Among well-known data quality issues, time referencing is fundamental in IoT deployments. Sensors generally send readings in the form of an event or a measurement of a parameter. Timestamps represent the exact moment when the readings happen. When the first QC was fitted with IoT sensors at the PoF, the deployment team soon faced clock-drift challenges in the industry-ready sensors, whereas custom sensors lacked a timestamp of any sort. These problems were addressed by adding timestamps at every node in the network (i.e., sensors, gateways, relay servers, and data services), and by re-synchronising the clocks with a common online time server when the drifts were identified, but two months worth of data lost its value.

Lesson 12. No timestamp, no value Without a timestamp reference, data loses its meaning because it cannot be matched with the real operation of the monitored asset. Not only is important to get a timestamp at the source but also at every other node in the network that the data is passing through. Many times, the clocks at the sensors drift causing data quality defects. Having a timestamp at other nodes supports the identification of these data quality defects and serve as the solution since the next node timestamp can be used. Sensors and gateways must be synchronised with a common time server used by the network and maintained when a clock drift is identified. Ideally, the time server should be used by the data services and the operational systems as well.

3.6 Data management

Data generated at the edge flow to data services that need to ingest and manage it. As an example, in a data lake –among the most popular architecture to manage IoT data–, data may be first stored on its raw format from the source, sometimes adding metadata of the time when each data point arrived and an identification of the source. Then, IoT data can be integrated with other operational data (e.g., crane operation data) while processing processing. Raw data is transformed through data pipelines that are customised to the final user or application, making data lakes flexible and scalable.

Lesson 13. Ensure concurrent storage When it comes to storage, data from IoT sensors can be produced rapidly which can cause concurrency problems. It is also important to partition the ingestion job adequately to prevent data losses if individual ingestion modules fail.

Lesson 14. Plan data life-cycle Data storage granularity is commonly ignored. Individual readings are sometimes stored at file level, causing indexing problems in the file system. Appropriate aggregation of readings must be plan to avoid slow data reading. Data storage capacity can become a constraint in the medium-long term. Not only because of the vast amount of data collected every minute but also in cases when data shall be pre-processed and stored again. Historical data storage and disposal criteria should be adopted from the very start to avoid overloading the data service.

4. CONCLUSIONS AND FUTURE WORK

IoT deployments often face challenges associated with sourcing, installation, calibration and communication of sensors. Sensors' location in spaces, position in the assets, and calibration must be considered in order to interpret data similarly across all devices. Communication or power drops will occur during their lifetime. After these drops, the sensors may require to be restarted and communication with the IoT network may need to be restored. Even for fully working sensors, it is vital to have a timestamp alongside every data reading. If the moment when an event or measurement happened at the source is unknown, data is meaningless. Additionally, clocks in IoT sensors tend to drift because of the aforementioned power and communication losses or because they live in a local network without access to a common time server. Thus, ensuring a common time reference for all sensing data becomes one of the most important challenges, as it directly impacts the levels of data quality.

High sampling rates affect the data ingestion process in terms of concurrency, and storage. Having to deal with high-volume, high-velocity of data is at the heart of most IoT deployments. Additionally, the variety of sensors becomes a variety of data streams, even if they are from the same provider, and thus, they require different pre-processing. Feeding real-time applications demands a good understanding of technology and the assurance of an acceptable end-to-end latency, from the edge — sensors — to the user — applications.

Ongoing work is focusing to develop a decision support system powered by artificial intelligence to analyse the data collected from the IoT deployment and predict any faults before they compromise crane operations.

ACKNOWLEDGEMENTS

This work was supported by the UK's Department for Digital, Culture, Media and Sport through the 5G Testbeds and Trials (5G Port of Felixstowe project). The authors acknowledge the support from Hutchison Ports, Three UK and Blue Mesh Solutions.

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