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CONDITION MONITORING OF TURBOMACHINERY WITH INTERNET-OF-THINGS (IOT)

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ABSTRACT

Condition monitoring is one of the critical process in turbomachinery equipment. As a factory equipment, Turbormachinery mostly transfers data via controllers such as programmable-logic-controller (PLC). Parameters of the machine health is transferred and monitored via local-area-network or wireless network to the control center. The technology of Internet-of-Things (IoT) has become matured and offers another alternative to transfer data, and this can be useful for condition monitoring on turbomachinery equipment. This project studies the vibration sensors suited for the project, the communication networks, and demonstrated the built prototype. Data collected from the vibration sensors will be transmitted via LoRa network to the cloud. LoRa is the long range, low power wireless network for data transmission, usually seen as an enabler for Internet-of-Things (IOT). The transmitted data will be received and display on devices. This method offers an innovative solution for condition monitoring on turbomachinery.

INTRODUCTION

Turbomachinery refers to the equipment that transfers energy between a rotor and a fluid, such as a mechanical wind turbine transfers energy from a fluid (air) to a rotor (generator), and a hydraulic compressor transfers energy from a rotor (pump) to a fluid (hydraulic fluid). Turbormachinery has been considered as plant equipment, and data are usually transferred via controller such as programmable-logic-controller (PLC). For example, data such as rpm, voltages and amps are transferred via local-area-network (LAN) or wireless network. Local-area-network for controllers exists such as MODBUS, DEVICENET, and etc., whereas commonly used wireless network in the factory is Wi-Fi. To transfer data effectively, new machines are usually compatible with various wireless network.

With the advances of microcontrollers and the reduced power consumption, Wireless Sensor Networks (WSN) has become a preferred solution for condition monitoring where manual monitoring is not efficient. A WSN supplemented with a controlling device can be used in many different areas. The monitoring of temperature and vibration parameters is critical in most turbomachinery as these variables directly affect the output. In remote area, limited power supplies are provided or the area is confined space or hard to reach. Hence, it is essential to develop a low-powered device for condition monitoring.

Condition monitoring is the system to monitor variables of machinery, as the data can be used for predictive or preventive maintenance. For example, data such as temperature, vibration, and rpm of the turbomachinery can be transferred via WSN for condition monitoring. Internet-of-Things (IoT) technology has become matured and offers another alternative to data transfer, and this can be useful for condition monitoring on turbomachinery equipment.

Internet-of-Things (IoT) is the network of physical devices, embedded with electronics, software, sensors, actuators, and network that enables the devices to exchange data. Each device can operate on its own, and can collaborate with other devices. Most of the times, IoT relies on wireless network to transmit data.

LoRa is the acronym of long range, low power network with modulation technique that provides long range transmission. The method uses spread-spectrum modulation, broadcasting a signal with entire bandwidth. This method improves the receiver sensitivity, robust to channel noise and insensitive to frequency offsets. LoRa is the physical layer (PHY) of the

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network.

LoRaWAN is the protocol for data link (MAC) of LoRa. The protocol is optimized for low cost and ideal for battery operated sensors. The protocol includes different nodes classes to optimize data transfer on network and battery lifetime. The network is constructed by security experts to be fully bi-directional, reliable and safe. Meanwhile, LoRa Alliance is standardizing the protocol for Low Power Wide Area Networks (LPWAN).

SYSTEM DESIGN

The proposed system has been mapped into a flow chart as shown in Figure 1. The flow chart consists of 3 development phases, such as data collection, data transfer and data retrieval.

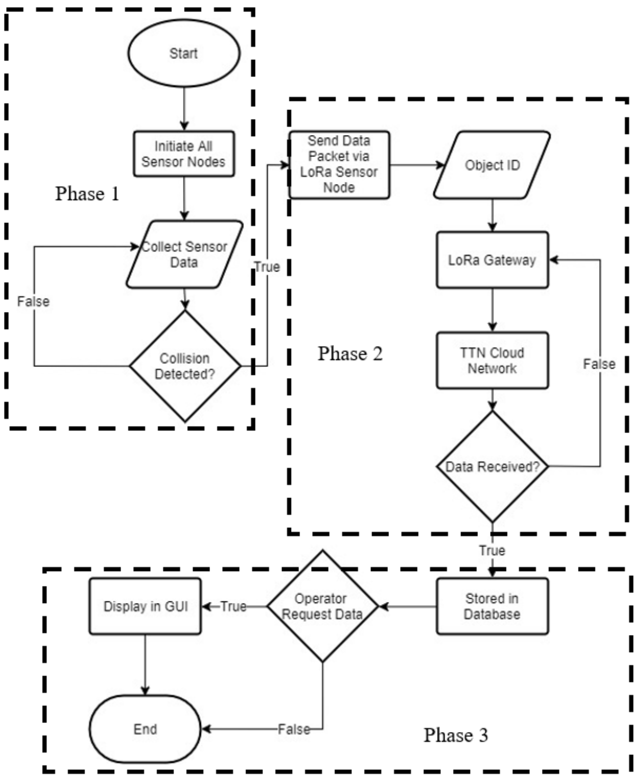

Figure 1: Flow Chart of the Development

The first phase emphasizes on sensors selection. This phase involves tests, selection and determination of the applicable sensors to measure vibration. A test instrument will be built to simulate vibration, consistent to the vibration amplitude produced by the turbomachinery. Hence, vibration simulated can be used to test the sensor capability and the sensing algorithm.

The next section focuses on the sensor communication network. Various communication protocols are studied, and the criteria such as power consumption, distance of transmission and bandwidth are investigated. The sensor selected from phase 1 will be integrated into the communication network as a working network. The network receives or transmits data packets from and to the sensors.

The final phase involves the implementation of the sensor and communication network. The sensor node developed incorporates the sensor and the transceiver module. A gateway will be developed to transfer data from the sensor node to the cloud, which can be further used for analysis. A Graphical-User-Interface (GUI) is developed to retrieve and display data from the cloud.

Sensor Hardware

Vibration refers to small displacement changes over time. The parameter is critical to turbomachinery as excessive vibration indicates that the equipment requires attention. Several variables are used to measure vibration, such as displacement, velocity and acceleration. There are advantages of each variables measurements. For example, velocity is used for equipment diagnosis and fatigue monitoring, whereas acceleration is used to measure dynamic fracture in machines (Fraden, 2015). Hence, acceleration measurement is suited in this application. It will be useful if the data on the range of the vibration magnitude is available. Sample measurements are taken from the vibrating machines in the industry with the average vibration of 0.5m/s^2.

For sensor selection, vibration detection is critical, in addition to criteria such as size, sensitivity, output, axis of detection and complexity in implementation. A table of comparison is as shown in Table 3.1. There are a total of 3 sensors to be considered; ADXL 345 Accelerometer, D7E1 Omron Sensor and Mini Sense 100 Sensor.

In this application, the criteria mentioned defines a better sensor. The applicable sensor will be small in dimension, as a small sensor will be convenient to be installed in turbomachinery and less subjected to physical disturbance. Also, it is straightforward to develop an integrated system with smaller components. In addition, sensitivity refers to the changes of output with respect to input. Sensitive sensor provides output with minimum vibration detected.

The output is essential because it determines the approach of analyzing data acquired from the device. The data collected in waveform signal is easier to be analyzed by numerical analysis. The number of axis of detection is determined by the axis where the sensor is functional. In turbomachinery, vibration occurs in almost all direction, and it is better to select sensors that functions in all directions.

Sensors can provide different measurements parameters but not all data are applicable for vibration detection. Because of a variety of high frequency measurements, certain sensors require large processing power. Hence, this increases the measurement complexity. A sensor with simple implementation is preferred.

Table 1: Criteria of Sensors

Criteria	ADXL 345 Accelerometer	D7E1 Omron Sensor	Mini Sense 100 Sensor

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Size	Medium	Large	Small
Sensitivity	High	Less	Less
Output	I2C 3-Axis analogue signal	0-5VDC (Digital Signal)	0-5VDC (Sine Waveform)
Axis of Detection	3 axis	All axis	All axis
Complexity of Implementation	Intermediate	Simple	Simple

Table 1 shows the applicable sensors for the project, as all sensors fulfil the criteria. All sensors are functional in all measurement directions. D7E1 is larger and the sensor is practical for implementation. ADXL 345 can provide accurate measurements but it is slightly more difficult to setup and post-process data. MiniSense 100 sensor is compact and produces output in sine wave which is ideal for post data processing. The proposed project would have a combination of all three sensors to reduce false positive signals as practiced by some researchers. The data from each sensor will be analyzed to confirm vibration parameters.

Communication Network

Communication network provides a medium for data transmission from the sensor to the user. There are a number of existing wireless communication methods, such as Wi-Fi, ZigBee, LTE, NB-IoT and LoRaWAN. These communication network will be studied to determine the applicable communication network for this project. A number of criteria are used in this comparison, such as bit rate bandwidth, power consumption, signal range and deployment cost.

Low bit rate is required as continuous data streaming is not necessary. Data is analyzed at the microcontroller, and the gateway acts as a center of data transmission. Subsequently A low bandwidth is required on this project because only abnormal vibration that exceeded certain threshold will be transferred. Hence, only small amount of data will be sent from the sensor node to the gateway, as data processing will be conducted in the microcontroller.

Coverage area is determined by signal range, and large coverage area requires less access points. However, signal range will be reduced by obstacles in between the transmitter and receiver and this should be taken into consideration. Hence, a system with larger range is preferred. Minimal power consumption is preferred as the costs of electricity can be reduced. Also, certain turbomachinery is located at some places with limited electricity and low power consumption can be an advantage. Deployment cost refers to the costs required to setup the system, or the equipment required to develop a working system. This cost increases with complex system and devices, and a low-cost system is preferred for implementation. The comparison between each communication system is shown in Table 2.

Table 2: Comparison of Communication Network

Criteria	Wi-Fi	ZigBee	LTE	LoRaWAN	NB-IoT
Bit Rate	54 Mbps	250 kbps	100 Mbps	27 kbps	250 kbps
Bandwidth	Very High	Low	High	Low	Low
Power Consumption	High	Low	Medium	Very Low	Very Low
Signal Range	< 30 m	< 100 m	< 30 km	< 15 km	< 15 km
Deployment Cost	High	Low	High	Medium	Low

Referring to Table 2, the criteria shows that there are 2 candidates for communication network: NB-IoT and LoRaWAN. Both network shares similar specifications and relatively convenient to scale up. They have large signal range with minimal power consumption. However, their drawback is the little bandwidth and low bit rate. However, for this project, low bandwidth and low bit rate is sufficient.

NB-IoT platform is available only in certain countries, but LoRaWAN is an open source system and can be configured fairly conveniently. LoRa transceivers has been classified as Short Range Devices (SRD) by Malaysian agency and frequency has been allocated for the network. Hence, LoRaWAN is selected for the project.

LoRa is the acronym for long range and low power network, ideal for IoT applications. The network is in the category of Low-Power Wide-Area Network (LPWAN), a chosen network for development. Generally, a basic LoRa system consists of a sensor module, a receiver, and a gateway. The sensor acquires measurements and transmits it into a receiver, and the receiver transmits the information into a gateway that enables the information to be stored in a cloud storage.

Other researchers have proposed the network in their project as well. Augustin *et al.* (2016) has developed a prototype of LoRa for data transfer, and the prototype transmitted data over a distance of 9 km radius. The prototype consumes about 50 µA in active measurement. The battery used to power the system lasts for more than two months. Power consumption can be further reduced by reducing the redundant peripherals on the circuit board. Other applications of LoRa network including smart cities or smart homes.

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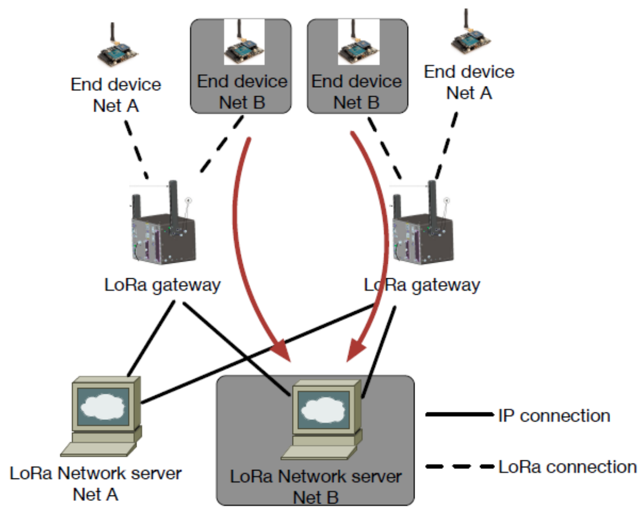

Figure 2: LoRaWAN System
(Augustin *et al*., 2016)

Adelantado *et al.* (2017) investigated the physical limitations of LoRa network and the transmission limitations. The study investigates the range of transmission, power consumption and the bandwidth of the LoRa network, and compared with other IoT communication systems that are currently available in the market. The results shows that LoRa is only applicable for transmitting small amount of data, such as sensor data of smart cities or smart home. However, application that requires high bandwidth. As such, large bandwidth application such as video transmission is not applicable to LoRa network due to the transmission of large quantity of data.

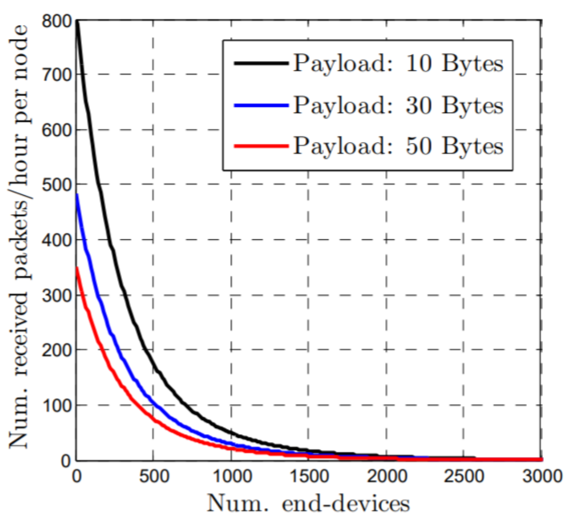

Figure 3: Data Transmission of LoRa Network
(Adelantado *et al*., 2016)

Figure 3 shows the data transmission of LoRa network, with number of received packets / hour per node vs. number of end-devices. As the number of devices grow, the payload decreases significantly. Through this figure, limitations of LoRa network is shown explicitly. This study can be improved with different functional modes of a LoRa system. For example, the network can be scaled up to handle large data stream by increasing bandwidth, and this shows that the system is flexible and can be improved per requirements.

As such, LoRa network has always been regarded a component of IoT. According to Bor *et al*., LoRa transceivers could be very useful to develop high performance IoT system with multi-hop and bi-directional network, enabling sensing and actuation. The transceivers can communicate long distance, consuming low energy and this enables us to develop more efficient IoT infrastructures. For example, LoRa SX1272 transceiver can transmit less than 15km. This transmission range has exceeded the rival zigbee platform. In addition, the LoRa transceivers have unique capability from the modulation program. Thus, these transceivers will be programmed to suit with the existing Medium Access Control (MAC) protocols in the IoT area. When developing IoT network using LoRa transceivers, their functionality should be focused on maximize communication performance and minimise energy consumption. (2016)

Power Requirements of Sensor Node

First, the power consumption of the sensor and LoRa sensor node will be determined. One vibration sensor consumes 30 mAH, and this power consumption remains constant as long as the sensor is active. Also, Arduino Uno microcontroller will be used in LoRa sensor node. The microcontroller consumes different amounts of power with different operation modes. For the standard operation, the microcontroller consumes 45 mAH. Hence, the sensor and LoRa sensor node consumes a total of 75 mAH.

Second, the power consumed by LoRa transmitter will be determined. LoRa transmitter is part of the LoRa sensor module and the power consumption will be considered in a different way. LoRa transmitter consumes 10mA when transmitting signal. In reality, this power consumption is much lower because the chip only transmits when it has to send a signal, or a certain threshold is violated.

Lastly, the power consumption of LoRa receiver and LoRa gateway device is not considered because these components will be located at the control center with plenty of power supply.

Proposed Prototype

A LoRa system prototype has been built, consists of LoRa sensor node and LoRa receiver module. This is as shown in Figure 4 (a) and 4 (b). The sensor node consists of sensors, battery, Arduino Uno controller and LoRa transmitter. The receiver module consists of LoRa receiver and gateway. In this project, the gateway is built with a Raspberry Pi because of low cost and open-source configurations. Figure 5 shows the complete LoRa system.

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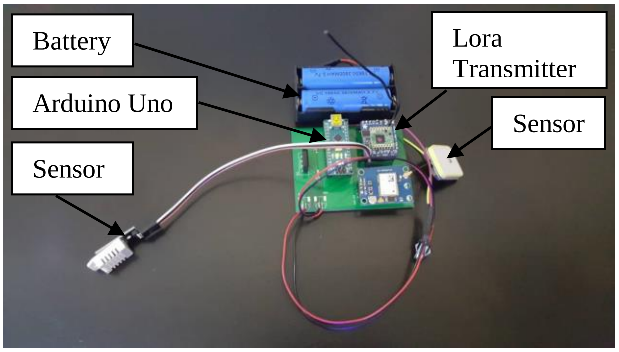

Figure 4 (a): LoRa Sensor Node

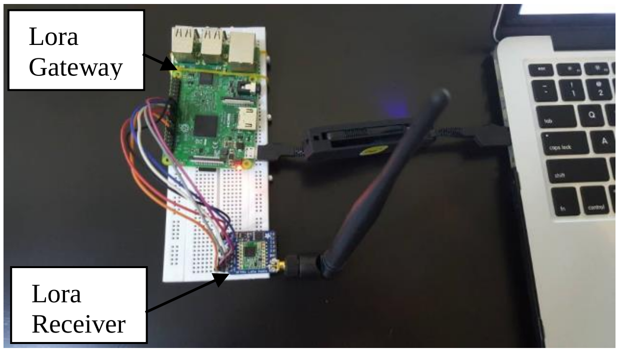

Figure 4 (b) LoRa Receiver Module

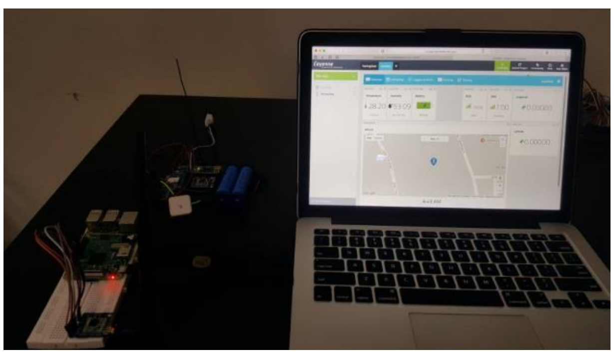

Figure 5: Complete System

For condition monitoring, vibration sensor will be mounted on a pump as shown in Figure 6. Pump is selected as a simple turbomachinery component. The application can be scaled up and applied to steam engine with the same principle. In this project, the sensor transmits data to LoRa sensor node via cable. The node transmits data with optimal range of 15km to the receiver, where the data is transmitted to the gateway, and to the cloud.

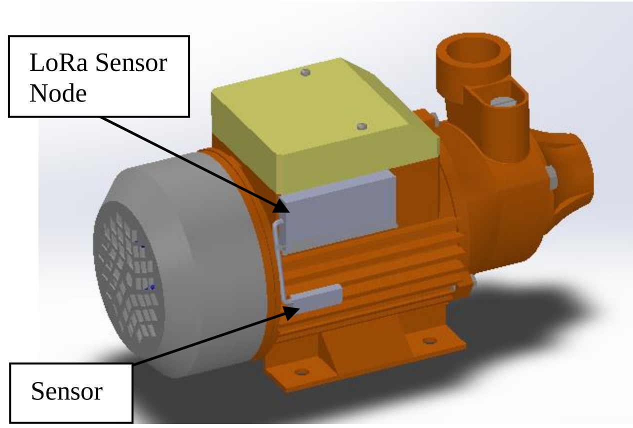

Figure 6: Sensor and LoRa Sensor Node on Pump

As shown in Figure 6, only 1 sensor is attached to the sensor node. Multiple sensors can be added and connected across different cross sectional area. The limit on the number of sensor is dependent upon the number of available pins and loads on LoRa sensor node. However, the higher the number of sensors, the more data and bandwidth to be transferred and this can potentially limit the application.

CONCLUSIONS

This project studies various vibration sensors, communication networks and determines the optimum elements in both fields. The elements are integrated into a working system for condition monitoring of turbomachinery via LoRa network. LoRa network is selected as it requires less energy, with long range of transfer, and applicable to condition monitoring of turbomachinery. Further work is to test the system in real turbomachinery.

NOMENCLATURE

IoT	= Internet-of-Things
LAN	= Local-area-network
LoRa	= Long range, low power network
LoRaWAN	= LoRa Wide-Area-Network protocol
LPWAN	= Low-Power Wide-Area Network
LTE	= Long Term Evaluation
MAC	= Medium access control
NB-IoT	= Narrow-band for Internet-of-Things
PHY	= Physical layer
SRD	= Short range devices
WSN	= Wireless sensor network

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